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Foreword and Preface

Foreword

This IPCC Special Report on Global Warming of 1.5°C was formally approved by the world's governments in 2018 – the year of IPCC's 30th anniversary celebrations.

During its three decades of existence, the IPCC has shed light on climate change, contributing to the understanding of its causes and consequences and the options for risk management through adaptation and mitigation. In these three decades, global warming has continued unabated and we have witnessed an acceleration in sea-level rise. Emissions of greenhouse gases due to human activities, the root cause of global warming, continue to increase, year after year.

Five years ago, the IPCC's Fifth Assessment Report provided the scientific input into the Paris Agreement, which aims to strengthen the global response to the threat of climate change by holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

Many countries considered that a level of global warming close to 2°C would not be safe and, at that time, there was only limited knowledge about the implications of a level of 1.5°C of warming for climate-related risks and in terms of the scale of mitigation ambition and its feasibility. Parties to the Paris Agreement therefore invited the IPCC to assess the impacts of global warming of 1.5°C above pre-industrial levels and the related emissions pathways that would achieve this enhanced global ambition.

At the start of the Sixth Assessment cycle, governments, in a plenary IPCC session, decided to prepare three special reports, including this one, and expanded the scope of this special report by framing the assessment in the context of sustainable development and efforts to eradicate poverty.

Sustainable development goals provide a new framework to consider climate action within the multiple dimensions of sustainability. This report is innovative in multiple ways. It shows the importance of integration across the traditional IPCC working groups and across disciplines within each chapter. Transitions, integrating adaptation and mitigation for each sector, are explored within six dimensions of feasibility, showing both low hanging fruits and barriers to overcome. It also provides scientific guidance on strategies to embed climate action within development strategies, and how to optimize choices that maximize benefits for multiple sustainable development dimensions and implement ethical and just transitions.

In his address to the UN General Assembly in 2018, Secretary-General António Guterres quoted World Meteorological Organization (WMO) data showing that the past two decades have included eighteen of the twenty warmest years since record-keeping began in 1850.

"*Climate change is moving faster than we are,*" said Secretary-General Guterres. "*We must listen to the Earth's best scientists,*" he added.

One month later the IPCC presented the Special Report on Global Warming of 1.5°C, based on the assessment of around 6,000 peer-review publications, most of them published in the last few years. This Special Report confirms that climate change is already affecting people, ecosystems and livelihoods all around the world. It shows that limiting warming to 1.5°C is possible within the laws of chemistry and physics but would require unprecedented transitions in all aspects of society. It finds that there are clear benefits to keeping warming to

1.5ºC rather than 2ºC or higher. Every bit of warming matters. And it shows that limiting warming to 1.5ºC can go hand in hand with achieving other global goals such as the Sustainable Development Agenda. Every year matters and every choice matters.

This Special Report also shows that recent trends in emissions and the level of international ambition indicated by nationally determined contributions, within the Paris Agreement, deviate from a track consistent with limiting warming to well below 2°C. Without increased and urgent mitigation ambition in the coming years, leading to a sharp decline in greenhouse gas emissions by 2030, global warming will surpass 1.5°C in the following decades, leading to irreversible loss of the most fragile ecosystems, and crisis after crisis for the most vulnerable people and societies.

The Special Report on Global Warming of 1.5°C supports efforts by the WMO and United Nations Environment Programme for a comprehensive assessment of our understanding of climate change to help step up action to respond to climate change, achieve climate-resilient development and foster an integrated approach to the provision of climate services at all scales of governance.

The IPCC worked in record time to deliver this report for the 24th Conference of Parties (COP24) to the United Nations Framework Convention on Climate Change (UNFCCC) and the Talanoa Dialogue. We would like to thank Hoesung Lee, Chair of the IPCC, for his leadership and guidance in the preparation of this Special Report. We commend the work undertaken by the authors of this Special Report and the many contributing authors and reviewers within a timeline of unprecedented severity; the leadership of the Co-Chairs of Working Groups I, II and III: Valérie Masson-Delmotte, Panmao Zhai, Hans-Otto Pörtner, Debra Roberts, Jim Skea and Priyadarshi R. Shukla; the oversight by the Bureau members of Working Groups I, II and III; and the implementation by the Technical Support Unit of Working Group I, supported by the Technical Support Units of Working Groups II and III. We are also grateful for the responsiveness of the international research community, who produced the knowledge assessed in the report, and thank the reviewers of the report for the thousands of comments that helped the authors strengthen the assessment.

Every bit of warming matters, every year matters, every choice matters

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3

Impacts of 1.5°C of Global Warming on Natural and Human Systems

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Executive Summary

This chapter builds on findings of AR5 and assesses new scientific evidence of changes in the climate system and the associated impacts on natural and human systems, with a specific focus on the magnitude and pattern of risks linked for global warming of 1.5°C above temperatures in the pre-industrial period. Chapter 3 explores observed impacts and projected risks to a range of natural and human systems, with a focus on how risk levels change from 1.5°C to 2°C of global warming. The chapter also revisits major categories of risk (Reasons for Concern, RFC) based on the assessment of new knowledge that has become available since AR5.

1.5°C and 2°C Warmer Worlds

The global climate has changed relative to the pre-industrial period, and there are multiple lines of evidence that these changes have had impacts on organisms and ecosystems, as well as on human systems and well-being (*high confidence*). The increase in global mean surface temperature (GMST), which reached 0.87°C in 2006–2015 relative to 1850–1900, has increased the frequency and magnitude of impacts (*high confidence*), strengthening evidence of how an increase in GMST of 1.5°C or more could impact natural and human systems (1.5°C versus 2°C). {3.3, 3.4, 3.5, 3.6, Cross-Chapter Boxes 6, 7 and 8 in this chapter}

Human-induced global warming has already caused multiple observed changes in the climate system (*high confidence*). Changes include increases in both land and ocean temperatures, as well as more frequent heatwaves in most land regions (*high confidence*). There is also *high confidence* that global warming has resulted in an increase in the frequency and duration of marine heatwaves. Further, there is substantial evidence that human-induced global warming has led to an increase in the frequency, intensity and/or amount of heavy precipitation events at the global scale (*medium confidence*), as well as an increased risk of drought in the Mediterranean region (*medium confidence*). {3.3.1, 3.3.2, 3.3.3, 3.3.4, Box 3.4}

Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4}

Several regional changes in climate are assessed to occur with global warming up to 1.5°C as compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}

There is no single '1.5°C warmer world' (*high confidence*). In addition to the overall increase in GMST, it is important to consider the size and duration of potential overshoots in temperature. Furthermore, there are questions on how the stabilization of an increase in GMST of 1.5°C can be achieved, and how policies might be able to influence the resilience of human and natural systems, and the nature of regional and subregional risks. Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of some ecosystems (*high confidence*). The rate of change for several types of risks may also have relevance, with potentially large risks in the case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C can be achieved at the end of the 21st century or later (*medium confidence*). If overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions is very small, which implies that large, immediate and unprecedented global efforts to mitigate greenhouse gases are required (*high confidence*). {3.2, 3.6.2, Cross-Chapter Box 8 in this chapter}

Robust[1] global differences in temperature means and extremes are expected if global warming reaches 1.5°C versus 2°C above the pre-industrial levels (*high confidence*). For oceans, regional surface temperature means and extremes are projected to be higher at 2°C compared to 1.5°C of global warming (*high confidence*). Temperature means and extremes are also projected to be higher at 2°C compared to 1.5°C in most land regions, with increases being 2–3 times greater than the increase in GMST projected for some regions (*high confidence*). Robust increases in temperature means and extremes are also projected at 1.5°C compared to present-day values (*high confidence*) {3.3.1, 3.3.2}. There are decreases in the occurrence of cold extremes, but substantial increases in their temperature, in particular in regions with snow or ice cover (*high confidence*) {3.3.1}.

Climate models project robust[1] differences in regional climate between present-day and global warming up to 1.5°C[2], and between 1.5°C and 2°C[2] *(high confidence)*, depending on the variable and region in question *(high confidence)*. Large, robust and widespread differences are expected for temperature extremes (*high confidence*). Regarding hot extremes, the strongest warming is expected to occur at mid-latitudes in the warm season (with increases of up to 3°C for 1.5°C of global warming, i.e., a factor of two) and at high latitudes in the cold season (with increases of up to 4.5°C at 1.5°C of global warming, i.e., a factor of three) (*high confidence*). The strongest warming of hot extremes is projected to occur in central and eastern North America, central and southern Europe, the Mediterranean region (including southern Europe, northern Africa and the Near East), western and central Asia, and southern Africa (*medium confidence*). The number of exceptionally hot days are expected to increase the most in the tropics, where interannual temperature variability is lowest; extreme heatwaves are thus projected to emerge earliest in these regions, and they are expected to already become widespread there at 1.5°C global warming (*high confidence*). Limiting global warming to 1.5°C instead of 2°C could result in around 420

[1] Robust is used here to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

[2] Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean near-surface air temperature.

million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to exceptional heatwaves, assuming constant vulnerability (*medium confidence*). {3.3.1, 3.3.2, Cross-Chapter Box 8 in this chapter}

Limiting global warming to 1.5°C would limit risks of increases in heavy precipitation events on a global scale and in several regions compared to conditions at 2°C global warming (*medium confidence*). The regions with the largest increases in heavy precipitation events for 1.5°C to 2°C global warming include: several high-latitude regions (e.g. Alaska/western Canada, eastern Canada/Greenland/Iceland, northern Europe and northern Asia); mountainous regions (e.g., Tibetan Plateau); eastern Asia (including China and Japan); and eastern North America (*medium confidence*). Tropical cyclones are projected to decrease in frequency but with an increase in the number of very intense cyclones (*limited evidence, low confidence*). Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C of global warming (*medium confidence*). Heavy precipitation, when aggregated at a global scale, is projected to be higher at 2°C than at 1.5°C of global warming (*medium confidence*) {3.3.3, 3.3.6}

Limiting global warming to 1.5°C is expected to substantially reduce the probability of extreme drought, precipitation deficits, and risks associated with water availability (i.e., water stress) in some regions (*medium confidence*). In particular, risks associated with increases in drought frequency and magnitude are projected to be substantially larger at 2°C than at 1.5°C in the Mediterranean region (including southern Europe, northern Africa and the Near East) and southern Africa (*medium confidence*). {3.3.3, 3.3.4, Box 3.1, Box 3.2}

Risks to natural and human systems are expected to be lower at 1.5°C than at 2°C of global warming (*high confidence*). This difference is due to the smaller rates and magnitudes of climate change associated with a 1.5°C temperature increase, including lower frequencies and intensities of temperature-related extremes. Lower rates of change enhance the ability of natural and human systems to adapt, with substantial benefits for a wide range of terrestrial, freshwater, wetland, coastal and ocean ecosystems (including coral reefs) (*high confidence*), as well as food production systems, human health, and tourism (*medium confidence*), together with energy systems and transportation (*low confidence*). {3.3.1, 3.4}

Exposure to multiple and compound climate-related risks is projected to increase between 1.5°C and 2°C of global warming with greater proportions of people both exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new – and exacerbating current – hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). Small island states and economically disadvantaged populations are particularly at risk (*high confidence*). {3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9, Box 3.5}

Global warming of 2°C would lead to an expansion of areas with significant increases in runoff, as well as those affected by flood hazard, compared to conditions at 1.5°C (*medium confidence*). Global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium confidence*) and an increase in flood hazard in some regions (*medium confidence*) compared to present-day conditions. {3.3.5}

The probability of a sea-ice-free Arctic Ocean[3] during summer is substantially higher at 2°C compared to 1.5°C of global warming (*medium confidence*). Model simulations suggest that at least one sea-ice-free Arctic summer is expected every 10 years for global warming of 2°C, with the frequency decreasing to one sea-ice-free Arctic summer every 100 years under 1.5°C (*medium confidence*). An intermediate temperature overshoot will have no long-term consequences for Arctic sea ice coverage, and hysteresis is not expected (*high confidence*). {3.3.8, 3.4.4.7}

Global mean sea level rise (GMSLR) is projected to be around 0.1 m (0.04 – 0.16 m) less by the end of the 21st century in a 1.5°C warmer world compared to a 2°C warmer world (*medium confidence*). Projected GMSLR for 1.5°C of global warming has an indicative range of 0.26 – 0.77m, relative to 1986–2005, (*medium confidence*). A smaller sea level rise could mean that up to 10.4 million fewer people (based on the 2010 global population and assuming no adaptation) would be exposed to the impacts of sea level rise globally in 2100 at 1.5°C compared to at 2°C. A slower rate of sea level rise enables greater opportunities for adaptation (*medium confidence*). There is *high confidence* that sea level rise will continue beyond 2100. Instabilities exist for both the Greenland and Antarctic ice sheets, which could result in multi-meter rises in sea level on time scales of century to millennia. There is *medium confidence* that these instabilities could be triggered at around 1.5°C to 2°C of global warming. {3.3.9, 3.4.5, 3.6.3}

The ocean has absorbed about 30% of the anthropogenic carbon dioxide, resulting in ocean acidification and changes to carbonate chemistry that are unprecedented for at least the last 65 million years (*high confidence*). Risks have been identified for the survival, calcification, growth, development and abundance of a broad range of marine taxonomic groups, ranging from algae to fish, with substantial evidence of predictable trait-based sensitivities (*high confidence*). There are multiple lines of evidence that ocean warming and acidification corresponding to 1.5°C of global warming would impact a wide range of marine organisms and ecosystems, as well as sectors such as aquaculture and fisheries (*high confidence*). {3.3.10, 3.4.4}

Larger risks are expected for many regions and systems for global warming at 1.5°C, as compared to today, with adaptation required now and up to 1.5°C. However, risks would be larger at 2°C of warming and an even greater effort would be needed for adaptation to a temperature increase of that magnitude (*high confidence*). {3.4, Box 3.4, Box 3.5, Cross-Chapter Box 6 in this chapter}

[3] Ice free is defined for the Special Report as when the sea ice extent is less than 106 km^2. Ice coverage less than this is considered to be equivalent to an ice-free Arctic Ocean for practical purposes in all recent studies.

Future risks at 1.5°C of global warming will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (*high confidence*). The impacts on natural and human systems would be greater if mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilize at 1.5°C without an overshoot (*high confidence*). The size and duration of an overshoot would also affect future impacts (e.g., irreversible loss of some ecosystems) (*high confidence*). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity. {3.6.1, 3.6.2, Cross-Chapter Boxes 7 and 8 in this chapter}

Climate Change Risks for Natural and Human systems

Terrestrial and Wetland Ecosystems

Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (*high confidence*). The number of species projected to lose over half of their climatically determined geographic range at 2°C global warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (*medium confidence*). Risks associated with other biodiversity-related factors, such as forest fires, extreme weather events, and the spread of invasive species, pests and diseases, would also be lower at 1.5°C than at 2°C of warming (*high confidence*), supporting a greater persistence of ecosystem services. {3.4.3, 3.5.2}

Constraining global warming to 1.5°C, rather than to 2°C and higher, is projected to have many benefits for terrestrial and wetland ecosystems and for the preservation of their services to humans (*high confidence*). Risks for natural and managed ecosystems are higher on drylands compared to humid lands. The global terrestrial land area projected to be affected by ecosystem transformations (13%, interquartile range 8–20%) at 2°C is approximately halved at 1.5°C global warming to 4% (interquartile range 2–7%) (*medium confidence*). Above 1.5°C, an expansion of desert terrain and vegetation would occur in the Mediterranean biome (*medium confidence*), causing changes unparalleled in the last 10,000 years (*medium confidence*). {3.3.2.2, 3.4.3.2, 3.4.3.5, 3.4.6.1, 3.5.5.10, Box 4.2}

Many impacts are projected to be larger at higher latitudes, owing to mean and cold-season warming rates above the global average (*medium confidence*). High-latitude tundra and boreal forest are particularly at risk, and woody shrubs are already encroaching into tundra (*high confidence*) and will proceed with further warming. Constraining warming to 1.5°C would prevent the thawing of an estimated permafrost area of 1.5 to 2.5 million km^2 over centuries compared to thawing under 2°C (*medium confidence*). {3.3.2, 3.4.3, 3.4.4}

Ocean Ecosystems

Ocean ecosystems are already experiencing large-scale changes, and critical thresholds are expected to be reached at 1.5°C and higher levels of global warming (*high confidence*). In the transition to 1.5°C of warming, changes to water temperatures are expected to drive some species (e.g., plankton, fish) to relocate to higher latitudes and cause novel ecosystems to assemble (*high confidence*). Other ecosystems (e.g., kelp forests, coral reefs) are relatively less able to move, however, and are projected to experience high rates of mortality and loss (*very high confidence*). For example, multiple lines of evidence indicate that the majority (70–90%) of warm water (tropical) coral reefs that exist today will disappear even if global warming is constrained to 1.5°C (*very high confidence*). {3.4.4, Box 3.4}

Current ecosystem services from the ocean are expected to be reduced at 1.5°C of global warming, with losses being even greater at 2°C of global warming (*high confidence*). The risks of declining ocean productivity, shifts of species to higher latitudes, damage to ecosystems (e.g., coral reefs, and mangroves, seagrass and other wetland ecosystems), loss of fisheries productivity (at low latitudes), and changes to ocean chemistry (e.g., acidification, hypoxia and dead zones) are projected to be substantially lower when global warming is limited to 1.5°C (*high confidence*). {3.4.4, Box 3.4}

Water Resources

The projected frequency and magnitude of floods and droughts in some regions are smaller under 1.5°C than under 2°C of warming (*medium confidence*). Human exposure to increased flooding is projected to be substantially lower at 1.5°C compared to 2°C of global warming, although projected changes create regionally differentiated risks (*medium confidence*). The differences in the risks among regions are strongly influenced by local socio-economic conditions (*medium confidence*). {3.3.4, 3.3.5, 3.4.2}

Risks of water scarcity are projected to be greater at 2°C than at 1.5°C of global warming in some regions (*medium confidence*). Depending on future socio-economic conditions, limiting global warming to 1.5°C, compared to 2°C, may reduce the proportion of the world population exposed to a climate change-induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Regions with particularly large benefits could include the Mediterranean and the Caribbean (*medium confidence*). Socio-economic drivers, however, are expected to have a greater influence on these risks than the changes in climate (*medium confidence*). {3.3.5, 3.4.2, Box 3.5}

Land Use, Food Security and Food Production Systems

Limiting global warming to 1.5°C, compared with 2°C, is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in

sub-Saharan Africa, Southeast Asia, and Central and South America; and in the CO_2-dependent nutritional quality of rice and wheat (*high confidence*). A loss of 7–10% of rangeland livestock globally is projected for approximately 2°C of warming, with considerable economic consequences for many communities and regions (*medium confidence*). {3.4.6, 3.6, Box 3.1, Cross-Chapter Box 6 in this chapter}

Reductions in projected food availability are larger at 2°C than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe and the Amazon (*medium confidence*). This suggests a transition from medium to high risk of regionally differentiated impacts on food security between 1.5°C and 2°C (*medium confidence*). Future economic and trade environments and their response to changing food availability (*medium confidence*) are important potential adaptation options for reducing hunger risk in low- and middle-income countries. {Cross-Chapter Box 6 in this chapter}

Fisheries and aquaculture are important to global food security but are already facing increasing risks from ocean warming and acidification *(medium confidence)*. These risks are projected to increase at 1.5°C of global warming and impact key organisms such as fin fish and bivalves (e.g., oysters), especially at low latitudes (*medium confidence*). Small-scale fisheries in tropical regions, which are very dependent on habitat provided by coastal ecosystems such as coral reefs, mangroves, seagrass and kelp forests, are expected to face growing risks at 1.5°C of warming because of loss of habitat (*medium confidence*). Risks of impacts and decreasing food security are projected to become greater as global warming reaches beyond 1.5°C and both ocean warming and acidification increase, with substantial losses likely for coastal livelihoods and industries (e.g., fisheries and aquaculture) (*medium to high confidence*). {3.4.4, 3.4.5, 3.4.6, Box 3.1, Box 3.4, Box 3.5, Cross-Chapter Box 6 in this chapter}

Land use and land-use change emerge as critical features of virtually all mitigation pathways that seek to limit global warming to 1.5°C (*high confidence*). Most least-cost mitigation pathways to limit peak or end-of-century warming to 1.5°C make use of carbon dioxide removal (CDR), predominantly employing significant levels of bioenergy with carbon capture and storage (BECCS) and/or afforestation and reforestation (AR) in their portfolio of mitigation measures (*high confidence*). {Cross-Chapter Box 7 in this chapter}

Large-scale deployment of BECCS and/or AR would have a far-reaching land and water footprint (*high confidence*). Whether this footprint would result in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, measures to limit agricultural expansion in order to protect natural ecosystems, and the potential to increase agricultural productivity (*medium agreement*). In addition, BECCS and/or AR would have substantial direct effects on regional climate through biophysical feedbacks, which are generally not included in Integrated Assessments Models (*high confidence*). {3.6.2, Cross-Chapter Boxes 7 and 8 in this chapter}

The impacts of large-scale CDR deployment could be greatly reduced if a wider portfolio of CDR options were deployed, if a holistic policy for sustainable land management were adopted, and if increased mitigation efforts were employed to strongly limit the demand for land, energy and material resources, including through lifestyle and dietary changes (*medium confidence*). In particular, reforestation could be associated with significant co-benefits if implemented in a manner than helps restore natural ecosystems (*high confidence*). {Cross-Chapter Box 7 in this chapter}

Human Health, Well-Being, Cities and Poverty

Any increase in global temperature (e.g., +0.5°C) is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*), and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence*). Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks for some vector-borne diseases, such as malaria and dengue fever are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*). Overall for vector-borne diseases, whether projections are positive or negative depends on the disease, region and extent of change (*high confidence*). Lower risks of undernutrition are projected at 1.5°C than at 2°C (*medium confidence*). Incorporating estimates of adaptation into projections reduces the magnitude of risks (*high confidence*). {3.4.7, 3.4.7.1, 3.4.8, 3.5.5.8}

Global warming of 2°C is expected to pose greater risks to urban areas than global warming of 1.5°C (*medium confidence*). The extent of risk depends on human vulnerability and the effectiveness of adaptation for regions (coastal and non-coastal), informal settlements and infrastructure sectors (such as energy, water and transport) (*high confidence*). {3.4.5, 3.4.8}

Poverty and disadvantage have increased with recent warming (about 1°C) and are expected to increase for many populations as average global temperatures increase from 1°C to 1.5°C and higher (*medium confidence*). Outmigration in agricultural-dependent communities is positively and statistically significantly associated with global temperature (*medium confidence*). Our understanding of the links of 1.5°C and 2°C of global warming to human migration are limited and represent an important knowledge gap. {3.4.10, 3.4.11, 5.2.2, Table 3.5}

Key Economic Sectors and Services

Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century (*medium confidence*). {3.5.2, 3.5.3}

The largest reductions in economic growth at 2°C compared to 1.5°C of warming are projected for low- and middle-income countries and regions (the African continent, Southeast Asia, India, Brazil and Mexico) (*low to medium confidence*). Countries

in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2°C (*medium confidence*). {3.5}

Global warming has already affected tourism, with increased risks projected under 1.5°C of warming in specific geographic regions and for seasonal tourism including sun, beach and snow sports destinations (*very high confidence*). Risks will be lower for tourism markets that are less climate sensitive, such as gaming and large hotel-based activities (*high confidence*). Risks for coastal tourism, particularly in subtropical and tropical regions, will increase with temperature-related degradation (e.g., heat extremes, storms) or loss of beach and coral reef assets (*high confidence*). {3.3.6, 3.4.4.12, 3.4.9.1, Box 3.4}

Small Islands, and Coastal and Low-lying areas

Small islands are projected to experience multiple inter-related risks at 1.5°C of global warming that will increase with warming of 2°C and higher levels (*high confidence*). Climate hazards at 1.5°C are projected to be lower compared to those at 2°C (*high confidence*). Long-term risks of coastal flooding and impacts on populations, infrastructures and assets (*high confidence*), freshwater stress (*medium confidence*), and risks across marine ecosystems (*high confidence*) and critical sectors (*medium confidence*) are projected to increase at 1.5°C compared to present-day levels and increase further at 2°C, limiting adaptation opportunities and increasing loss and damage (*medium confidence*). Migration in small islands (internally and internationally) occurs for multiple reasons and purposes, mostly for better livelihood opportunities (*high confidence*) and increasingly owing to sea level rise (*medium confidence*). {3.3.2.2, 3.3.6–9, 3.4.3.2, 3.4.4.2, 3.4.4.5, 3.4.4.12, 3.4.5.3, 3.4.7.1, 3.4.9.1, 3.5.4.9, Box 3.4, Box 3.5}

Impacts associated with sea level rise and changes to the salinity of coastal groundwater, increased flooding and damage to infrastructure, are projected to be critically important in vulnerable environments, such as small islands, low-lying coasts and deltas, at global warming of 1.5°C and 2°C (*high confidence*). Localized subsidence and changes to river discharge can potentially exacerbate these effects. Adaptation is already happening (*high confidence*) and will remain important over multi-centennial time scales. {3.4.5.3, 3.4.5.4, 3.4.5.7, 5.4.5.4, Box 3.5}

Existing and restored natural coastal ecosystems may be effective in reducing the adverse impacts of rising sea levels and intensifying storms by protecting coastal and deltaic regions (*medium confidence*). Natural sedimentation rates are expected to be able to offset the effect of rising sea levels, given the slower rates of sea level rise associated with 1.5°C of warming (*medium confidence*). Other feedbacks, such as landward migration of wetlands and the adaptation of infrastructure, remain important (*medium confidence*). {3.4.4.12, 3.4.5.4, 3.4.5.7}

Increased Reasons for Concern

There are multiple lines of evidence that since AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming levels of up to 2°C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high between 1.5°C and 2°C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1°C and 1.5°C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5°C and 2°C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5°C and 2.5°C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1°C and 2.5°C for RFC5 (Large-scale singular events) (*medium confidence*). {3.5.2}

1. **The category 'Unique and threatened systems' (RFC1) display a transition from high to very high risk which is now located between 1.5°C and 2°C of global warming** as opposed to at 2.6°C of global warming in AR5, owing to new and multiple lines of evidence for changing risks for coral reefs, the Arctic and biodiversity in general (*high confidence*). {3.5.2.1}

2. **In 'Extreme weather events' (RFC2), the transition from moderate to high risk is now located between 1.0°C and 1.5°C of global warming,** which is very similar to the AR5 assessment but is projected with greater confidence (*medium confidence*). The impact literature contains little information about the potential for human society to adapt to extreme weather events, and hence it has not been possible to locate the transition from 'high' to 'very high' risk within the context of assessing impacts at 1.5°C versus 2°C of global warming. There is thus *low confidence* in the level at which global warming could lead to very high risks associated with extreme weather events in the context of this report. {3.5}

3. **With respect to the 'Distribution of impacts' (RFC3) a transition from moderate to high risk is now located between 1.5°C and 2°C of global warming,** compared with between 1.6°C and 2.6°C global warming in AR5, owing to new evidence about regionally differentiated risks to food security, water resources, drought, heat exposure and coastal submergence (*high confidence*). {3.5}

4. **In 'global aggregate impacts' (RFC4) a transition from moderate to high levels of risk is now located between 1.5°C and 2.5°C of global warming,** as opposed to at 3.6°C of warming in AR5, owing to new evidence about global aggregate economic impacts and risks to Earth's biodiversity (*medium confidence*). {3.5}

5. **Finally, 'large-scale singular events' (RFC5), moderate risk is now located at 1°C of global warming and high risk is located at 2.5°C of global warming,** as opposed to at 1.6°C (moderate risk) and around 4°C (high risk) in AR5, because of new observations and models of the West Antarctic ice sheet (*medium confidence*). {3.3.9, 3.5.2, 3.6.3}

3.1 About the Chapter

Chapter 3 uses relevant definitions of a potential 1.5°C warmer world from Chapters 1 and 2 and builds directly on their assessment of gradual versus overshoot scenarios. It interacts with information presented in Chapter 2 via the provision of specific details relating to the mitigation pathways (e.g., land-use changes) and their implications for impacts. Chapter 3 also includes information needed for the assessment and implementation of adaptation options (presented in Chapter 4), as well as the context for considering the interactions of climate change with sustainable development and for the assessment of impacts on sustainability, poverty and inequalities at the household to subregional level (presented in Chapter 5).

This chapter is necessarily transdisciplinary in its coverage of the climate system, natural and managed ecosystems, and human systems and responses, owing to the integrated nature of the natural and human experience. While climate change is acknowledged as a centrally important driver, it is not the only driver of risks to human and natural systems, and in many cases, it is the interaction between these two broad categories of risk that is important (Chapter 1).

The flow of the chapter, linkages between sections, a list of chapter- and cross-chapter boxes, and a content guide for reading according to focus or interest are given in Figure 3.1. Key definitions used in the chapter are collected in the Glossary. Confidence language is used throughout this chapter and likelihood statements (e.g., *likely*, *very likely*) are provided when there is *high confidence* in the assessment.

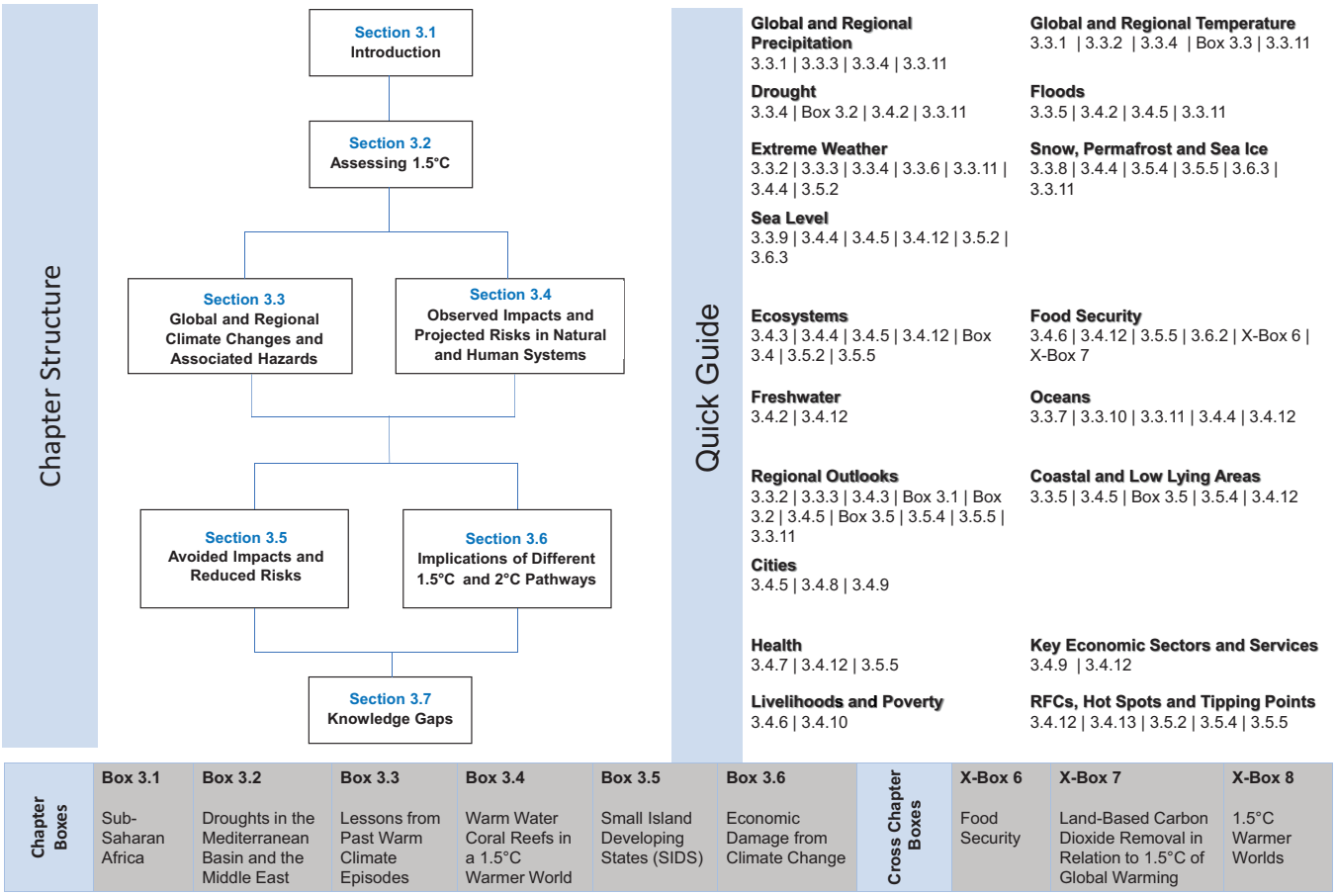


Figure 3.1 | Chapter 3 structure and quick guide.

The underlying literature assessed in Chapter 3 is broad and includes a large number of recent publications specific to assessments for 1.5°C of warming. The chapter also utilizes information covered in prior IPCC special reports, for example the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; IPCC, 2012), and many chapters from the IPCC WGII Fifth Assessment Report (AR5) that assess impacts on natural and managed ecosystems and humans, as well as adaptation options (IPCC, 2014b). For this reason, the chapter provides information based on a broad range of assessment methods. Details about the approaches used are presented in Section 3.2.

Section 3.3 gives a general overview of recent literature on observed climate change impacts as the context for projected future risks. With a few exceptions, the focus here is the analysis of transient responses at 1.5°C and 2°C of global warming, with simulations *of short-term stabilization scenarios* (Section 3.2) also assessed in some cases. In general, *long-term equilibrium stabilization responses* could not be

assessed owing to a lack of data and analysis. A detailed analysis of detection and attribution is not provided but will be the focus of the next IPCC assessment report (AR6). Furthermore, possible interventions in the climate system through radiation modification measures, which are not tied to reductions of greenhouse gas emissions or concentrations, are not assessed in this chapter.

Understanding the observed impacts and projected risks of climate change is crucial to comprehending how the world is likely to change under global warming of 1.5°C above temperatures in the pre-industrial period (with reference to 2°C). Section 3.4 explores the new literature and updates the assessment of impacts and projected risks for a large number of natural and human systems. By also exploring adaptation opportunities, where the literature allows, the section prepares the reader for discussions in subsequent chapters about opportunities to tackle both mitigation and adaptation. The section is mostly globally focused because of limited research on regional risks and adaptation options at 1.5°C and 2°C. For example, the risks of 1.5°C and 2°C of warming in urban areas, as well as the risks of health outcomes under these two warming scenarios (e.g. climate-related diseases, air quality impacts and mental health problems), were not considered because of a lack of projections of how these risks might change in a 1.5°C or 2°C warmer world. In addition, the complexity of many interactions of climate change with drivers of poverty, along with a paucity of relevant studies, meant it was not possible to detect and attribute many dimensions of poverty and disadvantage to climate change. Even though there is increasing documentation of climate-related impacts on places where indigenous people live and where subsistence-oriented communities are found, relevant projections of the risks associated with warming of 1.5°C and 2°C are necessarily limited.

To explore avoided impacts and reduced risks at 1.5°C compared with at 2°C of global warming, the chapter adopts the AR5 'Reasons for Concern' aggregated projected risk framework (Section 3.5). Updates in terms of the aggregation of risks are informed by the most recent literature and the assessments offered in Sections 3.3 and 3.4, with a focus on the impacts at 2°C of warming that could potentially be avoided if warming were constrained to 1.5°C. Economic benefits that would be obtained (Section 3.5.3), climate change 'hotspots' that could be avoided or reduced (Section 3.5.4 as guided by the assessments of Sections 3.3, 3.4 and 3.5), and tipping points that could be circumvented (Section 3.5.5) at 1.5°C compared to higher degrees of global warming are all examined. The latter assessments are, however, constrained to regional analyses, and hence this particular section does not include an assessment of specific losses and damages.

Section 3.6 provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C of global warming, including some scenarios involving temperature overshoot above 1.5°C global warming during the 21st century. Non-CO_2 implications and projected risks of mitigation pathways, such as changes to land use and atmospheric compounds, are presented and explored. Finally, implications for sea ice, sea level and permafrost beyond the end of the century are assessed.

The exhaustive assessment of literature specific to global warming of 1.5°C above the pre-industrial period, presented across all the sections in Chapter 3, highlights knowledge gaps resulting from the heterogeneous information available across systems, regions and sectors. Some of these gaps are described in Section 3.7.

3.2 How are Risks at 1.5°C and Higher Levels of Global Warming Assessed in this Chapter?

The methods that are applied for assessing observed and projected changes in climate and weather are presented in Section 3.2.1, while those used for assessing the observed impacts on and projected risks to natural and managed systems, and to human settlements, are described in Section 3.2.2. Given that changes in climate associated with 1.5°C of global warming were not the focus of past IPCC reports, dedicated approaches based on recent literature that are specific to the present report are also described. Background on specific methodological aspects (climate model simulations available for assessments at 1.5°C global warming, attribution of observed changes in climate and their relevance for assessing projected changes at 1.5°C and 2°C global warming, and the propagation of uncertainties from climate forcing to impacts on ecosystems) are provided in the Supplementary Material 3.SM.

3.2.1 How are Changes in Climate and Weather at 1.5°C versus Higher Levels of Warming Assessed?

Evidence for the assessment of changes to climate at 1.5°C versus 2°C can be drawn both from observations and model projections. Global mean surface temperature (GMST) anomalies were about +0.87°C (±0.10°C likely range) above pre-industrial industrial (1850–1900) values in the 2006-–2015 decade, with a recent warming of about 0.2°C (±0.10°C) per decade (Chapter 1). Human-induced global warming reached approximately 1°C (±0.2°C *likely* range) in 2017 (Chapter 1). While some of the observed trends may be due to internal climate variability, methods of detection and attribution can be applied to assess which part of the observed changes may be attributed to anthropogenic forcing (Bindoff et al., 2013b). Hence, evidence from attribution studies can be used to assess changes in the climate system that are already detectable at lower levels of global warming and would thus continue to change with a further 0.5°C or 1°C of global warming (see Supplementary Material 3.SM.1 and Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.3.11). A recent study identified significant changes in extremes for a 0.5°C difference in global warming based on the historical record (Schleussner et al., 2017). It should also be noted that attributed changes in extremes since 1950 that were reported in the IPCC AR5 report (IPCC, 2013) generally correspond to changes in global warming of about 0.5°C (see 3.SM.1)

Climate model simulations are necessary for the investigation of the response of the climate system to various forcings, in particular to forcings associated with higher levels of greenhouse gas concentrations. Model simulations include experiments with global and regional climate models, as well as impact models – driven with output from climate models – to evaluate the risk related to climate

change for natural and human systems (Supplementary Material 3.SM.1). Climate model simulations were generally used in the context of particular 'climate scenarios' from previous IPCC reports (e.g., IPCC, 2007, 2013). This means that emissions scenarios (IPCC, 2000) were used to drive climate models, providing different projections for given emissions pathways. The results were consequently used in a 'storyline' framework, which presents the development of climate in the course of the 21st century and beyond for a given emissions pathway. Results were assessed for different time slices within the model projections such as 2016–2035 ('near term', which is slightly below a global warming of 1.5°C according to most scenarios, Kirtman et al., 2013), 2046–2065 (mid-21st century, Collins et al., 2013), and 2081–2100 (end of 21st century, Collins et al., 2013). Given that this report focuses on climate change for a given mean global temperature response (1.5°C or 2°C), methods of analysis had to be developed and/or adapted from previous studies in order to provide assessments for the specific purposes here.

A major challenge in assessing climate change under 1.5°C, or 2°C (and higher levels), of global warming pertains to the **definition of a '1.5°C or 2°C climate projection'** (see also Cross-Chapter Box 8 in this chapter). Resolving this challenge includes the following considerations:

A. The need to distinguish between (i) **transient climate responses** (i.e., those that 'pass through' 1.5°C or 2°C of global warming), (ii) **short-term stabilization responses** (i.e., scenarios for the late 21st century that result in stabilization at a mean global warming of 1.5°C or 2°C by 2100), and (iii) **long-term equilibrium stabilization responses** (i.e., those occurring after several millennia once climate (temperature) equilibrium at 1.5°C or 2°C is reached). These responses can be very different in terms of climate variables and the inertia associated with a given climate forcing. A striking example is sea level rise (SLR). In this case, projected increases within the 21st century are minimally dependent on the scenario considered, yet they stabilize at very different levels for a long-term warming of 1.5°C versus 2°C (Section 3.3.9).

B. The '1.5°C or 2°C emissions scenarios' presented in Chapter 2 are targeted to hold warming below 1.5°C or 2°C with a certain probability (generally two-thirds) over the course, or at the end, of the 21st century. These scenarios should be seen as the operationalization of 1.5°C or 2°C warmer worlds. However, when these emission scenarios are used to drive climate models, some of the resulting simulations lead to warming above these respective thresholds (typically with a probability of one-third, see Chapter 2 and Cross-Chapter Box 8 in this chapter). This is due both to discrepancies between models and to internal climate variability. For this reason, the climate outcome for any of these scenarios, even those excluding an overshoot (see next point, C.), include some probability of reaching a global climate warming of more than 1.5°C or 2°C. Hence, a comprehensive assessment of climate risks associated with '1.5°C or 2°C climate scenarios' needs to include consideration of higher levels of warming (e.g., up to 2.5°C to 3°C, see Chapter 2 and Cross-Chapter Box 8 in this chapter).

C. Most of the '1.5°C scenarios', and some of the '2°C emissions scenarios' presented in Chapter 2 include a temperature overshoot during the course of the 21st century. This means that median temperature projections under these scenarios exceed the target warming levels over the course of the century (typically 0.5°C–1°C higher than the respective target levels at most), before warming returns to below 1.5°C or 2°C by 2100. During the overshoot phase, impacts would therefore correspond to higher transient temperature increases than 1.5°C or 2°C. For this reason, impacts of transient responses at these higher warming levels are also partly addressed in Cross-Chapter Box 8 in this chapter (on a 1.5°C warmer world), and some analyses for changes in extremes are also presented for higher levels of warming in Section 3.3 (Figures 3.5, 3.6, 3.9, 3.10, 3.12 and 3.13). Most importantly, different overshoot scenarios may have very distinct impacts depending on (i) the peak temperature of the overshoot, (ii) the length of the overshoot period, and (iii) the associated rate of change in global temperature over the time period of the overshoot. While some of these issues are briefly addressed in Sections 3.3 and 3.6, and in the Cross-Chapter Box 8, the definition of overshoot and related questions will need to be more comprehensively addressed in the IPCC AR6 report.

D. The levels of global warming that are the focus of this report (1.5°C and 2°C) are measured relative to the pre-industrial period. This definition requires an agreement on the exact reference time period (for 0°C of warming) and the time frame over which the global warming is assessed, typically 20 to 30 years in length. As discussed in Chapter 1, a climate with 1.5°C global warming is one in which temperatures averaged over a multi-decade time scale are 1.5°C above those in the pre-industrial reference period. Greater detail is provided in Cross-Chapter Box 8 in this chapter. Inherent to this is the observation that the mean temperature of a '1.5°C warmer world' can be regionally and temporally much higher (e.g., with regional annual temperature extremes involving warming of more than 6°C; see Section 3.3 and Cross-Chapter Box 8 in this chapter).

E. The interference of factors unrelated to greenhouse gases with mitigation pathways can strongly affect regional climate. For example, biophysical feedbacks from changes in land use and irrigation (e.g., Hirsch et al., 2017; Thiery et al., 2017), or projected changes in short-lived pollutants (e.g., Z. Wang et al., 2017), can have large influences on local temperatures and climate conditions. While these effects are not explicitly integrated into the scenarios developed in Chapter 2, they may affect projected changes in climate under 1.5°C of global warming. These issues are addressed in more detail in Section 3.6.2.2.

The assessment presented in the current chapter largely focuses on the analysis of **transient responses in climate at 1.5°C versus 2°C** and higher levels of global warming (see point A. above and Section 3.3). It generally uses the empirical scaling relationship (ESR) approach (Seneviratne et al., 2018c), also termed the 'time sampling' approach (James et al., 2017), which consists of sampling the response at 1.5°C and other levels of global warming from all available global climate model scenarios for the 21st century (e.g., Schleussner et al., 2016b;

Seneviratne et al., 2016; Wartenburger et al., 2017). The ESR approach focuses more on the derivation of a continuous relationship, while the term 'time sampling' is more commonly used when comparing a limited number of warming levels (e.g., 1.5°C versus 2°C). A similar approach in the case of regional climate model (RCM) simulations consists of sampling the RCM model output corresponding to the time frame at which the driving general circulation model (GCM) reaches the considered temperature level, for example, as done within IMPACT2C (Jacob and Solman, 2017), see description in Vautard et al. (2014). As an alternative to the ESR or time sampling approach, pattern scaling may be used. Pattern scaling is a statistical approach that describes relationships of specific climate responses as a function of global temperature change. Some assessments presented in this chapter are based on this method. The disadvantage of pattern scaling, however, is that the relationship may not perfectly emulate the models' responses at each location and for each global temperature level (James et al., 2017). Expert judgement is a third methodology that can be used to assess probable changes at 1.5°C or 2°C of global warming by combining changes that have been attributed to the observed time period (corresponding to warming of 1°C or less if assessed over a shorter period) with known projected changes at 3°C or 4°C above pre-industrial temperatures (Supplementary Material 3.SM.1). In order to assess effects induced by a 0.5°C difference in global warming, the historical record can be used at first approximation as a proxy, meaning that conditions are compared for two periods that have a 0.5°C difference in GMST warming (such as 1991–2010 and 1960–1979, e.g., Schleussner et al., 2017). This in particular also applies to attributed changes in extremes since 1950 that were reported in the IPCC AR5 report (IPCC, 2013; see also 3.SM.1). Using observations, however, it is not possible to account for potential non-linear changes that could occur above 1°C of global warming or as 1.5°C of warming is reached.

In some cases, assessments of **short-term stabilization responses** are also presented, derived using a subset of model simulations that reach a given temperature limit by 2100, or driven by sea surface temperature (SST) values consistent with such scenarios. This includes new results from the 'Half a degree additional warming, prognosis and projected impacts' (HAPPI) project (Section 1.5.2; Mitchell et al., 2017). Notably, there is evidence that for some variables (e.g., temperature and precipitation extremes), responses after short-term stabilization (i.e., approximately equivalent to the RCP2.6 scenario) are very similar to the transient response of higher-emissions scenarios (Seneviratne et al., 2016, 2018c; Wartenburger et al., 2017; Tebaldi and Knutti, 2018). This is, however, less the case for mean precipitation (e.g., Pendergrass et al., 2015), for which other aspects of the emissions scenarios appear relevant.

For the assessment of **long-term equilibrium stabilization responses**, this chapter uses results from existing simulations where available (e.g., for sea level rise), although the available data for this type of projection is limited for many variables and scenarios and will need to be addressed in more depth in the IPCC AR6 report.

Supplementary Material 3.SM.1 of this chapter includes further details of the climate models and associated simulations that were used to support the present assessment, as well as a background on detection and attribution approaches of relevance to assessing changes in climate at 1.5°C of global warming.

3.2.2 How are Potential Impacts on Ecosystems Assessed at 1.5°C versus Higher Levels of Warming?

Considering that the impacts observed so far are for a global warming lower than 1.5°C (generally up to the 2006–2015 decade, i.e., for a global warming of 0.87°C or less; see above), direct information on the impacts of a global warming of 1.5°C is not yet available. The global distribution of observed impacts shown in AR5 (Cramer et al., 2014), however, demonstrates that methodologies now exist which are capable of detecting impacts on systems strongly influenced by factors (e.g., urbanization and human pressure in general) or where climate may play only a secondary role in driving impacts. Attribution of observed impacts to greenhouse gas forcing is more rarely performed, but a recent study (Hansen and Stone, 2016) shows that most of the detected temperature-related impacts that were reported in AR5 (Cramer et al., 2014) can be attributed to anthropogenic climate change, while the signals for precipitation-induced responses are more ambiguous.

One simple approach for assessing possible impacts on natural and managed systems at 1.5°C versus 2°C consists of identifying impacts of a global 0.5°C of warming in the observational record (e.g., Schleussner et al., 2017) assuming that the impacts would scale linearly for higher levels of warming (although this may not be appropriate). Another approach is to use conclusions from analyses of past climates combined with modelling of the relationships between climate drivers and natural systems (Box 3.3). A more complex approach relies on laboratory or field experiments (Dove et al., 2013; Bonal et al., 2016), which provide useful information on the causal effect of a few factors, which can be as diverse as climate, greenhouse gases (GHG), management practices, and biological and ecological variables, on specific natural systems that may have unusual physical and chemical characteristics (e.g., Fabricius et al., 2011; Allen et al., 2017). This last approach can be important in helping to develop and calibrate impact mechanisms and models through empirical experimentation and observation.

Risks for natural and human systems are often assessed with impact models where climate inputs are provided by representative concentration pathway (RCP)-based climate projections. The number of studies projecting impacts at 1.5°C or 2°C of global warming has increased in recent times (see Section 3.4), even if the four RCP scenarios used in AR5 are not strictly associated with these levels of global warming. Several approaches have been used to extract the required climate scenarios, as described in Section 3.2.1. As an example, Schleussner et al. (2016b) applied a time sampling (or ESR) approach, described in Section 3.2.1, to estimate the differential effect of 1.5°C and 2°C of global warming on water availability and impacts on agriculture using an ensemble of simulations under the RCP8.5 scenario. As a further example using a different approach, Iizumi et al. (2017) derived a 1.5°C scenario from simulations with a crop model using an interpolation between the no-change (approximately 2010) conditions and the RCP2.6 scenario (with a global warming of 1.8°C in 2100), and they derived the corresponding 2°C scenario from RCP2.6 and RCP4.5 simulations in 2100. The Inter-Sectoral Impact Model

Integration and Intercomparison Project Phase 2 (ISIMIP2; Frieler et al., 2017) extended this approach to investigate a number of sectoral impacts on terrestrial and marine ecosystems. In most cases, risks are assessed by impact models coupled offline to climate models after bias correction, which may modify long-term trends (Grillakis et al., 2017).

Assessment of local impacts of climate change necessarily involves a change in scale, such as from the global scale to that of natural or human systems (Frieler et al., 2017; Reyer et al., 2017d; Jacob et al., 2018). An appropriate method of downscaling (Supplementary Material 3.SM.1) is crucial for translating perspectives on 1.5°C and 2°C of global warming to scales and impacts relevant to humans and ecosystems. A major challenge associated with this requirement is the correct reproduction of the variance of local to regional changes, as well as the frequency and amplitude of extreme events (Vautard et al., 2014). In addition, maintaining physical consistency between downscaled variables is important but challenging (Frost et al., 2011).

Another major challenge relates to the propagation of the uncertainties at each step of the methodology, from the global forcings to the global climate and from regional climate to impacts at the ecosystem level, considering local disturbances and local policy effects. The risks for natural and human systems are the result of complex combinations of global and local drivers, which makes quantitative uncertainty analysis difficult. Such analyses are partly done using multimodel approaches, such as multi-climate and multi-impact models (Warszawski et al., 2013, 2014; Frieler et al., 2017). In the case of crop projections, for example, the majority of the uncertainty is caused by variation among crop models rather than by downscaling outputs of the climate models used (Asseng et al., 2013). Error propagation is an important issue for coupled models. Dealing correctly with uncertainties in a robust probabilistic model is particularly important when considering the potential for relatively small changes to affect the already small signal associated with 0.5°C of global warming (Supplementary Material 3.SM.1). The computation of an impact per unit of climatic change, based either on models or on data, is a simple way to present the probabilistic ecosystem response while taking into account the various sources of uncertainties (Fronzek et al., 2011).

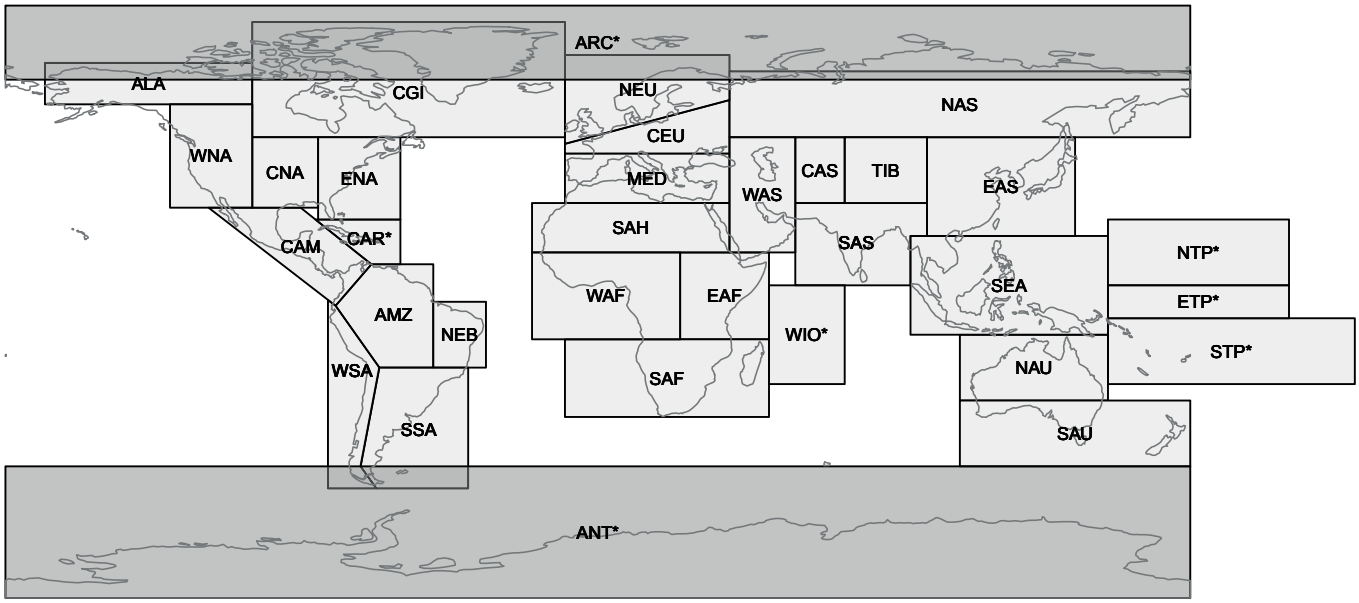
In summary, in order to assess risks at 1.5°C and higher levels of global warming, several things need to be considered. Projected climates under 1.5°C of global warming differ depending on temporal aspects and emission pathways. Considerations include whether global temperature is (i) temporarily at this level (i.e., is a transient phase on its way to higher levels of warming), (ii) arrives at 1.5°C, with or without overshoot, after stabilization of greenhouse gas concentrations, or (iii) is at this level as part of long-term climate equilibrium (complete only after several millennia). Assessments of impacts of 1.5°C of warming are generally based on climate simulations for these different possible pathways. Most existing data and analyses focus on transient impacts (i). Fewer data are available for dedicated climate model simulations that are able to assess pathways consistent with (ii), and very few data are available for the assessment of changes at climate equilibrium (iii). In some cases, inferences regarding the impacts of further warming of 0.5°C above present-day temperatures (i.e., 1.5°C of global warming) can also be drawn from observations of similar sized changes (0.5°C) that have occurred in the past, such as during the last 50 years. However, impacts can only be partly inferred from these types of observations, given the strong possibility of non-linear changes, as well as lag effects for some climate variables (e.g., sea level rise, snow and ice melt). For the impact models, three challenges are noted about the coupling procedure: (i) the bias correction of the climate model, which may modify the simulated response of the ecosystem, (ii) the necessity to downscale the climate model outputs to reach a pertinent scale for the ecosystem without losing physical consistency of the downscaled climate fields, and (iii) the necessity to develop an integrated study of the uncertainties.

3.3 Global and Regional Climate Changes and Associated Hazards

This section provides the assessment of changes in climate at 1.5°C of global warming relative to changes at higher global mean temperatures. Section 3.3.1 provides a brief overview of changes to global climate. Sections 3.3.2–3.3.11 provide assessments for specific aspects of the climate system, including regional assessments for temperature (Section 3.3.2) and precipitation (Section 3.3.3) means and extremes. Analyses of regional changes are based on the set of regions displayed in Figure 3.2. A synthesis of the main conclusions of this section is provided in Section 3.3.11. The section builds upon assessments from the IPCC AR5 WGI report (Bindoff et al., 2013a; Christensen et al., 2013; Collins et al., 2013; Hartmann et al., 2013; IPCC, 2013) and Chapter 3 of the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Seneviratne et al., 2012), as well as a substantial body of new literature related to projections of climate at 1.5°C and 2°C of warming above the pre-industrial period (e.g., Vautard et al., 2014; Fischer and Knutti, 2015; Schleussner et al., 2016b, 2017; Seneviratne et al., 2016, 2018c; Déqué et al., 2017; Maule et al., 2017; Mitchell et al., 2017, 2018a; Wartenburger et al., 2017; Zaman et al., 2017; Betts et al., 2018; Jacob et al., 2018; Kharin et al., 2018; Wehner et al., 2018b). The main assessment methods are as already detailed in Section 3.2.

3.3.1 Global Changes in Climate

There is *high confidence* that the increase in global mean surface temperature (GMST) has reached 0.87°C (±0.10°C *likely* range) above pre-industrial values in the 2006–2015 decade (Chapter 1). AR5 assessed that the globally averaged temperature (combined over land and ocean) displayed a warming of about 0.85°C [0.65°C to 1.06°C] during the period 1880–2012, with a large fraction of the detected global warming being attributed to anthropogenic forcing (Bindoff et al., 2013a; Hartmann et al., 2013; Stocker et al., 2013). While new evidence has highlighted that sampling biases and the choice of approaches used to estimate GMST (e.g., using water versus air temperature over oceans and using model simulations versus observations-based estimates) can affect estimates of GMST increase (Richardson et al., 2016; see also Supplementary Material 3.SM.2), the present assessment is consistent with that of AR5 regarding a detectable and dominant effect of anthropogenic forcing on observed trends in global temperature (also confirmed in Ribes et al., 2017). As highlighted in Chapter 1, human-induced warming



Abbreviation	Name	Abbreviation	Name	Abbreviation	Name	Abbreviation	Name
ALA	Alaska/N.W. Canada	CNA	Central North America	NEU	North Europe	TIB	Tibetan Plateau
AMZ	Amazon	EAF	East Africa	NTP*	Pacific Islands region[2]	WAF	West Africa
ANT*	Antarctica	EAS	East Asia	SAF	Southern Africa	WAS	West Asia
ARC*	Arctic	ENA	East North America	SAH	Sahara	WIO*	West Indian Ocean
CAM	Central America/Mexico	ETP*	Pacific Islands region[3]	SAS	South Asia	WNA	West North America
CAR*	small islands regions Caribbean	MED	South Europe/Mediterranean	SAU	South Australia/New Zealand	WSA	West Coast South America
CAS	Central Asia	NAS	North Asia	SEA	Southeast Asia		
CEU	Central Europe	NAU	North Australia	SSA	Southeastern South America		
CGI	Canada/Greenland/Iceland	NEB	North–East Brazil	STP*	Southern Topical Pacific		

Figure 3.2 | Regions used for regional analyses provided in Section 3.3. The choice of regions is based on the IPCC Fifth Assessment Report (AR5, Chapter 14, Christensen et al., 2013 and Annex 1: Atlas) and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, Chapter 3, Seneviratne et al., 2012), with seven additional regions in the Arctic, Antarctic and islands not included in the IPCC SREX report (indicated with asterisks). Analyses for regions with asterisks are provided in the Supplementary Material 3.SM.2

reached approximately 1°C (±0.2°C *likely* range) in 2017. More background on recent observed trends in global climate is provided in the Supplementary Material 3.SM.2.

A global warming of 1.5°C implies higher mean temperatures compared to during pre-industrial times in almost all locations, both on land and in oceans (*high confidence*) (Figure 3.3). In addition, a global warming of 2°C versus 1.5°C results in robust differences in the mean temperatures in almost all locations, both on land and in the ocean (*high confidence*). The land–sea contrast in warming is important and implies particularly large changes in temperature over land, with mean warming of more than 1.5°C in most land regions (*high confidence;* see Section 3.3.2 for more details). The largest increase in mean temperature is found in the high latitudes of the Northern Hemisphere (*high confidence*; Figure 3.3, see Section 3.3.2 for more details). Projections for precipitation are more uncertain, but they highlight robust increases in mean precipitation in the Northern Hemisphere high latitudes at 1.5°C global warming versus pre-industrial conditions, as well as at 2°C global warming versus pre-industrial conditions (*high confidence*) (Figure 3.3). There are consistent but less robust signals when comparing changes in mean precipitation at 2°C versus 1.5°C of global warming. Hence, it is assessed that there is *medium confidence* in an increase of mean precipitation in high-latitudes at 2°C versus 1.5°C of global warming (Figure 3.3). For droughts, changes in evapotranspiration and precipitation timing are also relevant (see Section 3.3.4). Figure 3.4 displays changes in temperature extremes (the hottest daytime temperature of the year, TXx, and the coldest night-time temperature of the year, TNn) and heavy precipitation (the annual maximum 5-day precipitation, Rx5day). These analyses reveal distinct patterns of changes, with the largest changes in TXx occurring on mid-latitude land and the largest changes in TNn occurring at high latitudes (both on land and in oceans). Differences in TXx and TNn compared to pre-industrial climate are robust at both global warming levels. Differences in TXx and TNn at 2°C versus 1.5°C of global warming are robust across most of the globe. Changes in heavy precipitation

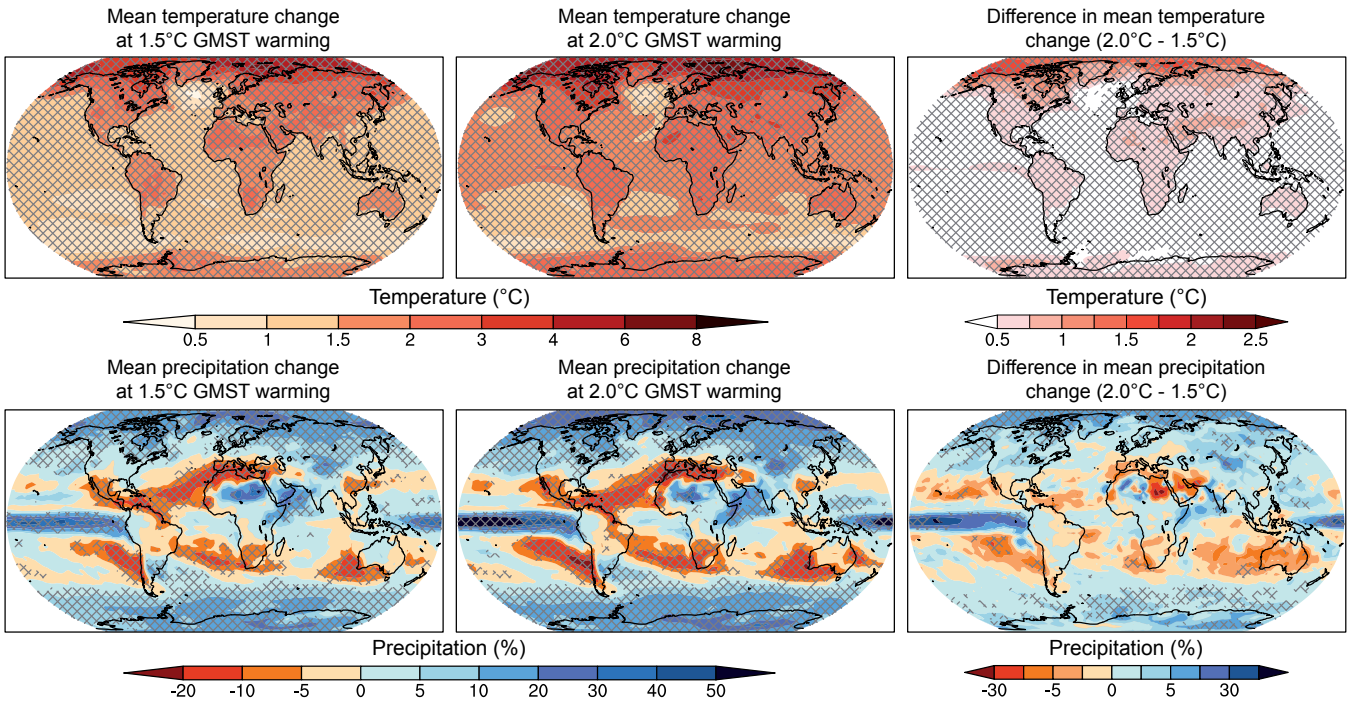


Figure 3.3 | Projected changes in mean temperature (top) and mean precipitation (bottom) at 1.5°C (left) and 2°C (middle) of global warming compared to the pre-industrial period (1861–1880), and the difference between 1.5°C and 2°C of global warming (right). Cross-hatching highlights areas where at least two-thirds of the models agree on the sign of change as a measure of robustness (18 or more out of 26). Values were assessed from the transient response over a 10-year period at a given warming level, based on Representative Concentration Pathway (RCP)8.5 Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations (adapted from Seneviratne et al., 2016 and Wartenburger et al., 2017, see Supplementary Material 3.SM.2 for more details). Note that the responses at 1.5°C of global warming are similar for RCP2.6 simulations (see Supplementary Material 3.SM.2). Differences compared to 1°C of global warming are provided in the Supplementary Material 3.SM.2.

are less robust, but particularly strong increases are apparent at high latitudes as well as in the tropics at both 1.5°C and 2°C of global warming compared to pre-industrial conditions. The differences in heavy precipitation at 2°C versus 1.5°C global warming are generally not robust at grid-cell scale, but they display consistent increases in most locations (Figure 3.4). However, as addressed in Section 3.3.3, statistically significant differences are found in several large regions and when aggregated over the global land area. We thus assess that there is *high confidence* regarding global-scale differences in temperature means and extremes at 2°C versus 1.5°C global warming, and *medium confidence* regarding global-scale differences in precipitation means and extremes. Further analyses, including differences at 1.5°C and 2°C global warming versus 1°C (i.e., present-day) conditions are provided in the Supplementary Material 3.SM.2.

These projected changes at 1.5°C and 2°C of global warming are consistent with the attribution of observed historical global trends in temperature and precipitation means and extremes (Bindoff et al., 2013a), as well as with some observed changes under the recent global warming of 0.5°C (Schleussner et al., 2017). These comparisons are addressed in more detail in Sections 3.3.2 and 3.3.3. Attribution studies have shown that there is *high confidence* that anthropogenic forcing has had a detectable influence on trends in global warming (*virtually certain* since the mid-20th century), in land warming on all continents except Antarctica (*likely* since the mid-20th century), in ocean warming since 1970 (*very likely*), and in increases in hot extremes and decreases in cold extremes since the mid-20th century (*very likely*) (Bindoff et al., 2013a). In addition, there is *medium confidence* that anthropogenic forcing has contributed to increases in mean precipitation at high latitudes in the Northern Hemisphere since the mid-20th century and to global-scale increases in heavy precipitation in land regions with sufficient observations over the same period (Bindoff et al., 2013a). Schleussner et al. (2017) showed, through analyses of recent observed tendencies, that changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991–2010 period compared with those for 1960–1979, with a global warming of approximately 0.5°C occurring between these two periods (*high confidence*). The observed tendencies over that time frame are thus consistent with attributed changes since the mid-20th century (*high confidence*).

The next sections assess changes in several different types of climate-related hazards. It should be noted that the different types of hazards are considered in isolation but some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards (*high confidence*). Two examples are sea level rise and heavy precipitation in some regions, possibly leading together to more flooding, and droughts and heatwaves, which can together increase the risk of fire occurrence. Such events, also called compound events, may substantially increase risks in some regions (e.g., AghaKouchak et al., 2014; Van Den Hurk et al., 2015; Martius et al., 2016; Zscheischler et al., 2018). A detailed assessment of physically-defined compound events was not possible as part of this report, but aspects related to overlapping multi-sector risks are highlighted in Sections 3.4 and 3.5.

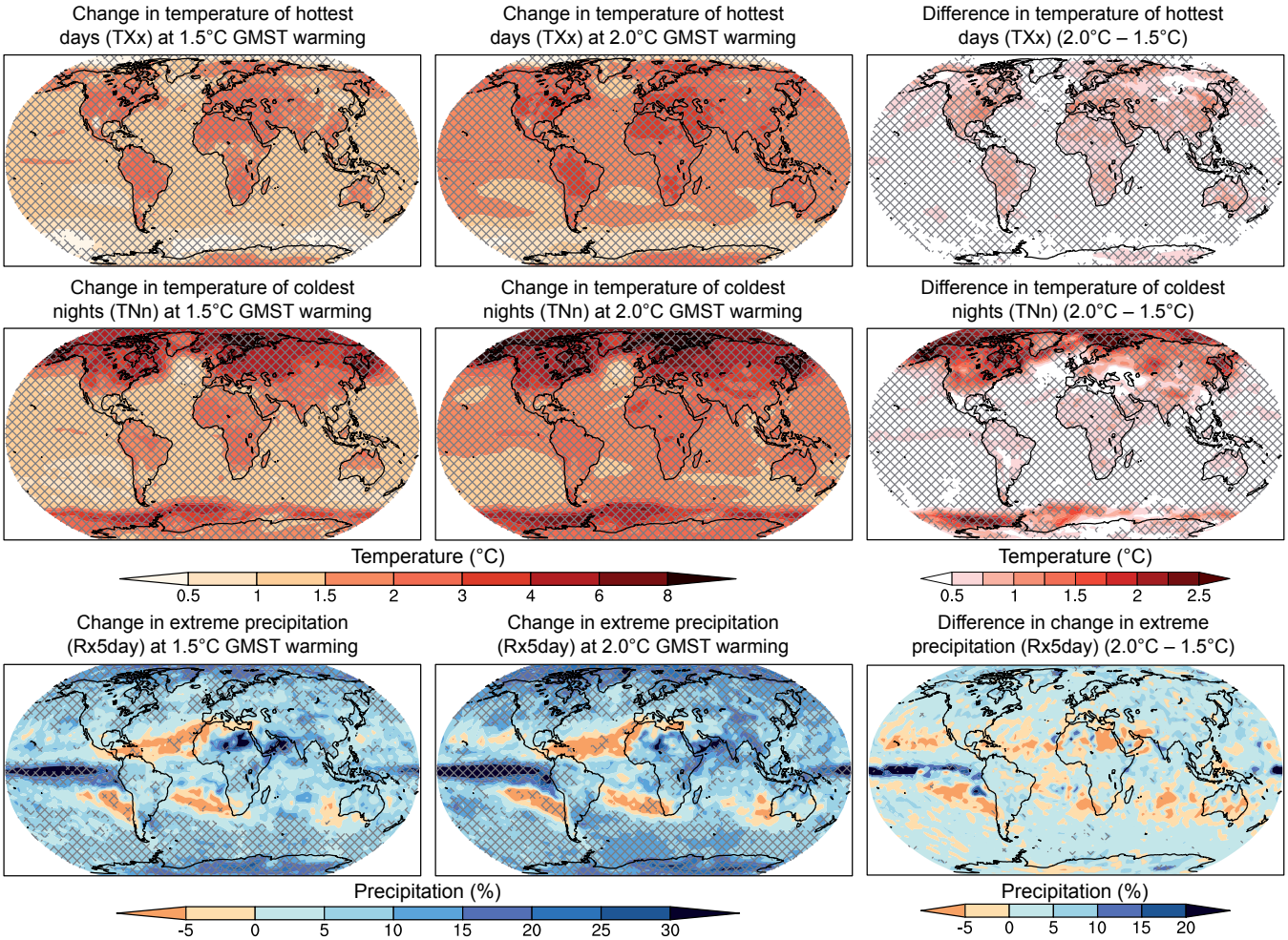


Figure 3.4 | Projected changes in extremes at 1.5°C (left) and 2°C (middle) of global warming compared to the pre-industrial period (1861–1880), and the difference between 1.5°C and 2°C of global warming (right). Cross-hatching highlights areas where at least two-thirds of the models agree on the sign of change as a measure of robustness (18 or more out of 26): temperature of annual hottest day (maximum temperature), TXx (top), and temperature of annual coldest night (minimum temperature), TNn (middle), and annual maximum 5-day precipitation, Rx5day (bottom). The underlying methodology and data basis are the same as for Figure 3.3 (see Supplementary Material 3.SM.2 for more details). Note that the responses at 1.5°C of global warming are similar for Representative Concentration Pathway (RCP)2.6 simulations (see Supplementary Material 3.SM.2). Differences compared to 1°C of global warming are provided in the Supplementary Material 3.SM.2.

3.3.2 Regional Temperatures on Land, Including Extremes

3.3.2.1 Observed and attributed changes in regional temperature means and extremes

While the quality of temperature measurements obtained through ground observational networks tends to be high compared to that of measurements for other climate variables (Seneviratne et al., 2012), it should be noted that some regions are undersampled. Cowtan and Way (2014) highlighted issues regarding undersampling, which is most problematic at the poles and over Africa, and which may lead to biases in estimated changes in GMST (see also Supplementary Material 3.SM.2 and Chapter 1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature. Despite this partly limited coverage, the attribution chapter of AR5 (Bindoff et al., 2013a) and recent papers (e.g., Sun et al., 2016; Wan et al., 2018) assessed that, over every continental region and in many sub-continental regions, anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century.

Based on the AR5 and SREX, as well as recent literature (see Supplementary Material 3.SM), there is *high confidence* (*very likely*) that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale on land. There is also *high confidence* (*likely*) that consistent changes are detectable on the continental scale in North America, Europe and Australia. There is *high confidence* that these observed changes in temperature extremes can be attributed to anthropogenic forcing (Bindoff et al., 2013a). As highlighted in Section 3.2, the observational record can be used to assess past changes associated with a global warming of 0.5°C. Schleussner et al. (2017) used this approach to assess observed changes in extreme indices for the 1991–2010 versus the 1960–1979 period, which corresponds to just about a 0.5°C GMST difference in the observed record (based on the Goddard Institute for Space Studies Surface Temperature Analysis

(GISTEMP) dataset, Hansen et al., 2010). They found that substantial changes due to 0.5°C of warming are apparent for indices related to hot and cold extremes, as well as for the Warm Spell Duration Indicator (WSDI). In particular, they identified that one-quarter of the land has experienced an intensification of hot extremes (maximum temperature on the hottest day of the year, TXx) by more than 1°C and a reduction in the intensity of cold extremes by at least 2.5°C (minimum temperature on the coldest night of the year, TNn). In addition, the same study showed that half of the global land mass has experienced changes in WSDI of more than six days, as well as an emergence of extremes outside the range of natural variability (Schleussner et al., 2017). Analyses from Schleussner et al. (2017) for temperature extremes are provided in the Supplementary Material 3.SM, Figure 3.SM.6. It should be noted that assessments of attributed changes in the IPCC SREX and AR5 reports were generally provided since 1950, for time frames also approximately corresponding to a 0.5°C global warming (3.SM).

3.3.2.2 Projected changes in regional temperature means and extremes at 1.5°C versus 2°C of global warming

There are several lines of evidence available for providing a regional assessment of projected changes in temperature means and extremes at 1.5°C versus 2°C of global warming (see Section 3.2). These include: analyses of changes in extremes as a function of global warming based on existing climate simulations using the empirical scaling relationship (ESR) and variations thereof (e.g., Schleussner et al., 2017; Dosio and Fischer, 2018; Seneviratne et al., 2018c; see Section 3.2 for details about the methodology); dedicated simulations of 1.5°C versus 2°C of global warming, for instance based on the Half a degree additional warming, prognosis and projected impacts (HAPPI) experiment (Mitchell et al., 2017) or other model simulations (e.g., Dosio et al., 2018; Kjellström et al., 2018); and analyses based on statistical pattern scaling approaches (e.g., Kharin et al., 2018). These different lines of evidence lead to qualitatively consistent results regarding changes in temperature means and extremes at 1.5°C of global warming compared to the pre-industrial climate and 2°C of global warming.

There are statistically significant differences in temperature means and extremes at 1.5°C versus 2°C of global warming, both in the global average (Schleussner et al., 2016b; Dosio et al., 2018; Kharin et al., 2018), as well as in most land regions (*high confidence*) (Wartenburger et al., 2017; Seneviratne et al., 2018c; Wehner et al., 2018b). Projected temperatures over oceans display significant increases in means and extremes between 1.5°C and 2°C of global warming (Figures 3.3 and 3.4). A general background on the available evidence on regional changes in temperature means and extremes at 1.5°C versus 2°C of global warming is provided in the Supplementary Material 3.SM.2. As an example, Figure 3.5 shows regionally-based analyses for the IPCC SREX regions (see Figure 3.2) of changes in the temperature of hot extremes as a function of global warming (corresponding analyses for changes in the temperature of cold extremes are provided in the Supplementary Material 3.SM.2). As demonstrated in these analyses, the mean response of the intensity of temperature extremes in climate models to changes in the global mean temperature is approximately linear and independent of the considered emissions scenario (Seneviratne et al., 2016; Wartenburger et al., 2017). Nonetheless, in the case of changes in the number of days exceeding a given threshold, changes are approximately exponential, with higher increases for rare events (Fischer and Knutti, 2015; Kharin et al., 2018); see also Figure 3.6. This behaviour is consistent with a linear increase in absolute temperature for extreme threshold exceedances (Whan et al., 2015).

As mentioned in Section 3.3.1, there is an important land–sea warming contrast, with stronger warming on land (see also Christensen et al., 2013; Collins et al., 2013; Seneviratne et al., 2016), which implies that regional warming on land is generally more than 1.5°C even when mean global warming is at 1.5°C. As highlighted in Seneviratne et al. (2016), this feature is generally stronger for temperature extremes (Figures 3.4 and 3.5; Supplementary Material 3.SM.2). For differences in regional temperature extremes at a mean global warming of 1.5°C versus 2°C, that is, a difference of 0.5°C in global warming, this implies differences of as much as 1°C–1.5°C in some locations, which are two to three times larger than the differences in global mean temperature. For hot extremes, the strongest warming is found in central and eastern North America, central and southern Europe, the Mediterranean, western and central Asia, and southern Africa (Figures 3.4 and 3.5) (*medium confidence*). These regions are all characterized by a strong soil-moisture–temperature coupling and projected increased dryness (Vogel et al., 2017), which leads to a reduction in evaporative cooling in the projections. Some of these regions also show a wide range of responses to temperature extremes, in particular central Europe and central North America, owing to discrepancies in the representation of the underlying processes in current climate models (Vogel et al., 2017). For mean temperature and cold extremes, the strongest warming is found in the northern high-latitude regions (*high confidence*). This is due to substantial ice-snow-albedo-temperature feedbacks (Figure 3.3 and Figure 3.4, middle) related to the known 'polar amplification' mechanism (e.g., IPCC, 2013; Masson-Delmotte et al., 2013).

Figure 3.7 displays maps of changes in the number of hot days (NHD) at 1.5°C and 2°C of GMST increase. Maps of changes in the number of frost days (FD) can be found in Supplementary Material 3.SM.2. These analyses reveal clear patterns of changes between the two warming levels, which are consistent with analysed changes in heatwave occurrence (e.g., Dosio et al., 2018). For the NHD, the largest differences are found in the tropics (*high confidence*), owing to the low interannual temperature variability there (Mahlstein et al., 2011), although absolute changes in hot temperature extremes tended to be largest at mid-latitudes (*high confidence*) (Figures 3.4 and 3.5). Extreme heatwaves are thus projected to emerge earliest in the tropics and to become widespread in these regions already at 1.5°C of global warming (*high confidence*). These results are consistent with other recent assessments. Coumou and Robinson (2013) found that 20% of the global land area, centred in low-latitude regions, is projected to experience highly unusual monthly temperatures during Northern Hemisphere summers at 1.5°C of global warming, with this number nearly doubling at 2°C of global warming.

Figure 3.8 features an objective identification of 'hotspots' / key risks in temperature indices subdivided by region, based on the ESR approach applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (Wartenburger et al., 2017). Note that results based on the HAPPI multimodel experiment (Mitchell et al., 2017) are similar (Seneviratne et al., 2018c). The considered regions follow

the classification used in Figure 3.2 and also include the global land areas. Based on these analyses, the following can be stated: significant changes in responses are found in all regions for most temperature indices, with the exception of i) the diurnal temperature range (DTR) in most regions, ii) ice days (ID), frost days (FD) and growing season length (GSL) (mostly in regions where differences are zero, because, e.g., there are no ice or frost days), iii) the minimum yearly value of the maximum daily temperature (TXn) in very few regions. In terms of the sign of the changes, warm extremes display an increase in intensity, frequency and duration (e.g., an increase in the temperature of the hottest day of the year (TXx) in all regions, an increase in the proportion of days with a maximum temperature above the 90th percentile of Tmax (TX90p) in all regions, and an increase in the length of the WSDI in all regions), while cold extremes display a decrease in intensity, frequency and duration (e.g., an increase in the temperature of the coldest night of the year (TNn) in all regions, a decrease in the proportion of days with a minimum temperature below the 10th percentile of Tmin (TN10p), and a decrease in the cold spell duration index (CSDI) in all regions). Hence, while warm extremes are intensified, cold extremes become less intense in affected regions.

Overall, large increases in hot extremes occur in many densely inhabited regions (Figure 3.5), for both warming scenarios compared to pre-industrial and present-day climate, as well as for 2°C versus 1.5°C GMST warming. For instance, Dosio et al. (2018) concluded, based on a modelling study, that 13.8% of the world population would be exposed to 'severe heatwaves' at least once every 5 years under 1.5°C of global warming, with a threefold increase (36.9%) under 2°C of GMST warming, corresponding to a difference of about 1.7 billion people between the two global warming levels. They also concluded that limiting global warming to 1.5°C would result in about 420 million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to 'exceptional heatwaves' compared to conditions at 2°C GMST warming. However, changes in vulnerability were not considered in their study. For this reason, we assess that there is *medium confidence* in their conclusions.

In summary, there is *high confidence* that there are robust and statistically significant differences in the projected temperature means and extremes at 1.5°C versus 2°C of global warming, both in the global average and in nearly all land regions[4] (*likely*). Further, the observational record reveals that substantial changes due to a 0.5°C GMST warming are apparent for indices related to hot and cold extremes, as well as for the WSDI (*likely*). A global warming of 2°C versus 1.5°C would lead to more frequent and more intense hot extremes in all land regions[4], as well as longer warm spells, affecting many densely inhabited regions (*very likely*). The strongest increases in the frequency of hot extremes are projected for the rarest events (*very likely*). On the other hand, cold extremes would become less intense and less frequent, and cold spells would be shorter (*very likely*). Temperature extremes on land would generally increase more than the global average temperature (*very likely*). Temperature increases of extreme hot days in mid-latitudes are projected to be up to two times the increase in GMST, that is, 3°C at 1.5°C GMST warming (*high confidence*). The highest levels of warming for extreme hot days are expected to occur in central and eastern North America, central and southern Europe, the Mediterranean, western and central Asia, and southern Africa (*medium confidence*). These regions have a strong soil-moisture-temperature coupling in common as well as increased dryness and, consequently, a reduction in evaporative cooling. However, there is a substantial range in the representation of these processes in models, in particular in central Europe and central North America (*medium confidence*). The coldest nights in high latitudes warm by as much as 1.5°C for a 0.5°C increase in GMST, corresponding to a threefold stronger warming (*high confidence*). NHD shows the largest differences between 1.5°C and 2°C in the tropics, because of the low interannual temperature variability there (*high confidence*); extreme heatwaves are thus projected to emerge earliest in these regions, and they are expected to become widespread already at 1.5°C of global warming (*high confidence*). Limiting global warming to 1.5°C instead of 2°C could result in around 420 million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to exceptional heatwaves, assuming constant vulnerability (*medium confidence*).

3.3.3 Regional Precipitation, Including Heavy Precipitation and Monsoons

This section addresses regional changes in precipitation on land, with a focus on heavy precipitation and consideration of changes to the key features of monsoons.

3.3.3.1 Observed and attributed changes in regional precipitation

Observed global changes in the water cycle, including precipitation, are more uncertain than observed changes in temperature (Hartmann et al., 2013; Stocker et al., 2013). There is *high confidence* that mean precipitation over the mid-latitude land areas of the Northern Hemisphere has increased since 1951 (Hartmann et al., 2013). For other latitudinal zones, area-averaged long-term positive or negative trends have *low confidence* because of poor data quality, incomplete data or disagreement amongst available estimates (Hartmann et al., 2013). There is, in particular, *low confidence* regarding observed trends in precipitation in monsoon regions, according to the SREX report (Seneviratne et al., 2012) and AR5 (Hartmann et al., 2013), as well as more recent publications (Singh et al., 2014; Taylor et al., 2017; Bichet and Diedhiou, 2018; see Supplementary Material 3.SM.2).

For heavy precipitation, AR5 (Hartmann et al., 2013) assessed that observed trends displayed more areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation (*likely*). In addition, for land regions where observational coverage is sufficient for evaluation, it was assessed that there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al., 2013a).

Regarding changes in precipitation associated with global warming of 0.5°C, the observed record suggests that increases in precipitation extremes can be identified for annual maximum 1-day precipitation

[4] Using the SREX definition of regions (Figure 3.2)

Continued page 194 >

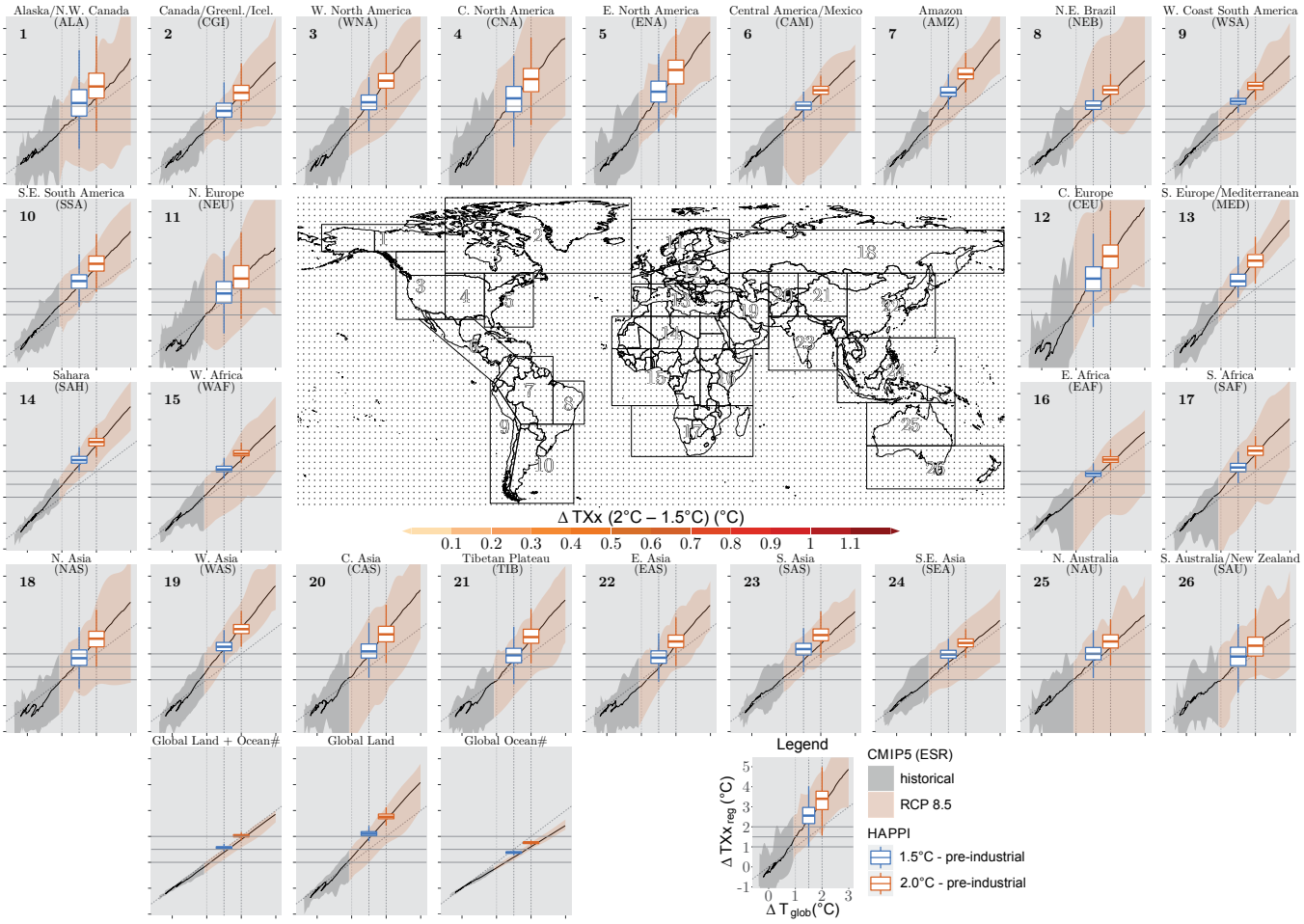


Figure 3.5 | Projected changes in annual maximum daytime temperature (TXx) as a function of global warming for IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (see Figure 3.2), based on an empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data (adapted from Seneviratne et al., 2016 and Wartenburger et al., 2017) together with projected changes from the Half a degree additional warming, prognosis and projected impacts (HAPPI) multimodel experiment (Mitchell et al., 2017; based on analyses in Seneviratne et al., 2018c) (bar plots on regional analyses and central plot, respectively). For analyses for other regions from Figure 3.2 (with asterisks), see Supplementary Material 3.SM.2. (The stippling indicates significance of the differences in changes between 1.5°C and 2°C of global warming based on all model simulations, using a two-sided paired Wilcoxon test (P = 0.01, after controlling the false discovery rate according to Benjamini and Hochberg, 1995). See Supplementary Material 3.SM.2 for details.

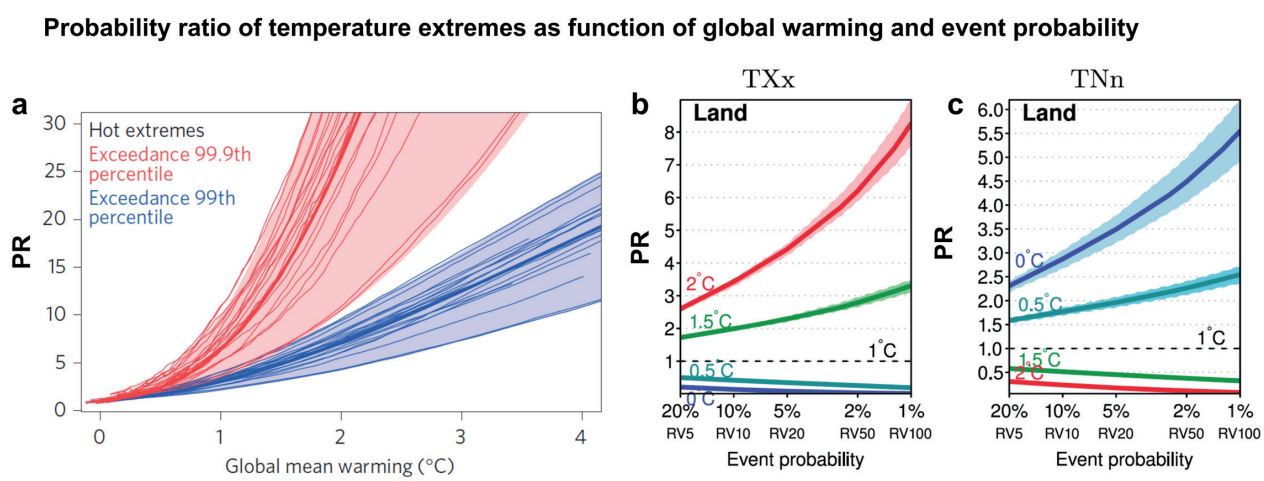


Figure 3.6 | Probability ratio (PR) of exceeding extreme temperature thresholds. (a) PR of exceeding the 99th (blue) and 99.9th (red) percentile of pre-industrial daily temperatures at a given warming level, averaged across land (from Fischer and Knutti, 2015). (b) PR for the hottest daytime temperature of the year (TXx). (c) PR for the coldest night of the year (TNn) for different event probabilities (with RV indicating return values) in the current climate (1°C of global warming). Shading shows the interquartile (25–75%) range (from Kharin et al., 2018).

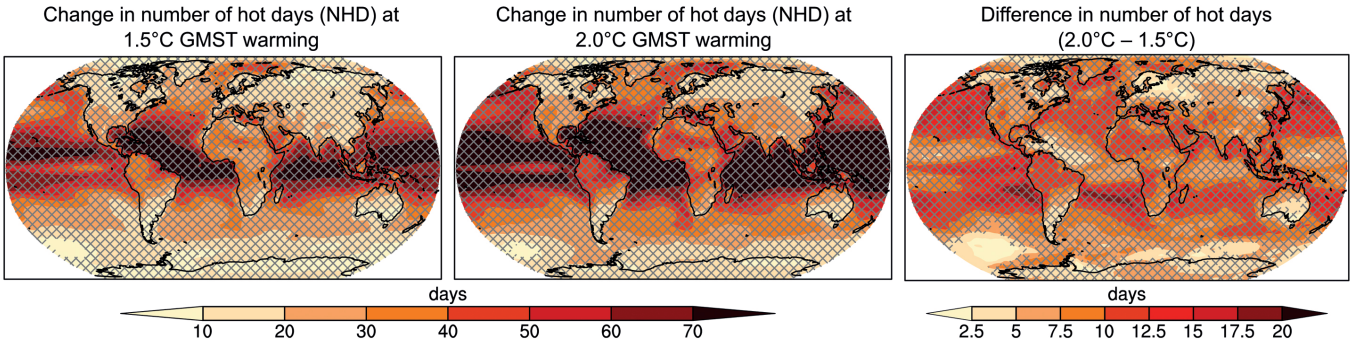


Figure 3.7 | Projected changes in the number of hot days (NHD; 10% warmest days) at 1.5°C (left) and at 2°C (middle) of global warming compared to the pre-industrial period (1861–1880), and the difference between 1.5°C and 2°C of warming (right). Cross-hatching highlights areas where at least two-thirds of the models agree on the sign of change as a measure of robustness (18 or more out of 26). The underlying methodology and the data basis are the same as for Figure 3.2 (see Supplementary Material 3.SM.2 for more details). Differences compared to 1°C global warming are provided in the Supplementary Material 3.SM.2.

	Global Land	ALA	AMZ	CAM	CAS	CEU	CGI	CNA	EAF	EAS	ENA	MED	NAS	NAU	NEB	NEU	SAF	SAH	SAS	SAU	SEA	SSA	TIB	WAF	WAS	WNA	WSA
T	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
CSDI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DTR	-	-	+	+	+	+	-	+	+	+	-	+	-	+	+	-	+	-	-	+	-	-	-	-	-	-	+
FD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
GSL	+	+	+	+	+	+	+	+		+	+	+	+	+		+	+	+	+	+	-	+	+		+	+	+
ID	-	-		-	-	-	-	-		-	-	-	-			-			-			-	-		-	-	-
SU	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TN10p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TN90p	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TNn	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TNx	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TR	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TX10p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TX90p	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TXn	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TXx	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
WSDI	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Figure 3.8 | Significance of differences in regional mean temperature and range of temperature indices between the 1.5°C and 2°C global mean temperature targets (rows). Definitions of indices: T: mean temperature; CSDI: cold spell duration index; DTR: diurnal temperature range; FD: frost days; GSL: growing season length; ID: ice days; SU: summer days; TN10p: proportion of days with a minimum temperature (TN) lower than the 10th percentile of TN; TN90p: proportion of days with TN higher than the 90th percentile of TN; TNn: minimum yearly value of TN; TNx: maximum yearly value of TN; TR: tropical nights; TX10p: proportion of days with a maximum temperature (TX) lower than the 10th percentile of TX; TX90p: proportion of days with TX higher than the 90th percentile of TX; TXn: minimum yearly value of TX; TXx: maximum yearly value of TX; WSDI: warm spell duration index. Columns indicate analysed regions and global land (see Figure 3.2 for definitions). Significant differences are shown in red shading, with increases indicated with + and decreases indicated with –, while non-significant differences are shown in grey shading. White shading indicates when an index is the same at the two global warming levels (i.e., zero changes). Note that decreases in CSDI, FD, ID, TN10p and TX10p are linked to increased temperatures on cold days or nights. Significance was tested using a two-sided paired Wilcoxon test (P=0.01, after controlling the false discovery rate according to Benjamini and Hochberg, 1995) (adapted from Wartenburger et al., 2017).

3.3.3.1 (continued)

(RX1day) and consecutive 5-day precipitation (RX5day) for GMST changes of this magnitude (Supplementary Material 3.SM.2, Figure 3.SM.7; Schleussner et al., 2017). It should be noted that assessments of attributed changes in the IPCC SREX and AR5 reports were generally provided since 1950, for time frames also approximately corresponding to a 0.5°C global warming (3.SM).

3.3.3.2 Projected changes in regional precipitation at 1.5°C versus 2°C of global warming

Figure 3.3 in Section 3.3.1 summarizes the projected changes in mean precipitation at 1.5°C and 2°C of global warming. Both warming levels display robust differences in mean precipitation compared to the pre-industrial period. Regarding differences at 2°C vs 1.5°C global warming, some regions are projected to display changes in mean precipitation at 2°C compared with that at 1.5°C of global warming in the CMIP5 multimodel average, such as decreases in the Mediterranean area, including southern Europe, the Arabian Peninsula and Egypt, or increases in high latitudes. The results, however, are less robust across models than for mean temperature. For instance, Déqué et al. (2017) investigated the impact of 2°C of global warming on precipitation over tropical Africa and found that average precipitation does not show a significant response, owing to two phenomena: (i) the number of days with rain decreases whereas the precipitation intensity increases, and (ii) the rainy season occurs later during the year, with less precipitation in early summer and more precipitation in late summer. The results from Déqué et al. (2017) regarding insignificant differences between 1.5°C and 2°C scenarios for tropical Africa are consistent with the results presented in Figure 3.3. For Europe, recent studies (Vautard et al., 2014; Jacob et al., 2018; Kjellström et al., 2018) have shown that 2°C of global warming was associated with a robust increase in mean precipitation over central and northern Europe in winter but only over northern Europe in summer, and with decreases in mean precipitation in central/southern Europe in summer. Precipitation changes reaching 20% have been projected for the 2°C scenario (Vautard et al., 2014) and are overall more pronounced than with 1.5°C of global warming (Jacob et al., 2018; Kjellström et al., 2018).

Regarding changes in heavy precipitation, Figure 3.9 displays projected changes in the 5-day maximum precipitation (Rx5day) as a function of global temperature increase, using a similar approach as in Figure 3.5. Further analyses are available in Supplementary Material 3.SM.2. These analyses show that projected changes in heavy precipitation are more uncertain than those for temperature extremes. However, the mean response of model simulations is generally robust and linear (see also Fischer et al., 2014; Seneviratne et al., 2016). As observed for temperature extremes, this response is also mostly independent of the considered emissions scenario (e.g., RCP2.6 versus RCP8.5; see also Section 3.2). This feature appears to be specific to heavy precipitation, possibly due to a stronger coupling with temperature, as the scaling of projections of mean precipitation changes with global warming shows some scenario dependency (Pendergrass et al., 2015).

Robust changes in heavy precipitation compared to pre-industrial conditions are found at both 1.5°C and 2°C global warming (Figure 3.4). This is also consistent with results for, for example, the European continent, although different indices for heavy precipitation changes have been analysed. Based on regional climate simulations, Vautard et al. (2014) found a robust increase in heavy precipitation everywhere in Europe and in all seasons, except southern Europe in summer at 2°C versus 1971–2000. Their findings are consistent with those of Jacob et al. (2014), who used more recent downscaled climate scenarios (EURO-CORDEX) and a higher resolution (12 km), but the change is not so pronounced in Teichmann et al. (2018). There is consistent agreement in the direction of change in heavy precipitation at 1.5°C of global warming over much of Europe, compared to 1971–2000 (Jacob et al., 2018).

Differences in heavy precipitation are generally projected to be small between 1.5°C and 2°C GMST warming (Figure 3.4 and 3.9 and Supplementary Material 3.SM.2, Figure 3.SM.10). Some regions display substantial increases, for instance southern Asia, but generally in less than two-thirds of the CMIP5 models (Figure 3.4, Supplementary Material 3.SM.2, Figure 3.SM.10). Wartenburger et al. (2017) suggested that there are substantial differences in heavy precipitation in eastern Asia at 1.5°C versus 2°C. Overall, while there is variation among regions, the global tendency is for heavy precipitation to increase at 2°C compared with at 1.5°C (see e.g., Fischer and Knutti, 2015 and Kharin et al., 2018, as illustrated in Figure 3.10 from this chapter; see also Betts et al., 2018).

AR5 assessed that the global monsoon, aggregated over all monsoon systems, is *likely* to strengthen, with increases in its area and intensity, while the monsoon circulation weakens (Christensen et al., 2013). A few publications provide more recent evaluations of projections of changes in monsoons for high-emission scenarios (e.g., Jiang and Tian, 2013; Jones and Carvalho, 2013; Sylla et al., 2015, 2016; Supplementary Material 3.SM.2). However, scenarios at 1.5°C or 2°C global warming would involve a substantially smaller radiative forcing than those assessed in AR5 and these more recent studies, and there appears to be no specific assessment of changes in monsoon precipitation at 1.5°C versus 2°C of global warming in the literature. Consequently, the current assessment is that there is *low confidence* regarding changes in monsoons at these lower global warming levels, as well as regarding differences in monsoon responses at 1.5°C versus 2°C.

Similar to Figure 3.8, Figure 3.11 features an objective identification of 'hotspots' / key risks outlined in heavy precipitation indices subdivided by region, based on the approach by Wartenburger et al. (2017). The considered regions follow the classification used in Figure 3.2 and also include global land areas. Hotspots displaying statistically significant changes in heavy precipitation at 1.5°C versus 2°C global warming are located in high-latitude (Alaska/western Canada, eastern Canada/Greenland/Iceland, northern Europe, northern Asia) and high-elevation (e.g., Tibetan Plateau) regions, as well as in eastern Asia (including China and Japan) and in eastern North America. Results are less consistent for other regions. Note that analyses for meteorological drought (lack of precipitation) are provided in Section 3.3.4.

In summary, observations and projections for mean and heavy precipitation are less robust than for temperature means and extremes (*high confidence*). Observations show that there are more areas with increases than decreases in the frequency, intensity and/or amount of

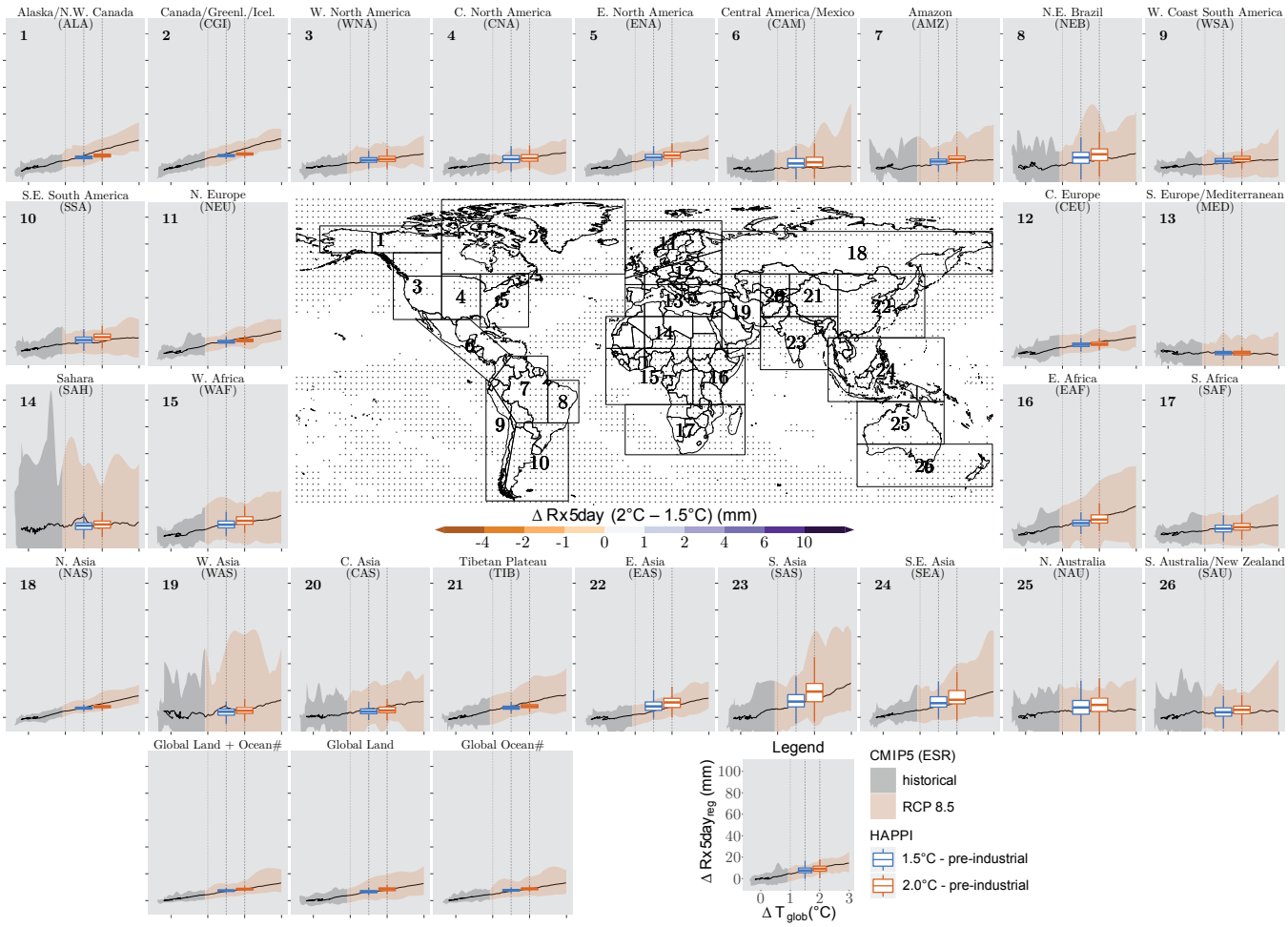


Figure 3.9 | Projected changes in annual 5-day maximum precipitation (Rx5day) as a function of global warming for IPCC Special Report on the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (see Figure 3.2), based on an empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data together with projected changes from the HAPPI multimodel experiment (bar plots on regional analyses and central plot). The underlying methodology and data basis are the same as for Figure 3.5 (see Supplementary Material 3.SM.2 for more details).

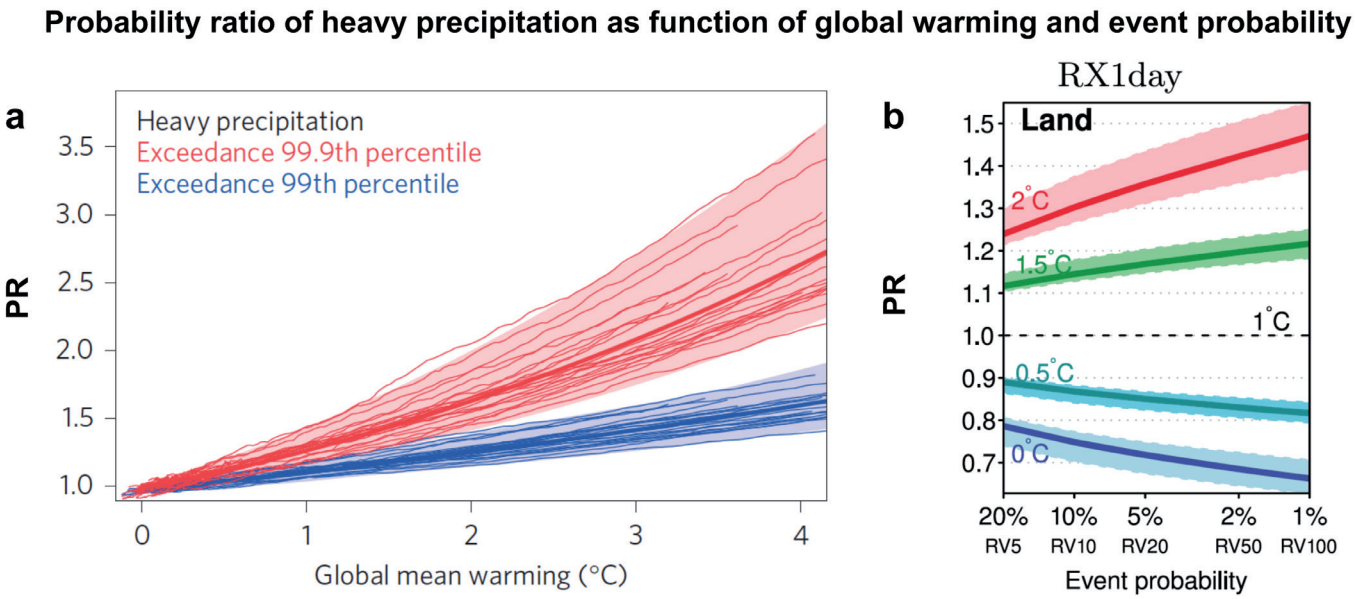


Figure 3.10 | Probability ratio (PR) of exceeding (heavy precipitation) thresholds. (a) PR of exceeding the 99th (blue) and 99.9th (red) percentile of pre-industrial daily precipitation at a given warming level, averaged across land (from Fischer and Knutti, 2015). (b) PR for precipitation extremes (RX1day) for different event probabilities (with RV indicating return values) in the current climate (1°C of global warming). Shading shows the interquartile (25–75%) range (from Kharin et al., 2018).

3.3.3.2 (continued)

heavy precipitation (*high confidence*). Several large regions display statistically significant differences in heavy precipitation at 1.5°C versus 2°C GMST warming, with stronger increases at 2°C global warming, and there is a global tendency towards increases in heavy precipitation on land at 2°C compared with 1.5°C warming (*high confidence*). Overall, regions that display statistically significant changes in heavy precipitation between 1.5°C and 2°C of global warming are located in high latitudes (Alaska/western Canada, eastern Canada/Greenland/Iceland, northern Europe, northern Asia) and high elevation (e.g., Tibetan Plateau), as well as in eastern Asia (including China and Japan) and in eastern North America (*medium confidence*). There is *low confidence* in projected changes in heavy precipitation in other regions.

	Global Land	ALA	AMZ	CAM	CAS	CEU	CGI	CNA	EAF	EAS	ENA	MED	NAS	NAU	NEB	NEU	SAF	SAH	SAS	SAU	SEA	SSA	TIB	WAF	WAS	WNA	WSA
PRCPTOT	+	+	-	+	+	+	+	+	-	+	+	-	+	-	-	+	-	+	-	-	+	-	+	+	-	+	-
CWD	-	+	-	-	-	-	+	+	-	-	+	-	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-
R95ptot	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	-	+	+	+	+	+	+	+
R99ptot	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+	+	+
Rx1day	+	+	+	+	+	+	+	+	+	+	+	-	+	-	+	+	-	+	+	+	+	+	+	+	+	+	+
Rx5day	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	-	+	+	+	-	+	+	+	-	+	+
SDII	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+	-	+	+
R1mm	+	+	-	-	-	-	+	-	-	+	+	-	+	-	-	+	-	-	-	-	-	-	+	-	-	+	-
R10mm	+	+	-	-	+	+	+	+	-	+	+	-	+	-	-	+	-	-	+	+	-	-	+	+	-	+	-
R20mm	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	-	+	+	+	+	+	+	+

Figure 3.11 | Significance of differences in regional mean precipitation and range of precipitation indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: PRCPTOT: mean precipitation; CWD: consecutive wet days; R10mm: number of days with precipitation >10 mm; R1mm: number of days with precipitation >1 mm; R20mm: number of days with precipitation >20 mm; R95ptot: proportion of rain falling as 95th percentile or higher; R99ptot: proportion of rain falling as 99th percentile or higher; RX1day: intensity of maximum yearly 1-day precipitation; RX5day: intensity of maximum yearly 5-day precipitation; SDII: Simple Daily Intensity Index. Columns indicate analysed regions and global land (see Figure 3.2 for definitions). Significant differences are shown in light blue (wetting tendency) or brown (drying tendency) shading, with increases indicated with '+' and decreases indicated with '–', while non-significant differences are shown in grey shading. The underlying methodology and the data basis are the same as in Figure 3.8 (see Supplementary Material 3.SM.2 for more details).

3.3.4 Drought and Dryness

3.3.4.1 Observed and attributed changes

The IPCC AR5 assessed that there was *low confidence* in the sign of drought trends since 1950 at the global scale, but that there was *high confidence* in observed trends in some regions of the world, including drought increases in the Mediterranean and West Africa and drought decreases in central North America and northwest Australia (Hartmann et al., 2013; Stocker et al., 2013). AR5 assessed that there was *low confidence* in the attribution of global changes in droughts and did not provide assessments for the attribution of regional changes in droughts (Bindoff et al., 2013a).

The recent literature does not suggest that the SREX and AR5 assessment of drought trends should be revised, except in the Mediterranean region. Recent publications based on observational and modelling evidence suggest that human emissions have substantially increased the probability of drought years in the Mediterranean region (Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017). Based on this evidence, there is *medium confidence* that enhanced greenhouse forcing has contributed to increased drying in the Mediterranean region (including southern Europe, northern Africa and the Near East) and that this tendency will continue to increase under higher levels of global warming.

3.3.4.2 Projected changes in drought and dryness at 1.5°C versus 2°C

There is *medium confidence* in projections of changes in drought and dryness. This is partly consistent with AR5, which assessed these projections as being '*likely* (*medium confidence*)' (Collins et al., 2013; Stocker et al., 2013). However, given this *medium confidence*, the current assessment does not include a likelihood statement, thereby maintaining consistency with the IPCC uncertainty guidance document (Mastrandrea et al., 2010) and the assessment of the IPCC SREX report (Seneviratne et al., 2012). The technical summary of AR5 (Stocker et al., 2013) assessed that soil moisture drying in the Mediterranean, southwestern USA and southern African regions was consistent with projected changes in the Hadley circulation and increased surface temperatures, and it concluded that there was *high confidence* in *likely* surface drying in these regions by the end of this century

Box 3.1 | Sub-Saharan Africa: Changes in Temperature and Precipitation Extremes

Sub-Saharan Africa has experienced the dramatic consequences of climate extremes becoming more frequent and more intense over the past decades (Paeth et al., 2010; Taylor et al., 2017). In order to join international efforts to reduce climate change, all African countries signed the Paris Agreement. In particular, through their nationally determined contributions (NDCs), they committed to contribute to the global effort to mitigate greenhouse gas (GHG) emissions with the aim to constrain global temperature increases to 'well below 2°C' and to pursue efforts to limit warming to '1.5°C above pre-industrial levels'. The target of limiting global warming to 1.5°C above pre-industrial levels is useful for conveying the urgency of the situation. However, it focuses the climate change debate on a temperature threshold (Section 3.3.2), while the potential impacts of these global warming levels on key sectors at local to regional scales, such as agriculture, energy and health, remain uncertain in most regions and countries of Africa (Sections 3.3.3, 3.3.4, 3.3.5 and 3.3.6).

Weber et al. (2018) found that at regional scales, temperature increases in sub-Saharan Africa are projected to be higher than the global mean temperature increase (at global warming of 1.5°C and at 2°C; see Section 3.3.2 for further background and analyses of climate model projections). Even if the mean global temperature anomaly is kept below 1.5°C, regions between 15°S and 15°N are projected to experience an increase in hot nights, as well as longer and more frequent heatwaves (e.g., Kharin et al., 2018). Increases would be even larger if the global mean temperature were to reach 2°C of global warming, with significant changes in the occurrence and intensity of temperature extremes in all sub-Saharan regions (Sections 3.3.1 and 3.3.2; Figures 3.4, 3.5 and 3.8).

West and Central Africa are projected to display particularly large increases in the number of hot days, both at 1.5°C and 2°C of global warming (Section 3.3.2). This is due to the relatively small interannual present-day variability in this region, which implies that climate-change signals can be detected earlier there (Section 3.3.2; Mahlstein et al., 2011). Projected changes in total precipitation exhibit uncertainties, mainly in the Sahel (Section 3.3.3 and Figure 3.8; Diedhiou et al., 2018). In the Guinea Coast and Central Africa, only a small change in total precipitation is projected, although most models (70%) indicate a decrease in the length of wet periods and a slight increase in heavy rainfall. Western Sahel is projected by most models (80%) to experience the strongest drying, with a significant increase in the maximum length of dry spells (Diedhiou et al., 2018). Above 2°C, this region could become more vulnerable to drought and could face serious food security issues (Cross-Chapter Box 6 and Section 3.4.6 in this chapter; Salem et al., 2017; Parkes et al., 2018). West Africa has thus been identified as a climate-change hotspot with negative impacts from climate change on crop yields and production (Cross-Chapter Box 6 and Section 3.4.6; Sultan and Gaetani, 2016; Palazzo et al., 2017). Despite uncertainty in projections for precipitation in West Africa, which is essential for rain-fed agriculture, robust evidence of yield loss might emerge. This yield loss is expected to be mainly driven by increased mean temperature, while potential wetter or drier conditions – as well as elevated CO_2 concentrations – could modulate this effect (Roudier et al., 2011; see also Cross-Chapter Box 6 and Section 3.4.6). Using Representative Concentration Pathway (RCP)8.5 Coordinated Regional Climate Downscaling Experiment (CORDEX) scenarios from 25 regional climate models (RCMs) forced with different general circulation models (GCMs), Klutse et al. (2018) noted a decrease in mean rainfall over West Africa in models with stronger warming for this region at 1.5°C of global warming (Section 3.3.4). Mba et al. (2018) used a similar approach and found a lack of consensus in the changes in precipitation over Central Africa (Figure 3.8 and Section 3.3.4), although there was a tendency towards a decrease in the maximum number of consecutive wet days (CWD) and a significant increase in the maximum number of consecutive dry days (CDD).

Over southern Africa, models agree on a positive sign of change for temperature, with temperature rising faster at 2°C (1.5°C–2.5°C) as compared to 1.5°C (0.5°C–1.5°C) of global warming. Areas in the south-western region, especially in South Africa and parts of Namibia and Botswana, are expected to experience the largest increases in temperature (Section 3.3.2; Engelbrecht et al., 2015; Maúre et al., 2018). The western part of southern Africa is projected to become drier with increasing drought frequency and number of heatwaves towards the end of the 21st century (Section 3.3.4; Engelbrecht et al., 2015; Dosio, 2017; Maúre et al., 2018). At 1.5°C, a robust signal of precipitation reduction is found over the Limpopo basin and smaller areas of the Zambezi basin in Zambia, as well as over parts of Western Cape in South Africa, while an increase is projected over central and western South Africa, as well as in southern Namibia (Section 3.3.4). At 2°C, the region is projected to face robust precipitation decreases of about 10–20% and increases in the number of CDD, with longer dry spells projected over Namibia, Botswana, northern Zimbabwe and southern Zambia. Conversely, the number of CWD is projected to decrease, with robust signals over Western Cape (Maúre et al., 2018). Projected reductions in stream flow of 5–10% in the Zambezi River basin have been associated with increased evaporation and transpiration rates resulting from a rise in temperature (Section 3.3.5; Kling et al., 2014), with issues for hydroelectric power across the region of southern Africa.

For Eastern Africa, Osima et al. (2018) found that annual rainfall projections show a robust increase in precipitation over Somalia and a less robust decrease over central and northern Ethiopia (Section 3.3.3). The number of CDD and CWD are projected to increase and decrease, respectively (Section 3.3.4). These projected changes could impact the agricultural and water sectors in the region (Cross-Chapter Box 6 in this chapter and Section 3.4.6).

under the RCP8.5 scenario. However, more recent assessments have highlighted uncertainties in dryness projections due to a range of factors, including variations between the drought and dryness indices considered, and the effects of enhanced CO_2 concentrations on plant water-use efficiency (Orlowsky and Seneviratne, 2013; Roderick et al., 2015). Overall, projections of changes in drought and dryness for high-emissions scenarios (e.g., RCP8.5, corresponding to about 4°C of global warming) are uncertain in many regions, although a few regions display consistent drying in most assessments (e.g., Seneviratne et al., 2012; Orlowsky and Seneviratne, 2013). Uncertainty is expected to be even larger for conditions with a smaller signal-to-noise ratio, such as for global warming levels of 1.5°C and 2°C.

Some published literature is now available on the evaluation of differences in drought and dryness occurrence at 1.5°C and 2°C of global warming for (i) precipitation minus evapotranspiration (P–E, a general measure of water availability; Wartenburger et al., 2017; Greve et al., 2018), (ii) soil moisture anomalies (Lehner et al., 2017; Wartenburger et al., 2017), (iii) consecutive dry days (CDD) (Schleussner et al., 2016b; Wartenburger et al., 2017), (iv) the 12-month standardized precipitation index (Wartenburger et al., 2017), (v) the Palmer drought severity index (Lehner et al., 2017), and (vi) annual mean runoff (Schleussner et al., 2016b, see also next section). These analyses have produced consistent findings overall, despite the known sensitivity of drought assessments to chosen drought indices (see above paragraph). These analyses suggest that increases in drought, dryness or precipitation deficits are projected at 1.5°C or 2°C global warming in some regions compared to the pre-industrial or present-day conditions, as well as between these two global warming levels, although there is substantial variability in signals depending on the considered indices or climate models (Lehner et al., 2017; Schleussner et al., 2017; Greve et al., 2018) (*medium confidence*). Generally, the clearest signals are found for the Mediterranean region (*medium confidence*).

Greve et al. (2018, Figure 3.12) derives the sensitivity of regional changes in precipitation minus evapotranspiration to global temperature changes. The simulations analysed span the full range of available emission scenarios, and the sensitivities are derived using a modified pattern scaling approach. The applied approach assumes linear dependencies on global temperature changes while thoroughly addressing associated uncertainties via resampling methods. Northern high-latitude regions display robust responses tending towards increased wetness, while subtropical regions display a tendency towards drying but with a large range of responses. While the internal variability and the scenario choice play an important role in the overall spread of the simulations, the uncertainty stemming from the climate model choice usually dominates, accounting for about half of the total uncertainty in most regions (Wartenburger et al., 2017; Greve et al., 2018). The sign of projections, that is, whether there might be increases or decreases in water availability under higher global warming levels, is particularly uncertain in tropical and mid-latitude regions. An assessment of the implications of limiting the global mean temperature increase to values below (i) 1.5°C or (ii) 2°C shows that constraining global warming to the 1.5°C target might slightly influence the mean

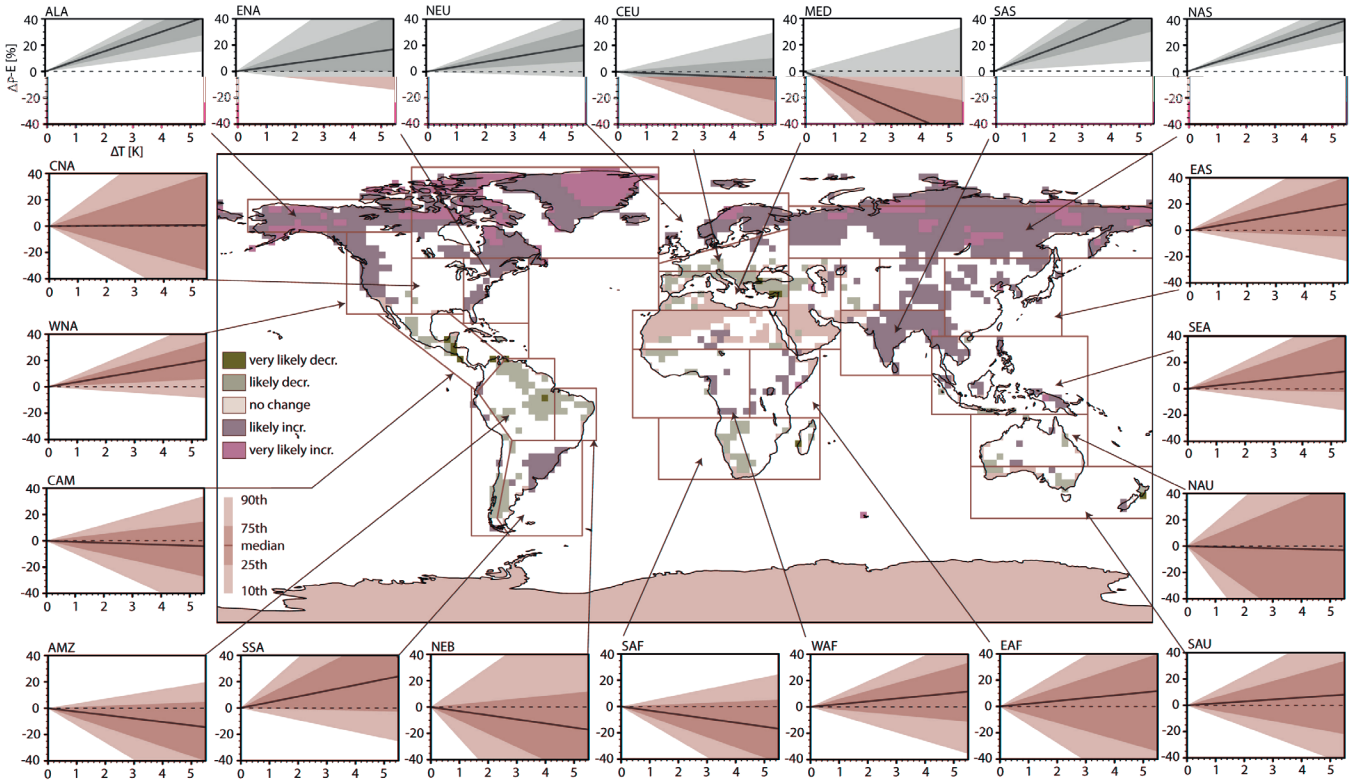


Figure 3.12 | Summary of the likelihood of increases/decreases in precipitation minus evapotranspiration (P–E) in Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations considering all scenarios and a representative subset of 14 climate models (one from each modelling centre). Panel plots show the uncertainty distribution of the sensitivity of P–E to global temperature change, averaged for most IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (see Figure 3.2) outlined in the map (from Greve et al., 2018).

response but could substantially reduce the risk of experiencing extreme changes in regional water availability (Greve et al., 2018).

The findings from the analysis for the mean response by Greve et al. (2018) are qualitatively consistent with results from Wartenburger et al. (2017), who used an ESR (Section 3.2) rather than a pattern scaling approach for a range of drought and dryness indices. They are also consistent with a study by Lehner et al. (2017), who assessed changes in droughts based on soil moisture changes and the Palmer-Drought Severity Index. Notably, these two publications do not provide a specific assessment of changes in the tails of the drought and dryness distribution. The conclusions of Lehner et al. (2017) are that (i) 'risks of consecutive drought years show little change in the US Southwest and Central Plains, but robust increases in Europe and the Mediterranean', and that (ii) 'limiting warming to 1.5°C may have benefits for future drought risk, but such benefits are regional, and in some cases highly uncertain'.

Figure 3.13 features projected changes in CDD as a function of global temperature increase, using a similar approach as for Figures 3.5 (based

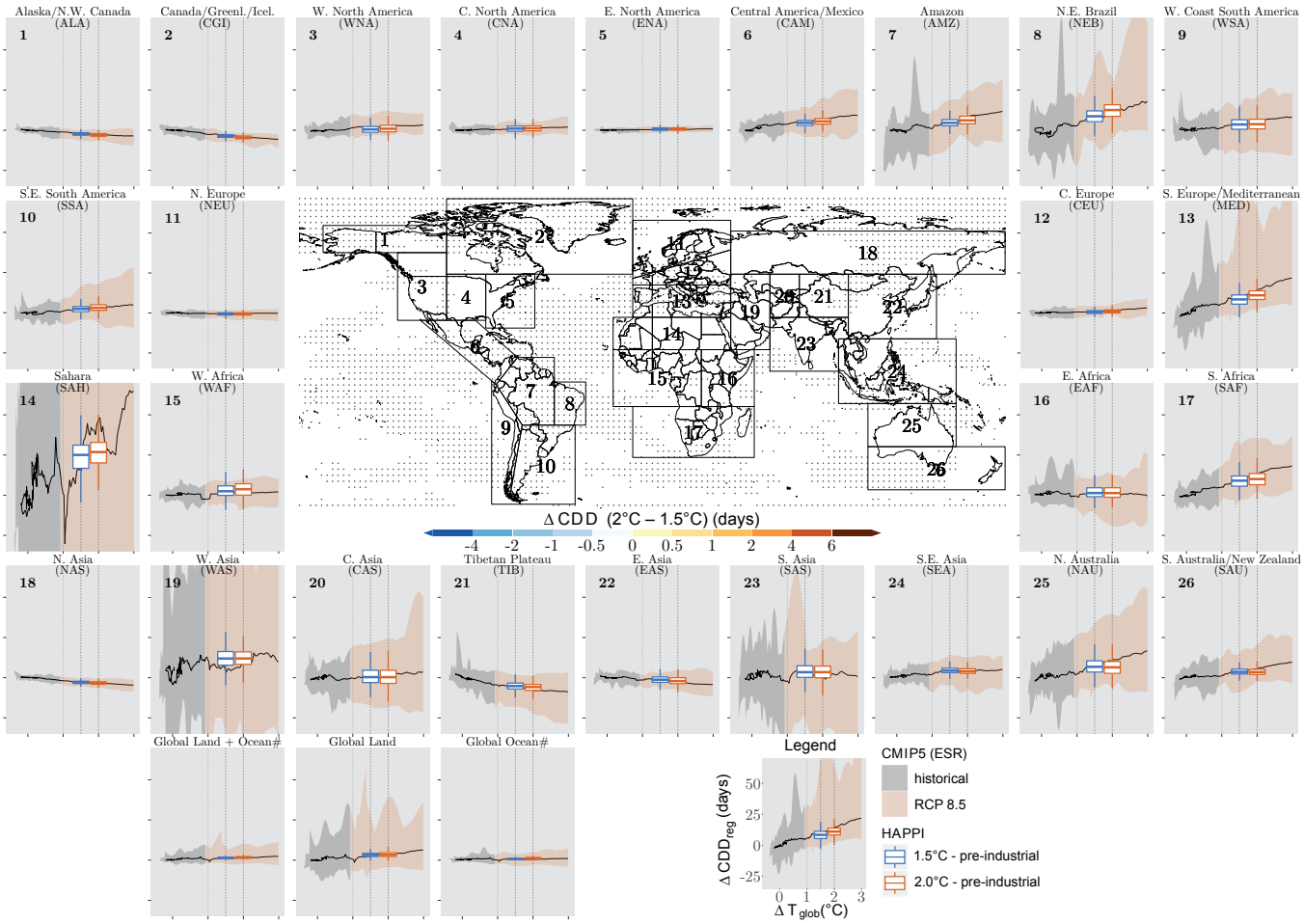


Figure 3.13 | Projected changes in consecutive dry days (CDD) as a function of global warming for IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions, based on an empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data together with projected changes from the HAPPI multimodel experiment (bar plots on regional analyses and central plot, respectively). The underlying methodology and the data basis are the same as for Figure 3.5 (see Supplementary Material 3.SM.2 for more details).

	Global Land	ALA	AMZ	CAM	CAS	CEU	CGI	CNA	EAF	EAS	ENA	MED	NAS	NAU	NEB	NEU	SAF	SAH	SAS	SAU	SEA	SSA	TIB	WAF	WAS	WNA	WSA
CDD	+	-	+	+	+	+	-	+	+	-	-	+	-	+	+	+	+	+	+	+	-	+	-	+	+	-	+
P – E	+	+	+	-	+	+	+	+	+	+	-	-	+	-	-	+	-	-	+	-	+	+	-	+	-	+	-
SMA	-	+	-	-	-	-	-	+	+	-	-	-	-	-	-	+	-	-	-	-	-	+	+	-	-	+	-
SPI12	+	+	-	+	+	+	+	+	-	+	+	-	+	-	-	+	-	-	-	-	+	-	+	-	-	+	+

Figure 3.14 | Significance of differences in regional drought and dryness indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: CDD: consecutive dry days; P–E: precipitation minus evapotranspiration; SMA: soil moisture anomalies; SPI12: 12-month Standarized Precipitation Index. Columns indicate analysed regions and global land (see Figure 3.2 for definitions). Significant differences are shown in light blue/brown shading (increases indicated with +, decreases indicated with –; light blue shading indicates decreases in dryness (decreases in CDD, or increases in P–E, SMA or SPI12) and light brown shading indicates increases in dryness (increases in CDD, or decreases in P–E, SMA or SPI12). Non-significant differences are shown in grey shading. The underlying methodology and the data basis are the same as for Figure 3.7 (see Supplementary Material 3.SM.2 for more details).

on Wartenburger et al., 2017). The figure also include results from the HAPPI experiment (Mitchell et al., 2017). Again, the CMIP5-based ESR estimates and the results of the HAPPI experiment agree well. Note that the responses vary widely among the considered regions.

Similar to Figures 3.8 and 3.11, Figure 3.14 features an objective identification of 'hotspots' / key risks in dryness indices subdivided by region, based on the approach by Wartenburger et al. (2017). This analysis reveals the following hotspots of drying (i.e. increases in CDD and/or decreases in P–E, soil moisture anomalies (SMA) and 12-month Standardized Precipitation Index (SPI12), with at least one of the indices displaying statistically significant drying): the Mediterranean region (MED; including southern Europe, northern Africa, and the Near East), northeastern Brazil (NEB) and southern Africa.

Consistent with this analysis, the available literature particularly supports robust increases in dryness and decreases in water availability in southern Europe and the Mediterranean with a shift from 1.5°C to 2°C of global warming (*medium confidence*) (Figure 3.13; Schleussner et al., 2016b; Lehner et al., 2017; Wartenburger et al., 2017; Greve et al., 2018; Samaniego et al., 2018). This region is already displaying substantial drying in the observational record (Seneviratne et al., 2012; Sheffield et al., 2012; Greve et al., 2014; Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017), which provides additional evidence supporting this tendency and suggests that it will be a hotspot of dryness change at global warming levels beyond 1.5°C (see also Box 3.2). The other identified hotspots, southern Africa and northeastern Brazil, also consistently display drying trends under higher levels of forcing in other publications (e.g., Orlowsky and Seneviratne, 2013), although no published studies could be found reporting observed drying trends in these regions. There are substantial increases in the risk of increased dryness (*medium confidence*) in both the Mediterranean region and Southern Africa at 2°C versus 1.5°C of global warming because these regions display significant changes in two dryness indicators (CDD and SMA) between these two global warming levels (Figure 3.14); the strongest effects are expected for extreme droughts (*medium confidence*) (Figure 3.12). There is *low confidence* elsewhere, owing to a lack of consistency in analyses with different models or different dryness indicators. However, in many regions there is *medium confidence* that most extreme risks of changes in dryness are avoided if global warming is constrained at 1.5°C instead of 2°C (Figure 3.12).

In summary, in terms of drought and dryness, limiting global warming to 1.5°C is expected to substantially reduce the probability of extreme changes in water availability in some regions compared to changes under 2°C of global warming (*medium confidence*). For shift from 1.5°C to 2°C of GMST warming, the available studies and analyses suggest strong increases in the probability of dryness and reduced water availability in the Mediterranean region (including southern Europe, northern Africa and the Near East) and in southern Africa (*medium confidence*). Based on observations and modelling experiments, a drying trend is already detectable in the Mediterranean region, that is, at global warming of less than 1°C (*medium confidence*).

Box 3.2 | Droughts in the Mediterranean Basin and the Middle East

Human society has developed in tandem with the natural environment of the Mediterranean basin over several millennia, laying the groundwork for diverse and culturally rich communities. Even if advances in technology may offer some protection from climatic hazards, the consequences of climatic change for inhabitants of this region continue to depend on the long-term interplay between an array of societal and environmental factors (Holmgren et al., 2016). As a result, the Mediterranean is an example of a region with high vulnerability where various adaptation responses have emerged. Previous IPCC assessments and recent publications project regional changes in climate under increased temperatures, including consistent climate model projections of increased precipitation deficit amplified by strong regional warming (Section 3.3.3; Seneviratne et al., 2012; Christensen et al., 2013; Collins et al., 2013; Greve and Seneviratne, 2015).

The long history of resilience to climatic change is especially apparent in the eastern Mediterranean region, which has experienced a strong negative trend in precipitation since 1960 (Mathbout et al., 2017) and an intense and prolonged drought episode between 2007 and 2010 (Kelley et al., 2015). This drought was the longest and most intense in the last 900 years (Cook et al., 2016). Some authors (e.g., Trigo et al., 2010; Kelley et al., 2015) assert that very low precipitation levels have driven a steep decline in agricultural productivity in the Euphrates and Tigris catchment basins, and displaced hundreds of thousands of people, mainly in Syria. Impacts on the water resources (Yazdanpanah et al., 2016) and crop performance in Iran have also been reported (Saeidi et al., 2017). Many historical periods of turmoil have coincided with severe droughts, for example the drought which occurred at the end of the Bronze Age approximately 3200 years ago (Kaniewski et al., 2015). In this instance, a number of flourishing eastern Mediterranean civilizations collapsed, and rural settlements re-emerged with agro-pastoral activities and limited long-distance trade. This illustrates how some vulnerable regions are forced to pursue drastic adaptive responses, including migration and societal structure changes.

The potential evolution of drought conditions under 1.5°C or 2°C of global warming (Section 3.3.4) can be analysed by comparing the 2008 drought (high temperature, low precipitation) with the 1960 drought (low temperature, low precipitation) (Kelley et al., 2015). Though the precipitation deficits were comparable, the 2008 drought was amplified by increased evapotranspiration induced by much higher temperatures (a mean increase of 1°C compared with the 1931–2008 period in Syria) and a large population increase (from

Box 3.2 (continued)

5 million in 1960 to 22 million in 2008). Koutroulis et al. (2016) reported that only 6% out of the total 18% decrease in water availability projected for Crete under 2°C of global warming at the end of the 21st century would be due to decreased precipitation, with the remaining 12% due to an increase in evapotranspiration. This study and others like it confirm an important risk of extreme drought conditions for the Middle East under 1.5°C of global warming (Jacob et al., 2018), with risks being even higher in continental locations than on islands; these projections are consistent with current observed changes (Section 3.3.4; Greve et al., 2014). Risks of drying in the Mediterranean region could be substantially reduced if global warming is limited to 1.5°C compared to 2°C or higher levels of warming (Section 3.4.3; Guiot and Cramer, 2016). Higher warming levels may induce high levels of vulnerability exacerbated by large changes in demography.

3.3.5 Runoff and Fluvial Flooding

3.3.5.1 Observed and attributed changes in runoff and river flooding

There has been progress since AR5 in identifying historical changes in streamflow and continental runoff. Using the available streamflow data, Dai (2016) showed that long-term (1948–2012) flow trends are statistically significant only for 27.5% of the world's 200 major rivers, with negative trends outnumbering the positive ones. Although streamflow trends are mostly not statistically significant, they are consistent with observed regional precipitation changes. From 1950 to 2012, precipitation and runoff have increased over southeastern South America, central and northern Australia, the central and northeastern United States, central and northern Europe, and most of Russia, and they have decreased over most of Africa, East and South Asia, eastern coastal Australia, the southeastern and northwestern United States, western and eastern Canada, the Mediterranean region and some regions of Brazil (Dai, 2016).

A large part of the observed regional trends in streamflow and runoff might have resulted from internal multi-decadal and multi-year climate variations, especially the Pacific decadal variability (PDV), the Atlantic Multi-Decadal Oscillation (AMO) and the El Niño–Southern Oscillation (ENSO), although the effect of anthropogenic greenhouse gases and aerosols could also be important (Hidalgo et al., 2009; Gu and Adler, 2013, 2015; Chiew et al., 2014; Luo et al., 2016; Gudmundsson et al., 2017). Additionally, other human activities can influence the hydrological cycle, such as land-use/land-cover change, modifications in river morphology and water table depth, construction and operation of hydropower plants, dikes and weirs, wetland drainage, and agricultural practices such as water withdrawal for irrigation. All of these activities can also have a large impact on runoff at the river basin scale, although there is less agreement over their influence on global mean runoff (Gerten et al., 2008; Sterling et al., 2012; Hall et al., 2014; Betts et al., 2015; Arheimer et al., 2017). Some studies suggest that increases in global runoff resulting from changes in land cover or land use (predominantly deforestation) are counterbalanced by decreases resulting from irrigation (Gerten et al., 2008; Sterling et al., 2012). Likewise, forest and grassland fires can modify the hydrological response at the watershed scale when the burned area is significant (Versini et al., 2013; Springer et al., 2015; Wine and Cadol, 2016).

Few studies have explored observed changes in extreme streamflow and river flooding since the IPCC AR5. Mallakpour and Villarini (2015) analysed changes of flood magnitude and frequency in the central United States by considering stream gauge daily records with at least 50 years of data ending no earlier than 2011. They showed that flood frequency has increased, whereas there was limited evidence of a decrease in flood magnitude in this region. Stevens et al. (2016) found a rise in the number of reported floods in the United Kingdom during the period 1884–2013, with flood events appearing more frequently towards the end of the 20th century. A peak was identified in 2012, when annual rainfall was the second highest in over 100 years. Do et al. (2017) computed the trends in annual maximum daily streamflow data across the globe over the 1966–2005 period. They found decreasing trends for a large number of stations in western North America and Australia, and increasing trends in parts of Europe, eastern North America, parts of South America, and southern Africa.

In summary, streamflow trends since 1950 are not statistically significant in most of the world's largest rivers (*high confidence*), while flood frequency and extreme streamflow have increased in some regions (*high confidence*).

3.3.5.2 Projected changes in runoff and river flooding at 1.5°C versus 2°C of global warming

Global-scale assessments of projected changes in freshwater systems generally suggest that areas with either positive or negative changes in mean annual streamflow are smaller for 1.5°C than for 2°C of global warming (Betts et al., 2018; Döll et al., 2018). Döll et al. (2018) found that only 11% of the global land area (excluding Greenland and Antarctica) shows a statistically significantly larger hazard at 2°C than at 1.5°C. Significant decreases are found for 13% of the global land area for both global warming levels, while significant increases are projected to occur for 21% of the global land area at 1.5°C, and rise to between 26% (Döll et al., 2018) and approximately 50% (Betts et al., 2018) at 2°C.

At the regional scale, projected runoff changes generally follow the spatial extent of projected changes in precipitation (see Section 3.3.3). Emerging literature includes runoff projections for different warming levels. For 2°C of global warming, an increase in runoff is projected for much of the high northern latitudes, Southeast Asia, East Africa, northeastern Europe, India, and parts of, Austria, China, Hungary, Norway, Sweden, the northwest Balkans and Sahel (Schleussner et al., 2016b; Donnelly et al., 2017; Döll et al., 2018; Zhai et al., 2018). Additionally, decreases are projected in the Mediterranean region, southern Australia, Central America, and central and southern South

America (Schleussner et al., 2016b; Donnelly et al., 2017; Döll et al., 2018). Differences between 1.5°C and 2°C would be most prominent in the Mediterranean, where the median reduction in annual runoff is expected to be about 9% (likely range 4.5–15.5%) at 1.5°C, while at 2°C of warming runoff could decrease by 17% (likely range 8–25%) (Schleussner et al., 2016b). Consistent with these projections, Döll et al. (2018) found that statistically insignificant changes in the mean annual streamflow around the Mediterranean region became significant when the global warming scenario was changed from 1.5°C to 2°C, with decreases of 10–30% between these two warming levels. Donnelly et al. (2017) found an intense decrease in runoff along both the Iberian and Balkan coasts with an increase in warming level.

Basin-scale projections of river runoff at different warming levels are available for many regions. Betts et al. (2018) assessed runoff changes in 21 of the world's major river basins at 1.5°C and 2°C of global warming (Figure 3.15). They found a general tendency towards increased runoff, except in the Amazon, Orange, Danube and Guadiana basins where the range of projections indicate decreased mean flows (Figure 3.13). In the case of the Amazon, mean flows are projected to decline by up to 25% at 2°C global warming (Betts et al., 2018). Gosling et al. (2017) analysed the impact of global warming of 1°C, 2°C and 3°C above pre-industrial levels on river runoff at the catchment scale, focusing on eight major rivers in different continents: Upper Amazon, Darling, Ganges, Lena, Upper Mississippi, Upper Niger, Rhine and Tagus. Their results show that the sign and magnitude of change with global warming for the Upper Amazon, Darling, Ganges, Upper Niger and Upper Mississippi is unclear, while the Rhine and Tagus may experience decreases in projected runoff and the Lena may experience increases. Donnelly et al. (2017) analysed the mean flow response to different warming levels for six major European rivers: Glomma, Wisla, Lule, Ebro, Rhine and Danube. Consistent with the increases in mean runoff projected for large parts of northern Europe, the Glomma, Wisla and Lule rivers could experience increased discharges with global warming while discharges from the Ebro could decrease, in part due to a decrease in runoff in southern Europe. In the case of the Rhine and Danube rivers, Donnelly et al. (2017) did not find clear results. Mean annual runoff of the Yiluo River catchment in northern China is projected to decrease by 22% at 1.5°C and by 21% at 2°C, while the mean annual runoff for the Beijiang River catchment in southern China is projected to increase by less than 1% at 1.5°C and 3% at 2°C in comparison to the studied baseline period (L. Liu et al., 2017).

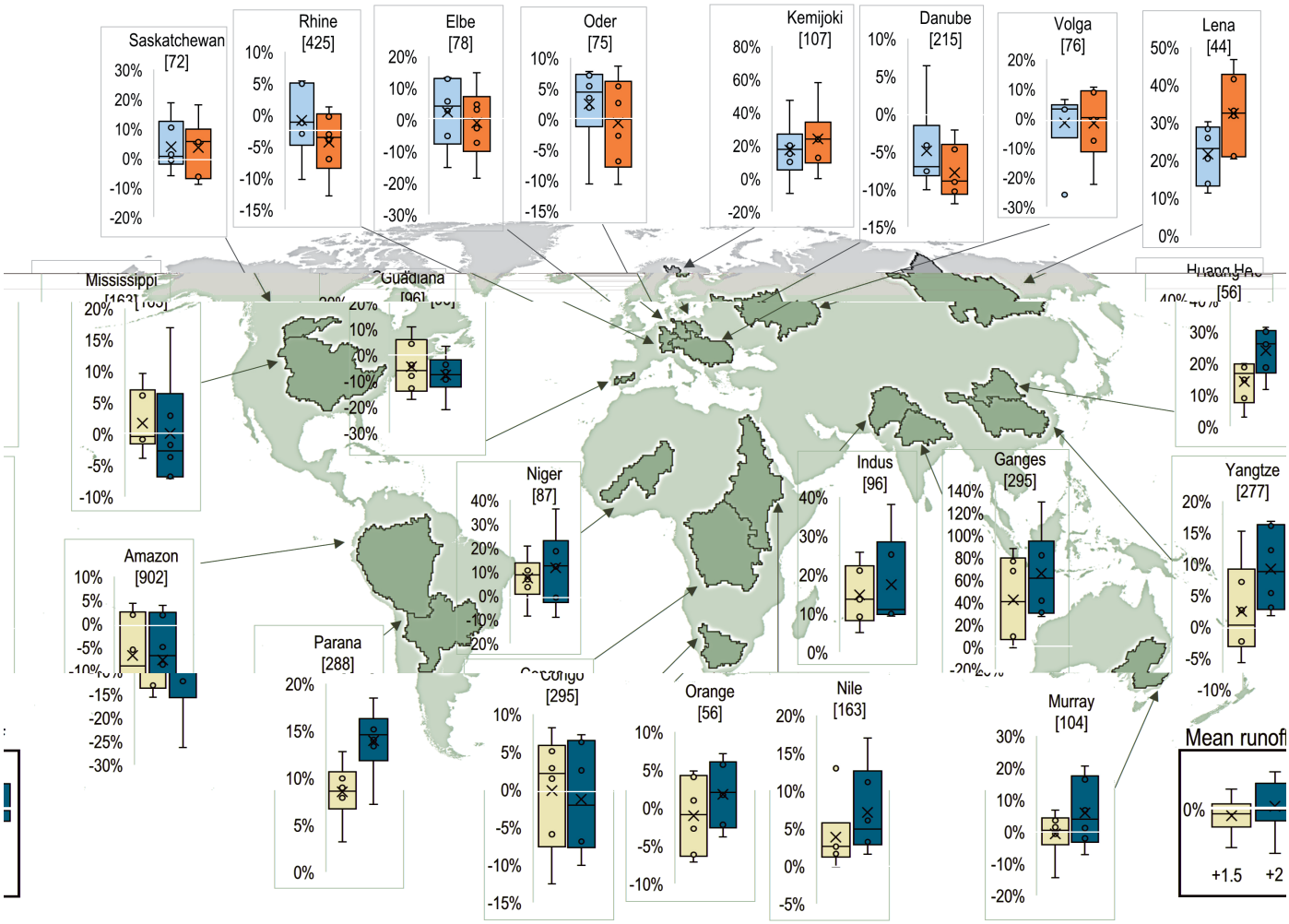


Figure 3.15 | Runoff changes in twenty-one of the world's major river basins at 1.5°C (blue) and 2°C (orange) of global warming, simulated by the Joint UK Land Environment Simulator (JULES) ecosystem–hydrology model under the ensemble of six climate projections. Boxes show the 25th and 75th percentile changes, whiskers show the range, circles show the four projections that do not define the ends of the range, and crosses show the ensemble means. Numbers in square brackets show the ensemble-mean flow in the baseline (millimetres of rain equivalent) (Source: Betts et al., 2018).

Chen et al. (2017) assessed the future changes in water resources in the Upper Yangtze River basin for the same warming levels and found a slight decrease in the annual discharge at 1.5°C but a slight increase at 2°C. Montroull et al. (2018) studied the hydrological impacts of the main rivers (Paraguay, Paraná, Iguazú and Uruguay) in La Plata basin in South America under 1.5°C and 2°C of global warming and for two emissions scenarios. The Uruguay basin shows increases in streamflow for all scenarios/warming targets except for the combination of RCP8.5/1.5°C of warming. The increase is approximately 15% above the 1981–2000 reference period for 2°C of global warming and the RCP4.5 scenario. For the other three rivers the sign of the change in mean streamflow depends strongly on the RCP and GCM used.

Marx et al. (2018) analysed how hydrological low flows in Europe are affected under different global warming levels (1.5°C, 2°C and 3°C). The Alpine region showed the strongest low flow increase, from 22% at 1.5°C to 30% at 2°C, because of the relatively large snow melt contribution, while in the Mediterranean low flows are expected to decrease because of the decreases in annual precipitation projected for that region. Döll et al. (2018) found that extreme low flows in the tropical Amazon, Congo and Indonesian basins could decrease by 10% at 1.5°C, whereas they could increase by 30% in the southwestern part of Russia under the same warming level. At 2°C, projected increases in extreme low flows are exacerbated in the higher northern latitudes and in eastern Africa, India and Southeast Asia, while projected decreases intensify in the Amazon basin, western United States, central Canada, and southern and western Europe, although not in the Congo basin or Indonesia, where models show less agreement.

Recent analyses of projections in river flooding and extreme runoff and flows are available for different global warming levels. At the global scale, Alfieri et al. (2017) assessed the frequency and magnitude of river floods and their impacts under 1.5°C, 2°C and 4°C global warming scenarios. They found that flood events with an occurrence interval longer than the return period of present-day flood protections are projected to increase in all continents under all considered warming levels, leading to a widespread increment in the flood hazard. Döll et al. (2018) found that high flows are projected to increase significantly on 11% and 21% of the global land area at 1.5°C and 2°C, respectively. Significantly increased high flows are expected to occur in South and Southeast Asia and Central Africa at 1.5°C, with this effect intensifying and including parts of South America at 2°C.

Regarding the continental scale, Donnelly et al. (2017) and Thober et al. (2018) explored climate change impacts on European high flows and/or floods under 1.5°C, 2°C and 3°C of global warming. Thober et al. (2018) identified the Mediterranean region as a hotspot of change, with significant decreases in high flows of –11% and –13% at 1.5°C and 2°C, respectively, mainly resulting from reduced precipitation (Box 3.2). In northern regions, high flows are projected to rise by 1% and 5% at 1.5°C and 2°C, respectively, owing to increasing precipitation, although floods could decrease by 6% in both scenarios because of less snowmelt. Donnelly et al. (2017) found that high runoff levels could rise in intensity, robustness and spatial extent over large parts of continental Europe with an increasing warming level. At 2°C, flood magnitudes are expected to increase significantly in Europe south of 60°N, except for some regions (Bulgaria, Poland and southern Spain); in contrast, they are projected to decrease at higher latitudes (e.g., in most of Finland, northwestern Russia and northern Sweden), with the exception of southern Sweden and some coastal areas in Norway where flood magnitudes may increase (Roudier et al., 2016). At the basin scale, Mohammed et al. (2017) found that floods are projected to be more frequent and flood magnitudes greater at 2°C than at 1.5°C in the Brahmaputra River in Bangladesh. In coastal regions, increases in heavy precipitation associated with tropical cyclones (Section 3.3.6) combined with increased sea levels (Section 3.3.9) may lead to increased flooding (Section 3.4.5).

In summary, there is *medium confidence* that global warming of 2°C above the pre-industrial period would lead to an expansion of the area with significant increases in runoff, as well as the area affected by flood hazard, compared to conditions at 1.5°C of global warming. A global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium confidence*) and to an increase in flood hazard in some regions (*medium confidence*) compared to present-day conditions.

3.3.6 Tropical Cyclones and Extratropical Storms

Most recent studies on observed trends in the attributes of tropical cyclones have focused on the satellite era starting in 1979 (Rienecker et al., 2011), but the study of observed trends is complicated by the heterogeneity of constantly advancing remote sensing techniques and instrumentation during this period (e.g., Landsea, 2006; Walsh et al., 2016). Numerous studies leading up to and after AR5 have reported a decreasing trend in the global number of tropical cyclones and/or the globally accumulated cyclonic energy (Emanuel, 2005; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Klotzbach and Landsea, 2015; Walsh et al., 2016). A theoretical physical basis for such a decrease to occur under global warming was recently provided by Kang and Elsner (2015). However, using a relatively short (20 year) and relatively homogeneous remotely sensed record, Klotzbach (2006) reported no significant trends in global cyclonic activity, consistent with more recent findings of Holland and Bruyère (2014). Such contradictions, in combination with the fact that the almost four-decade-long period of remotely sensed observations remains relatively short to distinguish anthropogenically induced trends from decadal and multi-decadal variability, implies that there is only *low confidence* regarding changes in global tropical cyclone numbers under global warming over the last four decades.

Studies in the detection of trends in the occurrence of very intense tropical cyclones (category 4 and 5 hurricanes on the Saffir-Simpson scale) over recent decades have yielded contradicting results. Most studies have reported increases in these systems (Emanuel, 2005; Webster et al., 2005; Klotzbach, 2006; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Walsh et al., 2016), in particular for the North Atlantic, North Indian and South Indian Ocean basins (e.g., Singh et al., 2000; Singh, 2010; Kossin et al., 2013; Holland and Bruyère, 2014; Walsh et al., 2016). In the North Indian Ocean over the Arabian Sea, an increase in the frequency of extremely severe cyclonic storms has been reported and attributed to anthropogenic warming (Murakami et al., 2017). However, to the east over the Bay of Bengal, tropical cyclones and severe tropical cyclones have exhibited decreasing trends over

the period 1961–2010, although the ratio between severe tropical cyclones and all tropical cyclones is increasing (Mohapatra et al., 2017). Moreover, studies that have used more homogeneous records, but were consequently limited to rather short periods of 20 to 25 years, have reported no statistically significant trends or decreases in the global number of these systems (Kamahori et al., 2006; Klotzbach and Landsea, 2015). Likewise, CMIP5 model simulations of the historical period have not produced anthropogenically induced trends in very intense tropical cyclones (Bender et al., 2010; Knutson et al., 2010, 2013; Camargo, 2013; Christensen et al., 2013), consistent with the findings of Klotzbach and Landsea (2015). There is consequently *low confidence* in the conclusion that the number of very intense cyclones is increasing globally.

General circulation model (GCM) projections of the changing attributes of tropical cyclones under high levels of greenhouse gas forcing (3°C to 4°C of global warming) consistently indicate decreases in the global number of tropical cyclones (Knutson et al., 2010, 2015; Sugi and Yoshimura, 2012; Christensen et al., 2013; Yoshida et al., 2017). A smaller number of studies based on statistical downscaling methodologies contradict these findings, however, and indicate increases in the global number of tropical cyclones under climate change (Emanuel, 2017). Most studies also indicate increases in the global number of very intense tropical cyclones under high levels of global warming (Knutson et al., 2015; Sugi et al., 2017), consistent with dynamic theory (Kang and Elsner, 2015), although a few studies contradict this finding (e.g., Yoshida et al., 2017). Hence, it is assessed that under 3°C to 4°C of warming that the global number of tropical cyclones would decrease whilst the number of very intense cyclones would increase (*medium confidence*).

To date, only two studies have directly explored the changing tropical cyclone attributes under 1.5°C versus 2°C of global warming. Using a high resolution global atmospheric model, Wehner et al. (2018a) concluded that the differences in tropical cyclone statistics under 1.5°C versus 2°C stabilization scenarios, as defined by the HAPPI protocols (Mitchell et al., 2017) are small. Consistent with the majority of studies performed for higher degrees of global warming, the total number of tropical cyclones is projected to decrease under global warming, whilst the most intense (categories 4 and 5) cyclones are projected to occur more frequently. These very intense storms are projected to be associated with higher peak wind speeds and lower central pressures under 2°C versus 1.5°C of global warming. The accumulated cyclonic energy is projected to decrease globally from 1.5°C to 2°C, in association with a decrease in the global number of tropical cyclones under progressively higher levels of global warming. It is also noted that heavy rainfall associated with tropical cyclones was assessed in the IPCC SREX as *likely* to increase under increasing global warming (Seneviratne et al., 2012). Two recent articles suggest that there is *high confidence* that the current level of global warming (i.e., about 1°C, see Section 3.3.1) increased the heavy precipitation associated with the 2017 Hurricane Harvey by about 15% or more (Risser and Wehner, 2017; van Oldenborgh et al., 2017). Hence, it can be inferred, under the assumption of linear dynamics, that further increases in heavy precipitation would occur under 1.5°C, 2°C and higher levels of global warming (*medium confidence*). Using a high resolution regional climate model, Muthige et al. (2018) explored the effects of different degrees of global warming on tropical cyclones over the southwest Indian Ocean, using transient simulations that downscaled a number of RCP8.5 GCM projections. Decreases in tropical cyclone frequencies are projected under both 1.5°C and 2°C of global warming. The decreases in cyclone frequencies under 2°C of global warming are somewhat larger than under 1.5°C, but no further decreases are projected under 3°C. This suggests that 2°C of warming, at least in these downscaling simulations, represents a type of stabilization level in terms of tropical cyclone formation over the southwest Indian Ocean and landfall over southern Africa (Muthige et al., 2018). There is thus *limited evidence* that the global number of tropical cyclones will be lower under 2°C compared to 1.5°C of global warming, but with an increase in the number of very intense cyclones (*low confidence*).

The global response of the mid-latitude atmospheric circulation to 1.5°C and 2°C of warming was investigated using the HAPPI ensemble with a focus on the winter season (Li et al., 2018). Under 1.5°C of global warming a weakening of storm activity over North America, an equatorward shift of the North Pacific jet exit and an equatorward intensification of the South Pacific jet are projected. Under an additional 0.5°C of warming a poleward shift of the North Atlantic jet exit and an intensification on the flanks of the Southern Hemisphere storm track are projected to become more pronounced. The weakening of the Mediterranean storm track that is projected under low mitigation emerges in the 2°C warmer world (Li et al., 2018). AR5 assessed that under high greenhouse gas forcing (3°C or 4°C of global warming) there is *low confidence* in projections of poleward shifts of the Northern Hemisphere storm tracks, while there is *high confidence* that there would be a small poleward shift of the Southern Hemisphere storm tracks (Stocker et al., 2013). In the context of this report, the assessment is that there is *limited evidence* and *low confidence* in whether any projected signal for higher levels of warming would be clearly manifested under 2°C of global warming.

3.3.7 Ocean Circulation and Temperature

It is *virtually certain* that the temperature of the upper layers of the ocean (0–700 m in depth) has been increasing, and that the global mean for sea surface temperature (SST) has been changing at a rate just behind that of GMST. The surfaces of three ocean basins has warmed over the period 1950–2016 (by 0.11°C, 0.07°C and 0.05°C per decade for the Indian, Atlantic and Pacific Oceans, respectively; Hoegh-Guldberg et al., 2014), with the greatest changes occurring at the highest latitudes. Isotherms (i.e., lines of equal temperature) of sea surface temperature (SST) are shifting to higher latitudes at rates of up to 40 km per year (Burrows et al., 2014; García Molinos et al., 2015). Long-term patterns of variability make detecting signals due to climate change complex, although the recent acceleration of changes to the temperature of the surface layers of the ocean has made the climate signal more distinct (Hoegh-Guldberg et al., 2014). There is also evidence of significant increases in the frequency of marine heatwaves in the observational record (Oliver et al., 2018), consistent with changes in mean ocean temperatures (*high confidence*). Increasing climate extremes in the ocean are associated with the general rise in global average surface temperature, as well as more intense patterns of climate variability (e.g., climate change intensification of ENSO) (Section 3.5.2.5). Increased heat in the upper layers of the ocean is

also driving more intense storms and greater rates of inundation in some regions, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas (Section 3.3.6).

Increasing land–sea temperature gradients have the potential to strengthen upwelling systems associated with the eastern boundary currents (Benguela, Canary, Humboldt and Californian Currents; Bakun, 1990). Observed trends support the conclusion that a general strengthening of longshore winds has occurred (Sydeman et al., 2014), but the implications of trends detected in upwelling currents themselves are unclear (Lluch-Cota et al., 2014). Projections of the scale of changes between 1°C and 1.5°C of global warming and between 1.5°C and 2°C are only informed by the changes during the past increase in GMST of 0.5°C (*low confidence*). However, evidence from GCM projections of future climate change indicates that a general strengthening of the Benguela, Canary and Humboldt upwelling systems under enhanced anthropogenic forcing (D. Wang et al., 2015) is projected to occur (*medium confidence*). This strengthening is projected to be stronger at higher latitudes. In fact, evidence from regional climate modelling is supportive of an increase in long-shore winds at higher latitudes, whereas long-shore winds may decrease at lower latitudes as a consequence of the poleward displacement of the subtropical highs under climate change (Christensen et al., 2007; Engelbrecht et al., 2009).

It is more likely than not that the Atlantic Meridional Overturning Circulation (AMOC) has been weakening in recent decades, given the detection of the cooling of surface waters in the North Atlantic and evidence that the Gulf Stream has slowed since the late 1950s (Rahmstorf et al., 2015b; Srokosz and Bryden, 2015; Caesar et al., 2018). There is only *limited evidence* linking the current anomalously weak state of AMOC to anthropogenic warming (Caesar et al., 2018). It is *very likely* that the AMOC will weaken over the 21st century. The best estimates and ranges for the reduction based on CMIP5 simulations are 11% (1– 24%) in RCP2.6 and 34% (12– 54%) in RCP8.5 (AR5). There is *no evidence* indicating significantly different amplitudes of AMOC weakening for 1.5°C versus 2°C of global warming.

3.3.8 Sea Ice

Summer sea ice in the Arctic has been retreating rapidly in recent decades. During the period 1997 to 2014, for example, the monthly mean sea ice extent during September (summer) decreased on average by 130,000 km² per year (Serreze and Stroeve, 2015). This is about four times as fast as the September sea ice loss during the period 1979 to 1996. Sea ice thickness has also decreased substantially, with an estimated decrease in ice thickness of more than 50% in the central Arctic (Lindsay and Schweiger, 2015). Sea ice coverage and thickness also decrease in CMIP5 simulations of the recent past, and are projected to decrease in the future (Collins et al., 2013). However, the modelled sea ice loss in most CMIP5 models is much smaller than observed losses. Compared to observations, the simulations are less sensitive to both global mean temperature rise (Rosenblum and Eisenman, 2017) and anthropogenic CO_2 emissions (Notz and Stroeve, 2016). This mismatch between the observed and modelled sensitivity of Arctic sea ice implies that the multi-model-mean responses of future sea ice evolution probably underestimates the sea ice loss for a given amount of global warming. To address this issue, studies estimating the future evolution of Arctic sea ice tend to bias correct the model simulations based on the observed evolution of Arctic sea ice in response to global warming. Based on such bias correction, pre-AR5 and post-AR5 studies generally agree that for 1.5°C of global warming relative to pre-industrial levels, the Arctic Ocean will maintain a sea ice cover throughout summer in most years (Collins et al., 2013; Notz and Stroeve, 2016; Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Sigmond et al., 2018). For 2°C of global warming, chances of a sea ice-free Arctic during summer are substantially higher (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Screen et al., 2018; Sigmond et al., 2018). Model simulations suggest that there will be at least one sea ice-free Arctic[5] summer after approximately 10 years of stabilized warming at 2°C, as compared to one sea ice-free summer after 100 years of stabilized warming at 1.5°C above pre-industrial temperatures (Jahn, 2018; Screen et al., 2018; Sigmond et al., 2018). For a specific given year under stabilized warming of 2°C, studies based on large ensembles of simulations with a single model estimate the likelihood of ice-free conditions as 35% without a bias correction of the underlying model (Sanderson et al., 2017; Jahn, 2018); as between 10% and >99% depending on the observational record used to correct the sensitivity of sea ice decline to global warming in the underlying model (Niederdrenk and Notz, 2018); and as 19% based on a procedure to correct for biases in the climatological sea ice coverage in the underlying model (Sigmond et al., 2018). The uncertainty of the first year of the occurrence of an ice-free Arctic Ocean arising from internal variability is estimated to be about 20 years (Notz, 2015; Jahn et al., 2016).

The more recent estimates of the warming necessary to produce an ice-free Arctic Ocean during summer are lower than the ones given in AR5 (about 2.6°C–3.1°C of global warming relative to pre-industrial levels or 1.6°C–2.1°C relative to present-day conditions), which were similar to the estimate of 3°C of global warming relative to pre-industrial levels (or 2°C relative to present-day conditions) by Mahlstein and Knutti (2012) based on bias-corrected CMIP3 models. Rosenblum and Eisenman (2016) explained why the sensitivity estimated by Mahlstein and Knutti (2012) might be too low, estimating instead that September sea ice in the Arctic would disappear at 2°C of global warming relative to pre-industrial levels (or about 1°C relative to present-day conditions), in line with the other recent estimates. Notz and Stroeve (2016) used the observed correlation between September sea ice extent and cumulative CO_2 emissions to estimate that the Arctic Ocean would become nearly free of sea ice during September with a further 1000 Gt of emissions, which also implies a sea ice loss at about 2°C of global warming. Some of the uncertainty in these numbers stems from the possible impact of aerosols (Gagne et al., 2017) and of volcanic forcing (Rosenblum and Eisenman, 2016). During winter, little Arctic sea ice is projected to be lost for either 1.5°C or 2°C of global warming (Niederdrenk and Notz, 2018).

[5] Ice free is defined for the Special Report as when the sea ice extent is less than 106 km². Ice coverage less than this is considered to be equivalent to an ice-free Arctic Ocean for practical purposes in all recent studies.

A substantial number of pre-AR5 studies found that there is no indication of hysteresis behaviour of Arctic sea ice under decreasing temperatures following a possible overshoot of a long-term temperature target (Holland et al., 2006; Schröder and Connolley, 2007; Armour et al., 2011; Sedláček et al., 2011; Tietsche et al., 2011; Boucher et al., 2012; Ridley et al., 2012). In particular, the relationship between Arctic sea ice coverage and GMST was found to be indistinguishable between a warming scenario and a cooling scenario. These results have been confirmed by post-AR5 studies (Li et al., 2013; Jahn, 2018), which implies *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea ice coverage.

In the Antarctic, sea ice shows regionally contrasting trends, such as a strong decrease in sea ice coverage near the Antarctic peninsula but increased sea ice coverage in the Amundsen Sea (Hobbs et al., 2016). Averaged over these contrasting regional trends, there has been a slow long-term increase in overall sea ice coverage in the Southern Ocean, although with comparably low ice coverage from September 2016 onwards. Collins et al. (2013) assessed *low confidence* in Antarctic sea ice projections because of the wide range of model projections and an inability of almost all models to reproduce observations such as the seasonal cycle, interannual variability and the long-term slow increase. No existing studies have robustly assessed the possible future evolution of Antarctic sea ice under low-warming scenarios.

In summary, the probability of a sea-ice-free Arctic Ocean during summer is substantially higher at 2°C compared to 1.5°C of global warming relative to pre-industrial levels, and there is *medium confidence* that there will be at least one sea ice-free Arctic summer after about 10 years of stabilized warming at 2°C, while about 100 years are required at 1.5°C. There is *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea ice coverage with regrowth on decadal time scales.

3.3.9 Sea Level

Sea level varies over a wide range of temporal and spatial scales, which can be divided into three broad categories. These are global mean sea level (GMSL), regional variation about this mean, and the occurrence of sea-level extremes associated with storm surges and tides. GMSL has been rising since the late 19th century from the low rates of change that characterized the previous two millennia (Church et al., 2013). Slowing in the reported rate over the last two decades (Cazenave et al., 2014) may be attributable to instrumental drift in the observing satellite system (Watson et al., 2015) and increased volcanic activity (Fasullo et al., 2016). Accounting for the former results in rates (1993 to mid-2014) between 2.6 and 2.9 mm yr^{-1} (Watson et al., 2015). The relative contributions from thermal expansion, glacier and ice-sheet mass loss, and freshwater storage on land are relatively well understood (Church et al., 2013; Watson et al., 2015) and their attribution is dominated by anthropogenic forcing since 1970 (15 ± 55% before 1950, 69 ± 31% after 1970) (Slangen et al., 2016).

There has been a significant advance in the literature since AR5, which has included the development of semi-empirical models (SEMs) into a broader emulation-based approach (Kopp et al., 2014; Mengel et al., 2016; Nauels et al., 2017) that is partially based on the results from more detailed, process-based modelling Church et al. (2013) assigned *low confidence* to SEMs because these models assume that the relation between climate forcing and GMSL is the same in the past (calibration) and future (projection). Probable future changes in the relative contributions of thermal expansion, glaciers and (in particular) ice sheets invalidate this assumption. However, recent emulation-based studies overcame this shortcoming by considering individual GMSL contributors separately, and they are therefore employed in this assessment. In this subsection, the process-based literature of individual contributors to GMSL is considered for scenarios close to 1.5°C and 2°C of global warming before emulation-based approaches are assessed.

A limited number of processes-based studies are relevant to GMSL in 1.5°C and 2°C worlds. Marzeion et al. (2018) used a global glacier model with temperature-scaled scenarios based on RCP2.6 to investigate the difference between 1.5°C and 2°C of global warming and found little difference between scenarios in the glacier contribution to GMSL for the year 2100 (54–97 mm relative to present-day levels for 1.5°C and 63–112 mm for 2°C, using a 90% confidence interval). This arises because glacier melt during the remainder of the century is dominated by the response to warming from pre-industrial to present-day levels, which is in turn a reflection of the slow response times of glaciers. Fürst et al. (2015) made projections of the Greenland ice sheet's contribution to GMSL using an ice-flow model forced by the regional climate model Modèle Atmosphérique Régional (MAR; considered by Church et al. (2013) to be the 'most realistic' such model). They projected an RCP2.6 range of 24–60 mm (1 standard deviation) by the end of the century (relative to the year 2000 and consistent with the assessment of Church et al. (2013); however, their projections do not allow the difference between 1.5°C and 2°C worlds to be evaluated.

The Antarctic ice sheet can contribute both positively, through increases in outflow (solid ice lost directly to the ocean), and negatively, through increases in snowfall (owing to the increased moisture-bearing capacity of a warmer atmosphere), to future GMSL rise. Frieler et al. (2015) suggested a range of 3.5–8.7% $°C^{-1}$ for this effect, which is consistent with AR5. Observations from the Amundsen Sea sector of Antarctica suggest an increase in outflow (Mouginot et al., 2014) over recent decades associated with grounding line retreat (Rignot et al., 2014) and the influx of relatively warm Circumpolar Deepwater (Jacobs et al., 2011). Literature on the attribution of these changes to anthropogenic forcing is still in its infancy (Goddard et al., 2017; Turner et al., 2017a). RCP2.6-based projections of Antarctic outflow (Levermann et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016, who include snowfall changes) are consistent with the AR5 assessment of Church et al. (2013) for end-of-century GMSL for RCP2.6, and do not support substantial additional GMSL rise by Marine Ice Sheet Instability or associated instabilities (see Section 3.6). While agreement is relatively good, concerns about the numerical fidelity of these models still exist, and this may affect the quality of their projections (Drouet et al., 2013; Durand and Pattyn, 2015). An assessment of Antarctic contributions beyond the end of the century, in particular related to the Marine Ice Sheet Instability, can be found in Section 3.6.

While some literature on process-based projections of GMSL for the period up to 2100 is available, it is insufficient for distinguishing

between emissions scenarios associated with 1.5°C and 2°C warmer worlds. This literature is, however, consistent with the assessment by Church et al. (2013) of a *likely* range of 0.28–0.61 m in 2100 (relative to 1986–2005), suggesting that the AR5 assessment is still appropriate.

Recent emulation-based studies show convergence towards this AR5 assessment (Table 3.1) and offer the advantage of allowing a comparison between 1.5°C and 2°C warmer worlds. Table 3.1 features a compilation of recent emulation-based and SEM studies.

Table 3.1 | Compilation of recent projections for sea level at 2100 (in cm) for Representative Concentration Pathway (RCP)2.6, and 1.5°C and 2°C scenarios. Upper and lower limits are shown for the 17-84% and 5-95% confidence intervals quoted in the original papers.

Study	Baseline	RCP2.6		1.5°C		2°C	
		67%	90%	67%	90%	67%	90%
AR5	1986–2005	28–61					
Kopp et al. (2014)	2000	37–65	29–82				
Jevrejeva et al. (2016)	1986–2005		29–58				
Kopp et al. (2016)	2000	28–51	24–61				
Mengel et al. (2016)	1986–2005	28–56					
Nauels et al. (2017)	1986–2005	35–56					
Goodwin et al. (2017)	1986–2005		31–59 45–70 45–72				
Schaeffer et al. (2012)	2000		52–96		54–99		56–105
Schleussner et al. (2016b)	2000			26–53		36–65	
Bittermann et al. (2017)	2000				29–46		39–61
Jackson et al. (2018)	1986–2005			30–58 40–77	20–67 28–93	35–64 47–93	24–74 32–117
Sanderson et al. (2017)					50–80		60–90
Nicholls et al. (2018)	1986–2005				24–54		31–65
Rasmussen et al. (2018)	2000			35–64	28–82	39–76	28–96
Goodwin et al. (2018)	1986–2005				26–62		30–69

There is little consensus between the reported ranges of GMSL rise (Table 3.1). Projections vary in the range 0.26–0.77 m and 0.35–0.93 m for 1.5°C and 2°C respectively for the 17–84% confidence interval (0.20–0.99 m and 0.24–1.17 m for the 5–95% confidence interval). There is, however, *medium agreement* that GMSL in 2100 would be 0.04–0.16 m higher in a 2°C warmer world compared to a 1.5°C warmer world based on the 17–84% confidence interval (0.00–0.24 m based on 5–95% confidence interval) with a value of around 0.1 m. There is *medium confidence* in this assessment because of issues associated with projections of the Antarctic contribution to GMSL that are employed in emulation-based studies (see above) and the issues previously identified with SEMs (Church et al., 2013).

Translating projections of GMSL to the scale of coastlines and islands requires two further steps. The first step accounts for regional changes associated with changing water and ice loads (such as Earth's gravitational field and rotation, and vertical land movement), as well as spatial differences in ocean heat uptake and circulation. The second step maps regional sea level to changes in the return periods of particular flood events to account for effects not included in global climate models, such as tides, storm surges, and wave setup and runup. Kopp et al. (2014) presented a framework to do this and gave an example application for nine sites located in the US, Japan, northern Europe and Chile. Of these sites, seven (all except those in northern Europe) were found to experience at least a quadrupling in the number of years in the 21st century with 1-in-100-year floods under RCP2.6 compared to under no future sea level rise. Rasmussen et al. (2018) used this approach to investigate the difference between 1.5°C and 2°C warmer worlds up to 2200. They found that the reduction in the frequency of 1-in-100-year floods in a 1.5°C compared to a 2°C warmer world would be greatest in the eastern USA and Europe, with ESL event frequency amplification being reduced by about a half and with smaller reductions for small island developing states (SIDS). This last result contrasts with the finding of Vitousek et al. (2017) that regions with low variability in extreme water levels (such as SIDS in the tropics) are particularly sensitive to GMSL rise, such that a doubling of frequency may be expected for even small (0.1–0.2 m) rises. Schleussner et al. (2011) emulated the AMOC based on a subset of CMIP-class climate models. When forced using global temperatures appropriate for the CP3-PD scenario (1°C of warming in 2100 relative to 2000 or about 2°C of warming relative to pre-industrial) the emulation suggests an 11% median reduction in AMOC strength at 2100 (relative to 2000) with an associated 0.04 m dynamic sea level rise along the New York City coastline.

In summary, there is *medium confidence* that GMSL rise will be about 0.1 m (within a 0.00–0.20 m range based on 17–84% confidence-interval projections) less by the end of the 21st century in a 1.5°C compared to a 2°C warmer world. Projections for 1.5°C and 2°C global warming cover the ranges 0.2–0.8 m and 0.3–1.00 m relative to 1986–2005, respectively (*medium confidence*). Sea level rise beyond 2100 is discussed in Section 3.6; however, recent literature strongly supports the assessment by Church et al. (2013) that sea level rise will continue well beyond 2100 (*high confidence*).

Box 3.3 | Lessons from Past Warm Climate Episodes

Climate projections and associated risk assessments for a future warmer world are based on climate model simulations. However, Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models do not include all existing Earth system feedbacks and may therefore underestimate both rates and extents of changes (Knutti and Sedláček, 2012). Evidence from natural archives of three moderately warmer (1.5°C–2°C) climate episodes in Earth's past help to assess such long-term feedbacks (Fischer et al., 2018).

While evidence over the last 2000 years and during the Last Glacial Maximum (LGM) was discussed in detail in the IPCC Fifth Assessment Report (Masson-Delmotte et al., 2013), the climate system response during past warm intervals was the focus of a recent review paper (Fischer et al., 2018) summarized in this Box. Examples of past warmer conditions with essentially modern physical geography include the Holocene Thermal Maximum (HTM; broadly defined as about 10–5 kyr before present (BP), where present is defined as 1950), the Last Interglacial (LIG; about 129–116 kyr BP) and the Mid Pliocene Warm Period (MPWP; 3.3–3.0 Myr BP).

Changes in insolation forcing during the HTM (Marcott et al., 2013) and the LIG (Hoffman et al., 2017) led to a global temperature up to 1°C higher than that in the pre-industrial period (1850–1900); high-latitude warming was 2°C–4°C (Capron et al., 2017), while temperature in the tropics changed little (Marcott et al., 2013). Both HTM and LIG experienced atmospheric CO_2 levels similar to pre-industrial conditions (Masson-Delmotte et al. 2013). During the MPWP, the most recent time period when CO_2 concentrations were similar to present-day levels, the global temperature was >1°C and Arctic temperatures about 8°C warmer than pre-industrial (Brigham-Grette et al., 2013).

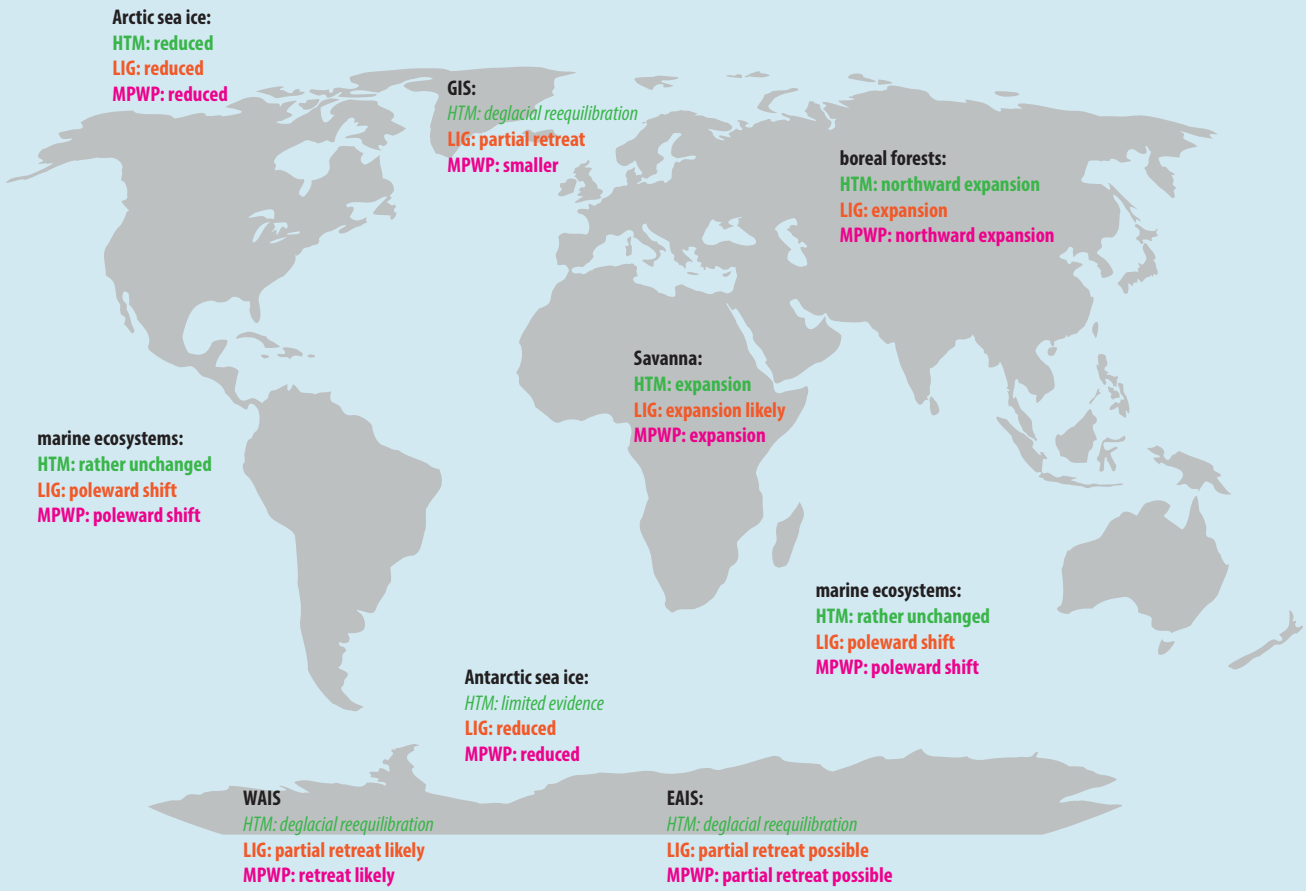
Although imperfect as analogues for the future, these regional changes can inform risk assessments such as the potential for crossing irreversible thresholds or amplifying anthropogenic changes (Box 3.3, Figure 1). For example, HTM and LIG greenhouse gas (GHG) concentrations show no evidence of runaway greenhouse gas releases under limited global warming. Transient releases of CO_2 and CH_4 may follow permafrost melting, but these occurrences may be compensated by peat growth over longer time scales (Yu et al., 2010). Warming may release CO_2 by enhancing soil respiration, counteracting CO_2 fertilization of plant growth (Frank et al., 2010). Evidence of a collapse of the Atlantic Meridional Overturning Circulation (AMOC) during these past events of limited global warming could not be found (Galaasen et al., 2014).

The distribution of ecosystems and biomes (major ecosystem types) changed significantly during past warming events, both in the ocean and on land. For example, some tropical and temperate forests retreated because of increased aridity, while savannas expanded (Dowsett et al., 2016). Further, poleward shifts of marine and terrestrial ecosystems, upward shifts in alpine regions, and reorganizations of marine productivity during past warming events are recorded in natural archives (Williams et al., 2009; Haywood et al., 2016). Finally, past warming events are associated with partial sea ice loss in the Arctic. The limited amount of data collected so far on Antarctic sea ice precludes firm conclusions about Southern Hemisphere sea ice losses (de Vernal et al., 2013).

Reconstructed global sea level rise of 6–9 m during the LIG and possibly >6 m during the MPWP requires a retreat of either the Greenland or Antarctic ice sheets or both (Dutton et al., 2015). While ice sheet and climate models suggest a substantial retreat of the West Antarctic ice sheet (WAIS) and parts of the East Antarctic ice sheet (DeConto and Pollard, 2016) during these periods, direct observational evidence is still lacking. Evidence for ice retreat in Greenland is stronger, although a complete collapse of the Greenland ice sheet during the LIG can be excluded (Dutton et al., 2015). Rates of past sea level rises under modest warming were similar to or up to two times larger than rises observed over the past two decades (Kopp et al., 2013). Given the long time scales required to reach equilibrium in a warmer world, sea level rise will likely continue for millennia even if warming is limited to 2°C.

Finally, temperature reconstructions from these past warm intervals suggest that current climate models underestimate regional warming at high latitudes (polar amplification) and long-term (multi-millennial) global warming. None of these past warm climate episodes involved the high rate of change in atmospheric CO_2 and temperatures that we are experiencing today (Fischer et al., 2018).

Box 3.3 (continued)



Box 3.3, Figure 1 | Impacts and responses of components of the Earth System. Summary of typical changes found for warmer periods in the paleorecord, as discussed by Fischer et al. (2018). All statements are relative to pre-industrial conditions. Statements in italics indicate that no conclusions can be drawn for the future. Note that significant spatial variability and uncertainty exists in the assessment of each component, and this figure therefore should not be referred to without reading the publication in detail. HTM: Holocene Thermal Maximum, LIG: Last Interglacial, MPWP: Mid Pliocene Warm Period. (Adapted from Fischer et al., 2018).

3.3.10 Ocean Chemistry

Ocean chemistry includes pH, salinity, oxygen, CO_2, and a range of other ions and gases, which are in turn affected by precipitation, evaporation, storms, river runoff, coastal erosion, up-welling, ice formation, and the activities of organisms and ecosystems (Stocker et al., 2013). Ocean chemistry is changing alongside increasing global temperature, with impacts projected at 1.5°C and, more so, at 2°C of global warming (Doney et al., 2014) (*medium to high confidence*). Projected changes in the upper layers of the ocean include altered pH, oxygen content and sea level. Despite its many component processes, ocean chemistry has been relatively stable for long periods of time prior to the industrial period (Hönisch et al., 2012). Ocean chemistry is changing under the influence of human activities and rising greenhouse gases (*virtually certain*; Rhein et al., 2013; Stocker et al., 2013). About 30% of CO_2 emitted by human activities, for example, has been absorbed by the upper layers of the ocean, where it has combined with water to produce a dilute acid that dissociates and drives ocean acidification (*high confidence*) (Cao et al., 2007; Stocker et al., 2013). Ocean pH has decreased by 0.1 pH units since the pre-industrial period, a shift that is unprecedented in the last 65 Ma (*high confidence*) (Ridgwell and Schmidt, 2010) or even 300 Ma of Earth's history (*medium confidence*) (Hönisch et al., 2012).

Ocean acidification is a result of increasing CO_2 in the atmosphere (*very high confidence*) and is most pronounced where temperatures are lowest (e.g., polar regions) or where CO_2-rich water is brought to the ocean surface by upwelling (Feely et al., 2008). Acidification can also be influenced by effluents from natural or disturbed coastal land use (Salisbury et al., 2008), plankton blooms (Cai et al., 2011), and the atmospheric deposition of acidic materials (Omstedt et al., 2015). These sources may not be directly attributable to climate change, but they may amplify the impacts of ocean acidification (Bates and Peters, 2007; Duarte et al., 2013). Ocean acidification also influences the ionic composition of seawater by changing the organic and inorganic speciation of trace metals (e.g., 20-fold increases in free ion

concentrations of metals such as aluminium) – with changes expected to have impacts although they are currently poorly documented and understood (*low confidence*) (Stockdale et al., 2016).

Oxygen varies regionally and with depth; it is highest in polar regions and lowest in the eastern basins of the Atlantic and Pacific Oceans and in the northern Indian Ocean (Doney et al., 2014; Karstensen et al., 2015; Schmidtko et al., 2017). Increasing surface water temperatures have reduced oxygen in the ocean by 2% since 1960, with other variables such as ocean acidification, sea level rise, precipitation, wind and storm patterns playing roles (Schmidtko et al., 2017). Changes to ocean mixing and metabolic rates, due to increased temperature and greater supply of organic carbon to deep areas, has increased the frequency of 'dead zones', areas where oxygen levels are so low that they no longer support oxygen dependent life (Diaz and Rosenberg, 2008). The changes are complex and include both climate change and other variables (Altieri and Gedan, 2015), and are increasing in tropical as well as temperate regions (Altieri et al., 2017).

Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e., precipitation versus evaporation). Some regions, such as northern oceans and the Arctic, have decreased in salinity, owing to melting glaciers and ice sheets, while others have increased in salinity, owing to higher sea surface temperatures and evaporation (Durack et al., 2012). These changes in salinity (i.e., density) are also potentially contributing to large-scale changes in water movement (Section 3.3.8).

3.3.11 Global Synthesis

Table 3.2 features a summary of the assessments of global and regional climate changes and associated hazards described in this chapter, based on the existing literature. For more details about observation and attribution in ocean and cryosphere systems, please refer to the upcoming IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) due to be released in 2019.

Table 3.2 | Summary of assessments of global and regional climate changes and associated hazards. Confidence and likelihood statements are quoted from the relevant chapter text and are omitted where no assessment was made, in which case the IPCC Fifth Assessment Report (AR5) assessment is given where available. GMST: global mean surface temperature, AMOC: Atlantic Meridional Overturning Circulation, GMSL: global mean sea level.

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present-day versus pre-industrial)	Projected change at 1.5°C of global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C of global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C of global warming
GMST anomaly	GMST anomalies were 0.87°C (±0.10°C *likely* range) above pre-industrial (1850–1900) values in the 2006–2015 decade, with a recent warming of about 0.2°C (±0.10°C) per decade (*high confidence*) [Chapter 1]	The observed 0.87°C GMST increase in the 2006–2015 decade compared to pre-industrial (1850–1900) conditions was mostly human-induced (*high confidence*) Human-induced warming reached about 1°C (±0.2°C *likely* range) above pre-industrial levels in 2017 [Chapter 1]	1.5°C	2°C	0.5°C
Temperature extremes	Overall decrease in the number of cold days and nights and overall increase in the number of warm days and nights at the global scale on land (*very likely*) Continental-scale increase in intensity and frequency of hot days and nights, and decrease in intensity and frequency of cold days and nights, in North America, Europe and Australia (*very likely*) Increases in frequency or duration of warm spell lengths in large parts of Europe, Asia and Australia (*high confidence* (*likely*)), as well as at the global scale *(medium confidence*) [Section 3.3.2]	Anthropogenic forcing has contributed to the observed changes in frequency and intensity of daily temperature extremes on the global scale since the mid-20th century (*very likely*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights (*very likely*) Warming of temperature extremes highest over land, including many inhabited regions (*high confidence*), with increases of up to 3°C in the mid-latitude warm season and up to 4.5°C in the high-latitude cold season (*high confidence*) Largest increase in frequency of unusually hot extremes in tropical regions (*high confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights (*very likely*) Warming of temperature extremes highest over land, including many inhabited regions (*high confidence*), with increases of up to 4°C in the mid-latitude warm season and up to 6°C in the high-latitude cold season (*high confidence*) Largest increase in frequency of unusually hot extremes in tropical regions (*high confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights (*high confidence*) Global-scale increase in length of warm spells and decrease in length of cold spells (*high confidence*) Strongest increase in frequency for the rarest and most extreme events (*high confidence*) Particularly large increases in hot extremes in inhabited regions (*high confidence*) [Section 3.3.2]

Table 3.2 (continued)

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present-day versus pre-industrial)	Projected change at 1.5°C of global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C of global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C of global warming
Heavy precipitation	More areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation (*likely*) [Section 3.3.3]	Human influence contributed to the global-scale tendency towards increases in the frequency, intensity and/or amount of heavy precipitation events (*medium confidence*) [Section 3.3.3; AR5 Chapter 10 (Bindoff et al., 2013a)]	Increases in frequency, intensity and/or amount heavy precipitation when averaged over global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Increases in frequency, intensity and/or amount heavy precipitation when averaged over global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Higher frequency, intensity and/or amount of heavy precipitation when averaged over global land, with positive trends in several regions (*medium confidence*) Several regions are projected to experience increases in heavy precipitation at 2°C versus 1.5°C (*medium confidence*), in particular in high-latitude and mountainous regions, as well as in eastern Asia and eastern North America (*medium confidence*) [Section 3.3.3]
Drought and dryness	*High confidence* in dryness trends in some regions, especially drying in the Mediterranean region (including southern Europe, northern Africa and the Near East) *Low confidence* in drought and dryness trends at the global scale [Section 3.3.4]	*Medium confidence* in attribution of drying trends in southern Europe (Mediterranean region) *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied [Section 3.3.4]	*Medium confidence* in drying trends in the Mediterranean region *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but substantial variability in signals depending on considered indices or climate model (*medium confidence*) [Section 3.3.4]	*Medium confidence* in drying trends in the Mediterranean region and Southern Africa *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but substantial variability in signals depending on considered indices or climate model (*medium confidence*). [Section 3.3.4]	*Medium confidence* in stronger drying trends in the Mediterranean region and Southern Africa *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied [Section 3.3.4]
Runoff and river flooding	Streamflow trends mostly not statistically significant (*high confidence*) Increase in flood frequency and extreme streamflow in some regions (*high confidence*) [Section 3.3.5]	Not assessed in this report	Expansion of the global land area with a significant increase in runoff (*medium confidence*) Increase in flood hazard in some regions (*medium confidence*) [Section 3.3.5]	Expansion of the global land area with a significant increase in runoff (*medium confidence*) Increase in flood hazard in some regions (*medium confidence*) [Section 3.3.5]	Expansion of the global land area with significant increase in runoff (*medium confidence*) Expansion in the area affected by flood hazard (*medium confidence*) [Section 3.3.5]
Tropical and extra-tropical cyclones	*Low confidence* in the robustness of observed changes [Section 3.3.6]	Not meaningful to assess given *low confidence* in changes, due to large interannual variability, heterogeneity of the observational record and contradictory findings regarding trends in the observational record	Increases in heavy precipitation associated with tropical cyclones (*medium confidence*)	Further increases in heavy precipitation associated with tropical cyclones (*medium confidence*)	Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). Limited evidence that the global number of tropical cyclones will be lower under 2°C of global warming compared to under 1.5°C of warming, but an increase in the number of very intense cyclones (*low confidence*)

Table 3.2 (continued)

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present-day versus pre-industrial)	Projected change at 1.5°C of global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C of global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C of global warming
Ocean circulation and temperature	Observed warming of the upper ocean, with slightly lower rates than global warming (*virtually certain*) Increased occurrence of marine heatwaves (*high confidence*) AMOC has been weakening over recent decades (*more likely than not*) [Section 3.3.7]	*Limited evidence* attributing the weakening of AMOC in recent decades to anthropogenic forcing [Section 3.3.7]	Further increases in ocean temperatures, including more frequent marine heatwaves (*high confidence*) AMOC will weaken over the 21st century and substantially so under high levels (more than 2°C) of global warming (*very likely*) [Section 3.3.7]		
Sea ice	Continuing the trends reported in AR5, the annual Arctic sea ice extent decreased over the period 1979–2012. The rate of this decrease was *very likely* between 3.5 and 4.1% per decade (0.45 to 0.51 million km^2 per decade) [AR5 Chapter 4 (Vaughan et al., 2013)]	Anthropogenic forcings are *very likely* to have contributed to Arctic sea ice loss since 1979 [AR5 Chapter 10 (Bindoff et al., 2013a)]	At least one sea-ice-free Arctic summer after about 100 years of stabilized warming (*medium confidence*) [Section 3.3.8]	At least one sea-ice-free Arctic summer after about 10 years of stabilized warming (*medium confidence*) [Section 3.3.8]	Probability of sea-ice-free Arctic summer greatly reduced at 1.5°C versus 2°C of global warming (*medium confidence*) [Section 3.3.8]
			Intermediate temperature overshoot has no long-term consequences for Arctic sea ice cover (*high confidence*) [3.3.8]		
Sea level	It is *likely* that the rate of GMSL rise has continued to increase since the early 20th century, with estimates that range from 0.000 [–0.002 to 0.002] mm yr^{-2} to 0.013 [0.007 to 0.019] mm yr^{-2} [AR5 Chapter 13 (Church et al., 2013)]	It is very *likely* that there is a substantial contribution from anthropogenic forcings to the global mean sea level rise since the 1970s [AR5 Chapter 10 (Bindoff et al., 2013a)]	Not assessed in this report	Not assessed in this report	GMSL rise will be about 0.1 m (0.00–0.20 m) less at 1.5°C versus 2°C global warming (*medium confidence*) [Section 3.3.9]
Ocean chemistry	Ocean acidification due to increased CO_2 has resulted in a 0.1 pH unit decrease since the pre-industrial period, which is unprecedented in the last 65 Ma (*high confidence*) [Section 3.3.10]	The oceanic uptake of anthropogenic CO_2 has resulted in acidification of surface waters (*very high confidence*). [Section 3.3.10]	Ocean chemistry is changing with global temperature increases, with impacts projected at 1.5°C and, more so, at 2°C of warming (*high confidence*) [Section 3.3.10]		

3.4 Observed Impacts and Projected Risks in Natural and Human Systems

3.4.1 Introduction

In Section 3.4, new literature is explored and the assessment of impacts and projected risks is updated for a large number of natural and human systems. This section also includes an exploration of adaptation opportunities that could be important steps towards reducing climate change, thereby laying the ground for later discussions on opportunities to tackle both mitigation and adaptation while at the same time recognising the importance of sustainable development and reducing the inequities among people and societies facing climate change.

Working Group II (WGII) of the IPCC Fifth Assessment Report (AR5) provided an assessment of the literature on the climate risk for natural and human systems across a wide range of environments, sectors and greenhouse gas scenarios, as well as for particular geographic regions (IPCC, 2014a, b). The comprehensive assessment undertaken by AR5 evaluated the evidence of changes to natural systems, and the impact on human communities and industry. While impacts varied substantially among systems, sectors and regions, many changes over the past 50 years could be attributed to human driven climate change and its impacts. In particular, AR5 attributed observed impacts in natural ecosystems to anthropogenic climate change, including changes in phenology, geographic and altitudinal range shifts in flora and fauna, regime shifts and increased tree mortality, all of which can reduce ecosystem functioning and services thereby impacting people. AR5 also reported increasing evidence of changing patterns of disease and invasive species, as well as growing risks for communities and industry, which are especially important with respect to sea level rise and human vulnerability.

One of the important themes that emerged from AR5 is that previous assessments may have under-estimated the sensitivity of natural and human systems to climate change. A more recent analysis of attribution

to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) confirmed that many impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of changes related to precipitation are by comparison less clear. Moreover, there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016). The observed changes in human systems are amplified by the loss of ecosystem services (e.g., reduced access to safe water) that are supported by biodiversity (Oppenheimer et al., 2014). Limited research on the risks of warming of 1.5°C and 2°C was conducted following AR5 for most key economic sectors and services, for livelihoods and poverty, and for rural areas. For these systems, climate is one of many drivers that result in adverse outcomes. Other factors include patterns of demographic change, socio-economic development, trade and tourism. Further, consequences of climate change for infrastructure, tourism, migration, crop yields and other impacts interact with underlying vulnerabilities, such as for individuals and communities engaged in pastoralism, mountain farming and artisanal fisheries, to affect livelihoods and poverty (Dasgupta et al., 2014).

Incomplete data and understanding of these lower-end climate scenarios have increased the need for more data and an improved understanding of the projected risks of warming of 1.5°C and 2°C for reference. In this section, the available literature on the projected risks, impacts and adaptation options is explored, supported by additional information and background provided in Supplementary Material 3.SM.3.1, 3.SM.3.2, 3.SM.3.4, and 3.SM.3.5. A description of the main assessment methods of this chapter is given in Section 3.2.2.

3.4.2 Freshwater Resources (Quantity and Quality)

3.4.2.1 Water availability

Working Group II of AR5 concluded that about 80% of the world's population already suffers from serious threats to its water security, as measured by indicators including water availability, water demand and pollution (Jiménez Cisneros et al., 2014). UNESCO (2011) concluded that climate change can alter the availability of water and threaten water security.

Although physical changes in streamflow and continental runoff that are consistent with climate change have been identified (Section 3.3.5), water scarcity in the past is still less well understood because the scarcity assessment needs to take into account various factors, such as the operations of water supply infrastructure and human water use behaviour (Mehran et al., 2017), as well as green water, water quality and environmental flow requirements (J. Liu et al., 2017). Over the past century, substantial growth in populations, industrial and agricultural activities, and living standards have exacerbated water stress in many parts of the world, especially in semi-arid and arid regions such as California in the USA (AghaKouchak et al., 2015; Mehran et al., 2015). Owing to changes in climate and water consumption behaviour, and particularly effects of the spatial distribution of population growth relative to water resources, the population under water scarcity increased from 0.24 billion (14% of the global population) in the 1900s to 3.8 billion (58%) in the 2000s. In that last period (2000s), 1.1 billion people (17% of the global population) who mostly live in South and East Asia, North Africa and the Middle East faced serious water shortage and high water stress (Kummu et al., 2016).

Over the next few decades, and for increases in global mean temperature less than about 2°C, AR5 concluded that changes in population will generally have a greater effect on water resource availability than changes in climate. Climate change, however, will regionally exacerbate or offset the effects of population pressure (Jiménez Cisneros et al., 2014).

The differences in projected changes to levels of runoff under 1.5°C and 2°C of global warming, particularly those that are regional, are described in Section 3.3.5. Constraining warming to 1.5°C instead of 2°C might mitigate the risks for water availability, although socio-economic drivers could affect water availability more than the risks posed by variation in warming levels, while the risks are not homogeneous among regions (*medium confidence*) (Gerten et al., 2013; Hanasaki et al., 2013; Arnell and Lloyd-Hughes, 2014; Schewe et al., 2014; Karnauskas et al., 2018). Assuming a constant population in the models used in his study, Gerten et al. (2013) determined that an additional 8% of the world population in 2000 would be exposed to new or aggravated water scarcity at 2°C of global warming. This value was almost halved – with 50% greater reliability – when warming was constrained to 1.5°C. People inhabiting river basins, particularly in the Middle East and Near East, are projected to become newly exposed to chronic water scarcity even if global warming is constrained to less than 2°C. Many regions, especially those in Europe, Australia and southern Africa, appear to be affected at 1.5°C if the reduction in water availability is computed for non-water-scarce basins as well as for water-scarce regions. Out of a contemporary population of approximately 1.3 billion exposed to water scarcity, about 3% (North America) to 9% (Europe) are expected to be prone to aggravated scarcity at 2°C of global warming (Gerten et al., 2013). Under the Shared Socio-Economic Pathway (SSP)2 population scenario, about 8% of the global population is projected to experience a severe reduction in water resources under warming of 1.7°C in 2021–2040, increasing to 14% of the population under 2.7°C in 2043–2071, based on the criteria of discharge reduction of either >20% or >1 standard deviation (Schewe et al., 2014). Depending on the scenarios of SSP1–5, exposure to the increase in water scarcity in 2050 will be globally reduced by 184–270 million people at about 1.5°C of warming compared to the impacts at about 2°C. However, the variation between socio-economic levels is larger than the variation between warming levels (Arnell and Lloyd-Hughes, 2014).

On many small islands (e.g., those constituting SIDS), freshwater stress is expected to occur as a result of projected aridity change. Constraining warming to 1.5°C, however, could avoid a substantial fraction of water stress compared to 2°C, especially across the Caribbean region, particularly on the island of Hispaniola (Dominican Republic and Haiti) (Karnauskas et al., 2018). Hanasaki et al. (2013) concluded that the projected range of changes in global irrigation water withdrawal (relative to the baseline of 1971–2000), using human configuration fixing non-meteorological variables for the period around 2000, are 1.1–2.3% and 0.6–2.0% lower at 1.5°C and 2°C, respectively. In the same study, Hanasaki et al. (2013) highlighted the importance of water

use scenarios in water scarcity assessments, but neither quantitative nor qualitative information regarding water use is available.

When the impacts on hydropower production at 1.5°C and 2°C are compared, it is found that mean gross potential increases in northern, eastern and western Europe, and decreases in southern Europe (Jacob et al., 2018; Tobin et al., 2018). The Baltic and Scandinavian countries are projected to experience the most positive impacts on hydropower production. Greece, Spain and Portugal are expected to be the most negatively impacted countries, although the impacts could be reduced by limiting warming to 1.5°C (Tobin et al., 2018). In Greece, Spain and Portugal, warming of 2°C is projected to decrease hydropower potential below 10%, while limiting global warming to 1.5°C would keep the reduction to 5% or less. There is, however, substantial uncertainty associated with these results due to a large spread between the climate models (Tobin et al., 2018).

Due to a combination of higher water temperatures and reduced summer river flows, the usable capacity of thermoelectric power plants using river water for cooling is expected to reduce in all European countries (Jacob et al., 2018; Tobin et al., 2018), with the magnitude of decreases being about 5% for 1.5°C and 10% for 2°C of global warming for most European countries (Tobin et al., 2018). Greece, Spain and Bulgaria are projected to have the largest reduction at 2°C of warming (Tobin et al., 2018).

Fricko et al. (2016) assessed the direct water use of the global energy sector across a broad range of energy system transformation pathways in order to identify the water impacts of a 2°C climate policy. This study revealed that there would be substantial divergence in water withdrawal for thermal power plant cooling under conditions in which the distribution of future cooling technology for energy generation is fixed, whereas adopting alternative cooling technologies and water resources would make the divergence considerably smaller.

3.4.2.2 Extreme hydrological events (floods and droughts)

Working Group II of AR5 concluded that socio-economic losses from flooding since the mid-20th century have increased mainly because of greater exposure and vulnerability (*high confidence*) (Jiménez Cisneros et al., 2014). There was *low confidence* due to limited evidence, however, that anthropogenic climate change has affected the frequency and magnitude of floods. WGII AR5 also concluded that there is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly owing to increased water demand (Jiménez Cisneros et al., 2014).

Since AR5, the number of studies related to fluvial flooding and meteorological drought based on long-term observed data has been gradually increasing. There has also been progress since AR5 in identifying historical changes in streamflow and continental runoff (Section 3.3.5). As a result of population and economic growth, increased exposure of people and assets has caused more damage due to flooding. However, differences in flood risks among regions reflect the balance among the magnitude of the flood, the populations, their vulnerabilities, the value of assets affected by flooding, and the capacity to cope with flood risks, all of which depend on socio-economic development conditions, as well as topography and hydro-climatic conditions (Tanoue et al., 2016). AR5 concluded that there was *low confidence* in the attribution of global changes in droughts (Bindoff et al., 2013b). However, recent publications based on observational and modelling evidence assessed that human emissions have substantially increased the probability of drought years in the Mediterranean region (Section 3.3.4).

WGII AR5 assessed that global flood risk will increase in the future, partly owing to climate change (*low to medium confidence*), with projected changes in the frequency of droughts longer than 12 months being more uncertain because of their dependence on accumulated precipitation over long periods (Jiménez Cisneros et al., 2014).

Increases in the risks associated with runoff at the global scale (*medium confidence*), and in flood hazard in some regions (*medium confidence*), can be expected at global warming of 1.5°C, with an overall increase in the area affected by flood hazard at 2°C (*medium confidence*) (Section 3.3.5). There are studies, however, that indicate that socio-economic conditions will exacerbate flood impacts more than global climate change, and that the magnitude of these impacts could be larger in some regions (Arnell and Lloyd-Hughes, 2014; Winsemius et al., 2016; Alfieri et al., 2017; Arnell et al., 2018; Kinoshita et al., 2018). Assuming constant population sizes, countries representing 73% of the world population will experience increasing flood risk, with an average increase of 580% at 4°C compared to the impact simulated over the baseline period 1976–2005. This impact is projected to be reduced to a 100% increase at 1.5°C and a 170% increase at 2°C (Alfieri et al., 2017). Alfieri et al. (2017) additionally concluded that the largest increases in flood risks would be found in the US, Asia, and Europe in general, while decreases would be found in only a few countries in eastern Europe and Africa. Overall, Alfieri et al. (2017) reported that the projected changes are not homogeneously distributed across the world land surface. Alfieri et al. (2018) studied the population affected by flood events using three case studies in European states, specifically central and western Europe, and found that the population affected could be limited to 86% at 1.5°C of warming compared to 93% at 2°C. Under the SSP2 population scenario, Arnell et al. (2018) found that 39% (range 36–46%) of impacts on populations exposed to river flooding globally could be avoided at 1.5°C compared to 2°C of warming.

Under scenarios SSP1–5, Arnell and Lloyd-Hughes (2014) found that the number of people exposed to increased flooding in 2050 under warming of about 1.5°C could be reduced by 26–34 million compared to the number exposed to increased flooding associated with 2°C of warming. Variation between socio-economic levels, however, is projected to be larger than variation between the two levels of global warming. Kinoshita et al. (2018) found that a serious increase in potential flood fatality (5.7%) is projected without any adaptation if global warming increases from 1.5°C to 2°C, whereas the projected increase in potential economic loss (0.9%) is relatively small. Nevertheless, their study indicates that socio-economic changes make a larger contribution to the potentially increased consequences of future floods, and about half of the increase in potential economic losses could be mitigated by autonomous adaptation.

There is limited information about the global and regional projected risks posed by droughts at 1.5°C and 2°C of global warming. However, hazards by droughts at 1.5°C could be reduced compared to the hazards at 2°C in some regions, in particular in the Mediterranean region and southern Africa (Section 3.3.4). Under constant socio-economic conditions, the population exposed to drought at 2°C of warming is projected to be larger than at 1.5°C (*low to medium confidence*) (Smirnov et al., 2016; Sun et al., 2017; Arnell et al., 2018; Liu et al., 2018). Under the same scenario, the global mean monthly number of people expected to be exposed to extreme drought at 1.5°C in 2021–2040 is projected to be 114.3 million, compared to 190.4 million at 2°C in 2041–2060 (Smirnov et al., 2016). Under the SSP2 population scenario, Arnell et al. (2018) projected that 39% (range 36–51%) of impacts on populations exposed to drought could be globally avoided at 1.5°C compared to 2°C warming.

Liu et al. (2018) studied the changes in population exposure to severe droughts in 27 regions around the globe for 1.5°C and 2°C of warming using the SSP1 population scenario compared to the baseline period of 1986–2005 based on the Palmer Drought Severity Index (PDSI). They concluded that the drought exposure of urban populations in most regions would be decreased at 1.5°C (350.2 ± 158.8 million people) compared to 2°C (410.7 ± 213.5 million people). Liu et al. (2018) also suggested that more urban populations would be exposed to severe droughts at 1.5°C in central Europe, southern Europe, the Mediterranean, West Africa, East and West Asia, and Southeast Asia, and that number of affected people would increase further in these regions at 2°C. However, it should be noted that the PDSI is known to have limitations (IPCC SREX, Seneviratne et al., 2012), and drought projections strongly depend on considered indices (Section 3.3.4); thus only *medium confidence* is assigned to these projections. In the Haihe River basin in China, a study has suggested that the proportion of the population exposed to droughts is projected to be reduced by 30.4% at 1.5°C but increased by 74.8% at 2°C relative to the baseline value of 339.65 million people in the 1986–2005 period, when assessing changes in droughts using the Standardized Precipitation-Evaporation Index, using a Penman–Monteith estimate of potential evaporation (Sun et al., 2017) .

Alfieri et al. (2018) estimated damage from flooding in Europe for the baseline period (1976–2005) at 5 billion euro of losses annually, with projections of relative changes in flood impacts that will rise with warming levels, from 116% at 1.5°C to 137% at 2°C.

Kinoshita et al. (2018) studied the increase of potential economic loss under SSP3 and projected that the smaller loss at 1.5°C compared to 2°C (0.9%) is marginal, regardless of whether the vulnerability is fixed at the current level or not. By analysing the differences in results with and without flood protection standards, Winsemius et al. (2016) showed that adaptation measures have the potential to greatly reduce present-day and future flood damage. They concluded that increases in flood-induced economic impacts (% gross domestic product, GDP) in African countries are mainly driven by climate change and that Africa's growing assets would become increasingly exposed to floods. Hence, there is an increasing need for long-term and sustainable investments in adaptation in Africa.

3.4.2.3 Groundwater

Working Group II of AR5 concluded that the detection of changes in groundwater systems, and attribution of those changes to climatic changes, are rare, owing to a lack of appropriate observation wells and an overall small number of studies (Jiménez Cisneros et al., 2014).

Since AR5, the number of studies based on long-term observed data continues to be limited. The groundwater-fed lakes in northeastern central Europe have been affected by climate and land-use changes, and they showed a predominantly negative lake-level trend in 1999–2008 (Kaiser et al., 2014).

WGII AR5 concluded that climate change is projected to reduce groundwater resources significantly in most dry subtropical regions (*high confidence*) (Jiménez Cisneros et al., 2014).

In some regions, groundwater is often intensively used to supplement the excess demand, often leading to groundwater depletion. Climate change adds further pressure on water resources and exaggerates human water demands by increasing temperatures over agricultural lands (Wada et al., 2017). Very few studies have projected the risks of groundwater depletion under 1.5°C and 2°C of global warming. Under 2°C of warming, impacts posed on groundwater are projected to be greater than at 1.5°C (*low confidence*) (Portmann et al., 2013; Salem et al., 2017).

Portmann et al. (2013) indicated that 2% (range 1.1–2.6%) of the global land area is projected to suffer from an extreme decrease in renewable groundwater resources of more than 70% at 2°C, with a clear mitigation at 1.5°C. These authors also projected that 20% of the global land surface would be affected by a groundwater reduction of more than 10% at 1.5°C of warming, with the percentage of land impacted increasing at 2°C. In a groundwater-dependent irrigated region in northwest Bangladesh, the average groundwater level during the major irrigation period (January–April) is projected to decrease in accordance with temperature rise (Salem et al., 2017).

3.4.2.4 Water quality

Working Group II of AR5 concluded that most observed changes to water quality from climate change are from isolated studies, mostly of rivers or lakes in high-income countries, using a small number of variables (Jiménez Cisneros et al., 2014). AR5 assessed that climate change is projected to reduce raw water quality, posing risks to drinking water quality with conventional treatment (*medium to high confidence*) (Jiménez Cisneros et al., 2014).

Since AR5, studies have detected climate change impacts on several indices of water quality in lakes, watersheds and regions (e.g., Patiño et al., 2014; Aguilera et al., 2015; Watts et al., 2015; Marszelewski and Pius, 2016; Capo et al., 2017). The number of studies utilising RCP scenarios at the regional or watershed scale have gradually increased since AR5 (e.g., Boehlert et al., 2015; Teshager et al., 2016; Marcinkowski et al., 2017). Few studies, have explored projected impacts on water quality under 1.5°C versus 2°C of warming, however, the differences are unclear (*low confidence*) (Bonte and

Zwolsman, 2010; Hosseini et al., 2017). The daily probability of exceeding the chloride standard for drinking water taken from Lake IJsselmeer (Andijk, the Netherlands) is projected to increase by a factor of about five at 2°C relative to the present-day warming level of 1°C since 1990 (Bonte and Zwolsman, 2010). Mean monthly dissolved oxygen concentrations and nutrient concentrations in the upper Qu'Appelle River (Canada) in 2050–2055 are projected to decrease less at about 1.5°C of warming (RCP2.6) compared to concentrations at about 2°C (RCP4.5) (Hosseini et al., 2017). In three river basins in Southeast Asia (Sekong, Sesan and Srepok), about 2°C of warming (corresponding to a 1.05°C increase in the 2030s relative to the baseline period 1981–2008, RCP8.5), impacts posed by land-use change on water quality are projected to be greater than at 1.5°C (corresponding to a 0.89°C increase in the 2030s relative to the baseline period 1981–2008, RCP4.5) (Trang et al., 2017). Under the same warming scenarios, Trang et al. (2017) projected changes in the annual nitrogen (N) and phosphorus (P) yields in the 2030s, as well as with combinations of two land-use change scenarios: (i) conversion of forest to grassland, and (ii) conversion of forest to agricultural land. The projected changes in N (P) yield are +7.3% (+5.1%) under a 1.5°C scenario and –6.6% (–3.6%) under 2°C, whereas changes under the combination of land-use scenarios are (i) +5.2% (+12.6%) at 1.5°C and +8.8% (+11.7%) at 2°C, and (ii) +7.5% (+14.9%) at 1.5°C and +3.7% (+8.8%) at 2°C (Trang et al., 2017).

3.4.2.5 Soil erosion and sediment load

Working Group II of AR5 concluded that there is little or no observational evidence that soil erosion and sediment load have been altered significantly by climate change (*low to medium confidence*) (Jiménez Cisneros et al., 2014). As the number of studies on climate change impacts on soil erosion has increased where rainfall is an important driver (Lu et al., 2013), studies have increasingly considered other factors, such as rainfall intensity (e.g., Shi and Wang, 2015; Li and Fang, 2016), snow melt, and change in vegetation cover resulting from temperature rise (Potemkina and Potemkin, 2015), as well as crop management practices (Mullan et al., 2012). WGII AR5 concluded that increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices (Jiménez Cisneros et al., 2014).

While the number of published studies of climate change impacts on soil erosion have increased globally since 2000 (Li and Fang, 2016), few articles have addressed impacts at 1.5°C and 2°C of global warming. The existing studies have found few differences in projected risks posed on sediment load under 1.5°C and 2°C (*low confidence*) (Cousino et al., 2015; Shrestha et al., 2016). The differences between average annual sediment load under 1.5°C and 2°C of warming are not clear, owing to complex interactions among climate change, land cover/surface and soil management (Cousino et al., 2015; Shrestha et al., 2016). Averages of annual sediment loads are projected to be similar under 1.5°C and 2°C of warming, in particular in the Great Lakes region in the USA and in the Lower Mekong region in Southeast Asia (Cross-Chapter Box 6 in this chapter, Cousino et al., 2015; Shrestha et al., 2016).

3.4.3 Terrestrial and Wetland Ecosystems

3.4.3.1 Biome shifts

Latitudinal and elevational shifts of biomes (major ecosystem types) in boreal, temperate and tropical regions have been detected (Settele et al., 2014) and new studies confirm these changes (e.g., shrub encroachment on tundra; Larsen et al., 2014). Attribution studies indicate that anthropogenic climate change has made a greater contribution to these changes than any other factor (*medium confidence*) (Settele et al., 2014).

An ensemble of seven Dynamic Vegetation Models driven by projected climates from 19 alternative general circulation models (GCMs) (Warszawski et al., 2013) shows 13% (range 8–20%) of biomes transforming at 2°C of global warming, but only 4% (range 2–7%) doing so at 1°C, suggesting that about 6.5% may be transformed at 1.5°C; these estimates indicate a doubling of the areal extent of biome shifts between 1.5°C and 2°C of warming (*medium confidence*) (Figure 3.16a). A study using the single ecosystem model LPJmL (Gerten et al., 2013) illustrated that biome shifts in the Arctic, Tibet, Himalayas, southern Africa and Australia would be avoided by constraining warming to 1.5°C compared with 2°C (Figure 3.16b). Seddon et al. (2016) quantitatively identified ecologically sensitive regions to climate change in most of the continents from tundra to tropical rainforest. Biome transformation may in some cases be associated with novel climates and ecological communities (Prober et al., 2012).

3.4.3.2 Changes in phenology

Advancement in spring phenology of 2.8 ± 0.35 days per decade has been observed in plants and animals in recent decades in most Northern Hemisphere ecosystems (between 30°N and 72°N), and these shifts have been attributed to changes in climate (*high confidence*) (Settele et al., 2014). The rates of change are particularly high in the Arctic zone owing to the stronger local warming (Oberbauer et al., 2013), whereas phenology in tropical forests appears to be more responsive to moisture stress (Zhou et al., 2014). While a full review cannot be included here, trends consistent with this earlier finding continue to be detected, including in the flowering times of plants (Parmesan and Hanley, 2015), in the dates of egg laying and migration in birds (newly reported in China; Wu and Shi, 2016), in the emergence dates of butterflies (Roy et al., 2015), and in the seasonal greening-up of vegetation as detected by satellites (i.e., in the normalized difference vegetation index, NDVI; Piao et al., 2015).

The potential for decoupling species–species interactions owing to differing phenological responses to climate change is well established (Settele et al., 2014), for example for plants and their insect pollinators (Willmer, 2012; Scaven and Rafferty, 2013). Mid-century projections of plant and animal phenophases in the UK clearly indicate that the timing of phenological events could change more for primary consumers (6.2 days earlier on average) than for higher trophic levels (2.5–2.9 days earlier on average) (Thackeray et al., 2016). This indicates the potential for phenological mismatch and associated risks for ecosystem functionality in the future under global warming of 2.1°C–2.7°C above pre-industrial levels. Further, differing responses

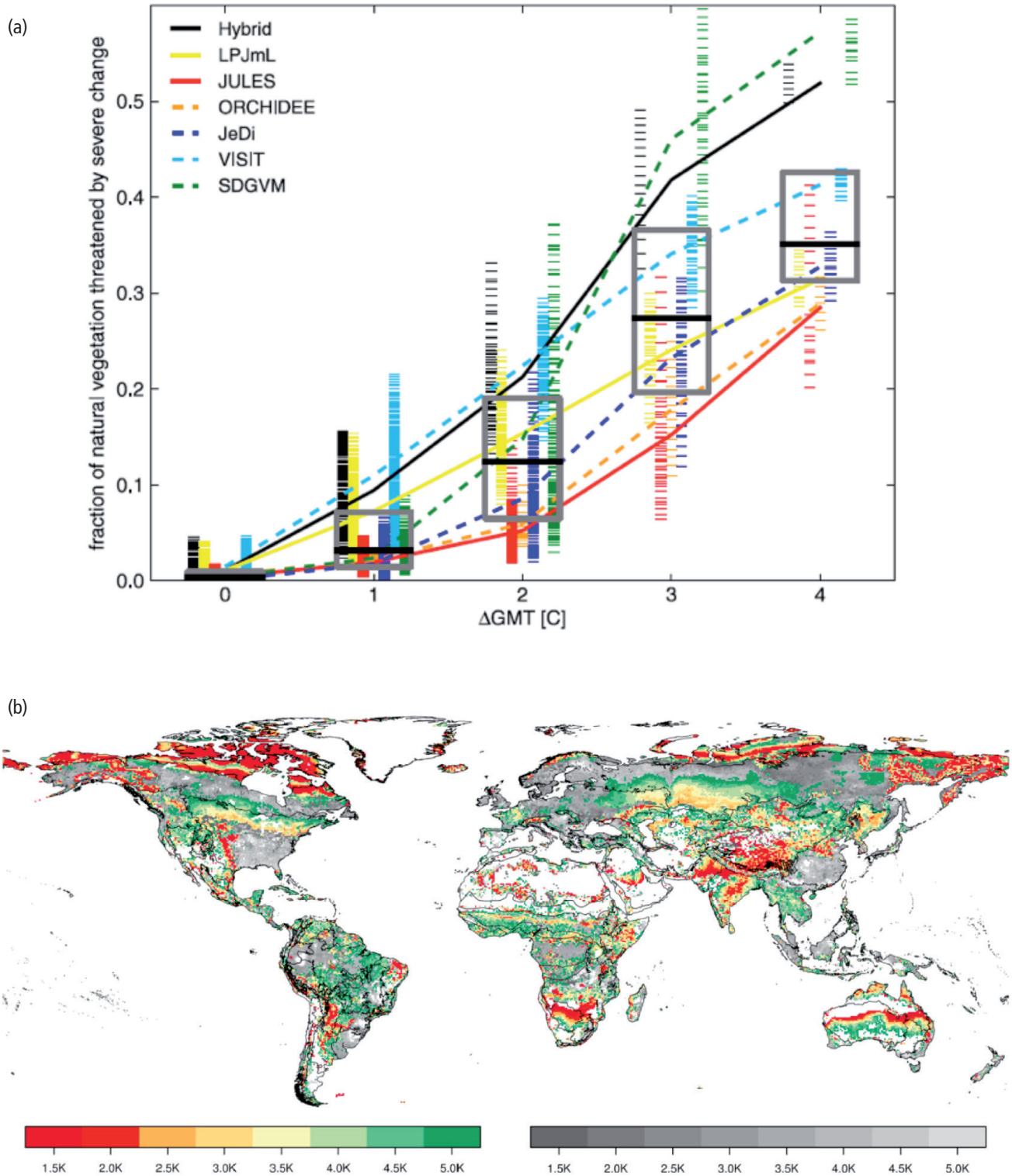


Figure 3.16 | (a) Fraction of global natural vegetation (including managed forests) at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems, models, global climate change models and Representative Concentration Pathways (RCPs). The colours represent the different ecosystem models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the temperature for a given year is the average over a 30-year window centred on that year. The boxes span the 25th and 75th percentiles across the entire ensemble. The short, horizontal stripes represent individual (annual) data points, the curves connect the mean value per ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation composition changes. Source: (Warszawski et al., 2013) (b) Threshold level of global temperature anomaly above pre-industrial levels that leads to significant local changes in terrestrial ecosystems. Regions with severe (coloured) or moderate (greyish) ecosystem transformation; delineation refers to the 90 biogeographic regions. All values denote changes found in >50% of the simulations. Source: (Gerten et al., 2013). Regions coloured in dark red are projected to undergo severe transformation under a global warming of 1.5°C while those coloured in light red do so at 2°C; other colours are used when there is no severe transformation unless global warming exceeds 2°C.

could alter community structure in temperate forests (Roberts et al., 2015). Specifically, temperate forest phenology is projected to advance by 14.3 days in the near term (2010–2039) and 24.6 days in the medium term (2040–2069), so as a first approximation the difference between 2°C and 1.5°C of global warming is about 10 days (Roberts et al., 2015). This phenological plasticity is not always adaptive and must be interpreted cautiously (Duputié et al., 2015), and considered in the context of accompanying changes in climate variability (e.g., increased risk of frost damage for plants or earlier emergence of insects resulting in mortality during cold spells). Another adaptive response of some plants is range expansion with increased vigour and altered herbivore resistance in their new range, analogous to invasive plants (Macel et al., 2017).

In summary, limiting warming to 1.5°C compared with 2°C may avoid advance in spring phenology (*high confidence*) by perhaps a few days (*medium confidence*) and hence decrease the risks of loss of ecosystem functionality due to phenological mismatch between trophic levels, and also of maladaptation coming from the sensitivity of many species to increased climate variability. Nevertheless, this difference between 1.5°C and 2°C of warming might be limited for plants that are able to expand their range.

3.4.3.3 Changes in species range, abundance and extinction

AR5 (Settele et al., 2014) concluded that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming: approximately 17 km poleward and 11 m up in altitude per decade. Recent trends confirm this finding; for example, the spatial and interspecific variance in bird populations in Europe and North America since 1980 were found to be well predicted by trends in climate suitability (Stephens et al., 2016). Further, a recent meta-analysis of 27 studies concerning a total of 976 species (Wiens, 2016) found that 47% of local extinctions (extirpations) reported across the globe during the 20th century could be attributed to climate change, with significantly more extinctions occurring in tropical regions, in freshwater habitats and for animals. IUCN (2018) lists 305 terrestrial animal and plant species from Pacific Island developing nations as being threatened by climate change and severe weather. Owing to lags in the responses of some species to climate change, shifts in insect pollinator ranges may result in novel assemblages with unknown implications for biodiversity and ecosystem function (Rafferty, 2017).

Warren et al. (2013) simulated climatically determined geographic range loss under 2°C and 4°C of global warming for 50,000 plant and animal species, accounting for uncertainty in climate projections and for the potential ability of species to disperse naturally in an attempt to track their geographically shifting climate envelope. This earlier study has now been updated and expanded to incorporate 105,501 species, including 19,848 insects, and new findings indicate that warming of 2°C by 2100 would lead to projected bioclimatic range losses of >50% in 18% (6–35%) of the 19,848 insects species, 8% (4–16%) of the 12,429 vertebrate species, and 16% (9–28%) of the 73,224 plant species studied (Warren et al., 2018a). At 1.5°C of warming, these values fall to 6% (1–18%) of the insects, 4% (2–9%) of the vertebrates and 8% (4–15%) of the plants studied. Hence, the number of insect species projected to lose over half of their geographic range is reduced by two-thirds when warming is limited to 1.5°C compared with 2°C, while the number of vertebrate and plant species projected to lose over half of their geographic range is halved (Warren et al., 2018a) (*medium confidence*). These findings are consistent with estimates made from an earlier study suggesting that range losses at 1.5°C were significantly lower for plants than those at 2°C of warming (Smith et al., 2018). It should be noted that at 1.5°C of warming, and if species' ability to disperse naturally to track their preferred climate geographically is inhibited by natural or anthropogenic obstacles, there would still remain 10% of the amphibians, 8% of the reptiles, 6% of the mammals, 5% of the birds, 10% of the insects and 8% of the plants which are projected to lose over half their range, while species on average lose 20–27% of their range (Warren et al., 2018a). Given that bird and mammal species can disperse more easily than amphibians and reptiles, a small proportion can expand their range as climate changes, but even at 1.5°C of warming the total range loss integrated over all birds and mammals greatly exceeds the integrated range gain (Warren et al., 2018a).

A number of caveats are noted for studies projecting changes to climatic range. This approach, for example, does not incorporate the effects of extreme weather events and the role of interactions between species. As well, trophic interactions may locally counteract the range expansion of species towards higher altitudes (Bråthen et al., 2018). There is also the potential for highly invasive species to become established in new areas as the climate changes (Murphy and Romanuk, 2014), but there is no literature that quantifies this possibility for 1.5°C of global warming.

Pecl et al. (2017) summarized at the global level the consequences of climate-change-induced species redistribution for economic development, livelihoods, food security, human health and culture. These authors concluded that even if anthropogenic greenhouse gas emissions stopped today, the effort for human systems to adapt to the most crucial effects of climate-driven species redistribution will be far-reaching and extensive. For example, key insect crop pollinator families (Apidae, Syrphidae and Calliphoridae; i.e., bees, hoverflies and blowflies) are projected to retain significantly greater geographic ranges under 1.5°C of global warming compared with 2°C (Warren et al., 2018a). In some cases, when species (such as pest and disease species) move into areas which have become climatically suitable they may become invasive or harmful to human or natural systems (Settele et al., 2014). Some studies are beginning to locate 'refugial' areas where the climate remains suitable in the future for most of the species currently present. For example, Smith et al. (2018) estimated that 5.5–14% more of the globe's terrestrial land area could act as climatic refugia for plants under 1.5°C of warming compared to 2°C.

There is no literature that directly estimates the proportion of species at increased risk of global (as opposed to local) commitment to extinction as a result of climate change, as this is inherently difficult to quantify. However, it is possible to compare the proportions of species at risk of very high range loss; for example, a discernibly smaller number of terrestrial species are projected to lose over 90% of their range at 1.5°C of global warming compared with 2°C (Figure 2 in Warren et al., 2018a). A link between very high levels of range loss and greatly increased extinction risk may be inferred (Urban, 2015). Hence, limiting global warming to 1.5°C compared with 2°C would be expected to reduce both range losses and associated extinction risks in terrestrial species (*high confidence*).

3.4.3.4 Changes in ecosystem function, biomass and carbon stocks

Working Group II of AR5 (Settele et al., 2014) concluded that there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the pre-industrial era and that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis. There is, however, no clear and consistent signal of a climate change contribution. In northern latitudes, the change in productivity has a lower velocity than the warming, possibly because of a lack of resource and vegetation acclimation mechanisms (M. Huang et al., 2017). Biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*), but they are vulnerable to loss of carbon to the atmosphere as a result of projected increases in the intensity of storms, wildfires, land degradation and pest outbreaks (Settele et al., 2014; Seidl et al., 2017). These losses are expected to contribute to a decrease in the terrestrial carbon sink. Anderegg et al. (2015) demonstrated that total ecosystem respiration at the global scale has increased in response to increases in night-time temperature (1 PgC yr^{-1} $°C^{-1}$, P=0.02).

The increase in total ecosystem respiration in spring and autumn, associated with higher temperatures, may convert boreal forests from carbon sinks to carbon sources (Hadden and Grelle, 2016). In boreal peatlands, for example, increased temperature may diminish carbon storage and compromise the stability of the peat (Dieleman et al., 2016). In addition, J. Yang et al. (2015) showed that fires reduce the carbon sink of global terrestrial ecosystems by 0.57 PgC yr^{-1} in ecosystems with large carbon stores, such as peatlands and tropical forests. Consequently, for adaptation purposes, it is necessary to enhance carbon sinks, especially in forests which are prime regulators within the water, energy and carbon cycles (Ellison et al., 2017). Soil can also be a key compartment for substantial carbon sequestration (Lal, 2014; Minasny et al., 2017), depending on the net biome productivity and the soil quality (Bispo et al., 2017).

AR5 assessed that large uncertainty remains regarding the land carbon cycle behaviour of the future (Ciais et al., 2013), with most, but not all, CMIP5 models simulating continued terrestrial carbon uptake under all four RCP scenarios (Jones et al., 2013). Disagreement between models outweighs differences between scenarios even up to the year 2100 (Hewitt et al., 2016; Lovenduski and Bonan, 2017). Increased atmospheric CO_2 concentrations are expected to drive further increases in the land carbon sink (Ciais et al., 2013; Schimel et al., 2015), which could persist for centuries (Pugh et al., 2016). Nitrogen, phosphorus and other nutrients will limit the terrestrial carbon cycle response to both elevated CO_2 and altered climate (Goll et al., 2012; Yang et al., 2014; Wieder et al., 2015; Zaehle et al., 2015; Ellsworth et al., 2017). Climate change may accelerate plant uptake of carbon (Gang et al., 2015) but also increase the rate of decomposition (Todd-Brown et al., 2014; Koven et al., 2015; Crowther et al., 2016). Ahlström et al. (2012) found a net loss of carbon in extra-tropical regions and the largest spread across model results in the tropics. The projected net effect of climate change is to reduce the carbon sink expected under CO_2 increase alone (Settele et al., 2014). Friend et al. (2014) found substantial uptake of carbon by vegetation under future scenarios when considering the effects of both climate change and elevated CO_2.

There is limited published literature examining modelled land carbon changes specifically under 1.5°C of warming, but existing CMIP5 models and published data are used in this report to draw some conclusions. For systems with significant inertia, such as vegetation or soil carbon stores, changes in carbon storage will depend on the rate of change of forcing and thus depend on the choice of scenario (Jones et al., 2009; Ciais et al., 2013; Sihi et al., 2017). To avoid legacy effects of the choice of scenario, this report focuses on the response of gross primary productivity (GPP) – the rate of photosynthetic carbon uptake – by the models, rather than by changes in their carbon store.

Figure 3.17 shows different responses of the terrestrial carbon cycle to climate change in different regions. The models show a consistent response of increased GPP in temperate latitudes of approximately 2 GtC yr^{-1} $°C^{-1}$. Similarly, Gang et al. (2015) projected a robust increase in the net primary productivity (NPP) of temperate forests. However, Ahlström et al. (2012) showed that this effect could be offset or reversed by increases in decomposition. Globally, most models project that GPP will increase or remain approximately unchanged (Hashimoto et al., 2013). This projection is supported by findings by Sakalli et al. (2017) for Europe using Euro-CORDEX regional models under a 2°C global warming for the period 2034–2063, which indicated that storage will increase by 5% in soil and by 20% in vegetation. However, using the same models Jacob et al. (2018) showed that limiting warming to 1.5°C instead of 2°C avoids an increase in ecosystem vulnerability (compared to a no-climate change scenario) of 40–50%.

At the global level, linear scaling is acceptable for net primary production, biomass burning and surface runoff, and impacts on terrestrial carbon storage are projected to be greater at 2°C than at 1.5°C (Tanaka et al., 2017). If global CO_2 concentrations and temperatures stabilize, or peak and decline, then both land and ocean carbon sinks – which are primarily driven by the continued increase in atmospheric CO_2 – will also decline and may even become carbon sources (Jones et al., 2016). Consequently, if a given amount of anthropogenic CO_2 is removed from the atmosphere, an equivalent amount of land and ocean anthropogenic CO_2 will be released to the atmosphere (Cao and Caldeira, 2010).

In conclusion, ecosystem respiration is expected to increase with increasing temperature, thus reducing soil carbon storage. Soil carbon storage is expected to be larger if global warming is restricted to 1.5°C, although some of the associated changes will be countered by enhanced gross primary production due to elevated CO_2 concentrations (i.e., the 'fertilization effect') and higher temperatures, especially at mid- and high latitudes (*medium confidence*).

3.4.3.5 Regional and ecosystem-specific risks

A large number of threatened systems, including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems, were assessed in AR5. These include Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succulent Karoo areas of South Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, it has been shown that impacts accrue with greater warming, and thus impacts at 2°C are expected to be greater than those at 1.5°C (*medium confidence*).

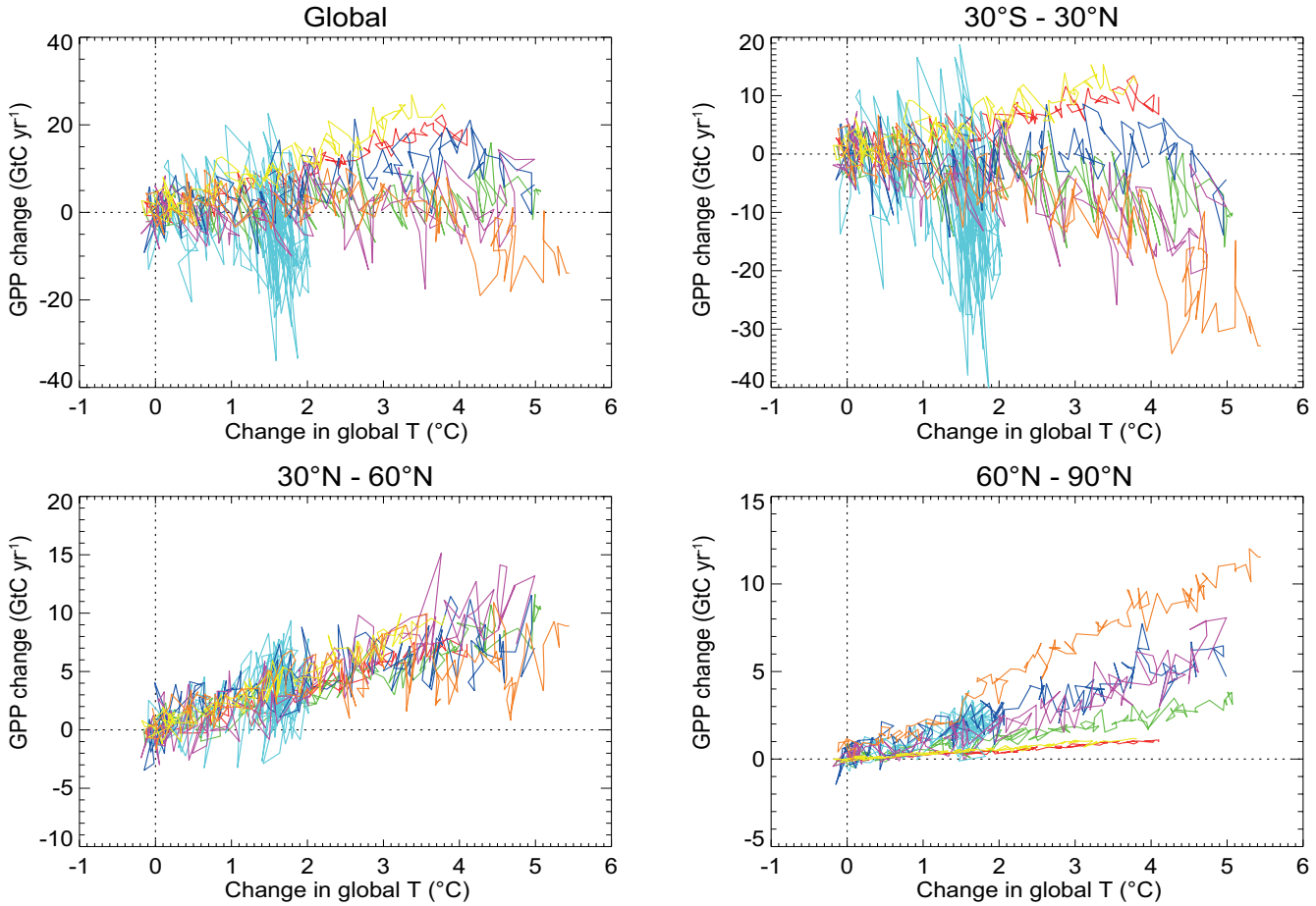


Figure 3.17 | The response of terrestrial productivity (gross primary productivity, GPP) to climate change, globally (top left) and for three latitudinal regions: 30°S–30°N; 30–60°N and 60–90°N. Data come from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (http://cmip-pcmdi.llnl.gov/cmip5/). Seven Earth System Models were used: Norwegian Earth System Model (NorESM-ME, yellow); Community Earth System Model (CESM, red); Institute Pierre Simon Laplace (IPLS)-CM5-LR (dark blue); Geophysical Fluid Dynamics Laboratory (GFDL, pale blue); Max Plank Institute-Earth System Model (MPI-ESM, pink); Hadley Centre New Global Environmental Model 2-Earth System (HadGEM2-ES, orange); and Canadian Earth System Model 2 (CanESM2, green). Differences in GPP between model simulations with ('1pctCO_2') and without ('esmfixclim1') the effects of climate change are shown. Data are plotted against the global mean temperature increase above pre-industrial levels from simulations with a 1% per year increase in CO_2 ('1pctCO_2').

The High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century (Section 3.3; Settele et al., 2014). The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016). Both of these processes facilitate the establishment of woody species in tundra areas. Arctic terrestrial ecosystems are being disrupted by delays in winter onset and mild winters associated with global warming (*high confidence*) (Cooper, 2014). Observational constraints suggest that stabilization at 1.5°C of warming would avoid the thawing of approximately 1.5 to 2.5 million km^2 of permafrost (*medium confidence*) compared with stabilization at 2°C (Chadburn et al., 2017), but the time scale for release of thawed carbon as CO_2 or CH_4 should be many centuries (Burke et al., 2017). In northern Eurasia, the growing season length is projected to increase by about 3–12 days at 1.5°C and 6–16 days at 2°C of warming (*medium confidence*) (Zhou et al., 2018). Aalto et al. (2017) predicted a 72% reduction in cryogenic land surface processes in northern Europe for RCP2.6 in 2040–2069 (corresponding to a global warming of approximately 1.6°C), with only slightly larger losses for RCP4.5 (2°C of global warming).

Projected impacts on forests as climate change occurs include increases in the intensity of storms, wildfires and pest outbreaks (Settele et al., 2014), potentially leading to forest dieback (*medium confidence*). Warmer and drier conditions in particular facilitate fire, drought and insect disturbances, while warmer and wetter conditions increase disturbances from wind and pathogens (Seidl et al., 2017). Particularly vulnerable regions are Central and South America, Mediterranean Basin, South Africa, South Australia where the drought risk will increase (see Figure 3.12). Including disturbances in simulations may influence productivity changes in European forests in response to climate change (Reyer et al., 2017b). There is additional evidence for the attribution of increased forest fire frequency in North America to anthropogenic climate change during 1984–2015, via the mechanism of increasing fuel aridity almost doubling the western USA forest fire area compared to what would have been expected in the absence of climate change (Abatzoglou and Williams, 2016). This projection is in line with expected fire risks, which indicate that fire frequency could increase over 37.8% of the global land area during 2010–2039 (Moritz et al., 2012), corresponding to a global warming level of approximately 1.2°C, compared with over 61.9% of the global land area in 2070–2099, corresponding to a warming of

approximately 3.5°C.[6] The values in Table 26-1 in a recent paper by Romero-Lankao et al. (2014) also indicate significantly lower wildfire risks in North America for near-term warming (2030–2040, considered a proxy for 1.5°C of warming) than at 2°C (*high confidence*).

The Amazon tropical forest has been shown to be close to its climatic limits (Hutyra et al., 2005), but this threshold may move under elevated CO_2 (Good et al., 2011). Future changes in rainfall, especially dry season length, will determine responses of the Amazon forest (Good et al., 2013). The forest may be especially vulnerable to combined pressure from multiple stressors, namely changes in climate and continued anthropogenic disturbance (Borma et al., 2013; Nobre et al., 2016). Modelling (Huntingford et al., 2013) and observational constraints (Cox et al., 2013) suggest that large-scale forest dieback is less likely than suggested under early coupled modelling studies (Cox et al., 2000; Jones et al., 2009). Nobre et al. (2016) estimated a climatic threshold of 4°C of warming and a deforestation threshold of 40%.

In many places around the world, the savanna boundary is moving into former grasslands. Woody encroachment, including increased tree cover and biomass, has increased over the past century, owing to changes in land management, rising CO_2 levels, and climate variability and change (often in combination) (Settele et al., 2014). For plant species in the Mediterranean region, shifts in phenology, range contraction and health decline have been observed with precipitation decreases and temperature increases (*medium confidence*) (Settele et al., 2014). Recent studies using independent complementary approaches have shown that there is a regional-scale threshold in the Mediterranean region between 1.5°C and 2°C of warming (Guiot and Cramer, 2016; Schleussner et al., 2016b). Further, Guiot and Cramer (2016) concluded that biome shifts unprecedented in the last 10,000 years can only be avoided if global warming is constrained to 1.5°C (*medium confidence*) – whilst 2°C of warming will result in a decrease of 12–15% of the Mediterranean biome area. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters. It is projected to lose about 20%, 45% and 80% of its current suitable climate area under 1°C, 2°C and 3°C of global warming, respectively, compared to 1961–1990 (*high confidence*) (Engelbrecht and Engelbrecht, 2016). In Australia, an increase in the density of trees and shrubs at the expense of grassland species is occurring across all major ecosystems and is projected to be amplified (NCCARF, 2013). Regarding Central America, Lyra et al. (2017) showed that the tropical rainforest biomass would be reduced by about 40% under global warming of 3°C, with considerable replacement by savanna and grassland. With a global warming of close to 1.5°C in 2050, a biomass decrease of 20% is projected for tropical rainforests of Central America (Lyra et al., 2017). If a linear response is assumed, this decrease may reach 30% (*medium confidence*).

Freshwater ecosystems are considered to be among the most threatened on the planet (Settele et al., 2014). Although peatlands cover only about 3% of the land surface, they hold one-third of the world's soil carbon stock (400 to 600 Pg) (Settele et al., 2014). When drained, this carbon is released to the atmosphere. At least 15% of peatlands have drained, mostly in Europe and Southeast Asia, and are responsible for 5% of human derived CO_2 emissions (Green and Page, 2017). Moreover, in the Congo basin (Dargie et al., 2017) and in the Amazonian basin (Draper et al., 2014), the peatlands store the equivalent carbon as that of a tropical forest. However, stored carbon is vulnerable to land-use change and future risk of drought, for example in northeast Brazil (*high confidence*) (Figure 3.12, Section 3.3.4.2). At the global scale, these peatlands are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Magrin et al., 2014). Wetland salinization, a widespread threat to the structure and ecological functioning of inland and coastal wetlands, is occurring at a high rate and large geographic scale (Section 3.3.6; Herbert et al., 2015). Settele et al. (2014) found that rising water temperatures are projected to lead to shifts in freshwater species distributions and worsen water quality. Some of these ecosystems respond non-linearly to changes in temperature. For example, Johnson and Poiani (2016) found that the wetland function of the Prairie Pothole region in North America is projected to decline at temperatures beyond a local warming of 2°C–3°C above present-day values (1°C local warming, corresponding to 0.6°C of global warming). If the ratio of local to global warming remains similar for these small levels of warming, this would indicate a global temperature threshold of 1.2°C–1.8°C of warming. Hence, constraining global warming to approximately 1.5°C would maintain the functioning of prairie pothole ecosystems in terms of their productivity and biodiversity, although a 20% increase of precipitation could offset 2°C of global warming (*high confidence*) (Johnson and Poiani, 2016).

3.4.3.6 Summary of implications for ecosystem services

In summary, constraining global warming to 1.5°C rather than 2°C has strong benefits for terrestrial and wetland ecosystems and their services (*high confidence*). These benefits include avoidance or reduction of changes such as biome transformations, species range losses, increased extinction risks (all *high confidence*) and changes in phenology (*high confidence*), together with projected increases in extreme weather events which are not yet factored into these analyses (Section 3.3). All of these changes contribute to disruption of ecosystem functioning and loss of cultural, provisioning and regulating services provided by these ecosystems to humans. Examples of such services include soil conservation (avoidance of desertification), flood control, water and air purification, pollination, nutrient cycling, sources of food, and recreation.

3.4.4 Ocean Ecosystems

The ocean plays a central role in regulating atmospheric gas concentrations, global temperature and climate. It also provides habitat to a large number of organisms and ecosystems that provide goods and services worth trillions of USD per year (e.g., Costanza et al., 2014; Hoegh-Guldberg et al., 2015). Together with local stresses (Halpern et al., 2015), climate change poses a major threat to an increasing number of ocean ecosystems (e.g., warm water or tropical coral reefs: *virtually certain*, WGII AR5) and consequently to many

[6] The approximate temperatures are derived from Figure 10.5a in Meehl et al. (2007), which indicates an ensemble average projection of 0.7°C or 3°C above 1980–1999 temperatures, which were already 0.5°C above pre-industrial values.

coastal communities that depend on marine resources for food, livelihoods and a safe place to live. Previous sections of this report have described changes in the ocean, including rapid increases in ocean temperature down to a depth of at least 700 m (Section 3.3.7). In addition, anthropogenic carbon dioxide has decreased ocean pH and affected the concentration of ions in seawater such as carbonate (Sections 3.3.10 and 3.4.4.5), both over a similar depth range. Increased ocean temperatures have intensified storms in some regions (Section 3.3.6), expanded the ocean volume and increased sea levels globally (Section 3.3.9), reduced the extent of polar summer sea ice (Section 3.3.8), and decreased the overall solubility of the ocean for oxygen (Section 3.3.10). Importantly, changes in the response to climate change rarely operate in isolation. Consequently, the effect of global warming of 1.5°C versus 2°C must be considered in the light of multiple factors that may accumulate and interact over time to produce complex risks, hazards and impacts on human and natural systems.

3.4.4.1 Observed impacts

Physical and chemical changes to the ocean resulting from increasing atmospheric CO_2 and other GHGs are already driving significant changes to ocean systems (*very high confidence*) and will continue to do so at 1.5°C, and more so at 2°C, of global warming above pre-industrial temperatures (Section 3.3.11). These changes have been accompanied by other changes such as ocean acidification, intensifying storms and deoxygenation (Levin and Le Bris, 2015). Risks are already significant at current greenhouse gas concentrations and temperatures, and they vary significantly among depths, locations and ecosystems, with impacts being singular, interactive and/or cumulative (Boyd et al., 2015).

3.4.4.2 Warming and stratification of the surface ocean

As atmospheric greenhouse gases have increased, the global mean surface temperature (GMST) has reached about 1°C above the pre-industrial period, and oceans have rapidly warmed from the ocean surface to the deep sea (*high confidence*) (Sections 3.3.7; Hughes and Narayanaswamy, 2013; Levin and Le Bris, 2015; Yasuhara and Danovaro, 2016; Sweetman et al., 2017). Marine organisms are already responding to these changes by shifting their biogeographical ranges to higher latitudes at rates that range from approximately 0 to 40 km yr^{-1} (Burrows et al., 2014; Chust, 2014; Bruge et al., 2016; Poloczanska et al., 2016), which has consequently affected the structure and function of the ocean, along with its biodiversity and foodwebs (*high confidence*). Movements of organisms does not necessarily equate to the movement of entire ecosystems. For example, species of reef-building corals have been observed to shift their geographic ranges, yet this has not resulted in the shift of entire coral ecosystems (*high confidence*) (Woodroffe et al., 2010; Yamano et al., 2011). In the case of 'less mobile' ecosystems (e.g., coral reefs, kelp forests and intertidal communities), shifts in biogeographical ranges may be limited, with mass mortalities and disease outbreaks increasing in frequency as the exposure to extreme temperatures increases (*very high confidence*) (Hoegh-Guldberg, 1999; Garrabou et al., 2009; Rivetti et al., 2014; Maynard et al., 2015; Krumhansl et al., 2016; Hughes et al., 2017b; see also Box 3.4). These trends are projected to become more pronounced at warming of 1.5°C, and more so at 2°C, above the pre-industrial period (Hoegh-Guldberg et al., 2007; Donner, 2009; Frieler et al., 2013; Horta E Costa et al., 2014; Vergés et al., 2014, 2016; Zarco-Perello et al., 2017) and are *likely* to result in decreases in marine biodiversity at the equator but increases in biodiversity at higher latitudes (Cheung et al., 2009; Burrows et al., 2014).

While the impacts of species shifting their ranges are mostly negative for human communities and industry, there are instances of short-term gains. Fisheries, for example, may expand temporarily at high latitudes in the Northern Hemisphere as the extent of summer sea ice recedes and NPP increases (*medium confidence*) (Cheung et al., 2010; Lam et al., 2016; Weatherdon et al., 2016). High-latitude fisheries are not only influenced by the effect of temperature on NPP but are also strongly influenced by the direct effects of changing temperatures on fish and fisheries (Section 3.4.4.9; Barange et al., 2014; Pörtner et al., 2014; Cheung et al., 2016b; Weatherdon et al., 2016). Temporary gains in the productivity of high-latitude fisheries are offset by a growing number of examples from low and mid-latitudes where increases in sea temperature are driving decreases in NPP, owing to the direct effects of elevated temperatures and/or reduced ocean mixing from reduced ocean upwelling, that is, increased stratification (*low-medium confidence*) (Cheung et al., 2010; Ainsworth et al., 2011; Lam et al., 2012, 2014, 2016; Bopp et al., 2013; Boyd et al., 2014; Chust et al., 2014; Hoegh-Guldberg et al., 2014; Poloczanska et al., 2014; Pörtner et al., 2014; Signorini et al., 2015). Reduced ocean upwelling has implications for millions of people and industries that depend on fisheries for food and livelihoods (Bakun et al., 2015; FAO, 2016; Kämpf and Chapman, 2016), although there is *low confidence* in the projection of the size of the consequences at 1.5°C. It is also important to appreciate these changes in the context of large-scale ocean processes such as the ocean carbon pump. The export of organic carbon to deeper layers of the ocean increases as NPP changes in the surface ocean, for example, with implications for foodwebs and oxygen levels (Boyd et al., 2014; Sydeman et al., 2014; Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015).

3.4.4.3 Storms and coastal runoff

Storms, wind, waves and inundation can have highly destructive impacts on ocean and coastal ecosystems, as well as the human communities that depend on them (IPCC, 2012; Seneviratne et al., 2012). The intensity of tropical cyclones across the world's oceans has increased, although the overall number of tropical cyclones has remained the same or decreased (*medium confidence*) (Section 3.3.6; Elsner et al., 2008; Holland and Bruyère, 2014). The direct force of wind and waves associated with larger storms, along with changes in storm direction, increases the risks of physical damage to coastal communities and to ecosystems such as mangroves (*low to medium confidence*) (Long et al., 2016; Primavera et al., 2016; Villamayor et al., 2016; Cheal et al., 2017) and tropical coral reefs (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017). These changes are associated with increases in maximum wind speed, wave height and the inundation, although trends in these variables vary from region to region (Section 3.3.5). In some cases, this can lead to increased exposure to related impacts, such as flooding, reduced water quality and increased sediment runoff (*medium-high confidence*) (Brodie et al., 2012; Wong et al., 2014; Anthony, 2016; AR5, Table 5.1).

Sea level rise also amplifies the impacts of storms and wave action (Section 3.3.9), with robust evidence that storm surges and damage are already penetrating farther inland than a few decades ago, changing conditions for coastal ecosystems and human communities. This is especially true for small islands (Box 3.5) and low-lying coastal communities, where issues such as storm surges can transform coastal areas (Section 3.4.5; Brown et al., 2018a). Changes in the frequency of extreme events, such as an increase in the frequency of intense storms, have the potential (along with other factors, such as disease, food web changes, invasive organisms and heat stress-related mortality; Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016; Clements et al., 2017) to overwhelm the capacity for natural and human systems to recover following disturbances. This has recently been seen for key ecosystems such as tropical coral reefs (Box 3.4), which have changed from coral-dominated ecosystems to assemblages dominated by other organisms such as seaweeds, with changes in associated organisms and ecosystem services (*high confidence*) (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017; Hoegh-Guldberg et al., 2017; Hughes et al., 2017a, b). The impacts of storms are amplified by sea level rise (Section 3.4.5), leading to substantial challenges today and in the future for cities, deltas and small island states in particular (Sections 3.4.5.2 to 3.4.5.4), as well as for coastlines and their associated ecosystems (Sections 3.4.5.5 to 3.4.5.7).

3.4.4.4 Ocean circulation

The movement of water within the ocean is essential to its biology and ecology, as well to the circulation of heat, water and nutrients around the planet (Section 3.3.7). The movement of these factors drives local and regional climates, as well as primary productivity and food production. Firmly attributing recent changes in the strength and direction of ocean currents to climate change, however, is complicated by long-term patterns and variability (e.g., Pacific decadal oscillation, PDO; Signorini et al., 2015) and a lack of records that match the long-term nature of these changes in many cases (Lluch-Cota et al., 2014). An assessment of the literature since AR5 (Sydeman et al., 2014), however, concluded that (overall) upwelling-favourable winds have intensified in the California, Benguela and Humboldt upwelling systems, but have weakened in the Iberian system and have remained neutral in the Canary upwelling system in over 60 years of records (1946–2012) (*medium confidence*). These conclusions are consistent with a growing consensus that wind-driven upwelling systems are likely to intensify under climate change in many upwelling systems (Sydeman et al., 2014; Bakun et al., 2015; Di Lorenzo, 2015), with potentially positive and negative consequences (Bakun et al., 2015).

Changes in ocean circulation can have profound impacts on marine ecosystems by connecting regions and facilitating the entry and establishment of species in areas where they were unknown before (e.g., 'tropicalization' of temperate ecosystems; Wernberg et al., 2012; Vergés et al., 2014, 2016; Zarco-Perello et al., 2017), as well as the arrival of novel disease agents (*low-medium confidence*) (Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016). For example, the herbivorous sea urchin *Centrostephanus rodgersii* has been reached Tasmania from the Australian mainland, where it was previously unknown, owing to a strengthening of the East Australian Current (EAC) that connects the two regions (*high confidence*) (Ling et al., 2009). As a consequence, the distribution and abundance of kelp forests has rapidly decreased, with implications for fisheries and other ecosystem services (Ling et al., 2009). These risks to marine ecosystems are projected to become greater at 1.5°C, and more so at 2°C (*medium confidence*) (Cheung et al., 2009; Pereira et al., 2010; Pinsky et al., 2013; Burrows et al., 2014).

Changes to ocean circulation can have even larger influence in terms of scale and impacts. Weakening of the Atlantic Meridional Overturning Circulation (AMOC), for example, is projected to be highly disruptive to natural and human systems as the delivery of heat to higher latitudes via this current system is reduced (Collins et al., 2013). Evidence of a slowdown of AMOC has increased since AR5 (Smeed et al., 2014; Rahmstorf et al., 2015a, b; Kelly et al., 2016), yet a strong causal connection to climate change is missing (*low confidence*) (Section 3.3.7).

3.4.4.5 Ocean acidification

Ocean chemistry encompasses a wide range of phenomena and chemical species, many of which are integral to the biology and ecology of the ocean (Section 3.3.10; Gattuso et al., 2014, 2015; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014). While changes to ocean chemistry are likely to be of central importance, the literature on how climate change might influence ocean chemistry over the short and long term is limited (*medium confidence*). By contrast, numerous risks from the specific changes associated with ocean acidification have been identified (Dove et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015; Albright et al., 2016), with the consensus that resulting changes to the carbonate chemistry of seawater are having, and are likely to continue to have, fundamental and substantial impacts on a wide variety of organisms (*high confidence*). Organisms with shells and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a large number of organisms and processes such as de-calcification, although there are some taxa that have not shown high-sensitivity to changes in CO_2, pH and carbonate concentrations (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015). Risks of these impacts also vary with latitude and depth, with the greatest changes occurring at high latitudes as well as deeper regions. The aragonite saturation horizon (i.e., where concentrations of calcium and carbonate fall below the saturation point for aragonite, a key crystalline form of calcium carbonate) is decreasing with depth as anthropogenic CO_2 penetrates deeper into the ocean over time. Under many models and scenarios, the aragonite saturation is projected to reach the surface by 2030 onwards, with a growing list of impacts and consequences for ocean organisms, ecosystems and people (Orr et al., 2005; Hauri et al., 2016).

Further, it is difficult to reliably separate the impacts of ocean warming and acidification. As ocean waters have increased in sea surface temperature (SST) by approximately 0.9°C they have also decreased by 0.2 pH units since 1870–1899 ('pre-industrial'; Table 1 in Gattuso et al., 2015; Bopp et al., 2013). As CO_2 concentrations continue to increase along with other GHGs, pH will decrease while sea temperature will increase, reaching 1.7°C and a decrease of 0.2 pH units (by 2100 under RCP4.5) relative to the pre-industrial period. These changes are likely to continue given the negative correlation of temperature and pH. Experimental manipulation of CO_2, temperature and consequently

acidification indicate that these impacts will continue to increase in size and scale as CO_2 and SST continue to increase in tandem (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013).

While many risks have been defined through laboratory and mesocosm experiments, there is a growing list of impacts from the field (*medium confidence*) that include community-scale impacts on bacterial assemblages and processes (Endres et al., 2014), coccolithophores (K.J.S. Meier et al., 2014), pteropods and polar foodwebs (Bednaršek et al., 2012, 2014), phytoplankton (Moy et al., 2009; Riebesell et al., 2013; Richier et al., 2014), benthic ecosystems (Hall-Spencer et al., 2008; Linares et al., 2015), seagrass (Garrard et al., 2014), and macroalgae (Webster et al., 2013; Ordonez et al., 2014), as well as excavating sponges, endolithic microalgae and reef-building corals (Dove et al., 2013; Reyes-Nivia et al., 2013; Fang et al., 2014), and coral reefs (Box 3.4; Fabricius et al., 2011; Allen et al., 2017). Some ecosystems, such as those from bathyal areas (i.e., 200–3000 m below the surface), are likely to undergo very large reductions in pH by the year 2100 (0.29 to 0.37 pH units), yet evidence of how deep-water ecosystems will respond is currently limited despite the potential planetary importance of these areas (*low to medium confidence*) (Hughes and Narayanaswamy, 2013; Sweetman et al., 2017).

3.4.4.6 Deoxygenation

Oxygen levels in the ocean are maintained by a series of processes including ocean mixing, photosynthesis, respiration and solubility (Boyd et al., 2014, 2015; Pörtner et al., 2014; Breitburg et al., 2018). Concentrations of oxygen in the ocean are declining (*high confidence*) owing to three main factors related to climate change: (i) heat-related stratification of the water column (less ventilation and mixing), (ii) reduced oxygen solubility as ocean temperature increases, and (iii) impacts of warming on biological processes that produce or consume oxygen such as photosynthesis and respiration (*high confidence*) (Bopp et al., 2013; Pörtner et al., 2014; Altieri and Gedan, 2015; Deutsch et al., 2015; Schmidtko et al., 2017; Shepherd et al., 2017; Breitburg et al., 2018). Further, a range of processes (Section 3.4.11) are acting synergistically, including factors not related to climate change, such as runoff and coastal eutrophication (e.g., from coastal farming and intensive aquaculture). These changes can lead to increased phytoplankton productivity as a result of the increased concentration of dissolved nutrients. Increased supply of organic carbon molecules from coastal run-off can also increase the metabolic activity of coastal microbial communities (Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015). Deep sea areas are likely to experience some of the greatest challenges, as abyssal seafloor habitats in areas of deep-water formation are projected to experience decreased water column oxygen concentrations by as much as 0.03 mL L^{-1} by 2100 (Levin and Le Bris, 2015; Sweetman et al., 2017).

The number of 'dead zones' (areas where oxygenated waters have been replaced by hypoxic conditions) has been growing strongly since the 1990s (Diaz and Rosenberg, 2008; Altieri and Gedan, 2015; Schmidtko et al., 2017). While attribution can be difficult because of the complexity of the processes involved, both related and unrelated to climate change, some impacts associated to deoxygenation (*low-medium confidence*) include the expansion of oxygen minimum zones (OMZ) (Turner et al., 2008; Carstensen et al., 2014; Acharya and Panigrahi, 2016; Lachkar et al., 2018), physiological impacts (Pörtner et al., 2014), and mortality and/or displacement of oxygen dependent organisms such as fish (Hamukuaya et al., 1998; Thronson and Quigg, 2008; Jacinto, 2011) and invertebrates (Hobbs and Mcdonald, 2010; Bednaršek et al., 2016; Seibel, 2016; Altieri et al., 2017). In addition, deoxygenation interacts with ocean acidification to present substantial separate and combined challenges for fisheries and aquaculture (*medium confidence*) (Hamukuaya et al., 1998; Bakun et al., 2015; Rodrigues et al., 2015; Feely et al., 2016; S. Li et al., 2016; Asiedu et al., 2017a; Clements and Chopin, 2017; Clements et al., 2017; Breitburg et al., 2018). Deoxygenation is expected to have greater impacts as ocean warming and acidification increase (*high confidence*), with impacts being larger and more numerous than today (e.g., greater challenges for aquaculture and fisheries from hypoxia), and as the number of hypoxic areas continues to increase. Risks from deoxygenation are *virtually certain* to increase as warming continues, although our understanding of risks at 1.5°C versus 2°C is incomplete (*medium confidence*). Reducing coastal pollution, and consequently the penetration of organic carbon into deep benthic habitats, is expected to reduce the loss of oxygen in coastal waters and hypoxic areas in general (*high confidence*) (Breitburg et al., 2018).

3.4.4.7 Loss of sea ice

Sea ice is a persistent feature of the planet's polar regions (Polyak et al., 2010) and is central to marine ecosystems, people (e.g., food, culture and livelihoods) and industries (e.g., fishing, tourism, oil and gas, and shipping). Summer sea ice in the Arctic, however, has been retreating rapidly in recent decades (Section 3.3.8), with an assessment of the literature revealing that a fundamental transformation is occurring in polar organisms and ecosystems, driven by climate change (*high confidence*) (Larsen et al., 2014). These changes are strongly affecting people in the Arctic who have close relationships with sea ice and associated ecosystems, and these people are facing major adaptation challenges as a result of sea level rise, coastal erosion, the accelerated thawing of permafrost, changing ecosystems and resources, and many other issues (Ford, 2012; Ford et al., 2015).

There is considerable and compelling evidence that a further increase of 0.5°C beyond the present-day average global surface temperature will lead to multiple levels of impact on a variety of organisms, from phytoplankton to marine mammals, with some of the most dramatic changes occurring in the Arctic Ocean and western Antarctic Peninsula (Turner et al., 2014, 2017b; Steinberg et al., 2015; Piñones and Fedorov, 2016).

The impacts of climate change on sea ice are part of the focus of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), due to be released in 2019, and hence are not covered comprehensively here. However, there is a range of responses to the loss of sea ice that are occurring and which increase at 1.5°C and further so with 2°C of global warming. Some of these changes are described briefly here. Photosynthetic communities, such macroalgae, phytoplankton and microalgae dwelling on the underside of floating sea ice are changing, owing to increased temperatures, light and nutrient levels. As sea ice retreats, mixing of

the water column increases, and phototrophs have increased access to seasonally high levels of solar radiation (*medium confidence*) (Dalpadado et al., 2014; W.N. Meier et al., 2014). These changes are expected to stimulate fisheries productivity in high-latitude regions by mid-century (*high confidence*) (Cheung et al., 2009, 2010, 2016b; Lam et al., 2014), with evidence that this is already happening for several high-latitude fisheries in the Northern Hemisphere, such as the Bering Sea, although these 'positive' impacts may be relatively short-lived (Hollowed and Sundby, 2014; Sundby et al., 2016). In addition to the impact of climate change on fisheries via impacts on net primary productivity (NPP), there are also direct effects of temperature on fish, which may in turn have a range of impacts (Pörtner et al., 2014). Sea ice in Antarctica is undergoing changes that exceed those seen in the Arctic (Maksym et al., 2011; Reid et al., 2015), with increases in sea ice coverage in the western Ross Sea being accompanied by strong decreases in the Bellingshausen and Amundsen Seas (Hobbs et al., 2016). While Antarctica is not permanently populated, the ramifications of changes to the productivity of vast regions, such as the Southern Ocean, have substantial implications for ocean foodwebs and fisheries globally.

3.4.4.8 Sea level rise

Mean sea level is increasing (Section 3.3.9), with substantial impacts already being felt by coastal ecosystems and communities (Wong et al., 2014) (*high confidence*). These changes are interacting with other factors, such as strengthening storms, which together are driving larger storm surges, infrastructure damage, erosion and habitat loss (Church et al., 2013; Stocker et al., 2013; Blankespoor et al., 2014). Coastal wetland ecosystems such as mangroves, sea grasses and salt marshes are under pressure from rising sea level (*medium confidence*) (Section 3.4.5; Di Nitto et al., 2014; Ellison, 2014; Lovelock et al., 2015; Mills et al., 2016; Nicholls et al., 2018), as well as from a wide range of other risks and impacts unrelated to climate change, with the ongoing loss of wetlands recently estimated at approximately 1% per annum across a large number of countries (Blankespoor et al., 2014; Alongi, 2015). While some ecosystems (e.g., mangroves) may be able to shift shoreward as sea levels increase, coastal development (e.g., buildings, seawalls and agriculture) often interrupts shoreward shifts, as well as reducing sediment supplies down some rivers (e.g., dams) due to coastal development (Di Nitto et al., 2014; Lovelock et al., 2015; Mills et al., 2016).

Responses to sea level rise challenges for ocean and coastal systems include reducing the impact of other stresses, such as those arising from tourism, fishing, coastal development, reduced sediment supply and unsustainable aquaculture/agriculture, in order to build ecological resilience (Hossain et al., 2015; Sutton-Grier and Moore, 2016; Asiedu et al., 2017a). The available literature largely concludes that these impacts will intensify under a 1.5°C warmer world but will be even higher at 2°C, especially when considered in the context of changes occurring beyond the end of the current century. In some cases, restoration of coastal habitats and ecosystems may be a cost-effective way of responding to changes arising from increasing levels of exposure to rising sea levels, intensifying storms, coastal inundation and salinization (Section 3.4.5 and Box 3.5; Arkema et al., 2013), although limitations of these strategies have been identified (e.g., Lovelock et al., 2015; Weatherdon et al., 2016).

3.4.4.9 Projected risks and adaptation options for oceans under global warming of 1.5°C or 2°C above pre-industrial levels

A comprehensive discussion of risk and adaptation options for all natural and human systems is not possible in the context and length of this report, and hence the intention here is to illustrate key risks and adaptation options for ocean ecosystems and sectors. This assessment builds on the recent expert consensus of Gattuso et al. (2015) by assessing new literature from 2015–2017 and adjusting the levels of risk from climate change in the light of literature since 2014. The original expert group's assessment (Supplementary Material 3.SM.3.2) was used as input for this new assessment, which focuses on the implications of global warming of 1.5°C as compared to 2°C. A discussion of potential adaptation options is also provided, the details of which will be further explored in later chapters of this special report. The section draws on the extensive analysis and literature presented in the Supplementary Material of this report (3.SM.3.2, 3.SM.3.3) and has a summary in Figures 3.18 and 3.20 which outline the added relative risks of climate change.

3.4.4.10 Framework organisms (tropical corals, mangroves and seagrass)

Marine organisms ('ecosystem engineers'), such as seagrass, kelp, oysters, salt marsh species, mangroves and corals, build physical structures or frameworks (i.e., sea grass meadows, kelp forests, oyster reefs, salt marshes, mangrove forests and coral reefs) which form the habitat for a large number of species (Gutiérrez et al., 2012). These organisms in turn provide food, livelihoods, cultural significance, and services such as coastal protection to human communities (Bell et al., 2011, 2018; Cinner et al., 2012; Arkema et al., 2013; Nurse et al., 2014; Wong et al., 2014; Barbier, 2015; Bell and Taylor, 2015; Hoegh-Guldberg et al., 2015; Mycoo, 2017; Pecl et al., 2017).

Risks of climate change impacts for seagrass and mangrove ecosystems were recently assessed by an expert group led by Short et al. (2016). Impacts of climate change were assessed to be similar across a range of submerged and emerged plants. Submerged plants such as seagrass were affected mostly by temperature extremes (Arias-Ortiz et al., 2018), and indirectly by turbidity, while emergent communities such as mangroves and salt marshes were most susceptible to sea level variability and temperature extremes, which is consistent with other evidence (Di Nitto et al., 2014; Sierra-Correa and Cantera Kintz, 2015; Osorio et al., 2016; Sasmito et al., 2016), especially in the context of human activities that reduce sediment supply (Lovelock et al., 2015) or interrupt the shoreward movement of mangroves though the construction of coastal infrastructure. This in turn leads to 'coastal squeeze' where coastal ecosystems are trapped between changing ocean conditions and coastal infrastructure (Mills et al., 2016). Projections of the future distribution of seagrasses suggest a poleward shift, which raises concerns that low-latitude seagrass communities may contract as a result of increasing stress levels (Valle et al., 2014).

Climate change (e.g., sea level rise, heat stress, storms) presents risk for coastal ecosystems such as seagrass (*high confidence*) and reef-building corals (*very high confidence*) (Figure 3.18, Supplementary Material 3.SM.3.2), with evidence of increasing concern since AR5 and

the conclusion that tropical corals may be even more vulnerable to climate change than indicated in assessments made in 2014 (Hoegh-Guldberg et al., 2014; Gattuso et al., 2015). The current assessment also considered the heatwave-related loss of 50% of shallow-water corals across hundreds of kilometres of the world's largest continuous coral reef system, the Great Barrier Reef. These large-scale impacts, plus the observation of back-to-back bleaching events on the Great Barrier Reef (predicted two decades ago, Hoegh-Guldberg, 1999) and arriving sooner than predicted (Hughes et al., 2017b, 2018), suggest that the research community may have underestimated climate risks for coral reefs (Figure 3.18). The general assessment of climate risks for mangroves prior to this special report was that they face greater risks from deforestation and unsustainable coastal development than from climate change (Alongi, 2008; Hoegh-Guldberg et al., 2014; Gattuso et al., 2015). Recent large-scale die-offs (Duke et al., 2017; Lovelock et al., 2017), however, suggest that risks from climate change may have been underestimated for mangroves as well. With the events of the last past three years in mind, risks are now considered to be undetectable to moderate (i.e., moderate risks now start at 1.3°C as opposed to 1.8°C; *medium confidence*). Consequently, when average global warming reaches 1.3°C above pre-industrial levels, the risk of climate change to mangroves are projected to be moderate (Figure 3.18) while tropical coral reefs will have reached a high level of risk as examplified by increasing damage from heat stress since the early 1980s. At global warming of 1.8°C above pre-industrial levels, seagrasses are projected to reach moderate to high levels of risk (e.g., damage resulting from sea level rise, erosion, extreme temperatures, and storms), while risks to mangroves from climate change are projected to remain moderate (e.g., not keeping up with sea level rise, and more frequent heat stress mortality) although there is *low certainty* as to when or if this important ecosystem is likely to transition to higher levels of additional risk from climate change (Figure 3.18).

Warm water (tropical) coral reefs are projected to reach a very high risk of impact at 1.2°C (Figure 3.18), with most available evidence suggesting that coral-dominated ecosystems will be non-existent at this temperature or higher (*high confidence*). At this point, coral abundance will be near zero at many locations and storms will contribute to 'flattening' the three-dimensional structure of reefs without recovery, as already observed for some coral reefs (Alvarez-Filip et al., 2009). The impacts of warming, coupled with ocean acidification, are expected to undermine the ability of tropical coral reefs to provide habitat for thousand of species, which together provide a range of ecosystem services (e.g., food, livelihoods, coastal protection, cultural services) that are important for millions of people (*high confidence*) (Burke et al., 2011).

Strategies for reducing the impact of climate change on framework organisms include reducing stresses not directly related to climate change (e.g., coastal pollution, overfishing and destructive coastal development) in order to increase their ecological resilience in the face of accelerating climate change impacts (World Bank, 2013; Ellison, 2014; Anthony et al., 2015; Sierra-Correa and Cantera Kintz, 2015; Kroon et al., 2016; O'Leary et al., 2017), as well as protecting locations where organisms may be more robust (Palumbi et al., 2014) or less exposed to climate change (Bongaerts et al., 2010; van Hooidonk et al., 2013; Beyer et al., 2018). This might involve cooler areas due to upwelling, or involve deep-water locations that experience less extreme conditions and impacts. Given the potential value of such locations for promoting the survival of coral communities under climate change, efforts to prevent their loss resulting from other stresses are important (Bongaerts et al., 2010, 2017; Chollett et al., 2010, 2014; Chollett and Mumby, 2013; Fine et al., 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015; Beyer et al., 2018). A full understanding of the role of refugia in reducing the loss of ecosystems has yet to be developed (*low to medium confidence*). There is also interest in *ex situ* conservation approaches involving the restoration of corals via aquaculture (Shafir et al., 2006; Rinkevich, 2014) or the use of 'assisted evolution' to help corals adapt to changing sea temperatures (van Oppen et al., 2015, 2017), although there are numerous challenges that must be surpassed if these approaches are to be cost-effective responses to preserving coral reefs under rapid climate change (*low confidence*) (Hoegh-Guldberg, 2012, 2014a; Bayraktarov et al., 2016).

High levels of adaptation are expected to be required to prevent impacts on food security and livelihoods in coastal populations (*medium confidence*). Integrating coastal infrastructure with changing ecosystems such as mangroves, seagrasses and salt marsh, may offer adaptation strategies as they shift shoreward as sea levels rise (*high confidence*). Maintaining the sediment supply to coastal areas would also assist mangroves in keeping pace with sea level rise (Shearman et al., 2013; Lovelock et al., 2015; Sasmito et al., 2016). For this reason, habitat for mangroves can be strongly affected by human actions such as building dams which reduce the sediment supply and hence the ability of mangroves to escape 'drowning' as sea level rises (Lovelock et al., 2015). In addition, integrated coastal zone management should recognize the importance and economic expediency of using natural ecosystems such as mangroves and tropical coral reefs to protect coastal human communities (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Elliff and Silva, 2017). Adaptation options include developing alternative livelihoods and food sources, ecosystem-based management/adaptation such as ecosystem restoration, and constructing coastal infrastructure that reduces the impacts of rising seas and intensifying storms (Rinkevich, 2015; Weatherdon et al., 2016; Asiedu et al., 2017a; Feller et al., 2017). Clearly, these options need to be carefully assessed in terms of feasibility, cost and scalability, as well as in the light of the coastal ecosystems involved (Bayraktarov et al., 2016).

3.4.4.11 Ocean foodwebs (pteropods, bivalves, krill and fin fish)

Ocean foodwebs are vast interconnected systems that transfer solar energy and nutrients from phytoplankton to higher trophic levels, including apex predators and commercially important species such as tuna. Here, we consider four representative groups of marine organisms which are important within foodwebs across the ocean, and which illustrate the impacts and ramifications of 1.5°C or higher levels of warming.

The first group of organisms, pteropods, are small pelagic molluscs that suspension feed and produce a calcium carbonate shell. They are highly abundant in temperate and polar waters where they are an important link in the foodweb between phytoplankton and a range of other organisms including fish, whales and birds. The second group,

bivalve molluscs (e.g., clams, oysters and mussels), are filter-feeding invertebrates. These invertebrate organisms underpin important fisheries and aquaculture industries, from polar to tropical regions, and are important food sources for a range of organisms including humans. The third group of organisms considered here is a globally significant group of invertebrates known as *euphausiid crustaceans* (krill), which are a key food source for many marine organisms and hence a major link between primary producers and higher trophic levels (e.g., fish, mammals and sea birds). Antarctic krill, *Euphausia superba*, are among the most abundant species in terms of mass and are consequently an essential component of polar foodwebs (Atkinson et al., 2009). The last group, fin fishes, is vitally important components of ocean foodwebs, contribute to the income of coastal communities, industries and nations, and are important to the foodsecurity and livelihood of hundreds of millions of people globally (FAO, 2016). Further background for this section is provided in Supplementary Material 3.SM.3.2.

There is a moderate risk to ocean foodwebs under present-day conditions (*medium to high confidence*) (Figure 3.18). Changing water chemistry and temperature are already affecting the ability of pteropods to produce their shells, swim and survive (Bednaršek et al., 2016). Shell dissolution, for example, has increased by 19–26% in both nearshore and offshore populations since the pre-industrial period (Feely et al., 2016). There is considerable concern as to whether these organisms are declining further, especially given the central importance in ocean foodwebs (David et al., 2017). Reviewing the literature reveals that pteropods are projected to face high risks of impact at average global temperatures 1.5°C above pre-industrial levels and increasing risks of impacts at 2°C (*medium confidence*).

As GMST increases by 1.5°C and more, the risk of impacts from ocean warming and acidification are expected to be moderate to high, except in the case of bivalves (mid-latitudes) where the risks of impacts are projected to be high to very high (Figure 3.18). Ocean warming and acidification are already affecting the life history stages of bivalve molluscs (e.g., Asplund et al., 2014; Mackenzie et al., 2014; Waldbusser et al., 2014; Zittier et al., 2015; Shi et al., 2016; Velez et al., 2016; Q. Wang et al., 2016; Castillo et al., 2017; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017). Impacts on adult bivalves include decreased growth, increased respiration and reduced calcification, whereas larval stages tend to show greater developmental abnormalities and increased mortality after exposure to these conditions (*medium to high confidence*) (Q. Wang et al., 2016; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017). Risks are expected to accumulate at higher temperatures for bivalve molluscs, with very high risks expected at 1.8°C of warming or more. This general pattern applies to low-latitude fin fish, which are expected to experience moderate to high risks of impact at 1.3°C of global warming (*medium confidence*), and very high risks at 1.8°C at low latitudes (*medium confidence*) (Figure 3.18).

Large-scale changes to foodweb structure are occurring in all oceans. For example, record levels of sea ice loss in the Antarctic (Notz and Stroeve, 2016; Turner et al., 2017b) translate into a loss of habitat and hence reduced abundance of krill (Piñones and Fedorov, 2016), with negative ramifications for the seabirds and whales which feed on krill (Croxall, 1992; Trathan and Hill, 2016) (*low-medium confidence*). Other influences, such as high rates of ocean acidification coupled with shoaling of the aragonite saturation horizon, are likely to also play key roles (Kawaguchi et al., 2013; Piñones and Fedorov, 2016). As with many risks associated with impacts at the ecosystem scale, most adaptation options focus on the management of stresses unrelated to climate change but resulting from human activities, such as pollution and habitat destruction. Reducing these stresses will be important in efforts to maintain important foodweb components. Fisheries management at local to regional scales will be important in reducing stress on foodweb organisms, such as those discussed here, and in helping communities and industries adapt to changing foodweb structures and resources (see further discussion of fisheries *per se* below; Section 3.4.6.3). One strategy is to maintain larger population levels of fished species in order to provide more resilient stocks in the face of challenges that are increasingly driven by climate change (Green et al., 2014; Bell and Taylor, 2015).

3.4.4.12 Key ecosystem services (e.g., carbon uptake, coastal protection, and tropical coral reef recreation)

The ocean provides important services, including the regulation of atmospheric composition via gas exchange across the boundary between ocean and atmosphere, and the storage of carbon in vegetation and soils associated with ecosystems such as mangroves, salt marshes and coastal peatlands. These services involve a series of physicochemical processes which are influenced by ocean chemistry, circulation, biology, temperature and biogeochemical components, as well as by factors other than climate (Boyd, 2015). The ocean is also a net sink for CO_2 (another important service), absorbing approximately 30% of human emissions from the burning of fossil fuels and modification of land use (IPCC, 2013). Carbon uptake by the ocean is decreasing (Iida et al., 2015), and there is increasing concern from observations and models regarding associated changes to ocean circulation (Sections 3.3.7 and 3.4.4., Rahmstorf et al., 2015b);. Biological components of carbon uptake by the ocean are also changing, with observations of changing net primary productivity (NPP) in equatorial and coastal upwelling systems (*medium confidence*) (Lluch-Cota et al., 2014; Sydeman et al., 2014; Bakun et al., 2015), as well as subtropical gyre systems (*low confidence*) (Signorini et al., 2015). There is general agreement that NPP will decline as ocean warming and acidification increase (*medium confidence*) (Bopp et al., 2013; Boyd et al., 2014; Pörtner et al., 2014; Boyd, 2015).

Projected risks of impacts from reductions in carbon uptake, coastal protection and services contributing to coral reef recreation suggest a transition from moderate to high risks at 1.5°C and higher (*low confidence*). At 2°C, risks of impacts associated with changes to carbon uptake are high (*high confidence*), while the risks associated with reduced coastal protection and recreation on tropical coral reefs are high, especially given the vulnerability of this ecosystem type, and others (e.g., seagrass and mangroves), to climate change (*medium confidence*) (Figure 3.18). Coastal protection is a service provided by natural barriers such as mangroves, seagrass meadows, coral reefs, and other coastal ecosystems, and it is important for protecting human communities and infrastructure against the impacts associated with rising sea levels, larger waves and intensifying storms (*high confidence*) (Gutiérrez et al., 2012; Kennedy et al., 2013; Ferrario et al., 2014; Barbier, 2015; Cooper et al., 2016; Hauer et al., 2016; Narayan et al., 2016). Both natural and human coastal

protection have the potential to reduce these impacts (Fu and Song, 2017). Tropical coral reefs, for example, provide effective protection by dissipating about 97% of wave energy, with 86% of the energy being dissipated by reef crests alone (Ferrario et al., 2014; Narayan et al., 2016). Mangroves similarly play an important role in coastal protection, as well as providing resources for coastal communities, but they are already under moderate risk of not keeping up with sea level rise due to climate change and to contributing factors, such as reduced sediment supply or obstacles to shoreward shifts (Saunders et al., 2014; Lovelock et al., 2015). This implies that coastal areas currently protected by mangroves may experience growing risks over time.

Risks for specific marine and coastal organisms, ecosystems and sectors

The key elements are presented here as a function of the risk level assessed between 1.5 and 2°C (Average global sea surface temperature).

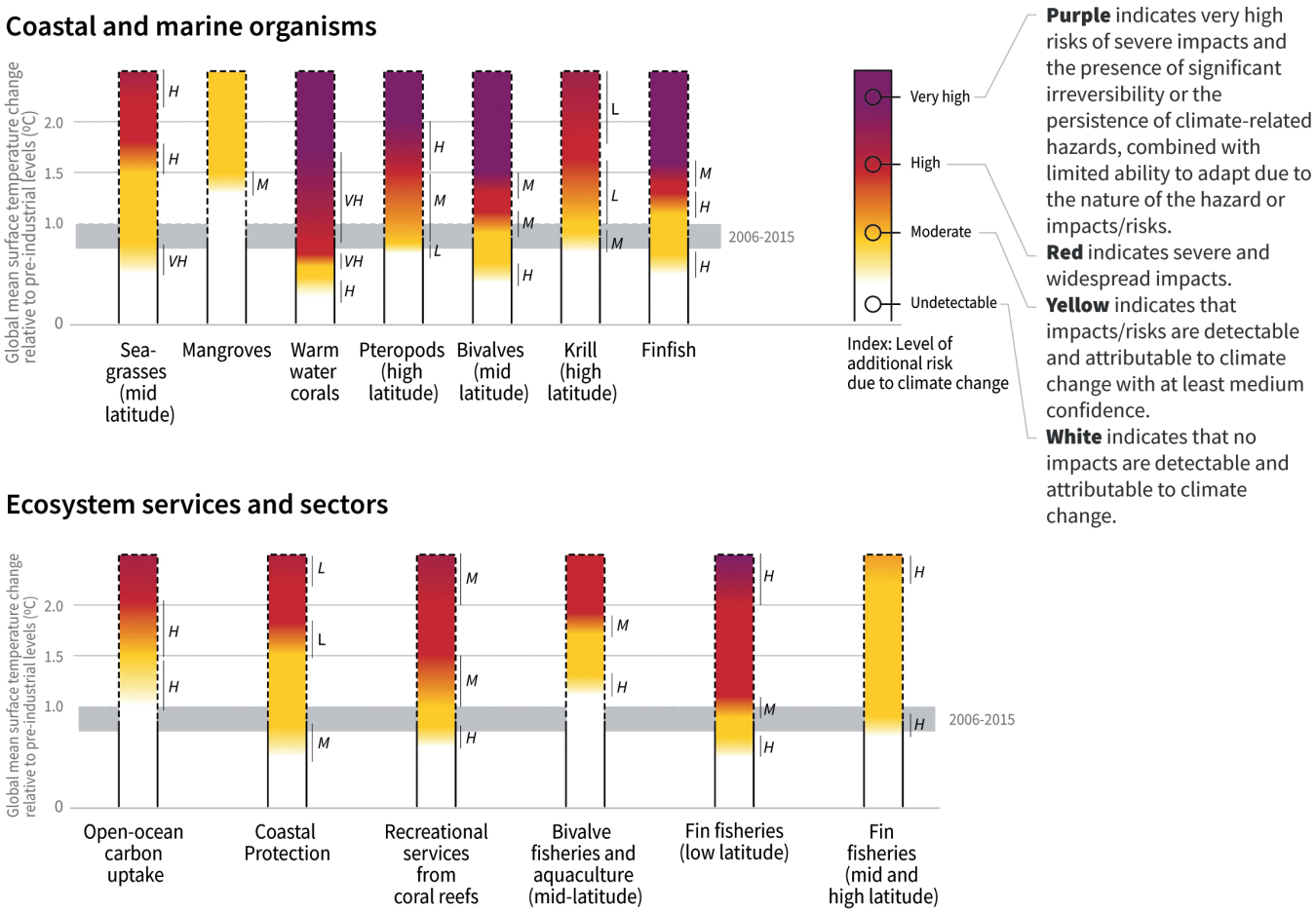


Figure 3.18 | Summary of additional risks of impacts from ocean warming (and associated climate change factors such ocean acidification) for a range of ocean organisms, ecosystems and sectors at 1.0°C, 1.5°C and 2.0°C of warming of the average sea surface temperature (SST) relative to the pre-industrial period. The grey bar represents the range of GMST for the most recent decade: 2006–2015. The assessment of changing risk levels and associated confidence were primarily derived from the expert judgement of Gattuso et al. (2015) and the lead authors and relevant contributing authors of Chapter 3 (SR1.5), while additional input was received from the many reviewers of the ocean systems section of SR1.5. Notes: (i) The analysis shown here is not intended to be comprehensive. The examples of organisms, ecosystems and sectors included here are intended to illustrate the scale, types and projection of risks for representative natural and human ocean systems. (ii) The evaluation of risks by experts did not consider genetic adaptation, acclimatization or human risk reduction strategies (mitigation and societal adaptation). (iii) As discussed elsewhere (Sections 3.3.10 and 3.4.4.5, Box 3.4; Gattuso et al., 2015), ocean acidification is also having impacts on organisms and ecosystems as carbon dioxide increases in the atmosphere. These changes are part of the responses reported here, although partitioning the effects of the two drivers is difficult at this point in time and hence was not attempted. (iv) Confidence levels for location of transition points between levels of risk (L = low, M = moderate, H = high and VH = very high) are assessed and presented here as in the accompanying study by Gattuso et al. (2015). Three transitions in risk were possible: W–Y (white to yellow), Y–R (yellow to red), and R–P (red to purple), with the colours corresponding to the level of additional risk posed by climate change. The confidence levels for these transitions were assessed, based on level of agreement and extent of evidence, and appear as letters associated with each transition (see key in diagram).

Tourism is one of the largest industries globally (Rosselló-Nadal, 2014; Markham et al., 2016; Spalding et al., 2017). A substantial part of the global tourist industry is associated with tropical coastal regions and islands, where tropical coral reefs and related ecosystems play important roles (Section 3.4.9.1) (*medium confidence*). Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries, particularly small island developing states (SIDS) (Section 3.4.9.1, Box 3.5; Weatherdon et al., 2016; Spalding et al., 2017). The direct relationship between increasing global temperatures, intensifying storms, elevated thermal stress, and the loss of tropical coral reefs has raised concern about the risks of climate change for local economies and industries based on tropical coral reefs. Risks to coral reef recreational services from climate change are considered here, as well as in Box 3.5, Section 3.4.9 and Supplementary Material 3.SM.3.2.

Adaptations to the broad global changes in carbon uptake by the ocean are limited and are discussed later in this report with respect to changes in NPP and implications for fishing industries. These adaptation options are broad and indirect, and the only other solution at large scale is to reduce the entry of CO_2 into the ocean. Strategies for adapting to reduced coastal protection involve (a) avoidance of vulnerable areas and hazards, (b) managed retreat from threatened locations, and/or (c) accommodation of impacts and loss of services (Bell, 2012; André et al., 2016; Cooper et al., 2016; Mills et al., 2016; Raabe and Stumpf, 2016; Fu and Song, 2017). Within these broad options, there are some strategies that involve direct human intervention, such as coastal hardening and the construction of seawalls and artificial reefs (Rinkevich, 2014, 2015; André et al., 2016; Cooper et al., 2016; Narayan et al., 2016), while others exploit opportunities for increasing coastal protection by involving naturally occurring oyster banks, coral reefs, mangroves, seagrass and other ecosystems (UNEP-WCMC, 2006; Scyphers et al., 2011; Zhang et al., 2012; Ferrario et al., 2014; Cooper et al., 2016). Natural ecosystems, when healthy, also have the ability to repair themselves after being damaged, which sets them apart from coastal hardening and other human structures that require constant maintenance (Barbier, 2015; Elliff and Silva, 2017). In general, recognizing and restoring coastal ecosystems may be more cost-effective than installing human structures, in that creating and maintaining structures is typically expensive (Temmerman et al., 2013; Mycoo, 2017).

Recent studies have increasingly stressed the need for coastal protection to be considered within the context of coastal land management, including protecting and ensuring that coastal ecosystems are able to undergo shifts in their distribution and abundance as climate change occurs (Clausen and Clausen, 2014; Martínez et al., 2014; Cui et al., 2015; André et al., 2016; Mills et al., 2016). Facilitating these changes will require new tools in terms of legal and financial instruments, as well as integrated planning that involves not only human communities and infrastructure, but also associated ecosystem responses and values (Bell, 2012; Mills et al., 2016). In this regard, the interactions between climate change, sea level rise and coastal disasters are increasingly being informed by models (Bosello and De Cian, 2014) with a widening appreciation of the role of natural ecosystems as an alternative to hardened coastal structures (Cooper et al., 2016). Adaptation options for tropical coral reef recreation include: (i) protecting and improving biodiversity and ecological function by minimizing the impact of stresses unrelated to climate change (e.g., pollution and overfishing), (ii) ensuring adequate levels of coastal protection by supporting and repairing ecosystems that protect coastal regions, (iii) ensuring fair and equitable access to the economic opportunities associated with recreational activities, and (iv) seeking and protecting supplies of water for tourism, industry and agriculture alongside community needs.

Box 3.4 | Warm-Water (Tropical) Coral Reefs in a 1.5°C Warmer World

Warm-water coral reefs face very high risks (Figure 3.18) from climate change. A world in which global warming is restricted to 1.5°C above pre-industrial levels would be a better place for coral reefs than that of a 2°C warmer world, in which coral reefs would mostly disappear (Donner et al., 2005; Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b; van Hooidonk et al., 2016; Frieler et al., 2017; Hughes et al., 2017a). Even with warming up until today (GMST for decade 2006–2015: 0.87°C; Chapter 1), a substantial proportion of coral reefs have experienced large-scale mortalities that have lead to much reduced coral populations (Hoegh-Guldberg et al., 2014). In the last three years alone (2016–2018), large coral reef systems such as the Great Barrier Reef (Australia) have lost as much as 50% of their shallow water corals (Hughes et al., 2017b).

Coral-dominated reefs are found along coastlines between latitudes 30°S and 30°N, where they provide habitat for over a million species (Reaka-Kudla, 1997) and food, income, coastal protection, cultural context and many other services for millions of people in tropical coastal areas (Burke et al., 2011; Cinner et al., 2012; Kennedy et al., 2013; Pendleton et al., 2016). Ultimately, coral reefs are underpinned by a mutualistic symbiosis between reef-building corals and dinoflagellates from the genus *Symbiodinium* (Hoegh-Guldberg et al., 2017). Warm-water coral reefs are found down to depths of 150 m and are dependent on light, making them distinct from the cold deep-water reef systems that extend down to depths of 2000 m or more. The difficulty in accessing deep-water reefs also means that the literature on the impacts of climate change on these systems is very limited by comparison to those on warm-water coral reefs (Hoegh-Guldberg et al., 2017). Consequently, this Box focuses on the impacts of climate change on warm-water (tropical) coral reefs, particularly with respect to their prospects under average global surface temperatures of 1.5°C and 2°C above the pre-industrial period.

Box 3.4 (continued)

The distribution and abundance of coral reefs has decreased by approximately 50% over the past 30 years (Gardner et al., 2005; Bruno and Selig, 2007; De'ath et al., 2012) as a result of pollution, storms, overfishing and unsustainable coastal development (Burke et al., 2011; Halpern et al., 2015; Cheal et al., 2017). More recently, climate change (i.e., heat stress; Hoegh-Guldberg, 1999; Baker et al., 2008; Spalding and Brown, 2015; Hughes et al., 2017b) has emerged as the greatest threat to coral reefs, with temperatures of just 1°C above the long-term summer maximum for an area (reference period 1985–1993) over 4–6 weeks being enough to cause mass coral bleaching (loss of the symbionts) and mortality (*very high confidence*) (WGII AR5, Box 18-2; Cramer et al., 2014). Ocean warming and acidification can also slow growth and calcification, making corals less competitive compared to other benthic organisms such as macroalgae or seaweeds (Dove et al., 2013; Reyes-Nivia et al., 2013, 2014). As corals disappear, so do fish and many other reef-dependent species, which directly impacts industries such as tourism and fisheries, as well as the livelihoods for many, often disadvantaged, coastal people (Wilson et al., 2006; Graham, 2014; Graham et al., 2015; Cinner et al., 2016; Pendleton et al., 2016). These impacts are exacerbated by increasingly intense storms (Section 3.3.6), which physically destroy coral communities and hence reefs (Cheal et al., 2017), and by ocean acidification (Sections 3.3.10 and 3.4.4.5), which can weaken coral skeletons, contribute to disease, and slow the recovery of coral communities after mortality events (*low to medium confidence*) (Gardner et al., 2005; Dove et al., 2013; Kennedy et al., 2013; Webster et al., 2013; Hoegh-Guldberg, 2014b; Anthony, 2016). Ocean acidification also leads to enhanced activity by decalcifying organisms such as excavating sponges (Kline et al., 2012; Dove et al., 2013; Fang et al., 2013, 2014; Reyes-Nivia et al., 2013, 2014).

The predictions of back-to-back bleaching events (Hoegh-Guldberg, 1999) have become the reality in the summers of 2016–2017 (e.g., Hughes et al., 2017b), as have projections of declining coral abundance (*high confidence*). Models have also become increasingly capable and are currently predicting the large-scale loss of coral reefs by mid-century under even low-emissions scenarios (Hoegh-Guldberg, 1999; Donner et al., 2005; Donner, 2009; van Hooidonk and Huber, 2012; Frieler et al., 2013; Hoegh-Guldberg et al., 2014; van Hooidonk et al., 2016). Even achieving emissions reduction targets consistent with the ambitious goal of 1.5°C of global warming under the Paris Agreement will result in the further loss of 70–90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2°C or more above the pre-industrial period (Frieler et al., 2013; Hoegh-Guldberg, 2014b; Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b; Hughes et al., 2017a).

The assumptions underpinning these assessments are considered to be highly conservative. In some cases, 'optimistic' assumptions in models include rapid thermal adaptation by corals of 0.2°C–1°C per decade (Donner et al., 2005) or 0.4°C per decade (Schleussner et al., 2016b), as well as very rapid recovery rates from impacts (e.g., five years in the case of Schleussner et al., 2016b). Adaptation to climate change at these high rates, has not been documented, and recovery from mass mortality tends to take much longer (>15 years; Baker et al., 2008). Probability analysis also indicates that the underlying increases in sea temperatures that drive coral bleaching and mortality are 25% less likely under 1.5°C when compared to 2°C (King et al., 2017). Spatial differences between the rates of heating suggest the possibility of temporary climate refugia (Caldeira, 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015; Keppel and Kavousi, 2015), which may play an important role in terms of the regeneration of coral reefs, especially if these refuges are protected from risks unrelated to climate change. Locations at higher latitudes are reporting the arrival of reef-building corals, which may be valuable in terms of the role of limited refugia and coral reef structures but will have low biodiversity (*high confidence*) when compared to present-day tropical reefs (Kersting et al., 2017). Similarly, deep-water (30–150 m) or mesophotic coral reefs (Bongaerts et al., 2010; Holstein et al., 2016) may play an important role because they avoid shallow water extremes (i.e., heat and storms) to some extent, although the ability of these ecosystems to assist in repopulating damaged shallow water areas may be limited (Bongaerts et al., 2017).

Given the sensitivity of corals to heat stress, even short periods of overshoot (i.e., decades) are expected to be extremely damaging to coral reefs. Losing 70–90% of today's coral reefs, however, will remove resources and increase poverty levels across the world's tropical coastlines, highlighting the key issue of equity for the millions of people that depend on these valuable ecosystems (Cross-Chapter Box 6; Spalding et al., 2014; Halpern et al., 2015). Anticipating these challenges to food and livelihoods for coastal communities will become increasingly important, as will adaptation options, such as the diversification of livelihoods and the development of new sustainable industries, to reduce the dependency of coastal communities on threatened ecosystems such as coral reefs (Cinner et al., 2012, 2016; Pendleton et al., 2016). At the same time, coastal communities will need to pre-empt changes to other services provided by coral reefs such as coastal protection (Kennedy et al., 2013; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014; Gattuso et al., 2015). Other threats and challenges to coastal living, such as sea level rise, will amplify challenges from declining coral reefs, specially for SIDS and low-lying tropical nations. Given the scale and cost of these interventions, implementing them earlier rather than later would be expedient.

3.4.5 Coastal and Low-Lying Areas, and Sea Level Rise

Sea level rise (SLR) is accelerating in response to climate change (Section 3.3.9; Church et al., 2013) and will produce significant impacts (*high confidence*). In this section, impacts and projections of SLR are reported at global and city scales (Sections 3.4.5.1 and 3.4.5.2) and for coastal systems (Sections 3.4.5.3 to 3.4.5.6). For some sectors, there is a lack of precise evidence of change at 1.5°C and 2°C of global warming. Adaptation to SLR is discussed in Section 3.4.5.7.

3.4.5.1 Global / sub-global scale

Sea level rise (SLR) and other oceanic climate changes are already resulting in salinization, flooding, and erosion and in the future are projected to affect human and ecological systems, including health, heritage, freshwater availability, biodiversity, agriculture, fisheries and other services, with different impacts seen worldwide (*high confidence*). Owing to the commitment to SLR, there is an overlapping uncertainty in projections at 1.5°C and 2°C (Schleussner et al., 2016b; Sanderson et al., 2017; Goodwin et al., 2018; Mengel et al., 2018; Nicholls et al., 2018; Rasmussen et al., 2018) and about 0.1 m difference in global mean sea level (GMSL) rise between 1.5°C and 2°C worlds in the year 2100 (Section 3.3.9, Table 3.3). Exposure and impacts at 1.5°C and 2°C differ at different time horizons (Schleussner et al., 2016b; Brown et al., 2018a, b; Nicholls et al., 2018; Rasmussen et al., 2018). However, these are distinct from impacts associated with higher increases in temperature (e.g., 4°C or more, as discussed in Brown et al., 2018a) over centennial scales. The benefits of climate change mitigation reinforce findings of earlier IPCC reports (e.g., Wong et al., 2014).

Table 3.3 shows the land and people exposed to SLR (assuming there is no adaptation or protection at all) using the Dynamic Interactive Vulnerability Assessment (DIVA) model (extracted from Brown et al., 2018a and Goodwin et al., 2018; see also Supplementary Material 3.SM, Table 3.SM.4). Thus, exposure increases even with temperature stabilization. The exposed land area is projected to at least double by 2300 using a RCP8.5 scenario compared with a mitigation scenario (Brown et al., 2018a). In the 21st century, land area exposed to sea level rise (assuming there is no adaptation or protection at all) is projected to be at least an order of magnitude larger than the cumulative land loss due to submergence (which takes into account defences) (Brown et al., 2016, 2018a) regardless of the SLR scenario applied. Slower rates of rise due to climate change mitigation may provide a greater opportunity for adaptation (*medium confidence*), which could substantially reduce impacts.

In agreement with the assessment in WGII AR5 Section 5.4.3.1 (Wong et al., 2014), climate change mitigation may reduce or delay coastal exposure and impacts (*very high confidence*). Adaptation has the potential to substantially reduce risk through a portfolio of available options (Sections 5.4.3.1 and 5.5 of Wong et al., 2014; Sections 6.4.2.3 and 6.6 of Nicholls et al., 2007). At 1.5°C in 2100, 31–69 million people (2010 population values) worldwide are projected to be exposed to flooding, assuming no adaptation or protection at all, compared with 32–79 million people (2010 population values) at 2°C in 2100 (Supplementary Material 3.SM, Table 3.SM.4; Rasmussen et al., 2018). As a result, up to 10.4 million more people would be exposed to sea level rise at 2°C compared with 1.5°C in 2100 (*medium confidence*). With a 1.5°C stabilization scenario in 2100, 62.7 million people per year are at risk from flooding, with this value increasing to 137.6 million people per year in 2300 (50th percentile, average across SSP1–5, no socio-economic change after 2100). These projections assume that no upgrade to current protection levels occurs (Nicholls et al., 2018). The number of people at risk increases by approximately 18% in 2030 if a 2°C scenario is used and by 266% in 2300 if an RCP8.5 scenario is considered (Nicholls et al., 2018). Through prescribed IPCC Special Report on Emissions Scenarios (SRES) SLR scenarios, Arnell et al. (2016) also found that the number of people exposed to flooding increased substantially at warming levels higher than 2°C, assuming no adaptation beyond current protection levels. Additionally, impacts increased in the second half of the 21st century.

Coastal flooding is projected to cost thousands of billions of USD annually, with damage costs under constant protection estimated at 0.3–5.0% of global gross domestic product (GDP) in 2100 under an RCP2.6 scenario (Hinkel et al., 2014). Risks are projected to be highest in South and Southeast Asia, assuming there is no upgrade to current protection levels, for all levels of climate warming (Arnell et al., 2016; Brown et al., 2016). Countries with at least 50 million people exposed to SLR (assuming no adaptation or protection at all) based on a 1,280 Pg C emissions scenario (approximately a 1.5°C temperature rise above today's level) include China, Bangladesh, Egypt, India, Indonesia, Japan, Philippines, United States and Vietnam (Clark et al., 2016). Rasmussen et al. (2018) and Brown et al. (2018a) project that similar countries would have high exposure to SLR in the 21st century using 1.5°C and 2°C scenarios. Thus, there is *high confidence* that SLR will have significant impacts worldwide in this century and beyond.

3.4.5.2 Cities

Observations of the impacts of SLR in cities are difficult to record because multiple drivers of change are involved. There are observations of ongoing and planned adaptation to SLR and extreme water levels in some cities (Araos et al., 2016; Nicholls et al., 2018), whilst other cities have yet to prepare for these impacts (*high confidence*) (see Section 3.4.8 and Cross-Chapter Box 9 in Chapter 4). There are limited observations and analyses of how cities will cope with higher and/or multi-centennial SLR, with the exception of Amsterdam, New York and London (Nicholls et al., 2018).

Coastal urban areas are projected to see more extreme water levels due to rising sea levels, which may lead to increased flooding and damage of infrastructure from extreme events (unless adaptation is undertaken), plus salinization of groundwater. These impacts may be enhanced through localized subsidence (Wong et al., 2014), which causes greater relative SLR. At least 136 megacities (port cities with a population greater than 1 million in 2005) are at risk from flooding due to SLR (with magnitudes of rise possible under 1.5°C or 2°C in the 21st century, as indicated in Section 3.3.9) unless further adaptation is undertaken (Hanson et al., 2011; Hallegatte et al., 2013). Many of these cities are located in South and Southeast Asia (Hallegatte et al., 2013; Cazenave and Cozannet, 2014; Clark et al., 2016; Jevrejeva et al., 2016). Jevrejeva et al. (2016) projected that more than 90% of global coastlines could experience SLR greater than 0.2 m with 2°C

of warming by 2040 (RCP8.5). However, for scenarios where 2°C is stabilized or occurs later in time, this figure is likely to differ because of the commitment to SLR. Raising existing dikes helps protect against SLR, substantially reducing risks, although other forms of adaptation exist. By 2300, dike heights under a non-mitigation scenario (RCP8.5) could be more than 2 m higher (on average for 136 megacities) than under climate change mitigation scenarios at 1.5°C or 2°C (Nicholls et al., 2018). Thus, rising sea levels commit coastal cities to long-term adaptation (*high confidence*).

3.4.5.3 Small islands

Qualitative physical observations of SLR (and other stresses) include inundation of parts of low-lying islands, land degradation due to saltwater intrusion in Kiribati and Tuvalu (Wairiu, 2017), and shoreline change in French Polynesia (Yates et al., 2013), Tuvalu (Kench et al., 2015, 2018) and Hawaii (Romine et al., 2013). Observations, models and other evidence indicate that unconstrained Pacific atolls have kept pace with SLR, with little reduction in size or net gain in land (Kench et al., 2015, 2018; McLean and Kench, 2015; Beetham et al., 2017). Whilst islands are highly vulnerable to SLR (*high confidence*), they are also reactive to change. Small islands are impacted by multiple climatic stressors, with SLR being a more important stressor to some islands than others (Sections 3.4.10, 4.3.5.6, 5.2.1, 5.5.3.3, Boxes 3.5, 4.3 and 5.3).

Observed adaptation to multiple drivers of coastal change, including SLR, includes retreat (migration), accommodation and defence. Migration (internal and international) has always been important on small islands (Farbotko and Lazrus, 2012; Weir et al., 2017), with changing environmental and weather conditions being just one factor in the choice to migrate (Sections 3.4.10, 4.3.5.6 and 5.3.2; Campbell and Warrick, 2014). Whilst flooding may result in migration or relocation, for example in Vunidogoloa, Fiji (McNamara and Des Combes, 2015; Gharbaoui and Blocher, 2016) and the Solomon Islands (Albert et al., 2017), in situ adaptation may be tried or preferred, for example stilted housing or raised floors in Tubigon, Bohol, Philippines (Jamero et al., 2017), raised roads and floors in Batasan and Ubay, Philippines (Jamero et al., 2018), and raised platforms for faluw in Leang, Federated States of Micronesia (Nunn et al., 2017). Protective features, such as seawalls or beach nourishment, are observed to locally reduce erosion and flood risk but can have other adverse implications (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014; AR5 Section 29.6.22).

There is a lack of precise, quantitative studies of projected impacts of SLR at 1.5°C and 2°C. Small islands are projected to be at risk and very sensitive to coastal climate change and other stressors (*high confidence*) (Nurse et al., 2014; Benjamin and Thomas, 2016; Ourbak and Magnan, 2017; Brown et al., 2018a; Nicholls et al., 2018; Rasmussen et al., 2018; AR5 Sections 29.3 and 29.4), such as oceanic warming, SLR (resulting in salinization, flooding and erosion), cyclones and mass coral bleaching and mortality (Section 3.4.4, Boxes 3.4 and 3.5). These impacts can have significant socio-economic and ecological implications, such as on health, agriculture and water resources, which in turn have impacts on livelihoods (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014). Combinations of drivers causing adverse impacts are important. For example, Storlazzi et al. (2018) found that the impacts of SLR and wave-induced flooding (within a temperature horizon equivalent of 1.5°C), could affect freshwater availability on Roi-Namur, Marshall Islands, but is also dependent on other extreme weather events. Freshwater resources may also be affected by a 0.40 m rise in sea level (which may be experienced with a 1.5°C warming) in other Pacific atolls (Terry and Chui, 2012). Whilst SLR is a major hazard for atolls, islands reaching higher elevations are also threatened given that there is often a lot of infrastructure located near the coast (*high confidence*) (Kumar and Taylor, 2015; Nicholls et al., 2018). Tens of thousands of people on small islands are exposed to SLR (Rasmussen et al., 2018). Giardino et al. (2018) found that hard defence structures on the island of Ebeye in the Marshall Islands were effective in reducing damage due to SLR at 1.5°C and 2°C. Additionally, damage was also reduced under mitigation scenarios compared with non-mitigation scenarios. In Jamaica and St Lucia, SLR and extreme sea levels are projected to threaten transport system infrastructure at 1.5°C unless further adaptation is undertaken (Monioudi et al., 2018). Slower rates of SLR will provide a greater opportunity for adaptation to be successful (*medium confidence*), but this may not be substantial enough on islands with a very low mean elevation. Migration and/or relocation may be an adaptation option (Section 3.4.10). Thomas and Benjamin (2017) highlight three areas of concern in the context of loss and damage at 1.5°C: a lack of data, gaps in financial assessments, and a lack of targeted policies or mechanisms to address these issues (Cross-Chapter Box 12 in Chapter 5). Small islands are projected to remain vulnerable to SLR (*high confidence*).

3.4.5.4 Deltas and estuaries

Observations of SLR and human influence are felt through salinization, which leads to mixing in deltas and estuaries, aquifers, leading to flooding (also enhanced by precipitation and river discharge), land degradation and erosion. Salinization is projected to impact freshwater sources and pose risks to ecosystems and human systems (Section 5.4; Wong et al., 2014). For instance, in the Delaware River estuary on the east coast of the USA, upward trends of salinity (measured since the 1900s), accounting for the effects of streamflow and seasonal variations, have been detected and SLR is a potential cause (Ross et al., 2015).

Z. Yang et al. (2015) found that future climate scenarios for the USA (A1B 1.6°C and B1 2°C in the 2040s) had a greater effect on salinity intrusion than future land-use/land-cover change in the Snohomish River estuary in Washington state (USA). This resulted in a shift in the salinity both upstream and downstream in low flow conditions. Projecting impacts in deltas needs an understanding of both fluvial discharge and SLR, making projections complex because the drivers operate on different temporal and spatial scales (Zaman et al., 2017; Brown et al., 2018b). The mean annual flood depth when 1.5°C is first projected to be reached in the Ganges-Brahmaputra delta may be less than the most extreme annual flood depth seen today, taking into account SLR, surges, tides, bathymetry and local river flows (Brown et al., 2018b). Further, increased river salinity and saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C of warming (Zaman et al., 2017). Salinization could impact agriculture and food security (Cross-Chapter Box 6 in this chapter). For 1.5°C or 2°C stabilization conditions in 2200 or 2300 plus surges, a minimum of 44% of the

Bangladeshi Ganges-Brahmaputra, Indian Bengal, Indian Mahanadi and Ghanese Volta delta land area (without defences) would be exposed unless sedimentation occurs (Brown et al., 2018b). Other deltas are similarly vulnerable. SLR is only one factor affecting deltas, and assessment of numerous geophysical and anthropogenic drivers of geomorphic change is important (Tessler et al., 2018). For example, dike building to reduce flooding and dam building (Gupta et al., 2012) restricts sediment movement and deposition, leading to enhanced subsidence, which can occur at a greater rate than SLR (Auerbach et al., 2015; Takagi et al., 2016). Although dikes remain essential for reducing flood risk today, promoting sedimentation is an advisable strategy (Brown et al., 2018b) which may involve nature-based solutions. Transformative decisions regarding the extent of sediment restrictive infrastructure may need to be considered over centennial scales (Brown et al., 2018b). Thus, in a 1.5°C or 2°C warmer world, deltas, which are home to millions of people, are expected to be highly threatened from SLR and localized subsidence (*high confidence*).

3.4.5.5 Wetlands

Observations indicate that wetlands, such as saltmarshes and mangrove forests, are disrupted by changing conditions (Sections 3.4.4.8; Wong et al., 2014; Lovelock et al., 2015), such as total water levels and sediment availability. For example, saltmarshes in Connecticut and New York, USA, measured from 1900 to 2012, have accreted with SLR but have lost marsh surface relative to tidal datums, leading to increased marsh flooding and further accretion (Hill and Anisfeld, 2015). This change stimulated marsh carbon storage and aided climate change mitigation.

Salinization may lead to shifts in wetland communities and their ecosystem functions (Herbert et al., 2015). Some projections of wetland change, with magnitudes (but not necessarily rates or timing) of SLR analogous to 1.5°C and 2°C of global warming, indicate a net loss of wetlands in the 21st century (e.g., Blankespoor et al., 2014; Cui et al., 2015; Arnell et al., 2016; Crosby et al., 2016), whilst others report a net gain with wetland transgression (e.g., Raabe and Stumpf, 2016 in the Gulf of Mexico). However, the feedback between wetlands and sea level is complex, with parameters such as a lack of accommodation space restricting inland migration, or sediment supply and feedbacks between plant growth and geomorphology (Kirwan and Megonigal, 2013; Ellison, 2014; Martínez et al., 2014; Spencer et al., 2016) still being explored. Reducing global warming from 2°C to 1.5°C will deliver long-term benefits, with natural sedimentation rates more likely keep up with SLR. It remains unclear how wetlands will respond and under what conditions (including other climate parameters) to a global temperature rise of 1.5°C and 2°C. However, they have great potential to aid and benefit climate change mitigation and adaptation (*medium confidence*) (Sections 4.3.2.2 and 4.3.2.3).

3.4.5.6 Other coastal settings

Numerous impacts have not been quantified at 1.5°C or 2°C but remain important. This includes systems identified in WGII AR5 (AR5 – Section 5.4 of Wong et al., 2014), such as beaches, barriers, sand dunes, rocky coasts, aquifers, lagoons and coastal ecosystems (for the last system, see Section 3.4.4.12). For example, SLR potentially affects erosion and accretion, and therefore sediment movement, instigating shoreline change (Section 5.4.2.1 of Wong et al., 2014), which could affect land-based ecosystems. Global observations indicate no overall clear effect of SLR on shoreline change (Le Cozannet et al., 2014), as it is highly site specific (e.g., Romine et al., 2013). Infrastructure and geological constraints reduce shoreline movement, causing coastal squeeze. In Japan, for example, SLR is projected to cause beach losses under an RCP2.6 scenario, which will worsen under RCP8.5 (Udo and Takeda, 2017). Further, compound flooding (the combined risk of flooding from multiple sources) has increased significantly over the past century in major coastal cities (Wahl et al., 2015) and is likely to increase with further development and SLR at 1.5°C and 2°C unless adaptation is undertaken. Thus, overall SLR will have a wide range of adverse effects on coastal zones (*medium confidence*).

3.4.5.7 Adapting to coastal change

Adaptation to coastal change from SLR and other drivers is occurring today (*high confidence*) (see Cross-Chapter Box 9 in Chapter 4), including migration, ecosystem-based adaptation, raising infrastructure and defences, salt-tolerant food production, early warning systems, insurance and education (Section 5.4.2.1 of Wong et al., 2014). Climate change mitigation will reduce the rate of SLR this century, decreasing the need for extensive and, in places, immediate adaptation. Adaptation will reduce impacts in human settings (*high confidence*) (Hinkel et al., 2014; Wong et al., 2014), although there is less certainty for natural ecosystems (Sections 4.3.2 and 4.3.3.3). While some ecosystems (e.g., mangroves) may be able to move shoreward as sea levels increase, coastal development (e.g., coastal building, seawalls and agriculture) often interrupt these transitions (Saunders et al., 2014). Options for responding to these challenges include reducing the impact of other stresses such as those arising from tourism, fishing, coastal development and unsustainable aquaculture/agriculture. In some cases, restoration of coastal habitats and ecosystems can be a cost-effective way of responding to changes arising from increasing levels of exposure from rising sea levels, changes in storm conditions, coastal inundation and salinization (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Spalding et al., 2014; Elliff and Silva, 2017).

Since AR5, planned and autonomous adaptation and forward planning have become more widespread (Araos et al., 2016; Nicholls et al., 2018), but continued efforts are required as many localities are in the early stages of adapting or are not adapting at all (Cross-Chapter Box 9 in Chapter 4; Araos et al., 2016). This is region and sub-sector specific, and also linked to non-climatic factors (Ford et al., 2015; Araos et al., 2016; Lesnikowski et al., 2016). Adaptation pathways (e.g., Ranger et al., 2013; Barnett et al., 2014; Rosenzweig and Solecki, 2014; Buurman and Babovic, 2016) assist long-term planning but are not widespread practices despite knowledge of long-term risks (Section 4.2.2). Furthermore, human retreat and migration are increasingly being considered as an adaptation response (Hauer et al., 2016; Geisler and Currens, 2017), with a growing emphasis on green adaptation. There are few studies on the adaptation limits to SLR where transformation change may be required (AR5-Section 5.5 of Wong et al., 2014; Nicholls et al., 2015). Sea level rise poses a long-term threat (Section 3.3.9), and adaptation will remain essential at the centennial scale under 1.5°C and 2°C of warming (*high confidence*).

Table 3.3 | Land and people exposed to sea level rise (SLR), assuming no protection at all. Extracted from Brown et al. (2018a) and Goodwin et al. (2018). SSP: Shared Socio-Economic Pathway; wrt: with respect to; *:Population held constant at 2100 level.

Climate scenario	Impact factor, assuming there is no adaptation or protection at all (50th, [5th-95th percentiles])	Year			
		2050	2100	2200	2300
1.5°C	Temperature rise wrt 1850–1900 (°C)	1.71 (1.44–2.16)	1.60 (1.26–2.33)	1.41 (1.15–2.10)	1.32 (1.12–1.81)
	SLR (m) wrt 1986–2005	0.20 (0.14–0.29)	0.40 (0.26–0.62)	0.73 (0.47–1.25)	1.00 (0.59–1.55)
	Land exposed (x10^3 km^2)	574 [558–597]	620 [575–669]	666 [595–772]	702 [666–853]
	People exposed, SSP1–5 (millions)	127.9–139.0 [123.4–134.0, 134.5–146.4]	102.7–153.5 [94.8–140.7, 102.7–153.5]	--	133.8–207.1 [112.3–169.6, 165.2–263.4]*
2°C	Temperature rise wrt 1850–1900 (° C)	1.76 (1.51–2.16)	2.03 (1.72–2.64)	1.90 (1.66–2.57)	1.80 (1.60–2.20)
	SLR (m) wrt 1986-2005	0.20 (0.14–0.29)	0.46 (0.30–0.69)	0.90 (0.58–1.50)	1.26 (0.74–1.90)
	Land exposed (x10^3 km^2)	575 [558–598]	637 [585–686]	705 [618–827]	767 [642–937]
	People exposed, SSP1–5 (millions)	128.1–139.2 [123.6–134.2, 134.7–146.6]	105.5–158.1 [97.0–144.1, 118.1–179.0]	--	148.3–233.0 [120.3–183.4, 186.4–301.8]*

Box 3.5 | Small Island Developing States (SIDS)

Box 3.5 (continued)

increased frequency of extreme La Niña events, exacerbating coastal impacts of projected global mean SLR (Widlansky et al., 2015). Changes to the frequency of extreme El Niño and La Niña events may also increase the frequency of droughts and floods in South Pacific islands (Box 4.2, Section 3.5.2; Cai et al., 2012).

Extreme precipitation in small island regions is often linked to tropical storms and contributes to the climate hazard (Khouakhi et al., 2017). Similarly, extreme sea levels for small islands, particularly in the Caribbean, are linked to tropical cyclone occurrence (Khouakhi and Villarini, 2017). Under a 1.5°C stabilization scenario, there is a projected decrease in the frequency of weaker tropical storms and an increase in the number of intense cyclones (Section 3.3.6; Wehner et al., 2018a). There are not enough studies to assess differences in tropical cyclone statistics for 1.5°C versus 2°C (Section 3.3.6). There are considerable differences in the adaptation responses to tropical cyclones across SIDS (Cross-Chapter Box 11 in Chapter 4).

Impacts on key natural and human systems

Projected increases in aridity and decreases in freshwater availability at 1.5°C of warming, along with additional risks from SLR and increased wave-induced run-up, might leave several atoll islands uninhabitable (Storlazzi et al., 2015; Gosling and Arnell, 2016). Changes in the availability and quality of freshwater, linked to a combination of changes to climate drivers, may adversely impact SIDS' economies (White and Falkland, 2010; Terry and Chui, 2012; Holding and Allen, 2015; Donk et al., 2018). Growth-rate projections based on temperature impacts alone indicate robust negative impacts on gross domestic product (GDP) per capita growth for SIDS (Sections 3.4.7.1, 3.4.9.1 and 3.5.4.9; Pretis et al., 2018). These impacts would be reduced considerably under 1.5°C but may be increased by escalating risks from climate-related extreme weather events and SLR (Sections 3.4.5.3, 3.4.9.4 and 3.5.3)

Marine systems and associated livelihoods in SIDS face higher risks at 2°C compared to 1.5°C (*medium to high confidence*). Mass coral bleaching and mortality are projected to increase because of interactions between rising ocean temperatures, ocean acidification, and destructive waves from intensifying storms (Section 3.4.4 and 5.2.3, Box 3.4). At 1.5°C, approximately 70–90% of global coral reefs are projected to be at risk of long-term degradation due to coral bleaching, with these values increasing to 99% at 2°C (Frieler et al., 2013; Schleussner et al., 2016b). Higher temperatures are also related to an increase in coral disease development, leading to coral degradation (Maynard et al., 2015). For marine fisheries, limiting warming to 1.5°C decreases the risk of species extinction and declines in maximum catch potential, particularly for small islands in tropical oceans (Cheung et al., 2016a).

Long-term risks of coastal flooding and impacts on populations, infrastructure and assets are projected to increase with higher levels of warming (*high confidence*). Tropical regions including small islands are expected to experience the largest increases in coastal flooding frequency, with the frequency of extreme water-level events in small islands projected to double by 2050 (Vitousek et al., 2017). Wave-driven coastal flooding risks for reef-lined islands may increase as a result of coral reef degradation and SLR (Quataert et al., 2015). Exposure to coastal hazards is particularly high for SIDS, with a significant share of population, infrastructure and assets at risk (Sections 3.4.5.3 and 3.4.9; Scott et al., 2012; Kumar and Taylor, 2015; Rhiney, 2015; Byers et al., 2018). Limiting warming to 1.5°C instead of 2°C would spare the inundation of lands currently home to 60,000 individuals in SIDS by 2150 (Rasmussen et al., 2018). However, such estimates do not consider shoreline response (Section 3.4.5) or adaptation.

Risks of impacts across sectors are projected to be higher at 1.5°C compared to the present, and will further increase at 2°C (*medium to high confidence*). Projections indicate that at 1.5°C there will be increased incidents of internal migration and displacement (Sections 3.5.5, 4.3.6 and 5.2.2; Albert et al., 2017), limited capacity to assess loss and damage (Thomas and Benjamin, 2017) and substantial increases in the risk to critical transportation infrastructure from marine inundation (Monioudi et al., 2018). The difference between 1.5°C and 2°C might exceed limits for normal thermoregulation of livestock animals and result in persistent heat stress for livestock animals in SIDS (Lallo et al., 2018).

At 1.5°C, limits to adaptation will be reached for several key impacts in SIDS, resulting in residual impacts, as well as loss and damage (Section 1.1.1, Cross-Chapter Box 12 in Chapter 5). Limiting temperature increase to 1.5°C versus 2°C is expected to reduce a number of risks, particularly when coupled with adaptation efforts that take into account sustainable development (Section 3.4.2 and 5.6.3.1, Box 4.3 and 5.3, Mycoo, 2017; Thomas and Benjamin, 2017). Region-specific pathways for SIDS exist to address climate change (Section 5.6.3.1, Boxes 4.6 and 5.3, Cross-Chapter Box 11 in Chapter 4).

3.4.6 Food, Nutrition Security and Food Production Systems (Including Fisheries and Aquaculture)

3.4.6.1 Crop production

Quantifying the observed impacts of climate change on food security and food production systems requires assumptions about the many non-climate variables that interact with climate change variables. Implementing specific strategies can partly or greatly alleviate the climate change impacts on these systems (Wei et al., 2017), whilst the degree of compensation is mainly dependent on the geographical area and crop type (Rose et al., 2016). Despite these uncertainties, recent studies confirm that observed climate change has already affected crop suitability in many areas, resulting in changes in the production levels of the main agricultural crops. These impacts are evident in many areas of the world, ranging from Asia (C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016) to America (Cho and McCarl, 2017) and Europe (Ramirez-Cabral et al., 2016), and they particularly affect the typical local crops cultivated in specific climate conditions (e.g., Mediterranean crops like olive and grapevine, Moriondo et al., 2013a, b).

Temperature and precipitation trends have reduced crop production and yields, with the most negative impacts being on wheat and maize (Lobell et al., 2011), whilst the effects on rice and soybean yields are less clear and may be positive or negative (Kim et al., 2013; van Oort and Zwart, 2018). Warming has resulted in positive effects on crop yield in some high-latitude areas (Jaggard et al., 2007; Supit et al., 2010; Gregory and Marshall, 2012; C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016; Daliakopoulos et al., 2017), and may make it possible to have more than one harvest per year (B. Chen et al., 2014; Sun et al., 2015). Climate variability has been found to explain more than 60% of the of maize, rice, wheat and soybean yield variations in the main global breadbaskets areas (Ray et al., 2015), with the percentage varying according to crop type and scale (Moore and Lobell, 2015; Kent et al., 2017). Climate trends also explain changes in the length of the growing season, with greater modifications found in the northern high-latitude areas (Qian et al., 2010; Mueller et al., 2015).

The rise in tropospheric ozone has already reduced yields of wheat, rice, maize and soybean by 3–16% globally (Van Dingenen et al., 2009). In some studies, increases in atmospheric CO_2 concentrations were found to increase yields by enhancing radiation and water use efficiencies (Elliott et al., 2014; Durand et al., 2018). In open-top chamber experiments with a combination of elevated CO_2 and 1.5°C of warming, maize and potato yields were observed to increase by 45.7% and 11%, respectively (Singh et al., 2013; Abebe et al., 2016). However, observations of trends in actual crop yields indicate that reductions as a result of climate change remain more common than crop yield increases, despite increased atmospheric CO_2 concentrations (Porter et al., 2014). For instance, McGrath and Lobell (2013) indicated that production stimulation at increased atmospheric CO_2 concentrations was mostly driven by differences in climate and crop species, whilst yield variability due to elevated CO_2 was only about 50–70% of the variability due to climate. Importantly, the faster growth rates induced by elevated CO_2 have been found to coincide with lower protein content in several important C3 cereal grains (Myers et al., 2014), although this may not always be the case for C4 grains, such as sorghum, under drought conditions (De Souza et al., 2015). Elevated CO_2 concentrations of 568–590 ppm (a range that corresponds approximately to RCP6 in the 2080s and hence a warming of 2.3°C–3.3°C (van Vuuren et al., 2011a, AR5 WGI Table 12.2) alone reduced the protein, micronutrient and B vitamin content of the 18 rice cultivars grown most widely in Southeast Asia, where it is a staple food source, by an amount sufficient to create nutrition-related health risks for 600 million people (Zhu et al., 2018). Overall, the effects of increased CO_2 concentrations alone during the 21st century are therefore expected to have a negative impact on global food security (*medium confidence*).

Crop yields in the future will also be affected by projected changes in temperature and precipitation. Studies of major cereals showed that maize and wheat yields begin to decline with 1°C–2°C of local warming and under nitrogen stress conditions at low latitudes (*high confidence*) (Porter et al., 2014; Rosenzweig et al., 2014). A few studies since AR5 have focused on the impacts on cropping systems for scenarios where the global mean temperature increase is within 1.5°C. Schleussner et al. (2016b) projected that constraining warming to 1.5°C rather than 2°C would avoid significant risks of declining tropical crop yield in West Africa, Southeast Asia, and Central and South America. Ricke et al. (2016) highlighted that cropland stability declines rapidly between 1°C and 3°C of warming, whilst Bassu et al. (2014) found that an increase in air temperature negatively influences the modelled maize yield response by –0.5 t ha^{-1} $°C^{-1}$ and Challinor et al. (2014) reported similar effect for tropical regions. Niang et al. (2014) projected significantly lower risks to crop productivity in Africa at 1.5°C compared to 2°C of warming. Lana et al. (2017) indicated that the impact of temperature increases on crop failure of maize hybrids would be much greater as temperatures increase by 2°C compared to 1.5°C (*high confidence*). J. Huang et al. (2017) found that limiting warming to 1.5°C compared to 2°C would reduce maize yield losses over drylands. Although Rosenzweig et al. (2017, 2018) did not find a clear distinction between yield declines or increases in some breadbasket regions between the two temperature levels, they generally did find projections of decreasing yields in breadbasket regions when the effects of CO_2 fertilization were excluded. Iizumi et al. (2017) found smaller reductions in maize and soybean yields at 1.5°C than at 2°C of projected warming, higher rice production at 2°C than at 1.5°C, and no clear differences for wheat on a global mean basis. These results are largely consistent with those of other studies (Faye et al., 2018; Ruane et al., 2018). In the western Sahel and southern Africa, moving from 1.5°C to 2°C of warming has been projected to result in a further reduction of the suitability of maize, sorghum and cocoa cropping areas and yield losses, especially for C3 crops, with rainfall change only partially compensating these impacts (Läderach et al., 2013; World Bank, 2013; Sultan and Gaetani, 2016).

A significant reduction has been projected for the global production of wheat (by 6.0 ± 2.9%), rice (by 3.2 ± 3.7%), maize (by 7.4 ± 4.5%), and soybean, (by 3.1%) for each degree Celsius increase in global mean temperature (Asseng et al., 2015; C. Zhao et al., 2017). Similarly, Li et al. (2017) indicated a significant reduction in rice yields for each degree Celsius increase, by about 10.3%, in the greater Mekong subregion (*medium confidence*; Cross-Chapter Box 6: Food Security in this chapter). Large rice and maize yield losses are to be expected in China, owing to climate extremes (*medium confidence*) (Wei et al., 2017; Zhang et al., 2017).

While not often considered, crop production is also negatively affected by the increase in both direct and indirect climate extremes. Direct extremes include changes in rainfall extremes (Rosenzweig et al., 2014), increases in hot nights (Welch et al., 2010; Okada et al., 2011), extremely high daytime temperatures (Schlenker and Roberts, 2009; Jiao et al., 2016; Lesk et al., 2016), drought (Jiao et al., 2016; Lesk et al., 2016), heat stress (Deryng et al., 2014, Betts et al., 2018), flooding (Betts et al., 2018; Byers et al., 2018), and chilling damage (Jiao et al., 2016), while indirect effects include the spread of pests and diseases (Jiao et al., 2014; van Bruggen et al., 2015), which can also have detrimental effects on cropping systems.

Taken together, the findings of studies on the effects of changes in temperature, precipitation, CO_2 concentration and extreme weather events indicate that a global warming of 2°C is projected to result in a greater reduction in global crop yields and global nutrition than global warming of 1.5°C (*high confidence*; Section 3.6).

3.4.6.2 Livestock production

Studies of climate change impacts on livestock production are few in number. Climate change is expected to directly affect yield quantity and quality (Notenbaert et al., 2017), as well as indirectly impacting the livestock sector through feed quality changes and spread of pests and diseases (Kipling et al., 2016) (*high confidence*). Increased warming and its extremes are expected to cause changes in physiological processes in livestock (i.e., thermal distress, sweating and high respiratory rates) (Mortola and Frappell, 2000) and to have detrimental effects on animal feeding, growth rates (André et al., 2011; Renaudeau et al., 2011; Collier and Gebremedhin, 2015) and reproduction (De Rensis et al., 2015). Wall et al. (2010) observed reduced milk yields and increased cow mortality as the result of heat stress on dairy cow production over some UK regions.

Further, a reduction in water supply might increase cattle water demand (Masike and Urich, 2008). Generally, heat stress can be responsible for domestic animal mortality increase and economic losses (Vitali et al., 2009), affecting a wide range of reproductive parameters (e.g., embryonic development and reproductive efficiency in pigs, Barati et al., 2008; ovarian follicle development and ovulation in horses, Mortensen et al., 2009). Much attention has also been dedicated to ruminant diseases (e.g., liver fluke, Fox et al., 2011; blue-tongue virus, Guis et al., 2012; foot-and-mouth disease (FMD), Brito et al. (2017); and zoonotic diseases, Njeru et al., 2016; Simulundu et al., 2017).

Climate change impacts on livestock are expected to increase. In temperate climates, warming is expected to lengthen the forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Similarly, a decrease in forage quality is expected for both natural grassland in France (Graux et al., 2013) and sown pastures in Australia (Perring et al., 2010). Water resource availability for livestock is expected to decrease owing to increased runoff and reduced groundwater resources. Increased temperature will likely induce changes in river discharge and the amount of water in basins, leading human and livestock populations to experience water stress, especially in the driest areas (i.e., sub-Saharan Africa and South Asia) (*medium confidence*) (Palmer et al., 2008). Elevated temperatures are also expected to increase methane production (Knapp et al., 2014; M.A. Lee et al., 2017). Globally, a decline in livestock of 7–10% is expected at about 2°C of warming, with associated economic losses between $9.7 and $12.6 billion (Boone et al., 2018).

3.4.6.3 Fisheries and aquaculture production

Global fisheries and aquaculture contribute a total of 88.6 and 59.8 million tonnes of fish and other products annually (FAO, 2016), and play important roles in the food security of a large number of countries (McClanahan et al., 2015; Pauly and Charles, 2015) as well as being essential for meeting the protein demand of a growing global population (Cinner et al., 2012, 2016; FAO, 2016; Pendleton et al., 2016). A steady increase in the risks associated with bivalve fisheries and aquaculture at mid-latitudes is coincident with increases in temperature, ocean acidification, introduced species, disease and other drivers (Lacoue-Labarthe et al., 2016; Clements and Chopin, 2017; Clements et al., 2017; Parker et al., 2017). Sea level rise and storm intensification pose a risk to hatcheries and other infrastructure (Callaway et al., 2012; Weatherdon et al., 2016), whilst others risks are associated with the invasion of parasites and pathogens (Asplund et al., 2014; Castillo et al., 2017). Specific human strategies have reduced these risks, which are expected to be moderate under RCP2.6 and very high under RCP8.5 (Gattuso et al., 2015). The risks related to climate change for fin fish (Section 3.4.4) are producing a number of challenges for small-scale fisheries (e.g., Kittinger, 2013; Pauly and Charles, 2015; Bell et al., 2018). Recent literature from 2015 to 2017 has described growing threats from rapid shifts in the biogeography of key species (Poloczanska et al., 2013, 2016; Burrows et al., 2014; García Molinos et al., 2015) and the ongoing rapid degradation of key ecosystems such as coral reefs, seagrass and mangroves (Section 3.4.4, Box 3.4). The acceleration of these changes, coupled with non-climate stresses (e.g., pollution, overfishing and unsustainable coastal development), are driving many small-scale fisheries well below the sustainable harvesting levels required to maintain these resources as a source of food (McClanahan et al., 2009, 2015; Cheung et al., 2010; Pendleton et al., 2016). As a result, future scenarios surrounding climate change and global population growth increasingly project shortages of fish protein for many regions, such as the Pacific Ocean (Bell et al., 2013, 2018) and Indian Ocean (McClanahan et al., 2015). Mitigation of these risks involves marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Kittinger, 2013; McClanahan et al., 2015; Song and Chuenpagdee, 2015; Weatherdon et al., 2016). Other threats concern the increasing incidence of alien species and diseases (Kittinger et al., 2013; Weatherdon et al., 2016).

Risks of impacts related to climate change on low-latitude small-scale fin fisheries are moderate today but are expected to reach very high levels by 1.1°C of global warming. Projections for mid- to high-latitude fisheries include increases in fishery productivity in some cases (Cheung et al., 2013; Hollowed et al., 2013; Lam et al., 2014; FAO, 2016). These projections are associated with the biogeographical shift of species towards higher latitudes (Fossheim et al., 2015), which brings benefits as well as challenges (e.g., increased production yet a greater risk of disease and invasive species; *low confidence*). Factors underpinning

the expansion of fisheries production to high-latitude locations include warming, increased light levels and mixing due to retreating sea ice (Cheung et al., 2009), which result in substantial increases in primary productivity and fish harvesting in the North Pacific and North Atlantic (Hollowed and Sundby, 2014).

Present-day risks for mid-latitude bivalve fisheries and aquaculture become undetectible up to 1.1°C of global warming, moderate at 1.3°C, and moderate to high up to 1.9°C (Figure 3.18). For instance, Cheung et al. (2016a), simulating the loss in fishery productivity at 1.5°C, 2°C and 3.5°C above the pre-industrial period, found that the potential global catch for marine fisheries will *likely* decrease by more than three million metric tonnes for each degree of warming. Low-latitude fin-fish fisheries have higher risks of impacts, with risks being moderate under present-day conditions and becoming high above 0.9°C and very high at 2°C of global warming. High-latitude fisheries are undergoing major transformations, and while production is increasing, present-day risk is moderate and is projected to remain moderate at 1.5°C and 2°C (Figure 3.18).

Adaptation measures can be applied to shellfish, large pelagic fish resources and biodiversity, and they include options such as protecting reproductive stages and brood stocks from periods of high ocean acidification (OA), stock selection for high tolerance to OA (*high confidence*) (Ekstrom et al., 2015; Rodrigues et al., 2015; Handisyde et al., 2016; Lee, 2016; Weatherdon et al., 2016; Clements and Chopin, 2017), redistribution of highly migratory resources (e.g., Pacific tuna) (*high confidence*), governance instruments such as international fisheries agreements (Lehodey et al., 2015; Matear et al., 2015), protection and regeneration of reef habitats, reduction of coral reef stresses, and development of alternative livelihoods (e.g., aquaculture; Bell et al., 2013, 2018).

3

Cross-Chapter Box 6 | Food Security

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Climate change influences food and nutritional security through its effects on food availability, quality, access and distribution (Paterson and Lima, 2010; Thornton et al., 2014; FAO, 2016). More than 815 million people were undernourished in 2016, and 11% of the world's population has experienced recent decreases in food security, with higher percentages in Africa (20%), southern Asia (14.4%) and the Caribbean (17.7%) (FAO et al., 2017). Overall, food security is expected to be reduced at 2°C of global warming compared to 1.5°C, owing to projected impacts of climate change and extreme weather on yields, crop nutrient content, livestock, fisheries and aquaculture and land use (cover type and management) (Sections 3.4.3.6, 3.4.4.12 and 3.4.6), (*high confidence*). The effects of climate change on crop yield, cultivation area, presence of pests, food price and supplies are projected to have major implications for sustainable development, poverty eradication, inequality and the ability of the international community to meet the United Nations sustainable development goals (SDGs; Cross-Chapter Box 4 in Chapter 1).

Goal 2 of the SDGs is to end hunger, achieve food security, improve nutrition and promote sustainable agriculture by 2030. This goal builds on the first millennium development goal (MDG-1) which focused on eradicating extreme poverty and hunger, through efforts that reduced the proportion of undernourished people in low- and middle-income countries from 23.3% in 1990 to 12.9% in 2015. Climate change threatens the capacity to achieve SDG 2 and could reverse the progress made already. Food security and agriculture are also critical to other aspects of sustainable development, including poverty eradication (SDG 1), health and well-being (SDG 3), clean water (SDG 6), decent work (SDG 8), and the protection of ecosystems on land (SDG 14) and in water (SDG 15) (UN, 2015, 2017; Pérez-Escamilla, 2017).

Increasing global temperature poses large risks to food security globally and regionally, especially in low-latitude areas (*medium confidence*) (Cheung et al., 2010; Rosenzweig et al., 2013; Porter et al., 2014; Rosenzweig and Hillel, 2015; Lam et al., 2016), with warming of 2°C projected to result in a greater reduction in global crop yields and global nutrition than warming of 1.5°C (*high confidence*) (Section 3.4.6), owing to the combined effects of changes in temperature, precipitation and extreme weather events, as well as increasing CO_2 concentrations. Climate change can exacerbate malnutrition by reducing nutrient availability and the quality of food products (*medium confidence*) (Cramer et al., 2014; Zhu et al., 2018). Generally, vulnerability to decreases in water and food availability is projected to be reduced at 1.5°C versus 2°C (Cheung et al., 2016a; Betts et al., 2018), especially in regions such as the African Sahel, the Mediterranean, central Europe, the Amazon, and western and southern Africa (*medium confidence*) (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018).

Cross-Chapter Box 6 (continued)

Rosenzweig et al. (2018) and Ruane et al. (2018) reported that the higher CO_2 concentrations associated with 2°C as compared to those at 1.5°C of global warming are projected to drive positive effects in some regions. Production can also benefit from warming in higher latitudes, with more fertile soils, favouring crops, and grassland production, in contrast to the situation at low latitudes (Section 3.4.6), and similar benefits could arise for high-latitude fisheries production (*high confidence*) (Section 3.4.6.3). Studies exploring regional climate change risks on crop production are strongly influenced by the use of different regional climate change projections and by the assumed strength of CO_2 fertilization effects (Section 3.6), which are uncertain. For C3 crops, theoretically advantageous CO_2 fertilization effects may not be realized in the field; further, they are often accompanied by losses in protein and nutrient content of crops (Section 3.6), and hence these projected benefits may not be realized. In addition, some micronutrients such as iron and zinc will accumulate less and be less available in food (Myers et al., 2014). Together, the impacts on protein availability may bring as many as 150 million people into protein deficiency by 2050 (Medek et al., 2017). However, short-term benefits could arise for high-latitude fisheries production as waters warm, sea ice contracts and primary productivity increases under climate change (*high confidence*) (Section 3.4.6.3; Cheung et al., 2010; Hollowed and Sundby, 2014; Lam et al., 2016; Sundby et al., 2016; Weatherdon et al., 2016).

Factors affecting the projections of food security include variability in regional climate projections, climate change mitigation (where land use is involved; see Section 3.6 and Cross-Chapter Box 7 in this chapter) and biological responses (*medium confidence*) (Section 3.4.6.1; McGrath and Lobell, 2013; Elliott et al., 2014; Pörtner et al., 2014; Durand et al., 2018), extreme events such as droughts and floods (*high confidence*) (Sections 3.4.6.1, 3.4.6.2; Rosenzweig et al., 2014; Wei et al., 2017), financial volatility (Kannan et al., 2000; Ghosh, 2010; Naylor and Falcon, 2010; HLPE, 2011), and the distributions of pests and disease (Jiao et al., 2014; van Bruggen et al., 2015). Changes in temperature and precipitation are projected to increase global food prices by 3–84% by 2050 (IPCC, 2013). Differences in price impacts of climate change are accompanied by differences in land-use change (Nelson et al., 2014b), energy policies and food trade (Mueller et al., 2011; Wright, 2011; Roberts and Schlenker, 2013). Fisheries and aquatic production systems (aquaculture) face similar challenges to those of crop and livestock sectors (Section 3.4.6.3; Asiedu et al., 2017a, b; Utete et al., 2018). Human influences on food security include demography, patterns of food waste, diet shifts, incomes and prices, storage, health status, trade patterns, conflict, and access to land and governmental or other assistance (Chapters 4 and 5). Across all these systems, the efficiency of adaptation strategies is uncertain because it is strongly linked with future economic and trade environments and their response to changing food availability (*medium confidence*) (Lobell et al., 2011; von Lampe et al., 2014; d'Amour et al., 2016; Wei et al., 2017).

Climate change impacts on food security can be reduced through adaptation (Hasegawa et al., 2014). While climate change is projected to decrease agricultural yield, the consequences could be reduced substantially at 1.5°C versus 2°C with appropriate investment (*high confidence*) (Neumann et al., 2010; Muller, 2011; Roudier et al., 2011), awareness-raising to help inform farmers of new technologies for maintaining yield, and strong adaptation strategies and policies that develop sustainable agricultural choices (Sections 4.3.2 and 4.5.3). In this regard, initiatives such as 'climate-smart' food production and distribution systems may assist via technologies and adaptation strategies for food systems (Lipper et al., 2014; Martinez-Baron et al., 2018; Whitfield et al., 2018), as well as helping meet mitigation goals (Harvey et al., 2014).

K.R. Smith et al. (2014) concluded that climate change will exacerbate current levels of childhood undernutrition and stunting through reduced food availability. As well, climate change can drive undernutrition-related childhood mortality, and increase disability-adjusted life years lost, with the largest risks in Asia and Africa (Supplementary Material 3.SM, Table 3.SM.12; Ishida et al., 2014; Hasegawa et al., 2016; Springmann et al., 2016). Studies comparing the health risks associated with reduced food security at 1.5°C and 2°C concluded that risks would be higher and the globally undernourished population larger at 2°C (Hales et al., 2014; Ishida et al., 2014; Hasegawa et al., 2016). Climate change impacts on dietary and weight-related risk factors are projected to increase mortality, owing to global reductions in food availability and consumption of fruit, vegetables and red meat (Springmann et al., 2016). Further, temperature increases are projected to reduce the protein and micronutrient content of major cereal crops, which is expected to further affect food and nutritional security (Myers et al., 2017; Zhu et al., 2018).

Strategies for improving food security often do so in complex settings such as the Mekong River basin in Southeast Asia. The Mekong is a major food bowl (Smajgl et al., 2015) but is also a climate change hotspot (de Sherbinin, 2014; Lebel et al., 2014). This area is also a useful illustration of the complexity of adaptation choices and actions in a 1.5°C warmer world. Climate projections include increased annual average temperatures and precipitation in the Mekong (Zhang et al., 2017), as well as increased flooding and related disaster risks (T.F. Smith et al., 2013; Ling et al., 2015; Zhang et al., 2016). Sea level rise and saline intrusion are ongoing risks to agricultural systems in this area by reducing soil fertility and limiting the crop productivity (Renaud et al., 2015). The main climate impacts in the Mekong are expected to be on ecosystem health, through salinity intrusion, biomass reduction and biodiversity losses (Le Dang et al., 2013; Smajgl et al., 2015); agricultural productivity and food security (Smajgl et al., 2015); livelihoods such as fishing and farming (D. Wu et al., 2013); and disaster risk (D. Wu et al., 2013; Hoang et al., 2016), with implications for human mortality and economic and infrastructure losses.

Cross-Chapter Box 6 (continued)

Adaptation imperatives and costs in the Mekong will be higher under higher temperatures and associated impacts on agriculture and aquaculture, hazard exposure, and infrastructure. Adaptation measures to meet food security include greater investment in crop diversification and integrated agriculture–aquaculture practices (Renaud et al., 2015), improvement of water-use technologies (e.g., irrigation, pond capacity improvement and rainwater harvesting), soil management, crop diversification, and strengthening allied sectors such as livestock rearing and aquaculture (ICEM, 2013). Ecosystem-based approaches, such as integrated water resources management, demonstrate successes in mainstreaming adaptation into existing strategies (Sebesvari et al., 2017). However, some of these adaptive strategies can have negative impacts that deepen the divide between land-wealthy and land-poor farmers (Chapman et al., 2016). Construction of high dikes, for example, has enabled triple-cropping, which benefits land-wealthy farmers but leads to increasing debt for land-poor farmers (Chapman and Darby, 2016).

Institutional innovation has happened through the Mekong River Commission (MRC), which is an intergovernmental body between Cambodia, Lao PDR, Thailand and Viet Nam that was established in 1995. The MRC has facilitated impact assessment studies, regional capacity building and local project implementation (Schipper et al., 2010), although the mainstreaming of adaptation into development policies has lagged behind needs (Gass et al., 2011). Existing adaptation interventions can be strengthened through greater flexibility of institutions dealing with land-use planning and agricultural production, improved monitoring of saline intrusion, and the installation of early warning systems that can be accessed by the local authorities or farmers (Renaud et al., 2015; Hoang et al., 2016; Tran et al., 2018). It is critical to identify and invest in synergistic strategies from an ensemble of infrastructural options (e.g., building dikes); soft adaptation measures (e.g., land-use change) (Smajgl et al., 2015; Hoang et al., 2018); combinations of top-down government-led (e.g., relocation) and bottom-up household strategies (e.g., increasing house height) (Ling et al., 2015); and community-based adaptation initiatives that merge scientific knowledge with local solutions (Gustafson et al., 2016, 2018; Tran et al., 2018). Special attention needs to be given to strengthening social safety nets and livelihood assets whilst ensuring that adaptation plans are mainstreamed into broader development goals (Sok and Yu, 2015; Kim et al., 2017). The combination of environmental, social and economic pressures on people in the Mekong River basin highlights the complexity of climate change impacts and adaptation in this region, as well as the fact that costs are projected to be much lower at 1.5°C than 2°C of global warming.

3.4.7 Human Health

Climate change adversely affects human health by increasing exposure and vulnerability to climate-related stresses, and decreasing the capacity of health systems to manage changes in the magnitude and pattern of climate-sensitive health outcomes (Cramer et al., 2014; Hales et al., 2014). Changing weather patterns are associated with shifts in the geographic range, seasonality and transmission intensity of selected climate-sensitive infectious diseases (e.g., Semenza and Menne, 2009), and increasing morbidity and mortality are associated with extreme weather and climate events (e.g., K.R. Smith et al., 2014). Health detection and attribution studies conducted since AR5 have provided evidence, using multistep attribution, that climate change is negatively affecting adverse health outcomes associated with heatwaves, Lyme disease in Canada, and *Vibrio* emergence in northern Europe (Mitchell, 2016; Mitchell et al., 2016; Ebi et al., 2017). The IPCC AR5 concluded there is *high* to *very high confidence* that climate change will lead to greater risks of injuries, disease and death, owing to more intense heatwaves and fires, increased risks of undernutrition, and consequences of reduced labour productivity in vulnerable populations (K.R. Smith et al., 2014).

3.4.7.1 Projected risk at 1.5°C and 2°C of global warming

The projected risks to human health of warming of 1.5°C and 2°C, based on studies of temperature-related morbidity and mortality, air quality and vector borne diseases assessed in and since AR5, are summarized in Supplementary Material 3.SM, Tables 3.SM.8, 3.SM.9 and 3.SM.10 (based on Ebi et al., 2018). Other climate-sensitive health outcomes, such as diarrheal diseases, mental health issues and the full range of sources of poor air quality, were not considered because of the lack of projections of how risks could change at 1.5°C and 2°C. Few projections were available for specific temperatures above pre-industrial levels; Supplementary Material 3.SM, Table 3.SM.7 provides the conversions used to translate risks projected for particular time slices to those for specific temperature changes (Ebi et al., 2018).

Temperature-related morbidity and mortality: The magnitude of projected heat-related morbidity and mortality is greater at 2°C than at 1.5°C of global warming (*very high confidence*)(Doyon et al., 2008; Jackson et al., 2010; Hanna et al., 2011; Huang et al., 2012; Petkova et al., 2013; Hajat et al., 2014; Hales et al., 2014; Honda et al., 2014; Vardoulakis et al., 2014; Garland et al., 2015; Huynen and Martens, 2015; Li et al., 2015; Schwartz et al., 2015; L. Wang et al., 2015; Guo et al., 2016; T. Li et al., 2016; Chung et al., 2017; Kendrovski et al., 2017; Mishra et al., 2017; Arnell et al., 2018; Mitchell et al., 2018b). The number of people exposed to heat events is projected to be greater at 2°C than at 1.5°C (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018). The extent to which morbidity and mortality are projected to increase varies by region, presumably because of differences in acclimatization, population vulnerability, the built environment, access to air conditioning and other factors (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018). Populations at highest risk include older adults, children,

women, those with chronic diseases, and people taking certain medications (*very high confidence*). Assuming adaptation takes place reduces the projected magnitude of risks (Hales et al., 2014; Huynen and Martens, 2015; T. Li et al., 2016).

In some regions, cold-related mortality is projected to decrease with increasing temperatures, although increases in heat-related mortality generally are projected to outweigh any reductions in cold-related mortality with warmer winters, with the heat-related risks increasing with greater degrees of warming (Huang et al., 2012; Hajat et al., 2014; Vardoulakis et al., 2014; Gasparrini et al., 2015; Huynen and Martens, 2015; Schwartz et al., 2015).

Occupational health: Higher ambient temperatures and humidity levels place additional stress on individuals engaging in physical activity. Safe work activity and worker productivity during the hottest months of the year would be increasingly compromised with additional climate change (*medium confidence*) (Dunne et al., 2013; Kjellstrom et al., 2013, 2018; Sheffield et al., 2013; Habibi Mohraz et al., 2016). Patterns of change may be complex; for example, at 1.5°C, there could be about a 20% reduction in areas experiencing severe heat stress in East Asia, compared to significant increases in low latitudes at 2°C (Lee and Min, 2018). The costs of preventing workplace heat-related illnesses through worker breaks suggest that the difference in economic loss between 1.5°C and 2°C could be approximately 0.3% of global gross domestic product (GDP) in 2100 (Takakura et al., 2017). In China, taking into account population growth and employment structure, high temperature subsidies for employees working on extremely hot days are projected to increase from 38.6 billion yuan yr^{-1} in 1979–2005 to 250 billion yuan yr^{-1} in the 2030s (about 1.5°C) (Zhao et al., 2016).

Air quality: Because ozone formation is temperature dependent, projections focusing only on temperature increase generally conclude that ozone-related mortality will increase with additional warming, with the risks higher at 2°C than at 1.5°C (*high confidence*) (Supplementary Material 3.SM, Table 3.SM.9; Heal et al., 2013; Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016; Dionisio et al., 2017; J.Y. Lee et al., 2017). Reductions in precursor emissions would reduce future ozone concentrations and associated mortality. Mortality associated with exposure to particulate matter could increase or decrease in the future, depending on climate projections and emissions assumptions (Supplementary Material 3.SM, Table 3.SM.8; Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016).

Malaria: Recent projections of the potential impacts of climate change on malaria globally and for Asia, Africa, and South America (Supplementary Material 3.SM, Table 3.SM.10) confirm that weather and climate are among the drivers of the geographic range, intensity of transmission, and seasonality of malaria, and that the relationships are not necessarily linear, resulting in complex patterns of changes in risk with additional warming (*very high confidence*) (Ren et al., 2016; Song et al., 2016; Semakula et al., 2017). Projections suggest that the burden of malaria could increase with climate change because of a greater geographic range of the Anopheles vector, longer season, and/or increase in the number of people at risk, with larger burdens at higher levels of warming, but with regionally variable patterns *(medium to high confidence*). Vector populations are projected to shift with climate change, with expansions and reductions depending on the degree of local warming, the ecology of the mosquito vector, and other factors (Ren et al., 2016).

***Aedes* (mosquito vector for dengue fever, chikungunya, yellow fever and Zika virus)**: Projections of the geographic distribution of *Aedes aegypti* and Ae. *albopictus* (principal vectors) or of the prevalence of dengue fever generally conclude that there will be an increase in the number of mosquitos and a larger geographic range at 2°C than at 1.5°C, and they suggest that more individuals will be at risk of dengue fever, with regional differences (*high confidence*) (Fischer et al., 2011, 2013; Colón-González et al., 2013, 2018; Bouzid et al., 2014; Ogden et al., 2014a; Mweya et al., 2016). The risks increase with greater warming. Projections suggest that climate change is projected to expand the geographic range of chikungunya, with greater expansions occurring at higher degrees of warming (Tjaden et al., 2017).

Other vector-borne diseases: Increased warming in North America and Europe could result in geographic expansions of regions (latitudinally and altitudinally) climatically suitable for West Nile virus transmission, particularly along the current edges of its transmission areas, and extension of the transmission season, with the magnitude and pattern of changes varying by location and level of warming (Semenza et al., 2016). Most projections conclude that climate change could expand the geographic range and seasonality of Lyme and other tick-borne diseases in parts of North America and Europe (Ogden et al., 2014b; Levi et al., 2015). The projected changes are larger with greater warming and under higher greenhouse gas emissions pathways. Projections of the impacts of climate change on leishmaniosis and Chagas disease indicate that climate change could increase or decrease future health burdens, with greater impacts occurring at higher degrees of warming (González et al., 2014; Ceccarelli and Rabinovich, 2015).

In summary, warming of 2°C poses greater risks to human health than warming of 1.5°C, often with the risks varying regionally, with a few exceptions (*high confidence*). There is *very high confidence* that each additional unit of warming could increase heat-related morbidity and mortality, and that adaptation would reduce the magnitude of impacts. There is *high confidence* that ozone-related mortality could increase if precursor emissions remain the same, and that higher temperatures could affect the transmission of some infectious diseases, with increases and decreases projected depending on the disease (e.g., malaria, dengue fever, West Nile virus and Lyme disease), region and degree of temperature change.

3.4.8 Urban Areas

There is new literature on urban climate change and its differential impacts on and risks for infrastructure sectors – energy, water, transport and buildings – and vulnerable populations, including those living in informal settlements (UCCRN, 2018). However, there is limited literature on the risks of warming of 1.5°C and 2°C in urban areas. Heat-related extreme events (Matthews et al., 2017), variability in precipitation (Yu et al., 2018) and sea level rise can directly affect urban areas (Section 3.4.5, Bader et al., 2018; Dawson et al., 2018). Indirect risks may arise from interactions between urban and natural systems.

Future warming and urban expansion could lead to more extreme heat stress (Argüeso et al., 2015; Suzuki-Parker et al., 2015). At 1.5°C of warming, twice as many megacities (such as Lagos, Nigeria and Shanghai, China) could become heat stressed, exposing more than 350 million more people to deadly heat by 2050 under midrange population growth. Without considering adaptation options, such as cooling from more reflective roofs, and overall characteristics of urban agglomerations in terms of land use, zoning and building codes (UCCRN, 2018), Karachi (Pakistan) and Kolkata (India) could experience conditions equivalent to the deadly 2015 heatwaves on an annual basis under 2°C of warming (Akbari et al., 2009; Oleson et al., 2010; Matthews et al., 2017). Warming of 2°C is expected to increase the risks of heatwaves in China's urban agglomerations (Yu et al., 2018). Stabilizing at 1.5°C of warming instead of 2°C could decrease mortality related to extreme temperatures in key European cities, assuming no adaptation and constant vulnerability (Jacob et al., 2018; Mitchell et al., 2018a). Holding temperature change to below 2°C but taking urban heat islands (UHI) into consideration, projections indicate that there could be a substantial increase in the occurrence of deadly heatwaves in cities. The urban impacts of these heatwaves are expected to be similar at 1.5°C and 2°C and substantially larger than under the present climate (Matthews et al., 2017; Yu et al., 2018). Increases in the intensity of UHI could exacerbate warming of urban areas, with projections ranging from a 6% decrease to a 30% increase for a doubling of CO_2 (McCarthy et al., 2010). Increases in population and city size, in the context of a warmer climate, are projected to increase UHI (Georgescu et al., 2012; Argüeso et al., 2014; Conlon et al., 2016; Kusaka et al., 2016; Grossman-Clarke et al., 2017).

For extreme heat events, an additional 0.5°C of warming implies a shift from the upper bounds of observed natural variability to a new global climate regime (Schleussner et al., 2016b), with distinct implications for the urban poor (Revi et al., 2014; Jean-Baptiste et al., 2018; UCCRN, 2018). Adverse impacts of extreme events could arise in tropical coastal areas of Africa, South America and Southeast Asia (Schleussner et al., 2016b). These urban coastal areas in the tropics are particularly at risk given their large informal settlements and other vulnerable urban populations, as well as vulnerable assets, including businesses and critical urban infrastructure (energy, water, transport and buildings) (McGranahan et al., 2007; Hallegatte et al., 2013; Revi et al., 2014; UCCRN, 2018). Mediterranean water stress is projected to increase from 9% at 1.5°C to 17% at 2°C compared to values in 1986–2005 period. Regional dry spells are projected to expand from 7% at 1.5°C to 11% at 2°C for the same reference period. Sea level rise is expected to be lower at 1.5°C than 2°C, lowering risks for coastal metropolitan agglomerations (Schleussner et al., 2016b).

Climate models are better at projecting implications of greenhouse gas forcing on physical systems than at assessing differential risks associated with achieving a specific temperature target (James et al., 2017). These challenges in managing risks are amplified when combined with the scale of urban areas and assumptions about socio-economic pathways (Krey et al., 2012; Kamei et al., 2016; Yu et al., 2016; Jiang and Neill, 2017).

In summary, in the absence of adaptation, in most cases, warming of 2°C poses greater risks to urban areas than warming of 1.5°C, depending on the vulnerability of the location (coastal or non-coastal) (*high confidence*), businesses, infrastructure sectors (energy, water and transport), levels of poverty, and the mix of formal and informal settlements.

3.4.9 Key Economic Sectors and Services

Climate change could affect tourism, energy systems and transportation through direct impacts on operations (e.g., sea level rise) and through impacts on supply and demand, with the risks varying significantly with geographic region, season and time. Projected risks also depend on assumptions with respect to population growth, the rate and pattern of urbanization, and investments in infrastructure. Table 3.SM.11 in Supplementary Material 3.SM summarizes the cited publications.

3.4.9.1 Tourism

The implications of climate change for the global tourism sector are far-reaching and are impacting sector investments, destination assets (environment and cultural), operational and transportation costs, and tourist demand patterns (Scott et al., 2016a; Scott and Gössling, 2018). Since AR5, observed impacts on tourism markets and destination communities continue to be not well analysed, despite the many analogue conditions (e.g., heatwaves, major hurricanes, wild fires, reduced snow pack, coastal erosion and coral reef bleaching) that are anticipated to occur more frequently with climate change. There is some evidence that observed impacts on tourism assets, such as environmental and cultural heritage, are leading to the development of 'last chance to see' tourism markets, where travellers visit destinations before they are substantially degraded by climate change impacts or to view the impacts of climate change on landscapes (Lemelin et al., 2012; Stewart et al., 2016; Piggott-McKellar and McNamara, 2017).

There is limited research on the differential risks of a 1.5° versus 2°C temperature increase and resultant environmental and socio-economic impacts in the tourism sector. The translation of these changes in climate resources for tourism into projections of tourism demand remains geographically limited to Europe. Based on analyses of tourist comfort, summer and spring/autumn tourism in much of western Europe may be favoured by 1.5°C of warming, but with negative effects projected for Spain and Cyprus (decreases of 8% and 2%, respectively, in overnight stays) and most coastal regions of the Mediterranean (Jacob et al., 2018). Similar geographic patterns of potential tourism gains (central and northern Europe) and reduced summer favourability (Mediterranean countries) are projected under 2°C (Grillakis et al., 2016). Considering potential changes in natural snow only, winter overnight stays at 1.5°C are projected to decline by 1–2% in Austria, Italy and Slovakia, with an additional 1.9 million overnight stays lost under 2°C of warming (Jacob et al., 2018). Using an econometric analysis of the relationship between regional tourism demand and climate conditions, Ciscar et al. (2014) projected that a 2°C warmer world would reduce European tourism by 5% (€15 billion yr^{-1}), with losses of up to 11% (€6 billion yr^{-1}) for southern Europe and a potential gain of €0.5 billion yr^{-1} in the UK.

There is growing evidence that the magnitude of projected impacts is temperature dependent and that sector risks could be much greater

with higher temperature increases and resultant environmental and socio-economic impacts (Markham et al., 2016; Scott et al., 2016a; Jones, 2017; Steiger et al., 2017). Studies from 27 countries consistently project substantially decreased reliability of ski areas that are dependent on natural snow, increased snowmaking requirements and investment in snowmaking systems, shortened and more variable ski seasons, a contraction in the number of operating ski areas, altered competitiveness among and within regional ski markets, and subsequent impacts on employment and the value of vacation properties (Steiger et al., 2017). Studies that omit snowmaking do not reflect the operating realities of most ski areas and overestimate impacts at 1.5°C–2°C. In all regional markets, the extent and timing of these impacts depend on the magnitude of climate change and the types of adaptive responses by the ski industry, skiers and destination communities. The decline in the number of former Olympic Winter Games host locations that could remain climatically reliable for future Olympic and Paralympic Winter Games has been projected to be much greater under scenarios warmer than 2°C (Scott et al., 2015; Jacob et al., 2018).

The tourism sector is also affected by climate-induced changes in environmental assets critical for tourism, including biodiversity, beaches, glaciers and other features important for environmental and cultural heritage. Limited analyses of projected risks associated with 1.5°C versus 2°C are available (Section 3.4.4.12). A global analysis of sea level rise (SLR) risk to 720 UNESCO Cultural World Heritage sites projected that about 47 sites might be affected under 1°C of warming, with this number increasing to 110 and 136 sites under 2°C and 3°C, respectively (Marzeion and Levermann, 2014). Similar risks to vast worldwide coastal tourism infrastructure and beach assets remain unquantified for most major tourism destinations and small island developing states (SIDS) that economically depend on coastal tourism. One exception is the projection that an eventual 1 m SLR could partially or fully inundate 29% of 900 coastal resorts in 19 Caribbean countries, with a substantially higher proportion (49–60%) vulnerable to associated coastal erosion (Scott and Verkoeyen, 2017).

A major barrier to understanding the risks of climate change for tourism, from the destination community scale to the global scale, has been the lack of integrated sectoral assessments that analyse the full range of potential compounding impacts and their interactions with other major drivers of tourism (Rosselló-Nadal, 2014; Scott et al., 2016b). When applied to 181 countries, a global vulnerability index including 27 indicators found that countries with the lowest risk are located in western and northern Europe, central Asia, Canada and New Zealand, while the highest sector risks are projected for Africa, the Middle East, South Asia and SIDS in the Caribbean, Indian and Pacific Oceans (Scott and Gössling, 2018). Countries with the highest risks and where tourism represents a significant proportion of the national economy (i.e., more than 15% of GDP) include many SIDS and least developed countries. Sectoral climate change risk also aligns strongly with regions where tourism growth is projected to be the strongest over the coming decades, including sub-Saharan Africa and South Asia, pointing to an important potential barrier to tourism development. The transnational implications of these impacts on the highly interconnected global tourism sector and the contribution of tourism to achieving the 2030 sustainable development goals (SDGs) remain important uncertainties.

In summary, climate is an important factor influencing the geography and seasonality of tourism demand and spending globally (*very high confidence*). Increasing temperatures are projected to directly impact climate-dependent tourism markets, including sun, beach and snow sports tourism, with lesser risks for other tourism markets that are less climate sensitive (*high confidence*). The degradation or loss of beach and coral reef assets is expected to increase risks for coastal tourism, particularly in subtropical and tropical regions (*high confidence*).

3.4.9.2 Energy systems

Climate change is projected to lead to an increased demand for air conditioning in most tropical and subtropical regions (Arent et al., 2014; Hong and Kim, 2015) (*high confidence*). Increasing temperatures will decrease the thermal efficiency of fossil, nuclear, biomass and solar power generation technologies, as well as buildings and other infrastructure (Arent et al., 2014). For example, in Ethiopia, capital expenditures through 2050 might either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario (Block and Strzepek, 2012).

Impacts on energy systems can affect gross domestic product (GDP). The economic damage in the United States from climate change is estimated to be, on average, roughly 1.2% cost of GDP per year per 1°C increase under RCP8.5 (Hsiang et al., 2017). Projections of GDP indicate that negative impacts of energy demand associated with space heating and cooling in 2100 will be greatest (median: –0.94% change in GDP) under 4°C (RCP8.5) compared with under 1.5°C (median: –0.05%), depending on the socio-economic conditions (Park et al., 2018). Additionally, projected total energy demands for heating and cooling at the global scale do not change much with increases in global mean surface temperature (GMST) of up to 2°C. A high degree of variability is projected between regions (Arnell et al., 2018).

Evidence for the impact of climate change on energy systems since AR5 is limited. Globally, gross hydropower potential is projected to increase (by 2.4% under RCP2.6 and by 6.3% under RCP8.5 for the 2080s), with the most growth expected in Central Africa, Asia, India and northern high latitudes (van Vliet et al., 2016). Byers et al. (2018) found that energy impacts at 2°C increase, including more cooling degree days, especially in tropical regions, as well as increased hydro-climatic risk to thermal and hydropower plants predominantly in Europe, North America, South and Southeast Asia and southeast Brazil. Donk et al. (2018) assessed future climate impacts on hydropower in Suriname and projected a decrease of approximately 40% in power capacity for a global temperature increase in the range of 1.5°C. At minimum and maximum increases in global mean temperature of 1.35°C and 2°C, the overall stream flow in Florida, USA is projected to increase by an average of 21%, with pronounced seasonal variations, resulting in increases in power generation in winter (+72%) and autumn (+15%) and decreases in summer (–14%; Chilkoti et al., 2017). Greater changes are projected at higher temperature increases. In a reference scenario with global mean temperatures rising by 1.7°C from 2005 to 2050, U.S. electricity demand in 2050 was 1.6–6.5% higher than in a control scenario with constant temperatures (McFarland et al., 2015). Decreased electricity generation of –15% is projected for Brazil starting in 2040, with values expected to decline to –28% later in the

century (de Queiroz et al., 2016). In large parts of Europe, electricity demand is projected to decrease, mainly owing to reduced heating demand (Jacob et al., 2018).

In Europe, no major differences in large-scale wind energy resources or in inter- or intra-annual variability are projected for 2016–2035 under RCP8.5 and RCP4.5 (Carvalho et al., 2017). However, in 2046–2100, wind energy density is projected to decrease in eastern Europe (–30%) and increase in Baltic regions (+30%). Intra-annual variability is expected to increase in northern Europe and decrease in southern Europe. Under RCP4.5 and RCP8.5, the annual energy yield of European wind farms as a whole, as projected to be installed by 2050, will remain stable (±5 yield for all climate models). However, wind farm yields are projected to undergo changes of up to 15% in magnitude at country and local scales and of 5% at the regional scale (Tobin et al., 2015, 2016). Hosking et al. (2018) assessed wind power generation over Europe for 1.5°C of warming and found the potential for wind energy to be greater than previously assumed in northern Europe. Additionally, Tobin et al. (2018) assessed impacts under 1.5°C and 2°C of warming on wind, solar photovoltaic and thermoelectric power generation across Europe. These authors found that photovoltaic and wind power might be reduced by up to 10%, and hydropower and thermoelectric generation might decrease by up to 20%, with impacts being limited at 1.5°C of warming but increasing as temperature increases (Tobin et al., 2018).

3.4.9.3 Transportation

Road, air, rail, shipping and pipeline transportation can be impacted directly or indirectly by weather and climate, including increases in precipitation and temperature; extreme weather events (flooding and storms); SLR; and incidence of freeze–thaw cycles (Arent et al., 2014). Much of the published research on the risks of climate change for the transportation sector has been qualitative.

The limited new research since AR5 supports the notion that increases in global temperatures will impact the transportation sector. Warming is projected to result in increased numbers of days of ice-free navigation and a longer shipping season in cold regions, thus affecting shipping and reducing transportation costs (Arent et al., 2014). In the North Sea Route, large-scale commercial shipping might not be possible until 2030 for bulk shipping and until 2050 for container shipping under RCP8.5. A 0.05% increase in mean temperature is projected from an increase in short-lived pollutants, as well as elevated CO_2 and non-CO_2 emissions, associated with additional economic growth enabled by the North Sea Route. (Yumashev et al., 2017). Open water vessel transit has the potential to double by mid-century, with a two to four month longer season (Melia et al., 2016).

3.4.10 Livelihoods and Poverty, and the Changing Structure of Communities

Multiple drivers and embedded social processes influence the magnitude and pattern of livelihoods and poverty, as well as the changing structure of communities related to migration, displacement and conflict (Adger et al., 2014). In AR5, evidence of a climate change signal was limited, with more evidence of impacts of climate change on the places where indigenous people live and use traditional ecological knowledge (Olsson et al., 2014).

3.4.10.1 Livelihoods and poverty

At approximately 1.5°C of global warming (2030), climate change is expected to be a poverty multiplier that makes poor people poorer and increases the poverty head count (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Poor people might be heavily affected by climate change even when impacts on the rest of population are limited. Climate change alone could force more than 3 million to 16 million people into extreme poverty, mostly through impacts on agriculture and food prices (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Unmitigated warming could reshape the global economy later in the century by reducing average global incomes and widening global income inequality (Burke et al., 2015b). The most severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia.

3.4.10.2 The changing structure of communities: migration, displacement and conflict

Migration: In AR5, the potential impacts of climate change on migration and displacement were identified as an emerging risk (Oppenheimer et al., 2014). The social, economic and environmental factors underlying migration are complex and varied; therefore, detecting the effect of observed climate change or assessing its possible magnitude with any degree of confidence is challenging (Cramer et al., 2014).

No studies have specifically explored the difference in risks between 1.5°C and 2°C of warming on human migration. The literature consistently highlights the complexity of migration decisions and the difficulties in attributing causation (e.g., Nicholson, 2014; Baldwin and Fornalé, 2017; Bettini, 2017; Constable, 2017; Islam and Shamsuddoha, 2017; Suckall et al., 2017). The studies on migration that have most closely explored the probable impacts of 1.5°C and 2°C have mainly focused on the direct effects of temperature and precipitation anomalies on migration or the indirect effects of these climatic changes through changing agriculture yield and livelihood sources (Mueller et al., 2014; Piguet and Laczko, 2014; Mastrorillo et al., 2016; Sudmeier-Rieux et al., 2017).

Temperature has had a positive and statistically significant effect on outmigration over recent decades in 163 countries, but only for agriculture-dependent countries (R. Cai et al., 2016). A 1°C increase in average temperature in the International Migration Database of the Organisation for Economic Co-operation and Development (OECD) was associated with a 1.9% increase in bilateral migration flows from 142 sending countries and 19 receiving countries, and an additional millimetre of average annual precipitation was associated with an increase in migration by 0.5% (Backhaus et al., 2015). In another study, an increase in precipitation anomalies from the long-term mean, was strongly associated with an increase in outmigration, whereas no significant effects of temperature anomalies were reported (Coniglio and Pesce, 2015).

Internal and international migration have always been important for small islands (Farbotko and Lazrus, 2012; Weir et al., 2017). There is rarely a single cause for migration (Constable, 2017). Numerous factors are important, including work, education, quality of life, family ties, access to resources, and development (Bedarff and Jakobeit, 2017; Speelman et al., 2017; Nicholls et al., 2018). Depending on the situation, changing weather, climate or environmental conditions might each be a factor in the choice to migrate (Campbell and Warrick, 2014).

Displacement: At 2°C of warming, there is a potential for significant population displacement concentrated in the tropics (Hsiang and Sobel, 2016). Tropical populations may have to move distances greater than 1000 km if global mean temperature rises by 2°C from 2011–2030 to the end of the century. A disproportionately rapid evacuation from the tropics could lead to a concentration of population in tropical margins and the subtropics, where population densities could increase by 300% or more (Hsiang and Sobel, 2016).

Conflict: A recent study has called for caution in relating conflict to climate change, owing to sampling bias (Adams et al., 2018). Insufficient consideration of the multiple drivers of conflict often leads to inconsistent associations being reported between climate change and conflict (e.g., Hsiang et al., 2013; Hsiang and Burke, 2014; Buhaug, 2015, 2016; Carleton and Hsiang, 2016; Carleton et al., 2016). There also are inconsistent relationships between climate change, migration and conflict (e.g., Theisen et al., 2013; Buhaug et al., 2014; Selby, 2014; Christiansen, 2016; Brzoska and Fröhlich, 2016; Burrows and Kinney, 2016; Reyer et al., 2017c; Waha et al., 2017). Across world regions and from the international to micro level, the relationship between drought and conflict is weak under most circumstances (Buhaug, 2016; von Uexkull et al., 2016). However, drought significantly increases the likelihood of sustained conflict for particularly vulnerable nations or groups, owing to the dependence of their livelihood on agriculture. This is particularly relevant for groups in the least developed countries (von Uexkull et al., 2016), in sub-Saharan Africa (Serdeczny et al., 2016; Almer et al., 2017) and in the Middle East (Waha et al., 2017). Hsiang et al. (2013) reported causal evidence and convergence across studies that climate change is linked to human conflicts across all major regions of the world, and across a range of spatial and temporal scales. A 1°C increase in temperature or more extreme rainfall increases the frequency of intergroup conflicts by 14% (Hsiang et al., 2013). If the world warms by 2°C–4°C by 2050, rates of human conflict could increase. Some causal associations between violent conflict and socio-political instability were reported from local to global scales and from hour to millennium time frames (Hsiang and Burke, 2014). A temperature increase of one standard deviation increased the risk of interpersonal conflict by 2.4% and intergroup conflict by 11.3% (Burke et al., 2015a). Armed-conflict risks and climate-related disasters are both relatively common in ethnically fractionalized countries, indicating that there is no clear signal that environmental disasters directly trigger armed conflicts (Schleussner et al., 2016a).

In summary, average global temperatures that extend beyond 1.5°C are projected to increase poverty and disadvantage in many populations globally (*medium confidence*). By the mid- to late 21st century, climate change is projected to be a poverty multiplier that makes poor people poorer and increases poverty head count, and the association between temperature and economic productivity is not linear (*high confidence*). Temperature has a positive and statistically significant effect on outmigration for agriculture-dependent communities (*medium confidence*).

3.4.11 Interacting and Cascading Risks

The literature on compound as well as interacting and cascading risks at warming of 1.5°C and 2°C is limited. Spatially compound risks, often referred to as hotspots, involve multiple hazards from different sectors overlapping in location (Piontek et al., 2014). Global exposures were assessed for 14 impact indicators, covering water, energy and land sectors, from changes including drought intensity and water stress index, cooling demand change and heatwave exposure, habitat degradation, and crop yields using an ensemble of climate and impact models (Byers et al., 2018). Exposures are projected to approximately double between 1.5°C and 2°C, and the land area affected by climate risks is expected to increase as warming progresses. For populations vulnerable to poverty, the exposure to climate risks in multiple sectors could be an order of magnitude greater (8–32 fold) in the high poverty and inequality scenarios (SSP3; 765–1,220 million) compared to under sustainable socio-economic development (SSP1; 23–85 million). Asian and African regions are projected to experience 85–95% of global exposure, with 91–98% of the exposed and vulnerable population (depending on SSP/GMT combination), approximately half of which are in South Asia. Figure 3.19 shows that moderate and large multi-sector impacts are prevalent at 1.5°C where vulnerable people live, predominantly in South Asia (mostly Pakistan, India and China), but that impacts spread to sub-Saharan Africa, the Middle East and East Asia at higher levels of warming. Beyond 2°C and at higher risk thresholds, the world's poorest populations are expected to be disproportionately impacted, particularly in cases (SSP3) of great inequality in Africa and southern Asia. Table 3.4 shows the number of exposed and vulnerable people at 1.5°C and 2°C of warming, with 3°C shown for context, for selected multi-sector risks.

3.4.12 Summary of Projected Risks at 1.5°C and 2°C of Global Warming

The information presented in Section 3.4 is summarized below in Table 3.5, which illustrates the growing evidence of increasing risks across a broad range of natural and human systems at 1.5°C and 2°C of global warming.

Figure 3.19 | Multi-sector risk maps for 1.5°C (top), 2°C (middle), and locations where 2°C brings impacts not experienced at 1.5°C (2°C–1.5°C; bottom). The maps in the left column show the full range of the multi-sector risk (MSR) score (0–9), with scores ≤5.0 shown with a transparency gradient and scores >5.0 shown with a colour gradient. Score must be >4.0 to be considered 'multi-sector'. The maps in the right column overlay the 2050 vulnerable populations (low income) under Shared Socio-Economic Pathway (SSP)2 (greyscale) with the multi-sector risk score >5.0 (colour gradient), thus indicating the concentrations of exposed and vulnerable populations to risks in multiple sectors. Source: Byers et al. (2018).

Table 3.4 | Number of exposed and vulnerable people at 1.5°C, 2°C, and 3°C for selected multi-sector risks under shared socioeconomic pathways (SSPs). Source: Byers et al., 2018

SSP2 (SSP1 to SSP3 range), millions	**1.5°C**		**2°C**		**3°C**	
Indicator	Exposed	Exposed and vulnerable	Exposed	Exposed and vulnerable	Exposed	Exposed and vulnerable
Water stress index	3340 (3032–3584)	496 (103–1159)	3658 (3080–3969)	586 (115–1347)	3920 (3202–4271)	662 (146–1480)
Heatwave event exposure	3960 (3546–4508)	1187 (410–2372)	5986 (5417–6710)	1581 (506–3218)	7909 (7286–8640)	1707 (537–3575)
Hydroclimate risk to power production	334 (326–337)	30 (6–76)	385 (374–389)	38 (9–94)	742 (725–739)	72 (16–177)
Crop yield change	35 (32–36)	8 (2–20)	362 (330–396)	81 (24–178)	1817 (1666–1992)	406 (118–854)
Habitat degradation	91 (92–112)	10 (4–31)	680 (314–706)	102 (23–234)	1357 (809–1501)	248 (75–572)
Multi-sector exposure						
Two indicators	1129 (1019–1250)	203 (42–487)	2726 (2132–2945)	562 (117–1220)	3500 (3212–3864)	707 (212–1545)
Three indicators	66 (66–68)	7 (0.9–19)	422 (297–447)	54 (8–138)	1472 (1177–1574)	237 (48–538)
Four indicators	5 (0.3–5.7)	0.3 (0–1.2)	11 (5–14)	0.5 (0–2)	258 (104–280)	33 (4–86)

Table 3.5 | Summary of projected risks to natural and human systems at 1.5°C and 2°C of global warming, and of the potential to adapt to these risks. Table summarizes the chapter text and with references supporting table entries found in the main chapter text. Risk magnitude is provided either as assessed levels of risk (very high: vh, high: h, medium: m, or low: l) or as quantitative examples of risk levels taken from the literature. Further compilations of quantified levels of risk taken from the literature may be found Tables 3.SM1-5 in the Supplementary Material. Similarly, potential to adapt is assessed from the literature by expert judgement as either high (h), medium (m), or low (l). Confidence in each assessed level/quantification of risk, or in each assessed adaptation potential, is indicated as very high (VH), high (H), medium (M), or low (L). Note that the use of l, m, h and vh here is distinct from the use of L, M, H and VH in Figures 3.18, 3.20 and 3.21.

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to 2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Freshwater	Precipitation, temperature, snowmelt	Water Stress	Around half compared to the risks at 2°C[1]	Additional 8% of the world population in 2000 exposed to new or aggravated water scarcity[1]	Up to 100% increase	M		Europe, Australia, southern Africa		3	l	l	M
		Fluvial flood	100% increase in the population affected compared to the impact simulated over the baseline period 1976–2005[2]	170% increase in the population affected compared to the impact simulated over the baseline period 1976–2005[2]	70% increase	M	USA, Asia, Europe		Africa, Oceania	2	l/m	l/m	M
		Drought	350.2 ± 158.8 million, changes in urban population exposure to severe drought at the globe scale[3]	410.7 ± 213.5 million, changes in urban population exposure to severe drought at the globe scale[3]	60.5 ± 84.1 million (±84.1 based on the SSP1 scenario) (based on PDSI estimate)	M	Central Europe, southern Europe, Mediterranean, West Africa, East and West Asia, Southeast Asia (based on PDSI estimate[#])			2	l/m	l/m	L
Terrestrial ecosystems	Temperature, precipitation	Species range loss	6% insects, 4% vertebrates, 8% plants, lose >50% range[4]	18% insects, 8% vertebrates, 16% plants lose >50% range[4]	Double or triple	M		Amazon, Europe, southern Africa		1,4	m	l	H
		Loss of ecosystem functioning and services	m	h		M				4			
		Shifts of biomes (major ecosystem types)	About 7% transformed[5]	13% (range 8–20%) transformed[5]	About double	M		Arctic, Tibet, Himalayas, South Africa, Australia		4			
	Heat and cold stress, warming, precipitation drought	Wildfire	h	h	Increased risk	M	Canada, USA and Mediterranean	Mediterranean	Central and South America, Australia, Russia, China, Africa	1, 2, 4, 5	l	l	M

Table 3.5 (continued)

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Ocean	Warming and stratification of the surface ocean	Loss of framework species (coral reefs)	vh	vh	Greater rate of loss: from 70–90% loss at 1.5°C to 99% loss at 2°C and above	H/very H	Tropical/ subtropical countries	Tropical/ subtropical countries	Southern Red Sea, Somalia, Yemen, deep water coral reefs	1,2	h	l	H
		Loss of framework species (seagrass)	m	h	Increase in risk	M	Tropical/ subtropical countries	Tropical/ subtropical countries	Southern Red Sea, Somalia, Yemen, Myanmar	1,2	m	l	M/H
		Loss of framework species (mangroves)	m	m	Uncertain and depends on other human activities	M/H	Tropical/ subtropical countries	Tropical/ subtropical countries	Southern Red Sea, Somalia, Yemen, Myanmar	1,3	m	l	L/M
		Disruption of marine foodwebs	h	vh	Large increase in risk	M	Global	Global	Deep sea	4	m	l	M/H
		Range migration of marine species and ecosystems	m	h	Large increase in risk	H	Global	Global	Deep sea	1	m	l	H
		Loss of fin fish and fisheries	h	h/vh	Large increase in risk	H	Global	Global	Deep sea, up-welling systems	4	m	m/l	M/H
	Ocean acidification and elevated sea temperatures	Loss of coastal ecosystems and protection	m	h	Increase in risk	M	Low-latitude tropical/ subtropical countries	Low-latitude tropical/subtropi-cal countries	Most regions – risks not well defined	1	m	m/l	M
		Loss of bivalves and bivalve fisheries	m/h	h/vh	Large increase in risk	H	Temperate countries with upwelling	Temperate countries with upwelling	Most regions – risks not well defined	4	m/h	l/m	M/H
		Changes to physiology and ecology of marine species	l/m	m	Increase in risk	H	Global	Global	Most regions – risks not well defined	4	l	l	M/H
	Reduced bulk ocean circulation and de-oxygenation	Increased hypoxic dead zones	l	l/m	Large increase in risk	L/M	Temperate countries with upwelling	Temperate countries with upwelling	Deep sea	4	m	l	M
		Changes to upwelling productivity	l	m	Increase in risk	L/M	Most upwelling regions	Most upwelling regions	Some upwelling systems	4	l	l	M

Table 3.5 (continued)

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Ocean	Intensified storms, precipitation plus sea level rise	Loss of coastal ecosystems	h	h/vh	Large increase in risk	H	Tropical/ subtropical countries	Tropical/ subtropical countries		1, 4	m	l	M
		Inundation and destruction of human/coastal infrastructure and livelihoods	h	h/vh	Large increase in risk	H	Global	Global		1, 5	m/h	m	M/L
	Loss of sea ice	Loss of habitat	h	vh	Large increase in risk	H	Polar regions	Polar regions		1	l	very l	H
		Increased productivity but changing fisheries	l/m	m/h	Large increase in risk	very H	Polar regions	Polar regions		1, 4	l	m/l	H
Coastal	Sea level rise, increased storminess	Area exposed (assuming no defences)	562–575th km^2 when 1.5°C first reached[6,7,8]	590–613th km^2 when 2°C first reached[6,7,8]	Increasing; 25–38th km^2 when temperatures are first reached, 10–17th km^2 in 2100 increasing to 16–230th km^2 in 2300[6,7,8]	M/H (dependent on population datasets)	Asia, small islands	Asia, small islands	Small islands	2, 3	m	m	M
		Population exposed (assuming no defences)	128–143 million when 1.5°C first reached	141–151 million when 2°C first reached	Increasing; 13–8 million when temperatures are first reached, 0–6 million people in 2100, increasing to 35–95 million people in 2300[6]	M/H (dependent on population datasets)	Asia, small islands	Asia, small islands	Small islands	2, 3	m	m	M
		People at risk accounting for defences (modelled in 1995)	2–28 million people yr^{-1} if defences are not upgraded from the modelled 1995 baseline[9]	15–53 million people yr^{-1} if defences are not upgraded from the modelled 1995 baseline[9]	Increasing with time, but highly dependent on adaptation[9]	M/H (dependent on adaptation)	Asia, small islands, potentially African nations	Asia, small islands	Small islands	2, 3, 4	m	m	M

Table 3.5 (continued)

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Food security and food production systems	Heat and cold stress, warming, precipitation, drought	Changes in ecosystem production	m/h	h	Large increase	M/H	Global	North America, Central and South America, Mediterranean basin, South Africa, Australia, Asia		2, 4, 5	h	m/h	M/H
	Heat and cold stress, warming, precipitation drought	Shift and composition change of biomes (major ecosystem types)	m/h	h	Moderate increase	L/M	Global	Global, tropical areas, Mediterranean	Africa, Asia	1, 2, 3, 4	l/m	l	L/M
Human health	Temperature	Heat-related morbidity and mortality	m	m/h	Risk increased	VH	All regions at risk	All regions	Africa	2, 3, 4	h	h	H
		Occupational heat stress	m	m/h	Risk increased	M	Tropical regions	Tropical regions	Africa	2, 3, 4	h	m	M
	Air quality	Ozone-related mortality	m (if precursor emissions remain the same)	m/h (if precursor emissions remain the same)	Risk increased	H	High income and emerging economies	High income and emerging economies	Africa, parts of Asia	2, 3, 4	l	l	M
	Temperature, precipitation	Undernutrition	m	m/h	Risk increased	H	Low-income countries in Africa and Asia	Low-income countries in Africa and Asia	Small islands	2, 3, 4	m	l	M
Key economic sectors	Temperature	Tourism (sun, beach, and snow sports)	m/h	h	Risk increased	VH	Coastal tourism, particularly in subtropical and tropical regions	Coastal tourism, particularly in subtropical and tropical regions	Africa	1, 2, 3	m	l	H

*RFC: 1 = unique and threatened systems, 2 = extreme events, 3 = unequal distribution of impacts, 4 = global aggregate impacts (economic + biodiversity), 5 = large-scale singular events.

PDSI-based drought estimates tend to overestimate drought impacts (see Section 3.3.4); hence projections with other drought indices may differ. Further quantifications may be found in Table 3.SM.1

[1] Gerten et al., 2013; [2] Alfieri et al., 2017; [3] Liu et al., 2018; [4] Warren et al., 2018a; [5] Warzawski et al., 2013; [6] Brown et al., 2018a; [7] Rasmussen et al., 2018; [8] Yokoki et al., 2018; [9] Nicholls et al., 2018.

3.4.13 Synthesis of Key Elements of Risk

Some elements of the assessment in Section 3.4 were synthesized into Figure 3.18 and 3.20, indicating the overall risk for a representative set of natural and human systems from increases in global mean surface temperature (GMST) and anthropogenic climate change. The elements included are supported by a substantive enough body of literature providing at least *medium confidence* in the assessment. The format for Figures 3.18 and 3.20 match that of Figure 19.4 of WGII AR5 Chapter 19 (Oppenheimer et al., 2014) indicating the levels of additional risk as colours: undetectable (white) to moderate (detected and attributed; yellow), from moderate to high (severe and widespread; red), and from high to very high (purple), the last of which indicates significant irreversibility or persistence of climate-related hazards combined with a much reduced capacity to adapt. Regarding the transition from undetectable to moderate, the impact literature assessed in AR5 focused on describing and quantifying linkages between weather and climate patterns and impact outcomes, with limited detection and attribution to anthropogenic climate change (Cramer et al., 2014). A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) confirmed that the impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of those impacts related to precipitation is only weakly evident or absent. Moreover, there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016).

The current synthesis is complementary to the synthesis in Section 3.5.2 that categorizes risks into 'Reasons for Concern' (RFCs), as described in Oppenheimer et al. (2014). Each element, or burning ember, presented here (Figures 3.18, 3.20) maps to one or more RFCs (Figure 3.21). It should be emphasized that risks to the elements assessed here are only a subset of the full range of risks that contribute to the RFCs. Figures 3.18 and 3.20 are not intended to replace the RFCs but rather to indicate how risks to particular elements of the Earth system accrue with global warming, through the visual burning embers format, with a focus on levels of warming of 1.5°C and 2°C. Key evidence assessed in earlier parts of this chapter is summarized to indicate the transition points between the levels of risk. In this regard, the assessed confidence in assigning the transitions between risk levels are as follows: L=Low, M=Medium, H=High, and VH=Very high levels of confidence. A detailed account of the procedures involved is provided in the Supplementary Material (3.SM.3.2 and 3.SM.3.3).

In terrestrial ecosystems (feeding into RFC1 and RFC4), detection and attribution studies show that impacts of climate change on terrestrial ecosystems began to take place over the past few decades, indicating a transition from no risk (white areas in Figure 3.20) to moderate risk below recent temperatures (*high confidence*) (Section 3.4.3). Risks to unique and threatened terrestrial ecosystems are generally projected to be higher under warming of 2°C compared to 1.5°C (Section 3.5.2.1), while at the global scale severe and widespread risks are projected to occur by 2°C of warming. These risks are associated with biome shifts and species range losses (Sections 3.4.3 and 3.5.2.4); however, because many systems and species are projected to be unable to adapt to levels of warming below 2°C, the transition to high risk (red areas in Figure 3.20) is located below 2°C (*high confidence*). With 3°C of warming, however, biome shifts and species range losses are expected to escalate to very high levels, and the systems are projected to have very little capacity to adapt (Figure 3.20) (*high confidence*) (Section 3.4.3).

In the Arctic (related to RFC1), the increased rate of summer sea ice melt was detected and attributed to climate change by the year 2000 (corresponding to warming of 0.7°C), indicating moderate risk. At 1.5°C of warming an ice-free Arctic Ocean is considered *unlikely*, whilst by 2°C of warming it is considered *likely* and this unique ecosystem is projected to be unable to adapt. Hence, a transition from high to very high risk is expected between 1.5°C and 2°C of warming.

For warm-water coral reefs, there is *high confidence* in the transitions between risk levels, especially in the growing impacts in the transition of warming from non-detectable (0.2°C to 0.4°C), and then successively higher levels risk until high and very high levels of risks by 1.2°C (Section 3.4.4 and Box 3.4). This assessment considered the heatwave-related loss of 50% of shallow water corals across hundreds of kilometres of the world's largest continuous coral reef system, the Great Barrier Reef, as well as losses at other sites globally. The major increase in the size and loss of coral reefs over the past three years, plus sequential mass coral bleaching and mortality events on the Great Barrier Reef, (Hoegh-Guldberg, 1999; Hughes et al., 2017b, 2018), have reinforced the scale of climate-change related risks to coral reefs. General assessments of climate-related risks for mangroves prior to this special report concluded that they face greater risks from deforestation and unsustainable coastal development than from climate change (Alongi, 2008; Hoegh-Guldberg et al., 2014; Gattuso et al., 2015). Recent climate-related die-offs (Duke et al., 2017; Lovelock et al., 2017), however, suggest that climate change risks may have been underestimated for mangroves as well, and risks have thus been assessed as undetectable to moderate, with the transition now starting at 1.3°C as opposed to 1.8°C as assessed in 2015 (Gattuso et al., 2015). Risks of impacts related to climate change on small-scale fisheries at low latitudes, many of which are dependent on ecosystems such as coral reefs and mangroves, are moderate today but are expected to reach high levels of risk around 0.9°C–1.1°C (*high confidence*) (Section 3.4.4.10).

The transition from undetectable to moderate risk (related to RFCs 3 and 4), shown as white to yellow in Figure 3.20, is based on AR5 WGII Chapter 7, which indicated with *high confidence* that climate change impacts on crop yields have been detected and attributed to climate change, and the current assessment has provided further evidence to confirm this (Section 3.4.6). Impacts have been detected in the tropics (AR5 WGII Chapters 7 and 18), and regional risks are projected to become high in some regions by 1.5°C of warming, and in many regions by 2.5°C, indicating a transition from moderate to high risk between 1.5°C and 2.5°C of warming (*medium confidence*).

Impacts from fluvial flooding (related to RFCs 2, 3 and 4) depend on the frequency and intensity of the events, as well as the extent of exposure and vulnerability of society (i.e., socio-economic conditions and the effect of non-climate stressors). Moderate risks posed by 1.5°C of warming are expected to continue to increase with higher

levels of warming (Sections 3.3.5 and 3.4.2), with projected risks being threefold the current risk in economic damages due to flooding in 19 countries for warming of 2°C, indicating a transition to high risk at this level (*medium confidence*). Because few studies have assessed the potential to adapt to these risks, there was insufficient evidence to locate a transition to very high risk (purple).

Climate-change induced sea level rise (SLR) and associated coastal flooding (related to RFCs 2, 3 and 4) have been detectable and attributable since approximately 1970 (Slangen et al., 2016), during which time temperatures have risen by 0.3°C (*medium confidence*) (Section 3.3.9). Analysis suggests that impacts could be more widespread in sensitive systems such as small islands (*high confidence*) (Section 3.4.5.3) and increasingly widespread by the 2070s (Brown et al., 2018a) as temperatures rise from 1.5°C to 2°C, even when adaptation measures are considered, suggesting a transition to high risk (Section 3.4.5). With 2.5°C of warming, adaptation limits are expected to be exceeded in sensitive areas, and hence a transition to very high risk is projected. Additionally, at this temperature, sea level rise could have adverse effects for centuries, posing significant risk to low-lying areas (*high confidence*) (Sections 3.4.5.7 and 3.5.2.5).

For heat-related morbidity and mortality (related to RFCs 2, 3 and 4), detection and attribution studies show heat-related mortality in some locations increasing with climate change (*high confidence*) (Section 3.4.7; Ebi et al., 2017). The projected risks of heat-related morbidity and mortality are generally higher under warming of 2°C than 1.5°C (*high confidence*), with projections of greater exposure to high ambient temperatures and increased morbidity and mortality (Section 3.4.7). Risk levels will depend on the rate of warming and the (related) level of adaptation, so a transition in risk from moderate (yellow) to high (red) is located between 1°C and 3°C (*medium confidence*).

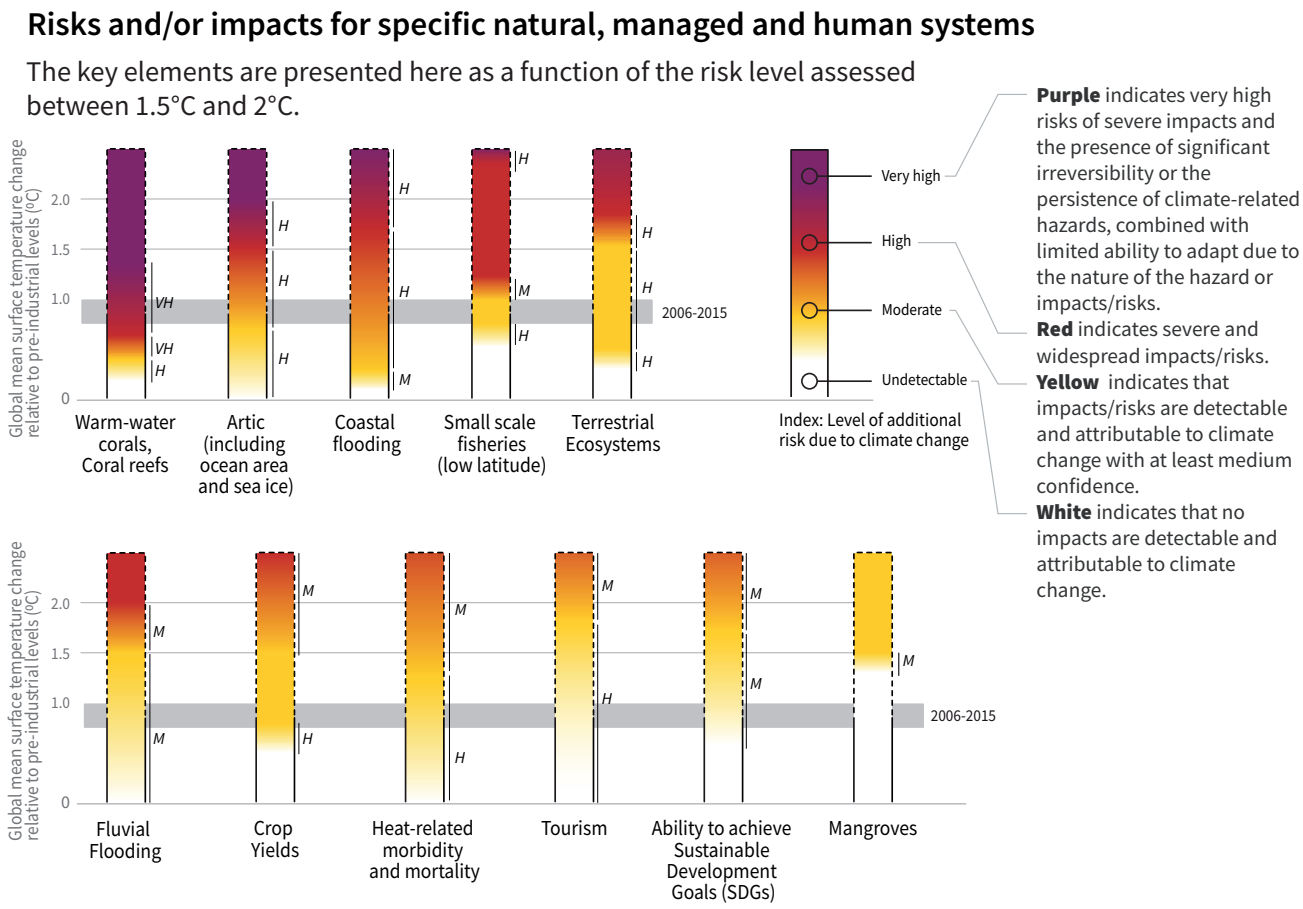

Figure 3.20 | The dependence of risks and/or impacts associated with selected elements of human and natural systems on the level of climate change, adapted from Figure 3.21 and from AR5 WGII Chapter 19, Figure 19.4, and highlighting the nature of this dependence between 0°C and 2°C warming above pre-industrial levels. The selection of impacts and risks to natural, managed and human systems is illustrative and is not intended to be fully comprehensive. Following the approach used in AR5, literature was used to make expert judgements to assess the levels of global warming at which levels of impact and/or risk are undetectable (white), moderate (yellow), high (red) or very high (purple). The colour scheme thus indicates the additional risks due to climate change. The transition from red to purple, introduced for the first time in AR4, is defined by a very high risk of severe impacts and the presence of significant irreversibility or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMST. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation independently of development pathway. The levels of risk illustrated reflect the judgements of the authors of Chapter 3 and Gattuso et al. (2015; for three marine elements). The grey bar represents the range of GMST for the most recent decade: 2006–2015.

For tourism (related to RFCs 3 and 4), changing weather patterns, extreme weather and climate events, and sea level rise are affecting many – but not all – global tourism investments, as well as environmental and cultural destination assets (Section 3.4.4.12), with 'last chance to see' tourism markets developing based on observed impacts on environmental and cultural heritage (Section 3.4.9.1), indicating a transition from undetectable to moderate risk between 0°C and 1.5°C of warming (*high confidence*). Based on limited analyses, risks to the tourism sector are projected to be larger at 2°C than at 1.5°C, with impacts on climate-sensitive sun, beach and snow sports tourism markets being greatest. The degradation or loss of coral reef systems is expected to increase the risks to coastal tourism in subtropical and tropical regions. A transition in risk from moderate to high levels of added risk from climate change is projcted to occur between 1.5°C and 3°C (*medium confidence*).

Climate change is already having large scale impacts on ecosystems, human health and agriculture, which is making it much more difficult to reach goals to eradicate poverty and hunger, and to protect health and life on land (Sections 5.1 and 5.2.1 in Chapter 5), suggesting a transition from undetectable to moderate risk for recent temperatures at 0.5°C of warming (*medium confidence*). Based on the limited analyses available, there is evidence and agreement that the risks to sustainable development are considerably less at 1.5°C than 2°C (Section 5.2.2), including impacts on poverty and food security. It is easier to achieve many of the sustainable development goals (SDGs) at 1.5°C, suggesting that a transition to higher risk will not begin yet at this level. At 2°C and higher levels of warming (e.g., RCP8.5), however, there are high risks of failure to meet SDGs such as eradicating poverty and hunger, providing safe water, reducing inequality and protecting ecosystems, and these risks are projected to become severe and widespread if warming increases further to about 3°C (*medium confidence*) (Section 5.2.3).

Disclosure statement: The selection of elements depicted in Figures 3.18 and 3.20 is not intended to be fully comprehensive and does not necessarily include all elements for which there is a substantive body of literature, nor does it necessarily include all elements which are of particular interest to decision-makers.

3.5 Avoided Impacts and Reduced Risks at 1.5°C Compared with 2°C of Global Warming

3.5.1 Introduction

Oppenheimer et al. (2014, AR5 WGII Chapter 19) provided a framework that aggregates projected risks from global mean temperature change into five categories identified as 'Reasons for Concern'. Risks are classified as moderate, high or very high and coloured yellow, red or purple, respectively, in Figure 19.4 of that chapter (AR5 WGII Chapter 19 for details and findings). The framework's conceptual basis and the risk judgements made by Oppenheimer et al. (2014) were recently reviewed, and most judgements were confirmed in the light of more recent literature (O'Neill et al., 2017). The approach of Oppenheimer et al. (2014) was adopted, with updates to the aggregation of risk informed by the most recent literature, for the analysis of avoided impacts at 1.5°C compared to 2°C of global warming presented in this section.

The regional economic benefits that could be obtained by limiting the global temperature increase to 1.5°C of warming, rather than 2°C or higher levels, are discussed in Section 3.5.3 in the light of the five RFCs explored in Section 3.5.2. Climate change hotspots that could be avoided or reduced by achieving the 1.5°C target are summarized in Section 3.5.4. The section concludes with a discussion of regional tipping points that could be avoided at 1.5°C compared to higher degrees of global warming (Section 3.5.5).

3.5.2 Aggregated Avoided Impacts and Reduced Risks at 1.5°C versus 2°C of Global Warming

A brief summary of the accrual of RFCs with global warming, as assessed in WGII AR5, is provided in the following sections, which leads into an update of relevant literature published since AR5. The new literature is used to confirm the levels of global warming at which risks are considered to increase from undetectable to moderate, from moderate to high, and from high to very high. Figure 3.21 modifies Figure 19.4 from AR5 WGII, and the following text in this subsection provides justification for the modifications. O'Neill et al. (2017) presented a very similar assessment to that of WGII AR5, but with further discussion of the potential to create 'embers' specific to socio-economic scenarios in the future. There is insufficient literature to do this at present, so the original, simple approach has been used here. As the focus of the present assessment is on the consequences of global warming of 1.5°C–2°C above the pre-industrial period, no assessment for global warming of 3°C or more is included in the figure (i.e., analysis is discontinued at 2.5°C).

3.5.2.1 RFC 1 – Unique and threatened systems

WGII AR5 Chapter 19 found that some unique and threatened systems are at risk from climate change at current temperatures, with increasing numbers of systems at potential risk of severe consequences at global warming of 1.6°C above pre-industrial levels. It was also observed that many species and ecosystems have a limited ability to adapt to the very large risks associated with warming of 2.6°C or more, particularly Arctic sea ice and coral reef systems (*high confidence*). In the AR5 analysis, a transition from white to yellow indicated that the onset of moderate risk was located below present-day global temperatures (*medium confidence*); a transition from yellow to red indicated that the onset of high risk was located at 1.6°C, and a transition from red to purple indicated that the onset of very high risk was located at about 2.6°C. This WGII AR5 analysis already implied that there would be a significant reduction in risks to unique and threatened systems if warming were limited to 1.5°C compared with 2°C. Since AR5, evidence of present-day impacts in these systems has continued to grow (Sections 3.4.2, 3.4.4 and 3.4.5), whilst new evidence has also accumulated for reduced risks at 1.5°C compared to 2°C of warming in Arctic ecosystems (Section 3.3.9), coral reefs (Section 3.4.4) and some other unique ecosystems (Section 3.4.3), as well as for biodiversity.

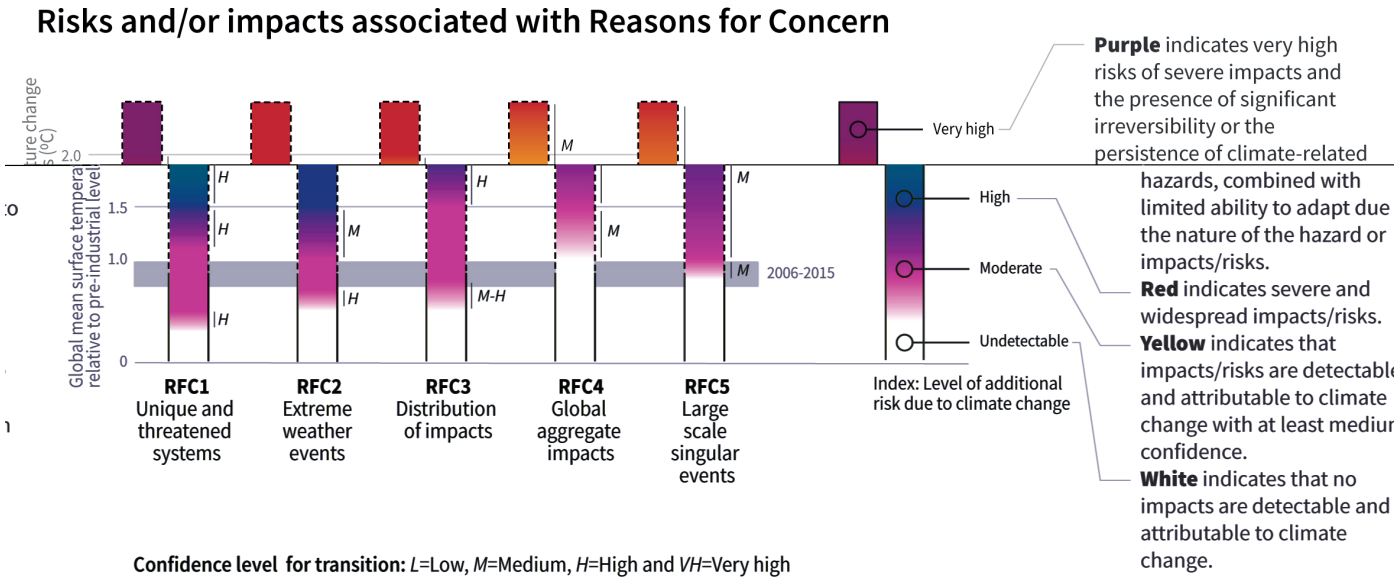

Figure 3.21 | The dependence of risks and/or impacts associated with the Reasons for Concern (RFCs) on the level of climate change, updated and adapted from WGII AR5 Ch 19, Figure 19.4 and highlighting the nature of this dependence between 0°C and 2°C warming above pre-industrial levels. As in the AR5, literature was used to make expert judgements to assess the levels of global warming at which levels of impact and/or risk are undetectable (white), moderate (yellow), high (red) or very high (purple). The colour scheme thus indicates the additional risks due to climate change. The transition from red to purple, introduced for the first time in AR4, is defined by very high risk of severe impacts and the presence of significant irreversibility, or persistence of climate-related hazards combined with a limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMST. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation (RFC 1, 3, 5) independently of development pathway. The rate and timing of impacts were taken into account in assessing RFC 1 and 5. The levels of risk illustrated reflect the judgements of the Ch 3 authors. **RFC1 Unique and threatened systems:** ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots. **RFC2 Extreme weather events:** risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. **RFC3 Distribution of impacts:** risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. **RFC4 Global aggregate impacts:** global monetary damage, global scale degradation and loss of ecosystems and biodiversity. **RFC5 Large-scale singular events:** are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets. The grey bar represents the range of GMST for the most recent decade: 2006–2015.

New literature since AR5 has provided a closer focus on the comparative levels of risk to coral reefs at 1.5°C versus 2°C of global warming. As assessed in Section 3.4.4 and Box 3.4, reaching 2°C will increase the frequency of mass coral bleaching and mortality to a point at which it will result in the total loss of coral reefs from the world's tropical and subtropical regions. Restricting overall warming to 1.5°C will still see a downward trend in average coral cover (70–90% decline by mid-century) but will prevent the total loss of coral reefs projected with warming of 2°C (Frieler et al., 2013). The remaining reefs at 1.5°C will also benefit from increasingly stable ocean conditions by the mid-to-late 21st century. Limiting global warming to 1.5°C during the course of the century may, therefore, open the window for many ecosystems to adapt or reassort geographically. This indicates a transition in risk in this system from high to very high (*high confidence*) at 1.5°C of warming and contributes to a lowering of the transition from high to very high (Figure 3.21) in this RFC1 compared to in AR5. Further details of risk transitions for ocean systems are described in Figure 3.18.

Substantial losses of Arctic Ocean summer ice were projected in WGI AR5 for global warming of 1.6°C, with a nearly ice-free Arctic Ocean being projected for global warming of more than 2.6°C. Since AR5, the importance of a threshold between 1°C and 2°C has been further emphasized in the literature, with sea ice projected to persist throughout the year for a global warming of less than 1.5°C, yet chances of an ice-free Arctic during summer being high at 2°C of warming (Section 3.3.8). Less of the permafrost in the Arctic is projected to thaw under 1.5°C of warming (17–44%) compared with under 2°C (28–53%) (Section 3.3.5.2; Chadburn et al., 2017), which is expected to reduce risks to both social and ecological systems in the Arctic. This indicates a transition in the risk in this system from high to very high between 1.5°C and 2°C of warming and contributes to a lowering of the transition from high to very high in this RFC1 compared to in AR5.

AR5 identified a large number of threatened systems, including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems. These include Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succulent Karoo areas of South Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, impacts accrue with greater warming and impacts at 2°C are expected to be greater than those at 1.5°C (*medium confidence*). One study since AR5 has shown that constraining global warming to 1.5°C would maintain the functioning of prairie pothole ecosystems in North America in terms of their productivity and biodiversity, whilst warming of 2°C would not do so (Johnson et al., 2016). The large proportion of insects projected to lose over half their range at 2°C of warming (25%) compared to at 1.5°C (9%) also suggests a significant loss of functionality in these threatened systems at 2°C of warming,

owing to the critical role of insects in nutrient cycling, pollination, detritivory and other important ecosystem processes (Section 3.4.3).

Unique and threatened systems in small island states and in systems fed by glacier meltwater were also considered to contribute to this RFC in AR5, but there is little new information about these systems that pertains to 1.5°C or 2°C of global warming. Taken together, the evidence suggests that the transition from high to very high risk in unique and threatened systems occurs at a lower level of warming, between 1.5°C and 2°C (*high confidence*), than in AR5, where this transition was located at 2.6°C. The transition from moderate to high risk relocates very slightly from 1.6°C to 1.5°C (*high confidence*). There is also *high confidence* in the location of the transition from low to moderate risk below present-day global temperatures.

3.5.2.2 RFC 2 – Extreme weather events

Reduced risks in terms of the likelihood of occurrence of extreme weather events are discussed in this sub-subsection for 1.5°C as compared to 2°C of global warming, for those extreme events where evidence is currently available based on the assessments of Section 3.3. AR5 assigned a moderate level of risk from extreme weather events at recent temperatures (1986–2005) owing to the attribution of heat and precipitation extremes to climate change, and a transition to high risk beginning below 1.6°C of global warming based on the magnitude, likelihood and timing of projected changes in risk associated with extreme events, indicating more severe and widespread impacts. The AR5 analysis already suggested a significant benefit of limiting warming to 1.5°C, as doing so might keep risks closer to the moderate level. New literature since AR5 has provided greater confidence in a reduced level of risks due to extreme weather events at 1.5°C versus 2°C of warming for some types of extremes (Section 3.3 and below; Figure 3.21).

Temperature: It is expected that further increases in the number of warm days/nights and decreases in the number of cold days/nights, and an increase in the overall temperature of hot and cold extremes would occur under 1.5°C of global warming relative to pre-industrial levels (*high confidence*) compared to under the present-day climate (1°C of warming), with further changes occurring towards 2°C of global warming (Section 3.3). As assessed in Sections 3.3.1 and 3.3.2, impacts of 0.5°C of global warming can be identified for temperature extremes at global scales, based on observations and the analysis of climate models. At 2°C of global warming, it is *likely* that temperature increases of more than 2°C would occur over most land regions in terms of extreme temperatures (up to 4°C–6°C depending on region and considered extreme index) (Section 3.3.2, Table 3.2). Regional increases in temperature extremes can be robustly limited if global warming is constrained to 1.5°C, with regional warmings of up to 3°C–4.5°C (Section 3.3.2, Table 3.2). Benefits obtained from this general reduction in extremes depend to a large extent on whether the lower range of increases in extremes at 1.5°C is sufficient for critical thresholds to be exceeded, within the context of wide-ranging aspects such as crop yields, human health and the sustainability of ecosystems.

Heavy precipitation: AR5 assessed trends in heavy precipitation for land regions where observational coverage was sufficient for assessment. It concluded with *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century, for a global warming of approximately 0.5°C (Section 3.3.3). A recent observation-based study likewise showed that a 0.5°C increase in global mean temperature has had a detectable effect on changes in precipitation extremes at the global scale (Schleussner et al., 2017), thus suggesting that there would be detectable differences in heavy precipitation at 1.5°C and 2°C of global warming. These results are consistent with analyses of climate projections, although they also highlight a large amount of regional variation in the sensitivity of changes in heavy precipitation (Section 3.3.3).

Droughts: When considering the difference between precipitation and evaporation (P–E) as a function of global temperature changes, the subtropics generally display an overall trend towards drying, whilst the northern high latitudes display a robust response towards increased wetting (Section 3.3.4, Figure 3.12). Limiting global mean temperature increase to 1.5°C as opposed to 2°C could substantially reduce the risk of reduced regional water availability in some regions (Section 3.3.4). Regions that are projected to benefit most robustly from restricted warming include the Mediterranean and southern Africa (Section 3.3.4).

Fire: Increasing evidence that anthropogenic climate change has already caused significant increases in fire area globally (Section 3.4.3) is in line with projected fire risks. These risks are projected to increase further under 1.5°C of global warming relative to the present day (Section 3.4.3). Under 1.2°C of global warming, fire frequency has been estimated to increase by over 37.8% of global land areas, compared to 61.9% of global land areas under 3.5°C of warming. For in-depth discussion and uncertainty estimates, see Meehl et al. (2007), Moritz et al. (2012) and Romero-Lankao et al. (2014).

Regarding extreme weather events (RFC2), the transition from moderate to high risk is located between 1°C and 1.5°C of global warming (Figure 3.21), which is very similar to the AR5 assessment but is assessed with greater confidence (*medium confidence*). The impact literature contains little information about the potential for human society to adapt to extreme weather events, and hence it has not been possible to locate the transition from high to very high risk within the context of assessing impacts at 1.5°C and 2°C of global warming. There is thus *low confidence* in the level at which global warming could lead to very high risks associated with extreme weather events in the context of this report.

3.5.2.3 RFC 3 – Distribution of impacts

Risks due to climatic change are unevenly distributed and are generally greater at lower latitudes and for disadvantaged people and communities in countries at all levels of development. AR5 located the transition from undetectable to moderate risk below recent temperatures, owing to the detection and attribution of regionally differentiated changes in crop yields (*medium to high confidence*; Figure 3.20), and new literature has continued to confirm this finding. Based on the assessment of risks to regional crop production and water resources, AR5 located the transition from moderate to high risk

between 1.6°C and 2.6°C above pre-industrial levels. Cross-Chapter Box 6 in this chapter highlights that at 2°C of warming, new literature shows that risks of food shortage are projected to emerge in the African Sahel, the Mediterranean, central Europe, the Amazon, and western and southern Africa, and that these are much larger than the corresponding risks at 1.5°C. This suggests a transition from moderate to high risk of regionally differentiated impacts between 1.5°C and 2°C above pre-industrial levels for food security (*medium confidence*) (Figure 3.20). Reduction in the availability of water resources at 2°C is projected to be greater than 1.5°C of global warming, although changes in socio-economics could have a greater influence (Section 3.4.2), with larger risks in the Mediterranean (Box 3.2); estimates of the magnitude of the risks remain similar to those cited in AR5. Globally, millions of people may be at risk from sea level rise (SLR) during the 21st century (Hinkel et al., 2014; Hauer et al., 2016), particularly if adaptation is limited. At 2°C of warming, more than 90% of global coastlines are projected to experience SLR greater than 0.2 m, suggesting regional differences in the risks of coastal flooding. Regionally differentiated multi-sector risks are already apparent at 1.5°C of warming, being more prevalent where vulnerable people live, predominantly in South Asia (mostly Pakistan, India and China), but these risks are projected to spread to sub-Saharan Africa, the Middle East and East Asia as temperature rises, with the world's poorest people disproportionately impacted at 2°C of warming (Byers et al., 2018). The hydrological impacts of climate change in Europe are projected to increase in spatial extent and intensity across increasing global warming levels of 1.5°C, 2°C and 3°C (Donnelly et al., 2017). Taken together, a transition from moderate to high risk is now located between 1.5°C and 2°C above pre-industrial levels, based on the assessment of risks to food security, water resources, drought, heat exposure and coastal submergence (*high confidence*; Figure 3.21).

3.5.2.4 RFC 4 – Global aggregate impacts

Oppenheimer et al. (2014) explained the inclusion of non-economic metrics related to impacts on ecosystems and species at the global level, in addition to economic metrics in global aggregate impacts. The degradation of ecosystem services by climate change and ocean acidification have generally been excluded from previous global aggregate economic analyses.

Global economic impacts: WGII AR5 found that overall global aggregate impacts become moderate at 1°C–2°C of warming, and the transition to moderate risk levels was therefore located at 1.6°C above pre-industrial levels. This was based on the assessment of literature using model simulations which indicated that the global aggregate economic impact will become significantly negative between 1°C and 2°C of warming (*medium confidence*), whilst there will be a further increase in the magnitude and likelihood of aggregate economic risks at 3°C of warming (*low confidence*).

Since AR5, three studies have emerged using two entirely different approaches which indicate that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5°C. The study by Warren et al. (2018c) used the integrated assessment model PAGE09 to estimate that avoided global economic damages of 22% (10–26%) accrue from constraining warming to 1.5°C rather than 2°C, 90% (77–93%) from 1.5°C rather than 3.66°C, and 87% (74–91%) from 2°C rather than 3.66°C. In the second study, Pretis et al. (2018) identified several regions where economic damages are projected to be greater at 2°C compared to 1.5°C of warming, further estimating that projected damages at 1.5°C remain similar to today's levels of economic damage. The third study, by M. Burke et al. (2018) used an empirical, statistical approach and found that limiting warming to 1.5°C instead of 2°C would save 1.5–2.0% of the gross world product (GWP) by mid-century and 3.5% of the GWP by end-of-century (see Figure 2A in M. Burke et al., 2018). Based on a 3% discount rate, this corresponds to 8.1–11.6 trillion USD and 38.5 trillion USD in avoided damages by mid- and end-of-century, respectively, agreeing closely with the estimate by Warren et al. (2018c) of 15 trillion USD. Under the no-policy baseline scenario, temperature rises by 3.66°C by 2100, resulting in a global gross domestic product (GDP) loss of 2.6% (5–95% percentile range 0.5–8.2%), compared with 0.3% (0.1–0.5%) by 2100 under the 1.5°C scenario and 0.5% (0.1–1.0%) in the 2°C scenario. Limiting warming to 1.5°C rather than 2°C by 2060 has also been estimated to result in co-benefits of 0.5–0.6% of the world GDP, owing to reductions in air pollution (Shindell et al., 2018), which is similar to the avoided damages identified for the USA (Box 3.6).

Two studies focusing only on the USA found that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5°C. Hsiang et al. (2017) found a mean difference of 0.35% GDP (range 0.2–0.65%), while Yohe (2017) identified a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree. Further, the avoided risks compared to a no-policy baseline are greater in the 1.5°C case (4%, range 2–7%) compared to the 2°C case (3.5%, range 1.8–6.5%). These analyses suggest that the point at which global aggregates of economic impacts become negative is below 2°C (*medium confidence*), and that there is a possibility that it is below 1.5°C of warming.

Oppenheimer et al. (2014) noted that the global aggregated damages associated with large-scale singular events has not been explored, and reviews of integrated modelling exercises have indicated a potential underestimation of global aggregate damages due to the lack of consideration of the potential for these events in many studies. Since AR5, further analyses of the potential economic consequences of triggering these large-scale singular events have indicated a two to eight fold larger economic impact associated with warming of 3°C than estimated in most previous analyses, with the extent of increase depending on the number of events incorporated. Lemoine and Traeger (2016) included only three known singular events whereas Y. Cai et al. (2016) included five.

Biome shifts, species range loss, increased risks of species extinction and risks of loss of ecosystem functioning and services: 13% (range 8–20%) of Earth's land area is projected to undergo biome shifts at 2°C of warming compared to approximately 7% at 1.5°C (*medium confidence*) (Section 3.4.3; Warszawski et al., 2013), implying a halving of biome transformations. Overall levels of species loss at 2°C of warming are similar to values found in previous studies for plants and vertebrates (Warren et al., 2013, 2018a), but insects have been found to be more sensitive to climate change, with 18% (6–35%) projected to lose over half their range at 2°C of warming

compared to 6% (1–18%) under 1.5°C of warming, corresponding to a difference of 66% (Section 3.4.3). The critical role of insects in ecosystem functioning therefore suggests that there will be impacts on global ecosystem functioning already at 2°C of warming, whilst species that lose large proportions of their range are considered to be at increased risk of extinction (Section 3.4.3.3). Since AR5, new literature has indicated that impacts on marine fish stocks and fisheries are lower under 1.5°C–2°C of global warming relative to pre-industrial levels compared to under higher warming scenarios (Section 3.4.6), especially in tropical and polar systems.

In AR5, the transition from undetectable to moderate impacts was considered to occur between 1.6°C and 2.6°C of global warming reflecting impacts on the economy and on biodiversity globally, whereas high risks were associated with 3.6°C of warming to reflect the high risks to biodiversity and accelerated effects on the global economy. New evidence suggests moderate impacts on the global aggregate economy and global biodiversity by 1.5°C of warming, suggesting a lowering of the temperature level for the transition to moderate risk to 1.5°C (Figure 3.21). Further, recent literature points to higher risks than previously assessed for the global aggregate economy and global biodiversity by 2°C of global warming, suggesting that the transition to a high risk level is located between 1.5°C and 2.5°C of warming (Figure 3.21), as opposed to at 3.6°C as previously assessed (*medium confidence*).

3.5.2.5 RFC 5 – Large-scale singular events

Large-scale singular events are components of the global Earth system that are thought to hold the risk of reaching critical tipping points under climate change, and that can result in or be associated with major shifts in the climate system. These components include:

- the cryosphere: West Antarctic ice sheet, Greenland ice sheet
- the thermohaline circulation: slowdown of the Atlantic Meridional Overturning Circulation (AMOC)
- the El Niño–Southern Oscillation (ENSO) as a global mode of climate variability
- role of the Southern Ocean in the global carbon cycle

AR5 assessed that the risks associated with these events become moderate between 0.6°C and 1.6°C above pre-industrial levels, based on early warning signs, and that risk was expected to become high between 1.6°C and 4.6°C based on the potential for commitment to large irreversible sea level rise from the melting of land-based ice sheets (*low to medium confidence*). The increase in risk between 1.6°C and 2.6°C above pre-industrial levels was assessed to be disproportionately large. New findings since AR5 are described in detail below.

Greenland and West Antarctic ice sheets and marine ice sheet instability (MISI): Various feedbacks between the Greenland ice sheet and the wider climate system, most notably those related to the dependence of ice melt on albedo and surface elevation, make irreversible loss of the ice sheet a possibility. Church et al. (2013) assessed this threshold to be at 2°C of warming or higher levels relative to pre-industrial temperature. Robinson et al. (2012) found a range for this threshold of 0.8°C–3.2°C (95% confidence). The threshold of global temperature increase that may initiate irreversible loss of the West Antarctic ice sheet and marine ice sheet instability (MISI) is estimated to lie be between 1.5°C and 2°C. The time scale for eventual loss of the ice sheets varies between millennia and tens of millennia and assumes constant surface temperature forcing during this period. If temperature were to decline subsequently the ice sheets might regrow, although the amount of cooling required is likely to be highly dependent on the duration and rate of the previous retreat. The magnitude of global sea level rise that could occur over the next two centuries under 1.5°C–2°C of global warming is estimated to be in the order of several tenths of a metre according to most studies (*low confidence*) (Schewe et al., 2011; Church et al., 2013; Levermann et al., 2014; Marzeion and Levermann, 2014; Fürst et al., 2015; Golledge et al., 2015), although a smaller number of investigations (Joughin et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016) project increases of 1–2 m. This body of evidence suggests that the temperature range of 1.5°C–2°C may be regarded as representing moderate risk, in that it may trigger MISI in Antarctica or irreversible loss of the Greenland ice sheet and it may be associated with sea level rise by as much as 1–2 m over a period of two centuries.

Thermohaline circulation (slowdown of AMOC): It is *more likely than not* that the AMOC has been weakening in recent decades, given the detection of cooling of surface waters in the North Atlantic and evidence that the Gulf Stream has slowed since the late 1950s (Rahmstorf et al., 2015b; Srokosz and Bryden, 2015; Caesar et al., 2018). There is limited evidence linking the recent weakening of the AMOC to anthropogenic warming (Caesar et al., 2018). It is *very likely* that the AMOC will weaken over the 21st century. Best estimates and ranges for the reduction based on CMIP5 simulations are 11% (1–24%) in RCP2.6 and 34% (12–54%) in RCP8.5 (AR5). There is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5°C versus 2°C of global warming, or of a shutdown of the AMOC at these global temperature thresholds. Associated risks are classified as low to moderate.

El Niño–Southern Oscillation (ENSO): Extreme El Niño events are associated with significant warming of the usually cold eastern Pacific Ocean, and they occur about once every 20 years (Cai et al., 2015). Such events reorganize the distribution of regions of organized convection and affect weather patterns across the globe. Recent research indicates that the frequency of extreme El Niño events increases linearly with the global mean temperature, and that the number of such events might double (one event every ten years) under 1.5°C of global warming (G. Wang et al., 2017). This pattern is projected to persist for a century after stabilization at 1.5°C, thereby challenging the limits to adaptation, and thus indicates high risk even at the 1.5°C threshold. La Niña event (the opposite or balancing event to El Niño) frequency is projected to remain similar to that of the present day under 1.5°C–2°C of global warming.

Role of the Southern Ocean in the global carbon cycle: The critical role of the Southern Ocean as a net sink of carbon might decline under global warming, and assessing this effect under 1.5°C compared to 2°C of global warming is a priority. Changes in ocean chemistry (e.g., oxygen content and ocean acidification), especially those associated with the deep sea, are associated concerns (Section 3.3.10).

For large-scale singular events (RFC5), moderate risk is now located at 1°C of warming and high risk is located at 2.5°C (Figure 3.21), as opposed to at 1.6°C (moderate risk) and around 4°C (high risk) in AR5, because of new observations and models of the West Antarctic ice sheet (*medium confidence*), which suggests that the ice sheet may be in the early stages of marine ice sheet instability (MISI). Very high risk is assessed as lying above 5°C because the growing literature on process-based projections of the West Antarctic ice sheet predominantly supports the AR5 assessment of an MISI contribution of several additional tenths of a metre by 2100.

3.5.3 Regional Economic Benefit Analysis for the 1.5°C versus 2°C Global Goals

This section reviews recent literature that has estimated the economic benefits of constraining global warming to 1.5°C compared to 2°C. The focus here is on evidence pertaining to specific regions, rather than on global aggregated benefits (Section 3.5.2.4). At 2°C of global warming, lower economic growth is projected for many countries than at 1.5°C of global warming, with low-income countries projected to experience the greatest losses (*low to medium confidence*) (M. Burke et al., 2018; Pretis et al., 2018). A critical issue for developing countries in particular is that advantages in some sectors are projected to be offset by increasing mitigation costs (Rogelj et al., 2013; M. Burke et al., 2018), with food production being a key factor. That is, although restraining the global temperature increase to 2°C is projected to reduce crop losses under climate change relative to higher levels of warming, the associated mitigation costs may increase the risk of hunger in low-income countries (*low confidence*) (Hasegawa et al., 2016). It is *likely* that the even more stringent mitigation measures required to restrict global warming to 1.5°C (Rogelj et al., 2013) will further increase these mitigation costs and impacts. International trade in food might be a key response measure for alleviating hunger in developing countries under 1.5°C and 2°C stabilization scenarios (IFPRI, 2018).

Although warming is projected to be the highest in the Northern Hemisphere under 1.5°C or 2°C of global warming, regions in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth (*low to medium confidence*) (Gallup et al., 1999; M. Burke et al., 2018; Pretis et al., 2018). Despite the uncertainties associated with climate change projections and econometrics (e.g., M. Burke et al., 2018), it is *more likely than not* that there will be large differences in economic growth under 1.5°C and 2°C of global warming for developing versus developed countries (M. Burke et al., 2018; Pretis et al., 2018). Statistically significant reductions in gross domestic product (GDP) per capita growth are projected across much of the African continent, Southeast Asia, India, Brazil and Mexico (*low to medium confidence*). Countries in the western parts of tropical Africa are projected to benefit most from restricting global warming to 1.5°C, as opposed to 2°C, in terms of future economic growth (Pretis et al., 2018). An important reason why developed countries in the tropics and subtropics are projected to benefit substantially from restricting global warming to 1.5°C is that present-day temperatures in these regions are above the threshold thought to be optimal for economic production (M. Burke et al., 2015b, 2018).

The world's largest economies are also projected to benefit from restricting warming to 1.5°C as opposed to 2°C (*medium confidence*), with the likelihood of such benefits being realized estimated at 76%, 85% and 81% for the USA, China and Japan, respectively (M. Burke et al., 2018). Two studies focusing only on the USA found that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5°C. Yohe (2017) found a mean difference of 0.35% GDP (range 0.2–0.65%), while Hsiang et al. (2017) identified a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree. Overall, no statistically significant changes in GDP are projected to occur over most of the developed world under 1.5°C of global warming in comparison to present-day conditions, but under 2°C of global warming impacts on GDP are projected to be generally negative (*low confidence*) (Pretis et al., 2018).

A caveat to the analyses of Pretis et al. (2018) and M. Burke et al. (2018) is that the effects of sea level rise were not included in the estimations of damages or future economic growth, implying a potential underestimation of the benefits of limiting warming to 1.5°C for the case where significant sea level rise is avoided at 1.5°C but not at 2°C.

3.5.4 Reducing Hotspots of Change for 1.5°C and 2°C of Global Warming

This subsection integrates Sections 3.3 and 3.4 in terms of climate-change-induced hotspots that occur through interactions across the physical climate system, ecosystems and socio-economic human systems, with a focus on the extent to which risks can be avoided or reduced by achieving the 1.5°C global warming goal (as opposed to the 2°C goal). Findings are summarized in Table 3.6.

3.5.4.1 Arctic sea ice

Ice-free Arctic Ocean summers are *very likely* at levels of global warming higher than 2°C (Notz and Stroeve, 2016; Rosenblum and Eisenman, 2016; Screen and Williamson, 2017; Niederdrenk and Notz, 2018). Some studies even indicate that the entire Arctic Ocean summer period will become ice free under 2°C of global warming, whilst others more conservatively estimate this probability to be in the order of 50% (Section 3.3.8; Sanderson et al., 2017). The probability of an ice-free Arctic in September at 1.5°C of global warming is low and substantially lower than for the case of 2°C of global warming (*high confidence*) (Section 3.3.8; Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018). There is, however, a single study that questions the validity of the 1.5°C threshold in terms of maintaining summer Arctic Ocean sea ice (Niederdrenk and Notz, 2018). In contrast to summer, little ice is projected to be lost during winter for either 1.5°C or 2°C of global warming (*medium confidence*) (Niederdrenk and Notz, 2018). The losses in sea ice at 1.5°C and 2°C of warming will result in habitat losses for organisms such as seals, polar bears, whales and sea birds (e.g., Larsen et al., 2014). There is *high agreement and robust evidence* that photosynthetic species will change because of sea ice retreat and related changes in temperature and radiation (Section 3.4.4.7), and this is *very likely* to benefit fisheries productivity in the Northern Hemisphere spring bloom system (Section 3.4.4.7).

3.5.4.2 Arctic land regions

In some Arctic land regions, the warming of cold extremes and the increase in annual minimum temperature at 1.5°C are stronger than the global mean temperature increase by a factor of two to three, meaning 3°C–4.5°C of regional warming at 1.5°C of global warming (e.g., northern Europe in Supplementary Material 3.SM, Figure 3.SM.5 see also Section 3.3.2.2 and Seneviratne et al., 2016). Moreover, over much of the Arctic, a further increase of 0.5°C in the global surface temperature, from 1.5°C to 2°C, may lead to further temperature increases of 2°C–2.5°C (Figure 3.3). As a consequence, biome (major ecosystem type) shifts are *likely* in the Arctic, with increases in fire frequency, degradation of permafrost, and tree cover *likely* to occur at 1.5°C of warming and further amplification of these changes expected under 2°C of global warming (e.g., Gerten et al., 2013; Bring et al., 2016). Rising temperatures, thawing permafrost and changing weather patterns are projected to increasingly impact people, infrastructure and industries in the Arctic (W.N. Meier et al., 2014) with these impacts larger at 2°C than at 1.5°C of warming (*medium confidence*).

3.5.4.3 Alpine regions

Alpine regions are generally regarded as climate change hotspots given that rich biodiversity has evolved in their cold and harsh climate, but with many species consequently being vulnerable to increases in temperature. Under regional warming, alpine species have been found to migrate upwards on mountain slopes (Reasoner and Tinner, 2009), an adaptation response that is obviously limited by mountain height and habitability. Moreover, many of the world's alpine regions are important from a water security perspective through associated glacier melt, snow melt and river flow (see Section 3.3.5.2 for a discussion of these aspects). Projected biome shifts are *likely* to be severe in alpine regions already at 1.5°C of warming and to increase further at 2°C (Gerten et al., 2013, Figure 1b; B. Chen et al., 2014).

3.5.4.4 Southeast Asia

Southeast Asia is a region highly vulnerable to increased flooding in the context of sea level rise (Arnell et al., 2016; Brown et al., 2016, 2018a). Risks from increased flooding are projected to rise from 1.5°C to 2°C of warming (*medium confidence*), with substantial increases projected beyond 2°C (Arnell et al., 2016). Southeast Asia displays statistically significant differences in projected changes in heavy precipitation, runoff and high flows at 1.5°C versus 2°C of warming, with stronger increases occurring at 2°C (Section 3.3.3; Wartenburger et al., 2017; Döll et al., 2018; Seneviratne et al., 2018c); thus, this region is considered a hotspot in terms of increases in heavy precipitation between these two global temperature levels (*medium confidence*) (Schleussner et al., 2016b; Seneviratne et al., 2016). For Southeast Asia, 2°C of warming by 2040 could lead to a decline by one-third in per capita crop production associated with general decreases in crop yields (Nelson et al., 2010). However, under 1.5°C of warming, significant risks for crop yield reduction in the region are avoided (Schleussner et al., 2016b). These changes pose significant risks for poor people in both rural regions and urban areas of Southeast Asia (Section 3.4.10.1), with these risks being larger at 2°C of global warming compared to 1.5°C (*medium confidence*).

3.5.4.5 Southern Europe and the Mediterranean

The Mediterranean is regarded as a climate change hotspot, both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature increase (e.g., Seneviratne et al., 2016) and in terms of of robust increases in the probability of occurrence of extreme droughts at 2°C vs 1.5°C global warming (Section 3.3.4). Low river flows are projected to decrease in the Mediterranean under 1.5°C of global warming (Marx et al., 2018), with associated significant decreases in high flows and floods (Thober et al., 2018), largely in response to reduced precipitation. The median reduction in annual runoff is projected to almost double from about 9% (*likely* range 4.5–15.5%) at 1.5°C to 17% (*likely* range 8–25%) at 2°C (Schleussner et al., 2016b). Similar results were found by Döll et al. (2018). Overall, there is *high confidence* that strong increases in dryness and decreases in water availability in the Mediterranean and southern Europe would occur from 1.5°C to 2°C of global warming. Sea level rise is expected to be lower for 1.5°C versus 2°C, lowering risks for coastal metropolitan agglomerations. The risks (assuming current adaptation) related to water deficit in the Mediterranean are high for global warming of 2°C but could be substantially reduced if global warming were limited to 1.5°C (Section 3.3.4; Guiot and Cramer, 2016; Schleussner et al., 2016b; Donnelly et al., 2017).

3.5.4.6 West Africa and the Sahel

West Africa and the Sahel are *likely* to experience increases in the number of hot nights and longer and more frequent heatwaves even if the global temperature increase is constrained to 1.5°C, with further increases expected at 2°C of global warming and beyond (e.g., Weber et al., 2018). Moreover, daily rainfall intensity and runoff is expected to increase (*low confidence*) towards 2°C and higher levels of global warming (Schleussner et al., 2016b; Weber et al., 2018), with these changes also being relatively large compared to the projected changes at 1.5°C of warming. Moreover, increased risks are projected in terms of drought, particularly for the pre-monsoon season (Sylla et al., 2015), with both rural and urban populations affected, and more so at 2°C of global warming as opposed to 1.5°C (Liu et al., 2018). Based on a World Bank (2013) study for sub-Saharan Africa, a 1.5°C warming by 2030 might reduce the present maize cropping areas by 40%, rendering these areas no longer suitable for current cultivars. Substantial negative impacts are also projected for sorghum suitability in the western Sahel (Läderach et al., 2013; Sultan and Gaetani, 2016). An increase in warming to 2°C by 2040 would result in further yield losses and damages to crops (i.e., maize, sorghum, wheat, millet, groundnut and cassava). Schleussner et al. (2016b) found consistently reduced impacts on crop yield for West Africa under 2°C compared to 1.5°C of global warming. There is *medium confidence* that vulnerabilities to water and food security in the African Sahel will be higher at 2°C compared to 1.5°C of global warming (Cheung et al., 2016a; Betts et al., 2018), and at 2°C these vulnerabilities are expected to be worse (*high evidence*) (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018). Under global warming of more than 2°C, the western Sahel might experience the strongest drying and experience serious food security issues (Ahmed et al., 2015; Parkes et al., 2018).

3.5.4.7 Southern Africa

The southern African region is projected to be a climate change hotspot in terms of both hot extremes (Figures 3.5 and 3.6) and drying (Figure 3.12). Indeed, temperatures have been rising in the subtropical regions of southern Africa at approximately twice the global rate over the last five decades (Engelbrecht et al., 2015). Associated elevated warming of the regional land-based hot extremes has occurred (Section 3.3; Seneviratne et al., 2016). Increases in the number of hot nights, as well as longer and more frequent heatwaves, are projected even if the global temperature increase is constrained to 1.5°C (*high confidence*), with further increases expected at 2°C of global warming and beyond (*high confidence*) (Weber et al., 2018).

Moreover, southern Africa is *likely* to generally become drier with reduced water availability under low mitigation (Niang et al., 2014; Engelbrecht et al., 2015; Karl et al., 2015; James et al., 2017), with this particular risk being prominent under 2°C of global warming and even under 1.5°C (Gerten et al., 2013). Risks are significantly reduced, however, under 1.5°C of global warming compared to under higher levels (Schleussner et al., 2016b). There are consistent and statistically significant increases in projected risks of increased meteorological drought in southern Africa at 2°C versus 1.5°C of warming (*medium confidence*). Despite the general rainfall reductions projected for southern Africa, daily rainfall intensities are expected to increase over much of the region (*medium confidence*), and increasingly so with higher levels of global warming. There is *medium confidence* that livestock in southern Africa will experience increased water stress under both 1.5°C and 2°C of global warming, with negative economic consequences (e.g., Boone et al., 2018). The region is also projected to experience reduced maize, sorghum and cocoa cropping area suitability, as well as yield losses under 1.5°C of warming, with further decreases occurring towards 2°C of warming (World Bank, 2013). Generally, there is *high confidence* that vulnerability to decreases in water and food availability is reduced at 1.5°C versus 2°C for southern Africa (Betts et al., 2018), whilst at 2°C these are expected to be higher (*high confidence*) (Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018).

3.5.4.8 Tropics

Worldwide, the largest increases in the number of hot days are projected to occur in the tropics (Figure 3.7). Moreover, the largest differences in the number of hot days for 1.5°C versus 2°C of global warming are projected to occur in the tropics (Mahlstein et al., 2011). In tropical Africa, increases in the number of hot nights, as well as longer and more frequent heatwaves, are projected under 1.5°C of global warming, with further increases expected under 2°C of global warming (Weber et al., 2018). Impact studies for major tropical cereals reveal that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Schleussner et al. (2016b) project that constraining warming to 1.5°C rather than 2°C would avoid significant risks of tropical crop yield declines in West Africa, Southeast Asia, and Central and South America. There is *limited evidence* and thus *low confidence* that these changes may result in significant population displacement from the tropics to the subtropics (e.g., Hsiang and Sobel, 2016).

3.5.4.9 Small islands

It is widely recognized that small islands are very sensitive to climate change impacts such as sea level rise, oceanic warming, heavy precipitation, cyclones and coral bleaching *(high confidence*) (Nurse et al., 2014; Ourbak and Magnan, 2017). Even at 1.5°C of global warming, the compounding impacts of changes in rainfall, temperature, tropical cyclones and sea level are likely to be significant across multiple natural and human systems. There are potential benefits to small island developing states (SIDS) from avoided risks at 1.5°C versus 2°C, especially when coupled with adaptation efforts. In terms of sea level rise, by 2150, roughly 60,000 fewer people living in SIDS will be exposed in a 1.5°C world than in a 2°C world (Rasmussen et al., 2018). Constraining global warming to 1.5°C may significantly reduce water stress (by about 25%) compared to the projected water stress at 2°C, for example in the Caribbean region (Karnauskas et al., 2018), and may enhance the ability of SIDS to adapt (Benjamin and Thomas, 2016). Up to 50% of the year is projected to be very warm in the Caribbean at 1.5°C, with a further increase by up to 70 days at 2°C versus 1.5°C (Taylor et al., 2018). By limiting warming to 1.5°C instead of 2°C in 2050, risks of coastal flooding (measured as the flood amplification factors for 100-year flood events) are reduced by 20–80% for SIDS (Rasmussen et al., 2018). A case study of Jamaica with lessons for other Caribbean SIDS demonstrated that the difference between 1.5°C and 2°C is *likely* to challenge livestock thermoregulation, resulting in persistent heat stress for livestock (Lallo et al., 2018).

3.5.4.10 Fynbos and shrub biomes

The Fynbos and succulent Karoo biomes of South Africa are threatened systems that were assessed in AR5. Similar shrublands exist in the semi-arid regions of other continents, with the Sonora-Mojave creosotebush-white bursage desert scrub ecosystem in the USA being a prime example. Impacts accrue across these systems with greater warming, with impacts at 2°C likely to be greater than those at 1.5°C (*medium confidence*). Under 2°C of global warming, regional warming in drylands is projected to be 3.2°C–4°C, and under 1.5°C of global warming, mean warming in drylands is projected to still be about 3°C. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters (*high confidence*). The Fynbos biome is projected to lose about 20%, 45% and 80% of its current suitable climate area relative to its present-day area under 1°C, 2°C and 3°C of warming, respectively (Engelbrecht and Engelbrecht, 2016), demonstrating the value of climate change mitigation in protecting this rich centre of biodiversity.

Table 3.6 | Emergence and intensity of climate change hotspots under different degrees of global warming.

Region and/or Phenomenon	Warming of 1.5°C or less	Warming of 1.5°C–2°C	Warming of 2°C–3°C
Arctic sea ice	Arctic summer sea ice is *likely* to be maintained Habitat losses for organisms such as polar bears, whales, seals and sea birds Benefits for Arctic fisheries	The risk of an ice-free Arctic in summer is about 50% or higher Habitat losses for organisms such as polar bears, whales,seals and sea birds may be critical if summers are ice free Benefits for Arctic fisheries	The Arctic is *very likely* to be ice free in summer Critical habitat losses for organisms such as polar bears, whales, seals and sea birds Benefits for Arctic fisheries
Arctic land regions	Cold extremes warm by a factor of 2–3, reaching up to 4.5°C (*high confidence*) Biome shifts in the tundra and permafrost deterioration are *likely*	Cold extremes warm by as much as 8°C (*high confidence*) Larger intrusions of trees and shrubs in the tundra than under 1.5°C of warming are *likely*; larger but constrained losses in permafrost are *likely*	Drastic regional warming is *very likely* A collapse in permafrost may occur (*low confidence*); a drastic biome shift from tundra to boreal forest is possible (*low confidence*)
Alpine regions	Severe shifts in biomes are *likely*	Even more severe shifts are *likely*	Critical losses in alpine habitats are *likely*
Southeast Asia	Risks for increased flooding related to sea level rise Increases in heavy precipitation events Significant risks of crop yield reductions are avoided	Higher risks of increased flooding related to sea level rise (*medium confidence*) Stronger increases in heavy precipitation events (*medium confidence*) One-third decline in per capita crop production (*medium confidence*)	Substantial increases in risks related to flooding from sea level rise Substantial increase in heavy precipitation and high-flow events Substantial reductions in crop yield
Mediterranean	Increase in probability of extreme drought (*medium confidence*) *Medium confidence* in reduction in runoff of about 9% (*likely* range 4.5–15.5%) Risk of water deficit (*medium confidence*)	Robust increase in probability of extreme drought (*medium confidence*) *Medium confidence* in further reductions (about 17%) in runoff (*likely* range 8–28%) Higher risks of water deficit (*medium confidence*)	Robust and large increases in extreme drought. Substantial reductions in precipitation and in runoff (*medium confidence*) Very high risks of water deficit (*medium confidence*)
West Africa and the Sahel	Increases in the number of hot nights and longer and more frequent heatwaves are *likely* Reduced maize and sorghum production is *likely*, with area suitable for maize production reduced by as much as 40% Increased risks of undernutrition	Further increases in number of hot nights and longer and more frequent heatwaves are *likely* Negative impacts on maize and sorghum production *likely* larger than at 1.5°C; *medium confidence* that vulnerabilities to food security in the African Sahel will be higher at 2°C compared to 1.5°C Higher risks of undernutrition	Substantial increases in the number of hot nights and heatwave duration and frequency (*very likely*) Negative impacts on crop yield may result in major regional food insecurities (*medium confidence*) High risks of undernutrition
Southern Africa	Reductions in water availability (*medium confidence*) Increases in number of hot nights and longer and more frequent heatwaves (*high confidence*) High risks of increased mortality from heatwaves High risk of undernutrition in communities dependent on dryland agriculture and livestock	Larger reductions in rainfall and water availability (*medium confidence*) Further increases in number of hot nights and longer and more frequent heatwaves (*high confidence*), associated increases in risks of increased mortality from heatwaves compared to 1.5°C warming (*high confidence*) Higher risks of undernutrition in communities dependent on dryland agriculture and livestock	Large reductions in rainfall and water availability (*medium confidence)* Drastic increases in the number of hot nights, hot days and heatwave duration and frequency to impact substantially on agriculture, livestock and human health and mortality (*high confidence*) Very high risks of undernutrition in communities dependent on dryland agriculture and livestock
Tropics	Increases in the number of hot days and hot nights as well as longer and more frequent heatwaves (*high confidence*) Risks to tropical crop yields in West Africa, Southeast Asia and Central and South America are significantly less than under 2°C of warming	The largest increase in hot days under 2°C compared to 1.5°C is projected for the tropics. Risks to tropical crop yields in West Africa, Southeast Asia and Central and South America could be extensive	Oppressive temperatures and accumulated heatwave duration *very likely* to directly impact human health, mortality and productivity Substantial reductions in crop yield *very likely*
Small islands	Land of 60,000 less people exposed by 2150 on SIDS compared to impacts under 2°C of global warming Risks for coastal flooding reduced by 20–80% for SIDS compared to 2°C of global warming Freshwater stress reduced by 25% Increase in the number of warm days for SIDS in the tropics Persistent heat stress in cattle avoided Loss of 70–90% of coral reefs	Tens of thousands of people displaced owing to inundation of SIDS High risks for coastal flooding Freshwater stress reduced by 25% compared to 2°C of global warming Freshwater stress from projected aridity Further increase of about 70 warm days per year Persistent heat stress in cattle in SIDS Loss of most coral reefs and weaker remaining structures owing to ocean acidification	Substantial and widespread impacts through inundation of SIDS, coastal flooding, freshwater stress, persistent heat stress and loss of most coral reefs (*very likely*)
Fynbos biome	About 30% of suitable climate area lost (*medium confidence*)	Increased losses (about 45%) of suitable climate area (*medium confidence*)	Up to 80% of suitable climate area lost (*medium confidence*)

3.5.5 Avoiding Regional Tipping Points by Achieving More Ambitious Global Temperature Goals

Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, an analysis is provided of how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming, whereas tipping points in the global climate system, referred to as large-scale singular events, were already discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7.

3.5.5.1 Arctic sea ice

Collins et al. (2013) discussed the loss of Artic sea ice in the context of potential tipping points. Climate models have been used to assess whether a bifurcation exists that would lead to the irreversible loss of Arctic sea ice (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) and to test whether the summer sea ice extent can recover after it has been lost (Schröder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011). These studies did not find evidence of bifurcation or indicate that sea ice returns within a few years of its loss, leading Collins et al. (2013) to conclude that there is little evidence for a tipping point in the transition from perennial to seasonal ice cover. No evidence has been found for irreversibility or tipping points, suggesting that year-round sea ice will return given a suitable climate (*medium confidence*) (Schröder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011).

3.5.5.2 Tundra

Tree growth in tundra-dominated landscapes is strongly constrained by the number of days with mean air temperature above 0°C. A potential tipping point exists where the number of days below 0°C decreases to the extent that the tree fraction increases significantly. Tundra-dominated landscapes have warmed more than the global average over the last century (Settele et al., 2014), with associated increases in fires and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016). These processes facilitate conditions for woody species establishment in tundra areas, and for the eventual transition of the tundra to boreal forest. The number of investigations into how the tree fraction may respond in the Arctic to different degrees of global warming is limited, and studies generally indicate that substantial increases will *likely* occur gradually (e.g., Lenton et al., 2008). Abrupt changes are only plausible at levels of warming significantly higher than 2°C (*low confidence*) and would occur in conjunction with a collapse in permafrost (Drijfhout et al., 2015).

3.5.5.3 Permafrost

Widespread thawing of permafrost potentially makes a large carbon store (estimated to be twice the size of the atmospheric store; Dolman et al., 2010) vulnerable to decomposition, which could lead to further increases in atmospheric carbon dioxide and methane and hence to further global warming. This feedback loop between warming and the release of greenhouse gas from thawing tundra represents a potential tipping point. However, the carbon released to the atmosphere from thawing permafrost is projected to be restricted to 0.09–0.19 Gt C yr^{-1} at 2°C of global warming and to 0.08–0.16 Gt C yr^{-1} at 1.5°C (E.J. Burke et al., 2018), which does not indicate a tipping point (*medium confidence*). At higher degrees of global warming, in the order of 3°C, a different type of tipping point in permafrost may be reached. A single model projection (Drijfhout et al., 2015) suggested that higher temperatures may induce a smaller ice fraction in soils in the tundra, leading to more rapidly warming soils and a positive feedback mechanism that results in permafrost collapse (*low confidence*). The disparity between the multi-millennial time scales of soil carbon accumulation and potentially rapid decomposition in a warming climate implies that the loss of this carbon to the atmosphere would be essentially irreversible (Collins et al., 2013).

3.5.5.4 Asian monsoon

At a fundamental level, the pressure gradient between the Indian Ocean and Asian continent determines the strength of the Asian monsoon. As land masses warm faster than the oceans, a general strengthening of this gradient, and hence of monsoons, may be expected under global warming (e.g., Lenton et al., 2008). Additional factors such as changes in albedo induced by aerosols and snow-cover change may also affect temperature gradients and consequently pressure gradients and the strength of the monsoon. In fact, it has been estimated that an increase of the regional land mass albedo to 0.5 over India would represent a tipping point resulting in the collapse of the monsoon system (Lenton et al., 2008). The overall impacts of the various types of radiative forcing under different emissions scenarios are more subtle, with a weakening of the monsoon north of about 25°N in East Asia but a strengthening south of this latitude projected by Jiang and Tian (2013) under high and modest emissions scenarios. Increases in the intensity of monsoon precipitation are *likely* under low mitigation (AR5). Given that scenarios of 1.5°C or 2°C of global warming would include a substantially smaller radiative forcing than those assessed in the study by Jiang and Tian (2013), there is *low confidence* regarding changes in monsoons at these low global warming levels, as well as regarding the differences between responses at 1.5°C versus 2°C of warming.

3.5.5.5 West African monsoon and the Sahel

Earlier work has identified 3°C of global warming as the tipping point leading to a significant strengthening of the West African monsoon and subsequent wettening (and greening) of the Sahel and Sahara (Lenton et al., 2008). AR5 (Niang et al., 2014), as well as more recent research through the Coordinated Regional Downscaling Experiment for Africa (CORDEX–AFRICA), provides a more uncertain view, however, in terms of the rainfall futures of the Sahel under low mitigation futures. Even if a wetter Sahel should materialize under 3°C of global warming (*low*

confidence), it should be noted that there would be significant offsets in the form of strong regional warming and related adverse impacts on crop yield, livestock mortality and human health under such low mitigation futures (Engelbrecht et al., 2015; Sylla et al., 2016; Weber et al., 2018).

3.5.5.6 Rainforests

A large portion of rainfall over the world's largest rainforests is recirculated (e.g., Lenton et al., 2008), which raises the concern that deforestation may trigger a threshold in reduced forest cover, leading to pronounced forest dieback. For the Amazon, this deforestation threshold has been estimated to be 40% (Nobre et al., 2016). Global warming of 3°C–4°C may also, independent of deforestation, represent a tipping point that results in a significant dieback of the Amazon forest, with a key forcing mechanism being stronger El Niño events bringing more frequent droughts to the region (Nobre et al., 2016). Increased fire frequencies under global warming may interact with and accelerate deforestation, particularly during periods of El Niño-induced droughts (Lenton et al., 2008; Nobre et al., 2016). Global warming of 3°C is projected to reduce the extent of tropical rainforest in Central America, with biomass being reduced by about 40%, which can lead to a large replacement of rainforest by savanna and grassland (Lyra et al., 2017). Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016) and observational constraints (Cox et al., 2013) suggest that pronounced rainforest dieback may only be triggered at 3°C–4°C (*medium confidence*), although pronounced biomass losses may occur at 1.5°C– 2°C of global warming.

3.5.5.7 Boreal forests

Boreal forests are likely to experience stronger local warming than the global average (WGII AR5; Collins et al., 2013). Increased disturbance from fire, pests and heat-related mortality may affect, in particular, the southern boundary of boreal forests (*medium confidence*) (Gauthier et al., 2015), with these impacts accruing with greater warming and thus impacts at 2°C would be expected to be greater than those at 1.5°C (*medium confidence*). A tipping point for significant dieback of the boreal forests is thought to exist, where increased tree mortality would result in the creation of large regions of open woodlands and grasslands, which would favour further regional warming and increased fire frequencies, thus inducing a powerful positive feedback mechanism (Lenton et al., 2008; Lenton, 2012). This tipping point has been estimated to exist between 3°C and 4°C of global warming (*low confidence*) (Lucht et al., 2006; Kriegler et al., 2009), but given the complexities of the various forcing mechanisms and feedback processes involved, this is thought to be an uncertain estimate.

3.5.5.8 Heatwaves, unprecedented heat and human health

Increases in ambient temperature are linearly related to hospitalizations and deaths once specific thresholds are exceeded (so there is not a tipping point per se). It is plausible that coping strategies will not be in place for many regions, with potentially significant impacts on communities with low adaptive capacity, effectively representing the occurrence of a local/regional tipping point. In fact, even if global warming is restricted to below 2°C, there could be a substantial increase in the occurrence of deadly heatwaves in cities if urban heat island effects are considered, with impacts being similar at 1.5°C and 2°C but substantially larger than under the present climate (Matthews et al., 2017). At 1.5°C of warming, twice as many megacities (such as Lagos, Nigeria, and Shanghai, China) than at present are *likely* to become heat stressed, potentially exposing more than 350 million more people to deadly heat stress by 2050. At 2°C of warming, Karachi (Pakistan) and Kolkata (India) could experience conditions equivalent to their deadly 2015 heatwaves on an annual basis (*medium confidence*). These statistics imply a tipping point in the extent and scale of heatwave impacts. However, these projections do not integrate adaptation to projected warming, for instance cooling that could be achieved with more reflective roofs and urban surfaces in general (Akbari et al., 2009; Oleson et al., 2010).

3.5.5.9 Agricultural systems: key staple crops

A large number of studies have consistently indicated that maize crop yield will be negatively affected under increased global warming, with negative impacts being higher at 2°C of warming than at 1.5°C (e.g., Niang et al., 2014; Schleussner et al., 2016b; J. Huang et al., 2017; Iizumi et al., 2017). Under 2°C of global warming, losses of 8–14% are projected in global maize production (Bassu et al., 2014). Under global warming of more than 2°C, regional losses are projected to be about 20% if they co-occur with reductions in rainfall (Lana et al., 2017). These changes may be classified as incremental rather than representing a tipping point. Large-scale reductions in maize crop yield, including the potential collapse of this crop in some regions, may exist under 3°C or more of global warming (*low confidence*) (e.g., Thornton et al., 2011).

3.5.5.10 Agricultural systems: livestock in the tropics and subtropics

The potential impacts of climate change on livestock (Section 3.4.6), in particular the direct impacts through increased heat stress, have been less well studied than impacts on crop yield, especially from the perspective of critical thresholds being exceeded. A case study from Jamaica revealed that the difference in heat stress for livestock between 1.5°C and 2°C of warming is likely to exceed the limits for normal thermoregulation and result in persistent heat stress for these animals (Lallo et al., 2018). It is plausible that this finding holds for livestock production in both tropical and subtropical regions more generally (*medium confidence*) (Section 3.4.6). Under 3°C of global warming, significant reductions in the areas suitable for livestock production could occur (*low confidence*), owing to strong increases in regional temperatures in the tropics and subtropics (*high confidence*). Thus, regional tipping points in the viability of livestock production may well exist, but little evidence quantifying such changes exists.

Table 3.7 | Summary of enhanced risks in the exceedance of regional tipping points under different global temperature goals.

Tipping point	Warming of 1.5°C or less	Warming of 1.5°C–2°C	Warming of up to 3°C
Arctic sea ice	Arctic summer sea ice is *likely* to be maintained Sea ice changes reversible under suitable climate restoration	The risk of an ice-free Arctic in summer is about 50% or higher Sea ice changes reversible under suitable climate restoration	Arctic is *very likely* to be ice free in summer Sea ice changes reversible under suitable climate restoration
Tundra	Decrease in number of growing degree days below 0°C Abrupt increases in tree cover are *unlikely*	Further decreases in number of growing degree days below 0°C Abrupt increased in tree cover are *unlikely*	Potential for an abrupt increase in tree fraction (*low confidence*)
Permafrost	17–44% reduction in permafrost Approximately 2 million km^2 more permafrost maintained than under 2°C of global warming (*medium confidence*) Irreversible loss of stored carbon	28–53% reduction in permafrost Irreversible loss of stored carbon	Potential for permafrost collapse (*low confidence*)
Asian monsoon	*Low confidence* in projected changes	*Low confidence* in projected changes	Increases in the intensity of monsoon precipitation *likely*
West African monsoon and the Sahel	Uncertain changes; *unlikely* that a tipping point is reached	Uncertain changes; *unlikely* that tipping point is reached	Strengthening of monsoon with wettening and greening of the Sahel and Sahara (*low confidence*) Negative associated impacts through increases in extreme temperature events
Rainforests	Reduced biomass, deforestation and fire increases pose uncertain risks to forest dieback	Larger biomass reductions than under 1.5°C of warming; deforestation and fire increases pose uncertain risk to forest dieback	Reduced extent of tropical rainforest in Central America and large replacement of rainforest by savanna and grassland Potential tipping point leading to pronounced forest dieback (*medium confidence*)
Boreal forests	Increased tree mortality at southern boundary of boreal forest (*medium confidence*)	Further increases in tree mortality at southern boundary of boreal forest (*medium confidence*)	Potential tipping point at 3°C–4°C for significant dieback of boreal forest (*low confidence*)
Heatwaves, unprecedented heat and human health	Substantial increase in occurrence of potentially deadly heatwaves (*likely*) More than 350 million more people exposed to deadly heat by 2050 under a midrange population growth scenario (*likely*)	Substantial increase in potentially deadly heatwaves (*likely*) Annual occurrence of heatwaves similar to the deadly 2015 heatwaves in India and Pakistan (*medium confidence*)	Substantial increase in potentially deadly heatwaves *very likely*
Agricultural systems: key staple crops	Global maize crop reductions of about 10%	Larger reductions in maize crop production than under 1.5°C of about 15%	Drastic reductions in maize crop globally and in Africa (*high confidence*) Potential tipping point for collapse of maize crop in some regions (*low confidence*)
Livestock in the tropics and subtropics	Increased heat stress	Onset of persistent heat stress (*medium confidence*)	Persistent heat stress *likely*

Box 3.6 | Economic Damages from Climate Change

Balancing the costs and benefits of mitigation is challenging because estimating the value of climate change damages depends on multiple parameters whose appropriate values have been debated for decades (for example, the appropriate value of the discount rate) or that are very difficult to quantify (for example, the value of non-market impacts; the economic effects of losses in ecosystem services; and the potential for adaptation, which is dependent on the rate and timing of climate change and on the socio-economic content). See Cross-Chapter Box 5 in Chapter 2 for the definition of the social cost of carbon and for a discussion of the economics of 1.5°C-consistent pathways and the social cost of carbon, including the impacts of inequality on the social cost of carbon.

Global economic damages of climate change are projected to be smaller under warming of 1.5°C than 2°C in 2100 (Warren et al., 2018c). The mean net present value of the costs of damages from warming in 2100 for 1.5°C and. 2°C (including costs associated with climate change-induced market and non-market impacts, impacts due to sea level rise, and impacts associated with large-scale discontinuities) are $54 and $69 trillion, respectively, relative to 1961–1990.

Box 3.6 (continued)

Values of the social cost of carbon vary when tipping points are included. The social cost of carbon in the default setting of the Dynamic Integrated Climate-Economy (DICE) model increases from \$15 tCO_2^{-1} to \$116 (range 50–166) tCO_2^{-1} when large-scale singularities or 'tipping elements' are incorporated (Y. Cai et al., 2016; Lemoine and Traeger, 2016). Lemoine and Traeger (2016) included optimization calculations that minimize welfare impacts resulting from the combination of climate change risks and climate change mitigation costs, showing that welfare is minimized if warming is limited to 1.5°C. These calculations excluded the large health co-benefits that accrue when greenhouse gas emissions are reduced (Section 3.4.7.1; Shindell et al., 2018).

The economic damages of climate change in the USA are projected to be large (Hsiang et al., 2017; Yohe, 2017). Hsiang et al. (2017) shows that the USA stand to lose -0.1 to 1.7% of the Gross Domestic Product (GDP) at 1.5°C warming. Yohe (2017) calculated transient temperature trajectories from a linear relationship with contemporaneous cumulative emissions under a median no-policy baseline trajectory that brings global emissions to roughly 93 $GtCO_2$ yr^{-1} by the end of the century (Fawcett et al., 2015), with 1.75°C per 1000 $GtCO_2$ as the median estimate. Associated aggregate economic damages in decadal increments through the year 2100 are estimated in terms of the percentage loss of GDP at the median, 5th percentile and 95th percentile transient temperature (Hsiang et al., 2017). The results for the baseline no-policy case indicate that economic damages along median temperature change and median damages (median-median) reach 4.5% of GDP by 2100, with an uncertainty range of 2.5% and 8.5% resulting from different combinations of temperature change and damages. Avoided damages from achieving a 1.5°C temperature limit along the median-median case are nearly 4% (range 2–7%) by 2100. Avoided damages from achieving a 2°C temperature limit are only 3.5% (range 1.8–6.5%). Avoided damages from achieving 1.5°C versus 2°C are modest at about 0.35% (range 0.20–0.65%) by 2100. The values of achieving the two temperature limits do not diverge significantly until 2040, when their difference tracks between 0.05 and 0.13%; the differences between the two temperature targets begin to diverge substantially in the second half of the century.

3.6 Implications of Different 1.5°C and 2°C Pathways

This section provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C of global warming. Some of these aspects are also addressed in more detail in Cross-Chapter Boxes 7 and 8 in this chapter.

3.6.1 Gradual versus Overshoot in 1.5°C Scenarios

All 1.5°C scenarios from Chapter 2 include some overshoot above 1.5°C of global warming during the 21st century (Chapter 2 and Cross-Chapter Box 8 in this chapter). The level of overshoot may also depend on natural climate variability. An overview of possible outcomes of 1.5°C-consistent mitigation scenarios for changes in the physical climate at the time of overshoot and by 2100 is provided in Cross-Chapter Box 8 on '1.5°C warmer worlds'. Cross-Chapter Box 8 also highlights the implications of overshoots.

3.6.2 Non-CO_2 Implications and Projected Risks of Mitigation Pathways

3.6.2.1 Risks arising from land-use changes in mitigation pathways

In mitigation pathways, land-use change is affected by many different mitigation options. First, mitigation of non-CO_2 emissions from agricultural production can shift agricultural production between regions via trade of agricultural commodities. Second, protection of carbon-rich ecosystems such as tropical forests constrains the area for agricultural expansion. Third, demand-side mitigation measures, such as less consumption of resource-intensive commodities (animal products) or reductions in food waste, reduce pressure on land (Popp et al., 2017; Rogelj et al., 2018). Finally, carbon dioxide removal (CDR) is a key component of most, but not all, mitigation pathways presented in the literature to date which constrain warming to 1.5°C or 2°C. Carbon dioxide removal measures that require land include bioenergy with carbon capture and storage (BECCS), afforestation and reforestation (AR), soil carbon sequestration, direct air capture, biochar and enhanced weathering (see Cross-Chapter Box 7 in this chapter). These potential methods are assessed in Section 4.3.7.

In cost-effective integrated assessment modelling (IAM) pathways recently developed to be consistent with limiting warming to 1.5°C, use of CDR in the form of BECCS and AR are fundamental elements (Chapter 2; Popp et al., 2017; Hirsch et al., 2018; Rogelj et al., 2018; Seneviratne et al., 2018c). The land-use footprint of CDR deployment in 1.5°C-consistent pathways can be substantial (Section 2.3.4, Figure 2.11), even though IAMs predominantly rely on second-generation biomass and assume future productivity increases in agriculture.

A body of literature has explored potential consequences of large-scale use of CDR. In this case, the corresponding land footprint by the end of the century could be extremely large, with estimates including: up to 18% of the land surface being used (Wiltshire and Davies-Barnard, 2015); vast acceleration of the loss of primary forest and natural grassland (Williamson, 2016) leading to increased greenhouse gas emissions (P. Smith et al., 2013, 2015); and potential loss of up to 10% of the current forested lands to biofuels (Yamagata et al., 2018). Other estimates reach 380–700 Mha or 21–64% of current arable cropland (Section 4.3.7). Boysen et al. (2017) found that in a scenario in which emissions reductions were sufficient only to limit warming to 2.5°C,

use of CDR to further limit warming to 1.7°C would result in the conversion of 1.1–1.5 Gha of land – implying enormous losses of both cropland and natural ecosystems. Newbold et al. (2015) found that biodiversity loss in the Representative Concentration Pathway (RCP)2.6 scenario could be greater than that in RCP4.5 and RCP6, in which there is more climate change but less land-use change. Risks to biodiversity conservation and agricultural production are therefore projected to result from large-scale bioenergy deployment pathways (P. Smith et al., 2013; Tavoni and Socolow, 2013). One study explored an extreme mitigation strategy encouraging biofuel expansion sufficient to limit warming to 1.5°C and found that this would be more disruptive to land use and crop prices than the impacts of a 2°C warmer world which has a larger climate signal and lower mitigation requirement (Ruane et al., 2018). However, it should again be emphasized that many of the pathways explored in Chapter 2 of this report follow strategies that explore how to reduce these issues. Chapter 4 provides an assessment of the land footprint of various CDR technologies (Section 4.3.7).

The degree to which BECCS has these large land-use footprints depends on the source of the bioenergy used and the scale at which BECCS is deployed. Whether there is competition with food production and biodiversity depends on the governance of land use, agricultural intensification, trade, demand for food (in particular meat), feed and timber, and the context of the whole supply chain (Section 4.3.7, Fajardy and Mac Dowell, 2017; Booth, 2018; Sterman et al., 2018).

The more recent literature reviewed in Chapter 2 explores pathways which limit warming to 2°C or below and achieve a balance between sources and sinks of CO_2 by using BECCS that relies on second-generation (or even third-generation) biofuels, changes in diet or more generally, management of food demand, or CDR options such as forest restoration (Chapter 2; Bajželj et al., 2014). Overall, this literature explores how to reduce the issues of competition for land with food production and with natural ecosystems (in particular forests) (Cross-Chapter Box 1 in Chapter 1; van Vuuren et al., 2009; Haberl et al., 2010, 2013; Bajželj et al., 2014; Daioglou et al., 2016; Fajardy and Mac Dowell, 2017).

Some IAMs manage this transition by effectively protecting carbon stored on land and focusing on the conversion of pasture area into both forest area and bioenergy cropland. Some IAMs explore 1.5°C-consistent pathways with demand-side measures such as dietary changes and efficiency gains such as agricultural changes (Sections 2.3.4 and 2.4.4), which lead to a greatly reduced CDR deployment and consequently land-use impacts (van Vuuren et al., 2018). In reality, however, whether this CDR (and bioenergy in general) has large adverse impacts on environmental and societal goals depends in large part on the governance of land use (Section 2.3.4; Obersteiner et al., 2016; Bertram et al., 2018; Humpenöder et al., 2018).

Rates of sequestration of 3.3 GtC ha^{-1} require 970 Mha of afforestation and reforestation (Smith et al., 2015). Humpenöder et al. (2014) estimated that in least-cost pathways afforestation would cover 2800 Mha by the end of the century to constrain warming to 2°C. Hence, the amount of land considered if least-cost mitigation is implemented by afforestation and reforestation could be up to three to five times greater than that required by BECCS, depending on the forest management used. However, not all of the land footprint of CDR is necessarily to be in competition with biodiversity protection. Where reforestation is the restoration of natural ecosystems, it benefits both carbon sequestration and conservation of biodiversity and ecosystem services (Section 4.3.7) and can contribute to the achievement of the Aichi targets under the Convention on Biological Diversity (CBD) (Leadley et al., 2016). However, reforestation is often not defined in this way (Section 4.3.8; Stanturf et al., 2014) and the ability to deliver biodiversity benefits is strongly dependent on the precise nature of the reforestation, which has different interpretations in different contexts and can often include agroforestry rather than restoration of pristine ecosystems (Pistorious and Kiff, 2017). However, 'natural climate solutions', defined as conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands and agricultural lands, are estimated to have the potential to provide 37% of the cost-effective CO_2 mitigation needed by southern Europe and the Mediterranean by 2030 – in order to have a >66% chance of holding warming to below 2°C (Griscom et al., 2017).

Any reductions in agricultural production driven by climate change and/or land management decisions related to CDR may (e.g., Nelson et al., 2014a; Dalin and Rodríguez-Iturbe, 2016) or may not (Muratori et al., 2016) affect food prices. However, these studies did not consider the deployment of second-generation (instead of first-generation) bioenergy crops, for which the land footprint can be much smaller.

Irrespective of any mitigation-related issues, in order for ecosystems to adapt to climate change, land use would also need to be carefully managed to allow biodiversity to disperse to areas that become newly climatically suitable for it (Section 3.4.1) and to protect the areas where the future climate will still remain suitable. This implies a need for considerable expansion of the protected area network (Warren et al., 2018b), either to protect existing natural habitat or to restore it (perhaps through reforestation, see above). At the same time, adaptation to climate change in the agricultural sector (Rippke et al., 2016) can require transformational as well as new approaches to land-use management; in order to meet the rising food demand of a growing human population, it is projected that additional land will need to be brought into production unless there are large increases in agricultural productivity (Tilman et al., 2011). However, future rates of deforestation may be underestimated in the existing literature (Mahowald et al., 2017a), and reforestation may therefore be associated with significant co-benefits if implemented to restore natural ecosystems (*high confidence*).

3.6.2.2 Biophysical feedbacks on regional climate associated with land-use changes

Changes in the biophysical characteristics of the land surface are known to have an impact on local and regional climates through changes in albedo, roughness, evapotranspiration and phenology, which can lead to a change in temperature and precipitation. This includes changes in land use through agricultural expansion/intensification (e.g., Mueller et al., 2016), reforestation/revegetation endeavours (e.g., Feng et al., 2016; Sonntag et al., 2016; Bright et al., 2017) and changes in land management (e.g., Luyssaert et al., 2014; Hirsch et al., 2017) that can

Figure 3.22 | Regional temperature scaling with carbon dioxide (CO_2) concentration (ppm) from 1850 to 2099 for two different regions defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) for central Europe (CEU) (a) and central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TXx) anomaly, and dashed lines correspond to the global mean temperature anomaly, where all temperature anomalies are relative to 1850–1870 and units are degrees Celsius. The black line in all panels denotes the three-member control ensemble mean, with the grey shaded regions corresponding to the ensemble range. The coloured lines represent the three-member ensemble means of the experiments corresponding to albedo +0.02 (cyan), albedo +0.04 (purple), albedo + 0.08 (orange), albedo +0.10 (red), irrigation (blue), and irrigation with albedo +0.10 (green). Adapted from Hirsch et al. (2017).

involve double cropping (e.g., Jeong et al., 2014; Mueller et al., 2015; Seifert and Lobell, 2015), irrigation (e.g., Lobell et al., 2009; Sacks et al., 2009; Cook et al., 2011; Qian et al., 2013; de Vrese et al., 2016; Pryor et al., 2016; Thiery et al., 2017), no-till farming and conservation agriculture (e.g., Lobell et al., 2006; Davin et al., 2014), and wood harvesting (e.g., Lawrence et al., 2012). Hence, the biophysical impacts of land-use changes are an important topic to assess in the context of low-emissions scenarios (e.g., van Vuuren et al., 2011b), in particular for 1.5°C warming levels (see also Cross-Chapter Box 7 in this chapter).

The magnitude of the biophysical impacts is potentially large for temperature extremes. Indeed, changes induced both by modifications in moisture availability and irrigation and by changes in surface albedo tend to be larger (i.e., stronger cooling) for hot extremes than for mean temperatures (e.g., Seneviratne et al., 2013; Davin et al., 2014; Wilhelm et al., 2015; Hirsch et al., 2017; Thiery et al., 2017). The reasons for reduced moisture availability are related to a strong contribution of moisture deficits to the occurrence of hot extremes in mid-latitude regions (Mueller and Seneviratne, 2012; Seneviratne et al., 2013). In the case of surface albedo, cooling associated with higher albedo (e.g., in the case of no-till farming) is more effective at cooling hot days because of the higher incoming solar radiation for these days (Davin et al., 2014). The overall effect of either irrigation or albedo has been found to be at the most in the order of about 1°C–2°C regionally for temperature extremes. This can be particularly important in the context of low-emissions scenarios because the overall effect is in this case of similar magnitude to the response to the greenhouse gas forcing (Figure 3.22; Hirsch et al., 2017; Seneviratne et al., 2018a,c).

In addition to the biophysical feedbacks from land-use change and land management on climate, there are potential consequences for particular ecosystem services. This includes climate change-induced changes in crop yield (e.g., Schlenker and Roberts, 2009; van der Velde et al., 2012; Asseng et al., 2013, 2015; Butler and Huybers, 2013; Lobell et al., 2014) which may be further exacerbated by competing demands for arable land between reforestation mitigation activities, crop growth for BECCS (Chapter 2), increasing food production to support larger populations, and urban expansion (see review by Smith et al., 2010). In particular, some land management practices may have further implications for food security, for instance throughincreases or decreases in yield when tillage is ceased in some regions (Pittelkow et al., 2014).

We note that the biophysical impacts of land use in the context of mitigation pathways constitute an emerging research topic. This topic, as well as the overall role of land-use change in climate change projections and socio-economic pathways, will be addressed in depth in the upcoming IPCC Special Report on Climate Change and Land Use due in 2019.

3.6.2.3 Atmospheric compounds (aerosols and methane)

There are multiple pathways that could be used to limit anthropogenic climate change, and the details of the pathways will influence the impacts of climate change on humans and ecosystems. Anthropogenic-driven changes in aerosols cause important modifications to the global climate (Bindoff et al., 2013a; Boucher et al., 2013b; P. Wu et al., 2013; Sarojini et al., 2016; H. Wang et al., 2016). Enforcement of strict air quality policies may lead to a large decrease in cooling aerosol emissions in the next few decades. These aerosol emission reductions may cause a warming comparable to that resulting from the increase in greenhouse gases by mid-21st century under low CO_2 pathways (Kloster et al., 2009; Acosta Navarro et al., 2017). Further background

is provided in Sections 2.2.2 and 2.3.1; Cross Chapter Box 1 in Chapter 1). Because aerosol effects on the energy budget are regional, strong regional changes in precipitation from aerosols may occur if aerosol emissions are reduced for air quality reasons or as a co-benefit from switches to sustainable energy sources (H. Wang et al., 2016). Thus, regional impacts, especially on precipitation, are very sensitive to 1.5°C-consistent pathways (Z. Wang et al., 2017).

Pathways which rely heavily on reductions in methane (CH_4) instead of CO_2 will reduce warming in the short term because CH_4 is such a stronger and shorter-lived greenhouse gas than CO_2, but will lead to stronger warming in the long term because of the much longer residence time of CO_2 (Myhre et al., 2013; Pierrehumbert, 2014). In addition, the dominant loss mechanism for CH_4 is atmospheric photo-oxidation. This conversion modifies ozone formation and destruction in the troposphere and stratosphere, therefore modifying the contribution of ozone to radiative forcing, as well as feedbacks on the oxidation rate of methane itself (Myhre et al., 2013). Focusing on pathways and policies which both improve air quality and reduce impacts of climate change can provide multiple co-benefits (Shindell et al., 2017). These pathways are discussed in detail in Sections 4.3.7 and 5.4.1 and in Cross-Chapter Box 12 in Chapter 5.

Atmospheric aerosols and gases can also modify the land and ocean uptake of anthropogenic CO_2; some compounds enhance uptake while others reduce it (Section 2.6.2; Ciais et al., 2013). While CO_2 emissions tend to encourage greater uptake of carbon by the land and the ocean (Ciais et al., 2013), CH_4 emissions can enhance ozone pollution, depending on nitrogen oxides, volatile organic compounds and other organic species concentrations, and ozone pollution tends to reduce land productivity (Myhre et al., 2013; B. Wang et al., 2017). Aside from inhibiting land vegetation productivity, ozone may also alter the CO_2, CH_4 and nitrogen (N_2O) exchange at the land–atmosphere interface and transform the global soil system from a sink to a source of carbon (B. Wang et al., 2017). Aerosols and associated nitrogen-based compounds tend to enhance the uptake of CO_2 in land and ocean systems through deposition of nutrients and modification of climate (Ciais et al., 2013; Mahowald et al., 2017b).

3

Cross-Chapter Box 7 | Land-Based Carbon Dioxide Removal in Relation to 1.5°C of Global Warming

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Climate and land form a complex system characterized by multiple feedback processes and the potential for non-linear responses to perturbation. Climate determines land cover and the distribution of vegetation, affecting above- and below-ground carbon stocks. At the same time, land cover influences global climate through altered biogeochemical processes (e.g., atmospheric composition and nutrient flow into oceans), and regional climate through changing biogeophysical processes including albedo, hydrology, transpiration and vegetation structure (Forseth, 2010).

Greenhouse gas (GHG) fluxes related to land use are reported in the 'agriculture, forestry and other land use' sector (AFOLU) and comprise about 25% (about 10–12 $GtCO_2eq\ yr^{-1}$) of anthropogenic GHG emissions (P. Smith et al., 2014). Reducing emissions from land use, as well as land-use change, are thus an important component of low-emissions mitigation pathways (Clarke et al., 2014), particularly as land-use emissions can be influenced by human actions such as deforestation, afforestation, fertilization, irrigation, harvesting, and other aspects of cropland, grazing land and livestock management (Paustian et al., 2006; Griscom et al., 2017; Houghton and Nassikas, 2018).

In the IPCC Fifth Assessment Report, the vast majority of scenarios assessed with a 66% or better chance of limiting global warming to 2°C by 2100 included carbon dioxide removal (CDR) – typically about 10 $GtCO_2\ yr^{-1}$ in 2100 or about 200–400 $GtCO_2$ over the course of the century (Smith et al., 2015; van Vuuren et al., 2016). These integrated assessment model (IAM) results were predominately achieved by using bioenergy with carbon capture and storage (BECCS) and/or afforestation and reforestation (AR). Virtually all scenarios that limit either peak or end-of-century warming to 1.5°C also use land-intensive CDR technologies (Rogelj et al., 2015; Holz et al., 2017; Kriegler et al., 2017; Fuss et al., 2018; van Vuuren et al., 2018). Again, AR (Sections 2.3 and 4.3.7) and BECCS (Sections 4.3.2. and 4.3.7) predominate. Other CDR options, such as the application of biochar to soil, soil carbon sequestration, and enhanced weathering (Section 4.3.7) are not yet widely incorporated into IAMs, but their deployment would also necessitate the use of land and/or changes in land management.

Integrated assessment models provide a simplified representation of land use and, with only a few exceptions, do not include biophysical feedback processes (e.g., albedo and evapotranspiration effects) (Kreidenweis et al., 2016) despite the importance of these processes for regional climate, in particular hot extremes (Section 3.6.2.2; Seneviratne et al., 2018c). The extent, location and impacts of large-scale land-use change described by existing IAMs can also be widely divergent, depending on model structure, scenario parameters, modelling objectives and assumptions (including regarding land availability and productivity) (Prestele et

Cross-Chapter Box 7 (continued)

al., 2016; Alexander et al., 2017; Popp et al., 2017; Seneviratne et al., 2018c). Despite these limitations, IAM scenarios effectively highlight the extent and nature of potential land-use transitions implicit in limiting warming to 1.5°C.

Cross-Chapter Box 7 Table 1 presents a comparison of the five CDR options assessed in this report. This illustrates that if BECCS and AR were to be deployed at a scale of 12 $GtCO_2$ yr^{-1} in 2100, for example, they would have a substantial land and water footprint. Whether this footprint would result in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, limit the expansion of agriculture at the expense of natural ecosystems, and increase agriculture productivity (Bonsch et al., 2016; Obersteiner et al., 2016; Bertram et al., 2018; Humpenöder et al., 2018). In comparison, the land and water footprints of enhanced weathering, soil carbon sequestration and biochar application are expected to be far less per $GtCO_2$ sequestered. These options may offer potential co-benefits by providing an additional source of nutrients or by reducing N_2O emissions, but they are also associated with potential side effects. Enhanced weathering would require massive mining activity, and providing feedstock for biochar would require additional land, even though a proportion of the required biomass is expected to come from residues (Woolf et al., 2010; Smith, 2016). For the terrestrial CDR options, permanence and saturation are important considerations, making their viability and long-term contributions to carbon reduction targets uncertain.

The technical, political and social feasibility of scaling up and implementing land-intensive CDR technologies (Cross-Chapter Box 3 in Chapter 1) is recognized to present considerable potential barriers to future deployment (Boucher et al., 2013a; Fuss et al., 2014, 2018; Anderson and Peters, 2016; Vaughan and Gough, 2016; Williamson, 2016; Minx et al., 2017, 2018; Nemet et al., 2018; Strefler et al., 2018; Vaughan et al., 2018). To investigate the implications of restricting CDR options should these barriers prove difficult to overcome, IAM studies (Section 2.3.4) have developed scenarios that limit – either implicitly or explicitly – the use of BECCS and bioenergy (Krey et al., 2014; Bauer et al., 2018; Rogelj et al., 2018) or the use of BECCS and afforestation (Strefler et al., 2018). Alternative strategies to limit future reliance on CDR have also been examined, including increased electrification, agricultural intensification, behavioural change, and dramatic improvements in energy and material efficiency (Bauer et al., 2018; Grubler et al., 2018; van Vuuren et al., 2018). Somewhat counterintuitively, scenarios that seek to limit the deployment of BECCs may result in increased land use, through greater deployment of bioenergy, and afforestation (Chapter 2, Box 2.1; Krey et al., 2014; Krause et al., 2017; Bauer et al., 2018; Rogelj et al., 2018). Scenarios aiming to minimize the total human land footprint (including land for food, energy and climate mitigation) also result in land-use change, for example by increasing agricultural efficiency and dietary change (Grubler et al., 2018).

The impacts of changing land use are highly context, location and scale dependent (Robledo-Abad et al., 2017). The supply of biomass for CDR (e.g., energy crops) has received particular attention. The literature identifies regional examples of where the use of land to produce biofuels might be sustainably increased (Jaiswal et al., 2017), where biomass markets could contribute to the provision of ecosystem services (Dale et al., 2017), and where bioenergy could increase the resilience of production systems and contribute to rural development (Kline et al., 2017). However, studies of global biomass potential provide only limited insight into the local feasibility of supplying large quantities of biomass on a global scale (Slade et al., 2014). Concerns about large-scale use of biomass for CDR include a range of potential consequences including greatly increased demand for freshwater use, increased competition for land, loss of biodiversity and/or impacts on food security (Section 3.6.2.1; Heck et al., 2018). The short- versus long-term carbon impacts of substituting biomass for fossil fuels, which are largely determined by feedstock choice, also remain a source of contention (Schulze et al., 2012; Jonker et al., 2014; Booth, 2018; Sterman et al., 2018).

Afforestation and reforestation can also present trade-offs between biodiversity, carbon sequestration and water use, and these strategies have a higher land footprint per tonne of CO_2 removed (Cunningham, 2015; Naudts et al., 2016; Smith et al., 2018). For example, changing forest management to strategies favouring faster growing species, greater residue extraction and shorter rotations may have a negative impact on biodiversity (de Jong et al., 2014). In contrast, reforestation of degraded land with native trees can have substantial benefits for biodiversity (Section 3.6). Despite these constraints, the potential for increased carbon sequestration through improved land stewardship measures is considered to be substantial (Griscom et al., 2017).

Evaluating the synergies and trade-offs between mitigation and adaptation actions, resulting land and climate impacts, and the myriad issues related to land-use governance will be essential to better understand the future role of CDR technologies. This topic will be addressed further in the IPCC Special Report on Climate Change and Land (SRCCL) due to be published in 2019.

Cross-Chapter Box 7 (continued next page)

Cross-Chapter Box 7 (continued)

Key messages:

Cost-effective strategies to limit peak or end-of-century warming to 1.5°C all include enhanced GHG removals in the AFOLU sector as part of their portfolio of measures (*high confidence*).

Large-scale deployment of land-based CDR would have far-reaching implications for land and water availability (*high confidence*). This may impact food production, biodiversity and the provision of other ecosystem services (*high confidence*).

The impacts of deploying land-based CDR at large scales can be reduced if a wider portfolio of CDR options is deployed, and if increased mitigation effort focuses on strongly limiting demand for land, energy and material resources, including through lifestyle and dietary changes (*medium confidence*).

Afforestation and reforestation may be associated with significant co-benefits if implemented appropriately, but they feature large land and water footprints if deployed at large scales (*medium confidence*).

Cross-Chapter Box 7, Table 1 | Comparison of land-based carbon removal options.
Sources: [a] assessed ranges by Fuss et al. (2018), see Figures in Section 4.3.7 for full literature range; [b] based on the 2100 estimate for mean potentials by Smith et al. (2015). Note that biophysical impacts of land-based CDR options besides albedo changes (e.g., through changes in evapotranspiration related to irrigation or land cover/use type) are not displayed.

Option	Potentials [a]	Cost [a]	Required land [b]	Required water [b]	Impact on nutrients [b]	Impact on albedo [b]	Saturation and permanence [a]
	$GtCO_2\ y^{-1}$	*$\$\ tCO_2^{-1}$*	*Mha $GtCO_2^{-1}$*	*$km^3\ GtCO_2^{-1}$*	*Mt N, P, K y^{-1}*	*No units*	*No units*
BECCS	0.5–5	100–200	31–58	60	Variable	Variable; depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g., no-till farming for crops)	Long-term governance of storage; limits on rates of bioenergy production and carbon sequestration
Afforestation & reforestation	0.5–3.6	5–50	80	92	0.5	Negative, or reduced GHG benefit where not negative	Saturation of forests; vulnerable to disturbance; post-AR forest management essential
Enhanced weathering	2–4	50–200	3	0.4	0	0	Saturation of soil; residence time from months to geological timescale
Biochar	0.3–2	30–120	16–100	0	N: 8.2, P: 2.7, K: 19.1	0.08–0.12	Mean residence times between decades to centuries, depending on soil type, management and environmental conditions
Soil carbon sequestration	2.3–5	0–100	0	0	N: 21.8, P: 5.5, K: 4.1	0	Soil sinks saturate and can reverse if poor management practices resume

3.6.3 Implications Beyond the End of the Century

3.6.3.1 Sea ice

Sea ice is often cited as a tipping point in the climate system (Lenton, 2012). Detailed modelling of sea ice (Schröder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011), however, suggests that summer sea ice can return within a few years after its artificial removal for climates in the late 20th and early 21st centuries. Further studies (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) modelled the removal of sea ice by raising CO_2 concentrations and studied subsequent regrowth by lowering CO_2. These studies suggest that changes in Arctic sea ice are neither irreversible nor exhibit bifurcation behaviour. It is therefore plausible that the extent of Arctic sea ice may quickly re-equilibrate to the end-of-century climate under an overshoot scenario.

3.6.3.2 Sea level

Policy decisions related to anthropogenic climate change will have a profound impact on sea level, not only for the remainder of this century but for many millennia to come (Clark et al., 2016). On these long time scales, 50 m of sea level rise (SLR) is possible (Clark et al., 2016). While it is *virtually certain* that sea level will continue to rise well beyond 2100, the amount of rise depends on future cumulative emissions (Church et al., 2013) as well as their profile over time (Bouttes et al., 2013; Mengel et al., 2018). Marzeion et al. (2018) found that 28–44% of present-day glacier volume is unsustainable in the present-day climate and that it would eventually melt over the course of a few centuries, even if there were no further climate change. Some components of SLR, such as thermal expansion, are only considered reversible on centennial time scales (Bouttes et al., 2013; Zickfeld et al., 2013), while the contribution from ice sheets may not be reversible under any plausible future scenario (see below).

Based on the sensitivities summarized by Levermann et al. (2013), the contributions of thermal expansion (0.20–0.63 m $°C^{-1}$) and glaciers (0.21 m $°C^{-1}$ but falling at higher degrees of warming mostly because of the depletion of glacier mass, with a possible total loss of about 0.6 m) amount to 0.5–1.2 m and 0.6–1.7 m in 1.5°C and 2°C warmer worlds, respectively. The bulk of SLR on greater than centennial time scales will therefore be caused by contributions from the continental ice sheets of Greenland and Antarctica, whose existence is threatened on multi-millennial time scales.

For Greenland, where melting from the ice sheet's surface is important, a well-documented instability exists where the surface of a thinning ice sheet encounters progressively warmer air temperatures that further promote melting and thinning. A useful indicator associated with this instability is the threshold at which annual mass loss from the ice sheet by surface melt exceeds mass gain by snowfall. Previous estimates put this threshold at about 1.9°C to 5.1°C above pre-industrial temperatures (Gregory and Huybrechts, 2006). More recent analyses, however, suggest that this threshold sits between 0.8°C and 3.2°C, with a best estimate at 1.6°C (Robinson et al., 2012). The continued decline of the ice sheet after this threshold has been passed is highly dependent on the future climate and varies between about 80% loss after 10,000 years to complete loss after as little as 2000 years (contributing about 6 m to SLR). Church et al. (2013) were unable to quantify a *likely* range for this threshold. They assigned *medium confidence* to a range greater than 2°C but less than 4°C, and had *low confidence* in a threshold of about 1°C. There is insufficient new literature to change this assessment.

The Antarctic ice sheet, in contrast, loses the mass gained by snowfall as outflow and subsequent melt to the ocean, either directly from the underside of floating ice shelves or indirectly by the melting of calved icebergs. The long-term existence of this ice sheet will also be affected by a potential instability (the marine ice sheet instability, MISI), which links outflow (or mass loss) from the ice sheet to water depth at the grounding line (i.e., the point at which grounded ice starts to float and becomes an ice shelf) so that retreat into deeper water (the bedrock underlying much of Antarctica slopes downwards towards the centre of the ice sheet) leads to further increases in outflow and promotes yet further retreat (Schoof, 2007). More recently, a variant on this mechanism was postulated in which an ice cliff forms at the grounding line and retreats rapidly though fracture and iceberg calving (DeConto and Pollard, 2016). There is a growing body of evidence (Golledge et al., 2015; DeConto and Pollard, 2016) that large-scale retreat may be avoided in emissions scenarios such as Representative Concentration Pathway (RCP)2.6 but that higher-emissions RCP scenarios could lead to the loss of the West Antarctic ice sheet and sectors in East Antarctica, although the duration (centuries or millennia) and amount of mass loss during such a collapse is highly dependent on model details and no consensus exists yet. Schoof (2007) suggested that retreat may be irreversible, although a rigorous test has yet to be made. In this context, overshoot scenarios, especially of higher magnitude or longer duration, could increase the risk of such irreversible retreat.

Church et al. (2013) noted that the collapse of marine sectors of the Antarctic ice sheet could lead to a global mean sea level (GMSL) rise above the likely range, and that there was *medium confidence* that this additional contribution 'would not exceed several tenths of a metre during the 21st century'.

The multi-centennial evolution of the Antarctic ice sheet has been considered in papers by DeConto and Pollard (2016) and Golledge et al. (2015). Both suggest that RCP2.6 is the only RCP scenario leading to long-term contributions to GMSL of less than 1.0 m. The long-term committed future of Antarctica and the GMSL contribution at 2100 are complex and require further detailed process-based modelling; however, a threshold in this contribution may be located close to 1.5°C to 2°C of global warming.

In summary, there is *medium confidence* that a threshold in the long-term GMSL contribution of both the Greenland and Antarctic ice sheets lies around 1.5°C to 2°C of global warming relative to pre-industrial; however, the GMSL associated with these two levels of global warming cannot be differentiated on the basis of the existing literature.

3.6.3.3 Permafrost

The slow rate of permafrost thaw introduces a lag between the transient degradation of near-surface permafrost and contemporary climate, so that the equilibrium response is expected to be 25–38% greater than the transient response simulated in climate models (Slater and Lawrence, 2013). The long-term, equilibrium Arctic permafrost loss to global warming was analysed by Chadburn et al. (2017). They used an empirical relation between recent mean annual air temperatures and the area underlain by permafrost coupled to Coupled Model Intercomparison Project Phase 5 (CMIP5) stabilization projections to 2300 for RCP2.6 and RCP4.5. Their estimate of the sensitivity of permafrost to warming is 2.9–5.0 million km^2 $°C^{-1}$ (1 standard deviation confidence interval), which suggests that stabilizing climate at 1.5°C as opposed to 2°C would reduce the area of eventual permafrost loss by 1.5 to 2.5 million km^2 (stabilizing at 56–83% as opposed to 43–72% of 1960–1990 levels). This work, combined with the assessment of Collins et al. (2013) on the link between global warming and permafrost loss, leads to the assessment that permafrost extent would be appreciably greater in a 1.5°C warmer world compared to in a 2°C warmer world (*low to medium confidence*).

3.7 Knowledge Gaps

Most scientific literature specific to global warming of 1.5°C is only just emerging. This has led to differences in the amount of information available and gaps across the various sections of this chapter. In general, the number of impact studies that specifically focused on 1.5°C lags behind climate-change projections in general, due in part to the dependence of the former on the latter. There are also insufficient studies focusing on regional changes, impacts and consequences at 1.5°C and 2°C of global warming.

The following gaps have been identified with respect to tools, methodologies and understanding in the current scientific literature specific to Chapter 3. The gaps identified here are not comprehensive but highlight general areas for improved understanding, especially regarding global warming at 1.5°C compared to 2°C and higher levels.

3.7.1 Gaps in Methods and Tools

- Regional and global climate model simulations for low-emissions scenarios such as a 1.5°C warmer world.
- Robust probabilistic models which separate the relatively small signal between 1.5°C versus 2°C from background noise, and which handle the many uncertainties associated with non-linearities, innovations, overshoot, local scales, and latent or lagging responses in climate.
- Projections of risks under a range of climate and development pathways required to understand how development choices affect the magnitude and pattern of risks, and to provide better estimates of the range of uncertainties.
- More complex and integrated socio-ecological models for predicting the response of terrestrial as well as coastal and oceanic ecosystems to climate and models which are more capable of separating climate effects from those associated with human activities.
- Tools for informing local and regional decision-making, especially when the signal is ambiguous at 1.5°C and/or reverses sign at higher levels of global warming.

3.7.2 Gaps in Understanding

3.7.2.1 Earth systems and 1.5°C of global warming

- The cumulative effects of multiple stresses and risks (e.g., increased storm intensity interacting with sea level rise and the effect on coastal people; feedbacks on wetlands due to climate change and human activities).
- Feedbacks associated with changes in land use/cover for low-emissions scenarios, for example feedback from changes in forest cover, food production, biofuel production, bio-energy with carbon capture and storage (BECCS), and associated unquantified biophysical impacts.
- The distinct impacts of different overshoot scenarios, depending on (i) the peak temperature of the overshoot, (ii) the length of the overshoot period, and (iii) the associated rate of change in global temperature over the time period of the overshoot.

3.7.2.2 Physical and chemical characteristics of a 1.5°C warmer world

- Critical thresholds for extreme events (e.g., drought and inundation) between 1.5°C and 2°C of warming for different climate models and projections. All aspects of storm intensity and frequency as a function of climate change, especially for 1.5°C and 2°C warmer worlds, and the impact of changing storminess on storm surges, damage, and coastal flooding at regional and local scales.
- The timing and implications of the release of stored carbon in Arctic permafrost in a 1.5°C warmer world and for climate stabilization by the end of the century.
- Antarctic ice sheet dynamics, global sea level, and links between seasonal and year-long sea ice in both polar regions.

3.7.2.3 Terrestrial and freshwater systems

- The dynamics between climate change, freshwater resources and socio-economic impacts for lower levels of warming.
- How the health of vegetation is likely to change, carbon storage in plant communities and landscapes, and phenomena such as the fertilization effect.
- The risks associated with species' maladaptation in response to climatic changes (e.g., effects of late frosts). Questions associated with issues such as the consequences of species advancing their spring phenology in response to warming, as well as the interaction between climate change, range shifts and local adaptation in a 1.5°C warmer world.
- The biophysical impacts of land use in the context of mitigation pathways.

3.7.2.4 Ocean Systems

- Deep sea processes and risks to deep sea habitats and ecosystems.
- How changes in ocean chemistry in a 1.5°C warmer world, including decreasing ocean oxygen content, ocean acidification and changes in the activity of multiple ion species, will affect natural and human systems.
- How ocean circulation is changing towards 1.5°C and 2°C warmer worlds, including vertical mixing, deep ocean processes, currents, and their impacts on weather patterns at regional to local scales.
- The impacts of changing ocean conditions at 1.5°C and 2°C of warming on foodwebs, disease, invading species, coastal protection, fisheries and human well-being, especially as organisms modify

their biogeographical ranges within a changing ocean.

- Specific linkages between food security and changing coastal and ocean resources.

3.7.2.5 Human systems

- The impacts of global and regional climate change at 1.5°C on food distribution, nutrition, poverty, tourism, coastal infrastructure and public health, particularly for developing nations.
- Health and well-being risks in the context of socio-economic and climate change at 1.5°C, especially in key areas such as occupational health, air quality and infectious disease.
- Micro-climates at urban/city scales and their associated risks for natural and human systems, within cities and in interaction with surrounding areas. For example, current projections do not integrate adaptation to projected warming by considering cooling that could be achieved through a combination of revised building codes, zoning and land use to build more reflective roofs and urban surfaces that reduce urban heat island effects.
- Implications of climate change at 1.5°C on livelihoods and poverty, as well as on rural communities, indigenous groups and marginalized people.
- The changing levels of risk in terms of extreme events, including storms and heatwaves, especially with respect to people being displaced or having to migrate away from sensitive and exposed systems such as small islands, low-lying coasts and deltas.

Cross-Chapter Box 8 | 1.5°C Warmer Worlds

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Introduction

The Paris Agreement includes goals of stabilizing global mean surface temperature (GMST) well below 2°C and 1.5°C above pre-industrial levels in the longer term. There are several aspects, however, that remain open regarding what a '1.5°C warmer world' could be like, in terms of mitigation (Chapter 2) and adaptation (Chapter 4), as well as in terms of projected warming and associated regional climate change (Chapter 3), which are overlaid on anticipated and differential vulnerabilities (Chapter 5). **Alternative '1.5°C warmer worlds' resulting from mitigation and adaptation choices, as well as from climate variability (climate 'noise'), can be vastly different,** as highlighted in this Cross-Chapter Box. In addition, the range of models underlying 1.5°C projections can be substantial and needs to be considered.

Key questions[7]:

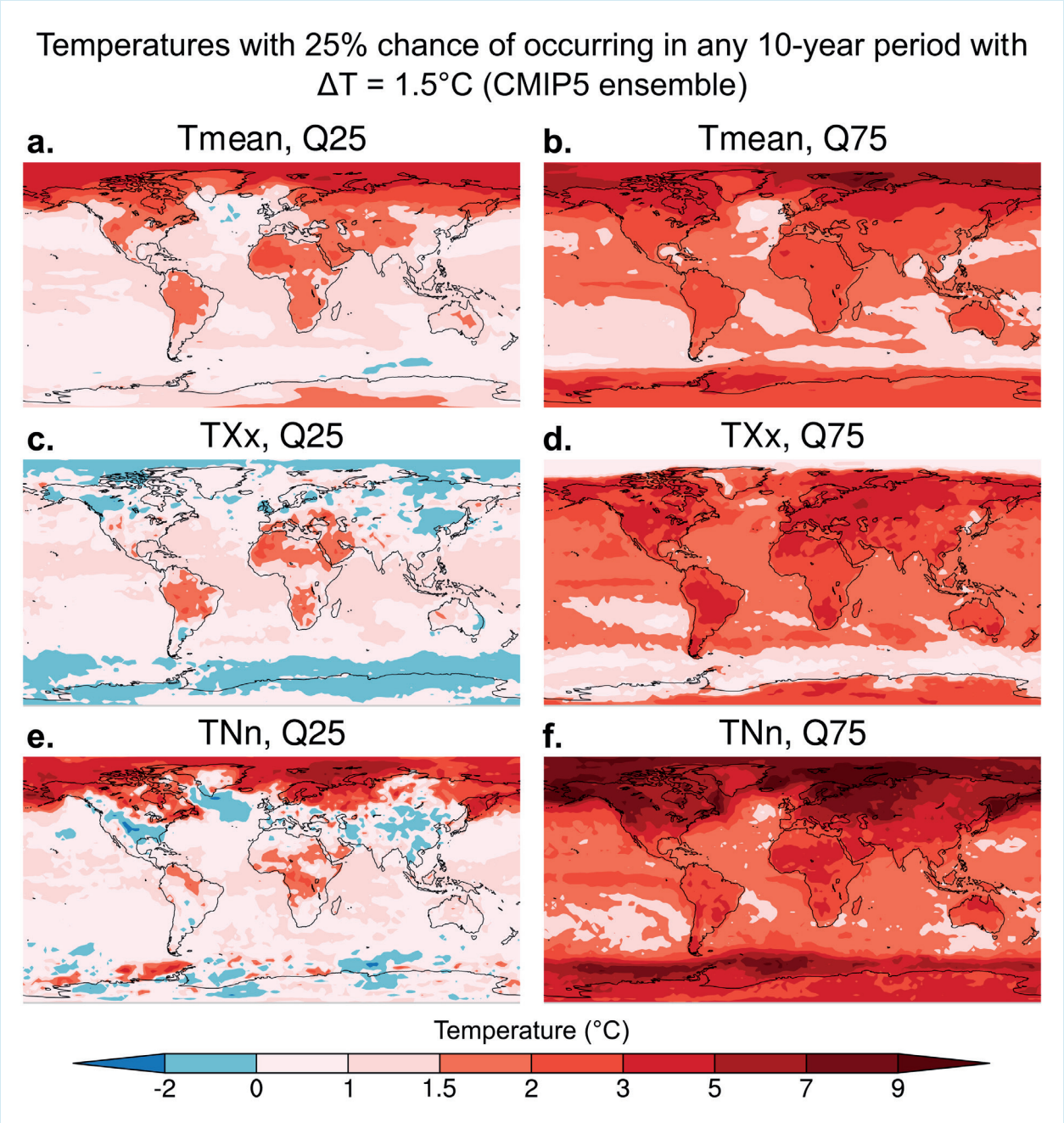
- **What is a 1.5°C global mean warming, how is it measured, and what temperature increase does it imply for single locations and at specific times?** Global mean surface temperature (GMST) corresponds to the globally averaged temperature of Earth derived from point-scale ground observations or computed in climate models (Chapters 1 and 3). Global mean surface temperature is additionally defined over a given time frame, for example averaged over a month, a year, or multiple decades. Because of climate variability, a climate-based GMST typically needs to be defined over several decades (typically 20 or 30 years; Chapter 3, Section 3.2). Hence, whether or when global warming reaches 1.5°C depends to some extent on the choice of pre-industrial reference period, whether 1.5°C refers to total or human-induced warming, and which variables and coverage are used to define GMST change (Chapter 1). By definition, because GMST is an average in time and space, there will be locations and time periods in which 1.5°C of warming is exceeded, even if the global mean warming is at 1.5°C. In some locations, these differences can be particularly large (Cross-Chapter Box 8, Figure 1).

- **What is the impact of different climate models for projected changes in climate at 1.5°C of global warming?** The range between single model simulations of projected regional changes at 1.5°C GMST increase can be substantial for regional responses (Chapter 3, Section 3.3). For instance, for the warming of cold extremes in a 1.5°C warmer world, some model simulations project a 3°C warming while others project more than 6°C of warming in the Arctic land areas (Cross-Chapter Box 8, Figure 2). For hot temperature extremes in the contiguous United States, the range of model simulations includes temperatures lower than pre-industrial values (–0.3°C) and a warming of 3.5°C (Cross-Chapter Box 8, Figure 2). Some regions display an even larger range (e.g., 1°C–6°C regional warming in hot extremes in central Europe at 1.5°C of warming; Chapter 3, Sections 3.3.1 and 3.3.2). This large spread is due to both modelling uncertainty and internal climate variability. While the range is large, it also highlights risks that can be avoided with near certainty in a 1.5°C warmer world compared to worlds at higher levels of warming (e.g., an 8°C warming of cold extremes in the Arctic is not reached at 1.5°C of global warming in the multimodel ensemble but could happen at 2°C of global warming; Cross-Chapter Box 8, Figure 2). Inferred projected ranges of regional responses (mean value, minimum and maximum) for different mitigation scenarios from Chapter 2 are displayed in Cross-Chapter Box 8, Table 1.

- **What is the impact of emissions pathways with, versus without, an overshoot?** All mitigation pathways projecting less than 1.5°C of global warming over or at the end of the 21st century include some probability of overshooting 1.5°C. These pathways include some periods with warming stronger than 1.5°C in the course of the coming decades and/or some probability of not reaching 1.5°C (Chapter 2, Section 2.2). This is inherent to the difficulty of limiting global warming to 1.5°C, given that we are already very close to this warming level. The implications of overshooting are large for risks to natural and human

[7] Part of this discussion is based on Seneviratne et al. (2018b).

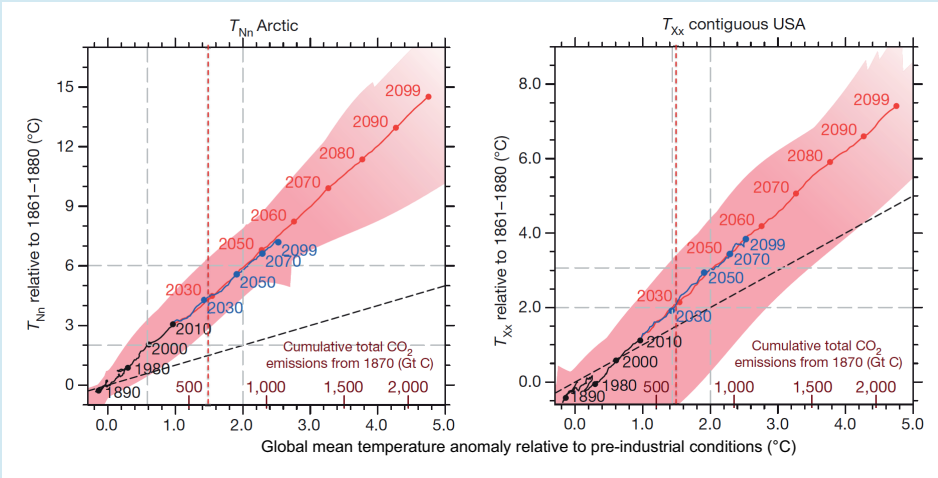
Cross-Chapter Box 8 (continued)



Cross-Chapter Box 8, Figure 1 | Range of projected realized temperatures at 1.5°C of global warming (due to stochastic noise and model-based spread). Temperatures with a 25% chance of occurrence at any location within a 10-year time frame are shown, corresponding to GMST anomalies of 1.5°C (Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel ensemble). The plots display the 25th percentile (Q25, left) and 75th percentile (Q75, right) values of mean temperature (Tmean), yearly maximum daytime temperature (TXx) and yearly minimum night-time temperature (TNn), sampled from all time frames with GMST anomalies of 1.5°C in Representative Concentration Pathway (RCP)8.5 model simulations of the CMIP5 ensemble. From Seneviratne et al. (2018b).

Cross-Chapter Box 8 (continued next page)

Cross-Chapter Box 8 (continued)



Cross-Chapter Box 8, Figure 2 | Spread of projected multimodel changes in minimum annual night-time temperature (TNn) in Arctic land (left) and in maximum annual daytime temperature (TXx) in the contiguous United States as a function of mean global warming in climate simulations. The multimodel range (due to model spread and internal climate variability) is indicated in red shading (minimum and maximum value based on climate model simulations). The multimodel mean value is displayed with solid red and blue lines for two emissions pathways (blue: Representative Concentration Pathway (RCP)4.5; red: RCP8.5). The dashed red line indicates projections for a 1.5°C warmer world. The dashed black line displays the 1:1 line. The figure is based on Figure 3 of Seneviratne et al. (2016).

systems, especially if the temperature at peak warming is high, because some risks may be long lasting and irreversible, such as the loss of some ecosystems (Chapter 3, Box 3.4). The chronology of emissions pathways and their implied warming is also important for the more slowly evolving parts of the Earth system, such as those associated with sea level rise. In addition, for several types of risks the rate of change may be most relevant (Loarie et al., 2009; LoPresti et al., 2015), with potentially large risks occurring in the case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. On the other hand, if overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate and unprecedented global efforts to mitigate GHGs are required (Cross-Chapter Box 8, Table 1; Chapter 4).

- **What is the probability of reaching 1.5°C of global warming if emissions compatible with 1.5°C pathways are followed?** Emissions pathways in a 'prospective scenario' (see Chapter 1, Section 1.2.3, and Cross-Chapter Box 1 in Chapter 1 on 'Scenarios and pathways') compatible with 1.5°C of global warming are determined based on their probability of reaching 1.5°C by 2100 (Chapter 2, Section 2.1), given current knowledge of the climate system response. These probabilities cannot be quantified precisely but are typically 50–66% in 1.5°C-consistent pathways (Section 1.2.3). This implies a one-in-two to one-in-three probability that global warming would exceed 1.5°C even under a 1.5°C-consistent pathway, including some possibility that global warming would be substantially over this value (generally about 5–10% probability; see Cross-Chapter Box 8, Table 1 and Seneviratne et al., 2018b). These alternative outcomes need to be factored into the decision-making process. To address this issue, 'adaptive' mitigation scenarios have been proposed in which emissions are continually adjusted to achieve a temperature goal (Millar et al., 2017). The set of dimensions involved in mitigation options (Chapter 4) is complex and need system-wide approaches to be successful. Adaptive scenarios could be facilitated by the global stocktake mechanism established in the Paris Agreement, and thereby transfer the risk of higher-than-expected warming to a risk of faster-than-expected mitigation efforts. However, there are some limits to the feasibility of such approaches because some investments, for example in infrastructure, are long term and also because the actual departure from an aimed pathway will need to be detected against the backdrop of internal climate variability, typically over several decades (Haustein et al., 2017; Seneviratne et al., 2018b). Avoiding impacts that depend on atmospheric composition as well as GMST (Baker et al., 2018) would also require limits on atmospheric CO_2 concentrations in the event of a lower-than-expected GMST response.

- **How can the transformation towards a 1.5°C warmer world be implemented?** This can be achieved in a variety of ways, such as decarbonizing the economy with an emphasis on demand reductions and sustainable lifestyles, or, alternatively, with an emphasis on large-scale technological solutions, amongst many other options (Chapter 2, Sections 2.3 and 2.4; Chapter 4, Sections 4.1 and 4.4.4). Different portfolios of mitigation measures come with distinct synergies and trade-offs with respect to other societal objectives. Integrated solutions and approaches are required to achieve multiple societal objectives simultaneously (see Chapter 4, Section 4.5.4 for a set of synergies and trade-offs).

Cross-Chapter Box 8 (continued)

- **What determines risks and opportunities in a 1.5°C warmer world?** The risks to natural, managed and human systems in a 1.5°C warmer world will depend not only on uncertainties in the regional climate that results from this level of warming, but also very strongly on the methods that humanity uses to limit global warming to 1.5°C. This is particularly the case for natural ecosystems and agriculture (see Cross-Chapter Box 7 in this chapter and Chapter 4, Section 4.3.2). The risks to human systems will also depend on the magnitude and effectiveness of policies and measures implemented to increase resilience to the risks of climate change and on development choices over coming decades, which will influence the underlying vulnerabilities and capacities of communities and institutions for responding and adapting.

- **Which aspects are not considered, or only partly considered, in the mitigation scenarios from Chapter 2?** These include biophysical impacts of land use, water constraints on energy infrastructure, and regional implications of choices of specific scenarios for tropospheric aerosol concentrations or the modulation of concentrations of short-lived climate forcers, that is, greenhouse gases (Chapter 3, Section 3.6.3). Such aspects of development pathways need to be factored into comprehensive assessments of the regional implications of mitigation and adaptation measures. On the other hand, some of these aspects are assessed in Chapter 4 as possible options for mitigation and adaptation to a 1.5°C warmer world.

- **Are there commonalities to all alternative 1.5°C warmer worlds?** Human-driven warming linked to CO_2 emissions is nearly irreversible over time frames of 1000 years or more (Matthews and Caldeira, 2008; Solomon et al., 2009). The GSMT of the Earth responds to the cumulative amount of CO_2 emissions. Hence, all 1.5°C stabilization scenarios require both net CO_2 emissions and multi-gas CO_2-forcing-equivalent emissions to be zero at some point (Chapter 2, Section 2.2). This is also the case for stabilization scenarios at higher levels of warming (e.g., at 2°C); the only difference is the projected time at which the net CO_2 budget is zero.

  Hence, a transition to decarbonization of energy use is necessary in all scenarios. It should be noted that **all scenarios of Chapter 2 include approaches for carbon dioxide removal (CDR)** in order to achieve the net zero CO_2 emissions budget. **Most of these use carbon capture and storage (CCS)** in addition to reforestation, although to varying degrees (Chapter 4, Section 4.3.7). Some potential pathways to 1.5°C of warming in 2100 would minimize the need for CDR (Obersteiner et al., 2018; van Vuuren et al., 2018). Taking into account the implementation of CDR, the CO_2-induced warming by 2100 is determined by the difference between the total amount of CO_2 generated (that can be reduced by early decarbonization) and the total amount permanently stored out of the atmosphere, for example by geological sequestration (Chapter 4, Section 4.3.7).

- **What are possible storylines of 'warmer worlds' at 1.5°C versus higher levels of global warming?** Cross-Chapter Box 8, Table 2 features possible storylines based on the scenarios of Chapter 2, the impacts of Chapters 3 and 5, and the options of Chapter 4. These storylines are not intended to be comprehensive of all possible future outcomes. Rather, they are intended as plausible scenarios of alternative warmer worlds, with two storylines that include stabilization at 1.5°C (Scenario 1) or close to 1.5°C (Scenario 2), and one storyline missing this goal and consequently only including reductions of CO_2 emissions and efforts towards stabilization at higher temperatures (Scenario 3).

Summary:

There is no single '1.5°C warmer world'. Impacts can vary strongly for different worlds characterized by a 1.5°C global warming. Important aspects to consider (besides the changes in global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of the increase in global surface temperature at 1.5°C could be achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of regional and subregional risks.

The implications of overshooting are large for risks to natural and human systems, especially if the temperature at peak warming is high, because some risks may be long lasting and irreversible, such as the loss of some ecosystems. In addition, for several types of risks, the rate of change may be most relevant, with potentially large risks occurring in the case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. If overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate and unprecedented global efforts to mitigate GHGs are required.

The time frame for initiating major mitigation measures is essential in order to reach a 1.5°C (or even a 2°C) global stabilization of climate warming (see consistent cumulative CO_2 emissions up to peak warming in Cross-Chapter Box 8, Table 1). If mitigation pathways are not rapidly activated, much more expensive and complex adaptation measures will have to be taken to avoid the impacts of higher levels of global warming on the Earth system.

Cross-Chapter Box 8 (continued next page)

Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 1 | Different worlds resulting from 1.5°C and 2°C mitigation (prospective) pathways, including 66% (probable) best-case outcome, and 5% worst-case outcome, based on Chapter 2 scenarios and Chapter 3 assessments of changes in regional climate. Note that the pathway characteristics estimates are based on computations with the MAGICC model (Meinshausen et al., 2011) consistent with the set-up used in AR5 WGIII (Clarke et al., 2014), but are uncertain and will be subject to updates and adjust-ments (see Chapter 2 for details). Updated from Seneviratne et al. (2018b).

		B1.5_LOS (below 1.5°C with low overshoot) with 2/3 ´probable best-case outcome´[a]	B1.5_LOS (below 1.5°C with low overshoot) with 1/20 ´worst-case outcome´[b]	L20 (lower than 2°C) with 2/3 ´probable best-case outcome´[a]	L20 (lower than 2°C) with 1/20 ´worst-case outcome´[b]
General characteristics of pathway	**Overshoot > 1.5°C in 21st century[c]**	**Yes (51/51)**	**Yes (51/51)**	**Yes (72/72)**	**Yes (72/72)**
	Overshoot > 2°C in 21st century	**No (0/51)**	**Yes (37/51)**	**No (72/72)**	**Yes (72/72)**
	Cumulative CO_2 emissions up to peak warming (relative to 2016)[d] [$GtCO_2$]	610–760	590–750	1150–1460	1130–1470
	Cumulative CO_2 emissions up to 2100 (relative to 2016)[d] [$GtCO_2$]	170–560		1030–1440	
	Global GHG emissions in 2030[d] [$GtCO_2$ y-1]	19–23		31–38	
	Years of global net zero CO_2 emissions[d]	2055–2066		2082–2090	
Possible climate range at peak warming (regional+global)	**Global mean temperature anomaly at peak warming**	**1.7°C (1.66°C–1.72°C)**	**2.05°C (2.00°C–2.09°C)**	**2.11°C (2.05°C–2.17°C)**	**2.67°C (2.59°C–2.76°C)**
	Warming in the Arctic[e] (TNn[f])	4.93°C (4.36, 5.52)	6.02°C (5.12, 6.89)	6.24°C (5.39, 7.21)	7.69°C (6.69, 8.93)
	Warming in Central North America[e] (TXx[g])	2.65°C (1.92, 3.15)	3.11°C (2.37, 3.63)	3.18°C (2.50, 3.71)	4.06°C (3.35, 4.63)
	Warming in Amazon region[e] (TXx)	2.55°C (2.23, 2.83)	3.07°C (2.74, 3.46)	3.16°C (2.84, 3.57)	4.05°C (3.62, 4.46)
	Drying in the Mediterranean region[e,h]	–1.11 (–2.24, –0.41)	–1.28 (–2.44, –0.51)	–1.38 (–2.58, –0.53)	–1.56 (–3.19, –0.67)
	Increase in heavy precipitation events[e] in Southern Asia[i]	9.94% (6.76, 14.00)	11.94% (7.52, 18.86)	12.68% (7.71, 22.39)	19.67% (11.56, 27.24)
Possible climate range in 2100 (regional+global)	**Global mean temperature warming in 2100**	**1.46°C (1.41°C–1.51°C)**	**1.87°C (1.81°C–1.94°C)**	**2.06°C (1.99°C–2.15°C)**	**2.66°C (2.56°C–2.76°C)**
	Warming in the Arctic[j] (TNn)	4.28°C (3.71, 4.77)	5.50°C (4.74, 6.21)	6.08°C (5.20, 6.94)	7.63°C (6.66, 8.90)
	Warming in Central North America[j] (TXx)	2.31°C (1.56, 2.66)	2.83°C (2.03, 3.49)	3.12°C (2.38, 3.67)	4.06°C (3.33, 4.59)
	Warming in Amazon region[j] (TXx)	2.22°C (2.00, 2.45)	2.76°C (2.50, 3.07)	3.10°C (2.75, 3.49)	4.03°C (3.62, 4.45)
	Drying in the Mediterranean region[j]	–0.95 (–1.98, –0.30)	–1.10 (–2.17, –0.51)	–1.26 (–2.43, –0.52)	–1.55 (–3.17, –0.67)
	Increase in heavy precipitation events in Southern Asia[j]	8.38% (4.63, 12.68)	10.34% (6.64, 16.07)	12.02% (7.41, 19.62)	19.72% (11.34, 26.95)

Notes:

a) 66th percentile for global temperature (that is, 66% likelihood of being at or below values)

b) 95th percentile for global temperature (that is, 5% likelihood of being at or above values)

c) All 1.5°C scenarios include a substantial probability of overshooting above 1.5°C global warming before returning to 1.5°C.

d) Interquartile range (25th percentile, q25, and 75th percentile, q75)

e) The regional projections in these rows provide the median and the range [q25, q75] associated with the median global temperature outcomes of the considered mitigation scenarios at peak warming.

f) TNn: Annual minimum night-time temperature

g) TXx: Annual maximum day-time temperature

h) Indicates drying of soil moisture expressed in units of standard deviations of pre-industrial climate (1861–1880) variability (where –1 is dry; –2 is severely dry; and –3 is very severely dry);

i) Rx5day: the annual maximum consecutive 5-day precipitation.

j) As for footnote e, but for the regional responses associated with the median global temperature outcomes of the considered mitigation scenarios in 2100

Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 2 | Storylines of possible worlds resulting from different mitigation options. The storylines build upon Cross-Chapter Box 8, Table 1 and the assessments of Chapters 1–5. Only a few of the many possible storylines were chosen and they are presented for illustrative purposes.

Scenario 1 [one possible storyline among best-case scenarios]: **Mitigation:** early move to decarbonization, decarbonization designed to minimize land footprint, coordination and rapid action of the world's nations towards 1.5°C goal by 2100 **Internal climate variability:** probable (66%) best-case outcome for global and regional climate responses	**In 2020, strong participation and support for the Paris Agreement and its ambitious goals for reducing CO_2 emissions by an almost unanimous international community led to a time frame for net zero emissions that is compatible with halting global warming at 1.5°C by 2100.** There is strong participation in all major world regions at the national, state and/or city levels. Transport is strongly decarbonized through a shift to electric vehicles, with more cars with electric than combustion engines being sold by 2025 (Chapter 2, Section 2.4.3; Chapter 4, Section 4.3.3). Several industry-sized plants for carbon capture and storage are installed and tested in the 2020s (Chapter 2, Section 2.4.2; Chapter 4, Sections 4.3.4 and 4.3.7). Competition for land between bioenergy cropping, food production, and biodiversity conservation is minimized by sourcing bioenergy for carbon capture and storage from agricultural wastes, algae and kelp farms (Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2). Agriculture is intensified in countries with coordinated planning associated with a drastic decrease in food waste (Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2). This leaves many natural ecosystems relatively intact, supporting continued provision of most ecosystem services, although relocation of species towards higher latitudes and elevations still results in changes in local biodiversity in many regions, particularly in mountain, tropical, coastal and Arctic ecosystems (Chapter 3, Section 3.4.3). Adaptive measures such as the establishment of corridors for the movement of species and parts of ecosystems become a central practice within conservation management (Chapter 3, Section 3.4.3; Chapter 4, Section 4.3.2). The movement of species presents new challenges for resource management as novel ecosystems, as well as pests and disease, increase (Cross-Chapter Box 6 in Chapter 3). Crops are grown on marginal land, no-till agriculture is deployed, and large areas are reforested with native trees (Chapter 2, Section 2.4.4; Chapter 3, Section 3.6.2; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2). Societal preference for healthy diets reduces meat consumption and associated GHG emissions (Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 6 in Chapter 3). By 2100, global mean temperature is on average 0.5°C warmer than it was in 2018 (Chapter 1, Section 1.2.1). Only a minor temperature overshoot occurs during the century (Chapter 2, Section 2.2). In mid-latitudes, frequent hot summers and precipitation events tend to be more intense (Chapter 3, Section 3.3). Coastal communities struggle with increased inundation associated with rising sea levels and more frequent and intense heavy rainfall (Chapter 3, Sections 3.3.2 and 3.3.9; Chapter 4, Section 4.3.2; Chapter 5, Box 5.3 and Section 5.3.2; Cross-Chapter Box 12 in Chapter 5), and some respond by moving, in many cases with consequences for urban areas. In the tropics, in particular in megacities, there are frequent deadly heatwaves whose risks are reduced by proactive adaptation (Chapter 3, Sections 3.3.1 and 3.4.8; Chapter 4, Section 4.3.8), overlaid on a suite of development challenges and limits in disaster risk management (Chapter 4, Section 4.3.3; Chapter 5, Sections 5.2.1 and 5.2.2; Cross-Chapter Box 12 in Chapter 5). Glaciers extent decreases in most mountainous areas (Chapter 3, Sections 3.3.5 and 3.5.4). Reduced Arctic sea ice opens up new shipping lanes and commercial corridors (Chapter 3, Section 3.3.8; Chapter 4, Box 4.3). Small island developing states (SIDS), as well as coastal and low-lying areas, have faced significant changes but have largely persisted in most regions (Chapter 3, Sections 3.3.9 and 3.5.4, Box 3.5). The Mediterranean area becomes drier (Chapter 3, Section 3.3.4 and Box 3.2) and irrigation of crops expands, drawing the water table down in many areas (Chapter 3, Section 3.4.6). The Amazon is reasonably well preserved, through avoided risk of droughts (Chapter 3, Sections 3.3.4 and 3.4.3; Chapter 4, Box 4.3) and reduced deforestation (Chapter 2, Section 2.4.4; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2), and the forest services are working with the pattern observed at the beginning of the 21st century (Chapter 4, Box 4.3). While some climate hazards become more frequent (Chapter 3, Section 3.3), timely adaptation measures help reduce the associated risks for most, although poor and disadvantaged groups continue to experience high climate risks to their livelihoods and well-being (Chapter 5, Section 5.3.1; Cross-Chapter Box 12 in Chapter 5; Chapter 3, Boxes 3.4 and 3.5; Cross-Chapter Box 6 in Chapter 3). Summer sea ice has not completely disappeared from the Arctic (Chapter 3, Section 3.4.4.7) and coral reefs, having been driven to a low level (10–30% of levels in 2018), have partially recovered by 2100 after extensive dieback (Chapter 3, Section 3.4.4.10 and Box 3.4). The Earth system, while warmer, is still recognizable compared to the 2000s, and no major tipping points are reached (Chapter 3, Section 3.5.2.5). Crop yields remain relatively stable (Chapter 3, Section 3.4). Aggregate economic damage of climate change impacts is relatively small, although there are some local losses associated with extreme weather events (Chapter 3, Section 3.5; Chapter 4). Human well-being remains overall similar to that in 2020 (Chapter 5, Section 5.2.2).
Scenario 2 [one possible storyline among mid-case scenarios]: **Mitigation:** delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), overshoot at 2°C, decrease towards 1.5°C afterward, no efforts to minimize the land and water footprints of bioenergy **Internal climate variability:** 10% worst-case outcome (2020s) followed by normal internal climate variability	**The international community continues to largely support the Paris Agreement and agrees in 2020 on reduction targets for CO_2 emissions and time frames for net zero emissions. However, these targets are not ambitious enough to reach stabilization at 2°C of warming, let alone 1.5°C.** In the 2020s, internal climate variability leads to higher warming than projected, in a reverse development to what happened in the so-called 'hiatus' period of the 2000s. Temperatures are regularly above 1.5°C of warming, although radiative forcing is consistent with a warming of 1.2°C or 1.3°C. Deadly heatwaves in major cities (Chicago, Kolkata, Beijing, Karachi, São Paulo), droughts in southern Europe, southern Africa and the Amazon region, and major flooding in Asia, all intensified by the global and regional warming (Chapter 3, Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.4.8; Cross-Chapter Box 11 in Chapter 4), lead to increasing levels of public unrest and political destabilization (Chapter 5, Section 5.2.1). An emergency global summit in 2025 moves to much more ambitious climate targets. Costs for rapidly phasing out fossil fuel use and infrastructure, while rapidly expanding renewables to reduce emissions, are much higher than in Scenario 1, owing to a failure to support economic measures to drive the transition (Chapter 4). Disruptive technologies become crucial to face up to the adaptation measures needed (Chapter 4, Section 4.4.4).

Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 2 *(continued)*

Scenario 2 [one possible storyline among mid-case scenarios]: **Mitigation:** delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), overshoot at 2°C, decrease towards 1.5°C afterward, no efforts to minimize the land and water footprints of bioenergy **Internal climate variability:** 10% worst-case outcome (2020s) followed by normal internal climate variability	Temperature peaks at 2°C of warming by the middle of the century before decreasing again owing to intensive implementation of bioenergy plants with carbon capture and storage (Chapter 2), without efforts to minimize the land and water footprint of bioenergy production (Cross-Chapter Box 7 in Chapter 3). Reaching 2°C of warming for several decades eliminates or severely damages key ecosystems such as coral reefs and tropical forests (Chapter 3, Section 3.4). The elimination of coral reef ecosystems and the deterioration of their calcified frameworks, as well as serious losses of coastal ecosystems such as mangrove forests and seagrass beds (Chapter 3, Boxes 3.4 and 3.5, Sections 3.4.4.10 and 3.4.5), leads to much reduced levels of coastal defence from storms, winds and waves. These changes increase the vulnerability and risks facing communities in tropical and subtropical regions, with consequences for many coastal communities (Cross-Chapter Box 12 in Chapter 5). These impacts are being amplified by steadily rising sea levels (Chapter 3, Section 3.3.9) and intensifying storms (Chapter 3, Section 3.4.4.3). The intensive area required for the production of bioenergy, combined with increasing water stress, puts pressure on food prices (Cross-Chapter Box 6 in Chapter 3), driving elevated rates of food insecurity, hunger and poverty (Chapter 4, Section 4.3.2; Cross-Chapter Box 6 in Chapter 3; Cross-Chapter Box 11 in Chapter 4). Crop yields decline significantly in the tropics, leading to prolonged famines in some African countries (Chapter 3, Section 3.4; Chapter 4, Section 4.3.2). Food trumps environment in terms of importance in most countries, with the result that natural ecosystems decrease in abundance, owing to climate change and land-use change (Cross-Chapter Box 7 in Chapter 3). The ability to implement adaptive action to prevent the loss of ecosystems is hindered under the circumstances and is consequently minimal (Chapter 3, Sections 3.3.6 and 3.4.4.10). Many natural ecosystems, in particular in the Mediterranean, are lost because of the combined effects of climate change and land-use change, and extinction rates increase greatly (Chapter 3, Section 3.4 and Box 3.2). By 2100, warming has decreased but is still stronger than 1.5°C, and the yields of some tropical crops are recovering (Chapter 3, Section 3.4.3). Several of the remaining natural ecosystems experience irreversible climate change-related damages whilst others have been lost to land-use change, with very rapid increases in the rate of species extinctions (Chapter 3, Section 3.4; Cross-Chapter Box 7 in Chapter 3; Cross-Chapter Box 11 in Chapter 4). Migration, forced displacement, and loss of identity are extensive in some countries, reversing some achievements in sustainable development and human security (Chapter 5, Section 5.3.2). Aggregate economic impacts of climate change damage are small, but the loss in ecosystem services creates large economic losses (Chapter 4, Sections 4.3.2 and 4.3.3). The health and well-being of people generally decrease from 2020, while the levels of poverty and disadvantage increase considerably (Chapter 5, Section 5.2.1).
Scenario 3 [one possible storyline among worst-case scenarios]: **Mitigation:** uncoordinated action, major actions late in the 21st century, 3°C of warming in 2100 **Internal climate variability:** unusual (ca. 10%) best-case scenario for one decade, followed by normal internal climate variability	**In 2020, despite past pledges, the international support for the Paris Agreement starts to wane. In the years that follow, CO_2 emissions are reduced at the local and national level but efforts are limited and not always successful.** Radiative forcing increases and, due to chance, the most extreme events tend to happen in less populated regions and thus do not increase global concerns. Nonetheless, there are more frequent heatwaves in several cities and less snow in mountain resorts in the Alps, Rockies and Andes (Chapter 3, Section 3.3). Global warming of 1.5°C is reached by 2030 but no major changes in policies occur. Starting with an intense El Niño–La Niña phase in the 2030s, several catastrophic years occur while global warming starts to approach 2°C. There are major heatwaves on all continents, with deadly consequences in tropical regions and Asian megacities, especially for those ill-equipped for protecting themselves and their communities from the effects of extreme temperatures (Chapter 3, Sections 3.3.1, 3.3.2 and 3.4.8). Droughts occur in regions bordering the Mediterranean Sea, central North America, the Amazon region and southern Australia, some of which are due to natural variability and others to enhanced greenhouse gas forcing (Chapter 3, Section 3.3.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 11 in Chapter 4). Intense flooding occurs in high-latitude and tropical regions, in particular in Asia, following increases in heavy precipitation events (Chapter 3, Section 3.3.3). Major ecosystems (coral reefs, wetlands, forests) are destroyed over that period (Chapter 3, Section 3.4), with massive disruption to local livelihoods (Chapter 5, Section 5.2.2 and Box 5.3; Cross-Chapter Box 12 in Chapter 5). An unprecedented drought leads to large impacts on the Amazon rainforest (Chapter 3, Sections 3.3.4 and 3.4), which is also affected by deforestation (Chapter 2). A hurricane with intense rainfall and associated with high storm surges (Chapter 3, Section 3.3.6) destroys a large part of Miami. A two-year drought in the Great Plains in the USA and a concomitant drought in eastern Europe and Russia decrease global crop production (Chapter 3, Section 3.3.4), resulting in major increases in food prices and eroding food security. Poverty levels increase to a very large scale, and the risk and incidence of starvation increase considerably as food stores dwindle in most countries; human health suffers (Chapter 3, Section 3.4.6.1; Chapter 4, Sections 4.3.2 and 4.4.3; Chapter 5, Section 5.2.1). There are high levels of public unrest and political destabilization due to the increasing climatic pressures, resulting in some countries becoming dysfunctional (Chapter 4, Sections 4.4.1 and 4.4.2). The main countries responsible for the CO_2 emissions design rapidly conceived mitigation plans and try to install plants for carbon capture and storage, in some cases without sufficient prior testing (Chapter 4, Section 4.3.6). Massive investments in renewable energy often happen too late and are uncoordinated; energy prices soar as a result of the high demand and lack of infrastructure. In some cases, demand cannot be met, leading to further delays. Some countries propose to consider sulphate-aerosol based Solar Radiation Modification (SRM) (Chapter 4, Section 4.3.8); however, intensive international negotiations on the topic take substantial time and are inconclusive because of overwhelming concerns about potential impacts on monsoon rainfall and risks in case of termination (Cross-Chapter Box 10 in Chapter 5). Global and regional temperatures continue to increase strongly while mitigation solutions are being developed and implemented.

Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 2 *(continued)*

Scenario 3 [one possible storyline among worst-case scenarios]: **Mitigation:** uncoordinated action, major actions late in the 21st century, 3°C of warming in 2100 **Internal climate variability:** unusual (ca. 10%) best-case scenario for one decade, followed by normal internal climate variability	Global mean warming reaches 3°C by 2100 but is not yet stabilized despite major decreases in yearly CO_2 emissions, as a net zero CO_2 emissions budget could not yet be achieved and because of the long lifetime of CO_2 concentrations (Chapters 1, 2 and 3). The world as it was in 2020 is no longer recognizable, with decreasing life expectancy, reduced outdoor labour productivity, and lower quality of life in many regions because of too frequent heatwaves and other climate extremes (Chapter 4, Section 4.3.3). Droughts and stress on water resources renders agriculture economically unviable in some regions (Chapter 3, Section 3.4; Chapter 4, Section 4.3.2) and contributes to increases in poverty (Chapter 5, Section 5.2.1; Cross-Chapter Box 12 in Chapter 5). Progress on the sustainable development goals is largely undone and poverty rates reach new highs (Chapter 5, Section 5.2.3). Major conflicts take place (Chapter 3, Section 3.4.9.6; Chapter 5, Section 5.2.1). Almost all ecosystems experience irreversible impacts, species extinction rates are high in all regions, forest fires escalate, and biodiversity strongly decreases, resulting in extensive losses to ecosystem services. These losses exacerbate poverty and reduce quality of life (Chapter 3, Section 3.4; Chapter 4, Section 4.3.2). Life for many indigenous and rural groups becomes untenable in their ancestral lands (Chapter 4, Box 4.3; Cross-Chapter Box 12 in Chapter 5). The retreat of the West Antarctic ice sheet accelerates (Chapter 3, Sections 3.3 and 3.6), leading to more rapid sea level rise (Chapter 3, Section 3.3.9; Chapter 4, Section 4.3.2). Several small island states give up hope of survival in their locations and look to an increasingly fragmented global community for refuge (Chapter 3, Box 3.5; Cross-Chapter Box 12 in Chapter 5). Aggregate economic damages are substantial, owing to the combined effects of climate changes, political instability, and losses of ecosystem services (Chapter 4, Sections 4.4.1 and 4.4.2; Chapter 3, Box 3.6 and Section 3.5.2.4). The general health and well-being of people is substantially reduced compared to the conditions in 2020 and continues to worsen over the following decades (Chapter 5, Section 5.2.3).

Frequently Asked Questions

FAQ 3.1 | What are the Impacts of 1.5°C and 2°C of Warming?

Summary: *The impacts of climate change are being felt in every inhabited continent and in the oceans. However, they are not spread uniformly across the globe, and different parts of the world experience impacts differently. An average warming of 1.5°C across the whole globe raises the risk of heatwaves and heavy rainfall events, amongst many other potential impacts. Limiting warming to 1.5°C rather than 2°C can help reduce these risks, but the impacts the world experiences will depend on the specific greenhouse gas emissions 'pathway' taken. The consequences of temporarily overshooting 1.5°C of warming and returning to this level later in the century, for example, could be larger than if temperature stabilizes below 1.5°C. The size and duration of an overshoot will also affect future impacts.*

Human activity has warmed the world by about 1°C since pre-industrial times, and the impacts of this warming have already been felt in many parts of the world. This estimate of the increase in global temperature is the average of many thousands of temperature measurements taken over the world's land and oceans. Temperatures are not changing at the same speed everywhere, however: warming is strongest on continents and is particularly strong in the Arctic in the cold season and in mid-latitude regions in the warm season. This is due to self-amplifying mechanisms, for instance due to snow and ice melt reducing the reflectivity of solar radiation at the surface, or soil drying leading to less evaporative cooling in the interior of continents. This means that some parts of the world have already experienced temperatures greater than 1.5°C above pre-industrial levels.

Extra warming on top of the approximately 1°C we have seen so far would amplify the risks and associated impacts, with implications for the world and its inhabitants. This would be the case even if the global warming is held at 1.5°C, just half a degree above where we are now, and would be further amplified at 2°C of global warming. Reaching 2°C instead of 1.5°C of global warming would lead to substantial warming of extreme hot days in all land regions. It would also lead to an increase in heavy rainfall events in some regions, particularly in the high latitudes of the Northern Hemisphere, potentially raising the risk of flooding. In addition, some regions, such as the Mediterranean, are projected to become drier at 2°C versus 1.5°C of global warming. The impacts of any additional warming would also include stronger melting of ice sheets and glaciers, as well as increased sea level rise, which would continue long after the stabilization of atmospheric CO_2 concentrations.

Change in climate means and extremes have knock-on effects for the societies and ecosystems living on the planet. Climate change is projected to be a poverty multiplier, which means that its impacts are expected to make the poor poorer and the total number of people living in poverty greater. The 0.5°C rise in global temperatures that we have experienced in the past 50 years has contributed to shifts in the distribution of plant and animal species, decreases in crop yields and more frequent wildfires. Similar changes can be expected with further rises in global temperature.

Essentially, the lower the rise in global temperature above pre-industrial levels, the lower the risks to human societies and natural ecosystems. Put another way, limiting warming to 1.5°C can be understood in terms of 'avoided impacts' compared to higher levels of warming. Many of the impacts of climate change assessed in this report have lower associated risks at 1.5°C compared to 2°C.

Thermal expansion of the ocean means sea level will continue to rise even if the increase in global temperature is limited to 1.5°C, but this rise would be lower than in a 2°C warmer world. Ocean acidification, the process by which excess CO_2 is dissolving into the ocean and increasing its acidity, is expected to be less damaging in a world where CO_2 emissions are reduced and warming is stabilized at 1.5°C compared to 2°C. The persistence of coral reefs is greater in a 1.5°C world than that of a 2°C world, too.

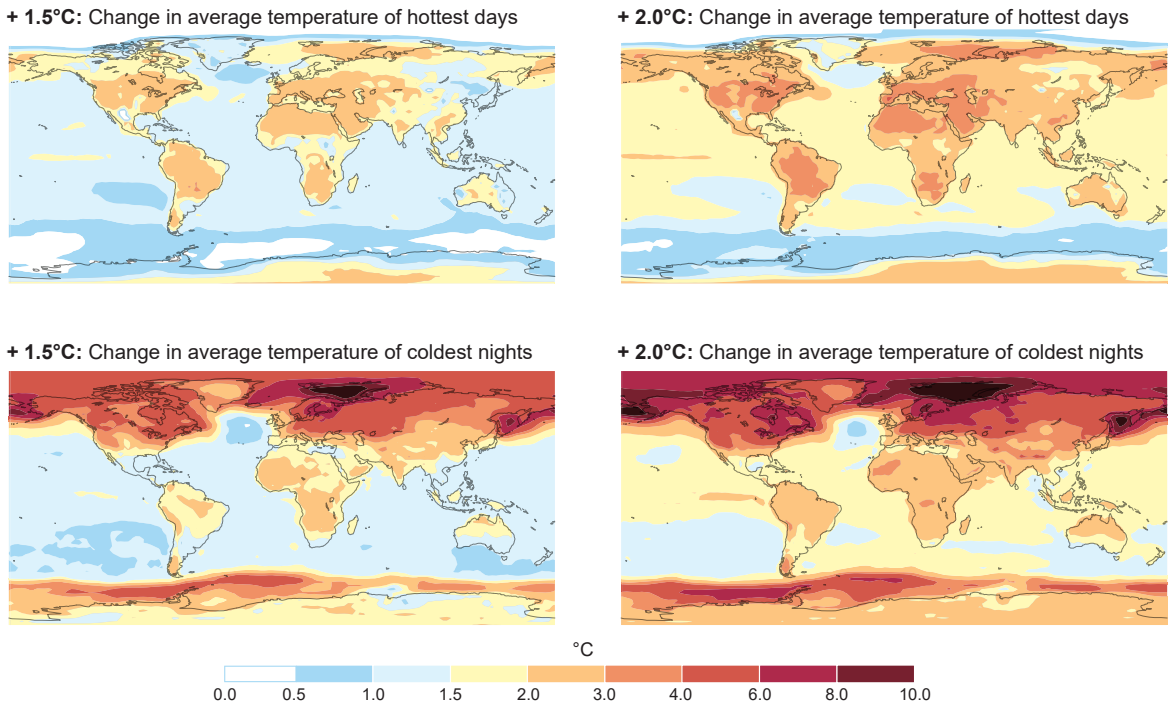
The impacts of climate change that we experience in future will be affected by factors other than the change in temperature. The consequences of 1.5°C of warming will additionally depend on the specific greenhouse gas emissions 'pathway' that is followed and the extent to which adaptation can reduce vulnerability. This IPCC Special Report uses a number of 'pathways' to explore different possibilities for limiting global warming to 1.5°C above pre-industrial levels. One type of pathway sees global temperature stabilize at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before declining later in the century (known as an 'overshoot' pathway).

(continued on next page)

Such pathways would have different associated impacts, so it is important to distinguish between them for planning adaptation and mitigation strategies. For example, impacts from an overshoot pathway could be larger than impacts from a stabilization pathway. The size and duration of an overshoot would also have consequences for the impacts the world experiences. For instance, pathways that overshoot 1.5°C run a greater risk of passing through 'tipping points', thresholds beyond which certain impacts can no longer be avoided even if temperatures are brought back down later on. The collapse of the Greenland and Antarctic ice sheets on the time scale of centuries and millennia is one example of a tipping point.

FAQ3.1:**Impact of 1.5°C and 2.0°C global warming**

Temperature rise is not uniform across the world. Some regions will experience greater increases in the temperature of hot days and cold nights than others.



FAQ 3.1, Figure 1 | Temperature change is not uniform across the globe. Projected changes are shown for the average temperature of the annual hottest day (top) and the annual coldest night (bottom) with 1.5°C of global warming (left) and 2°C of global warming (right) compared to pre-industrial levels.

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4

Strengthening and Implementing the Global Response

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Executive Summary

Limiting warming to 1.5°C above pre-industrial levels would require transformative systemic change, integrated with sustainable development. Such change would require the upscaling and acceleration of the implementation of far-reaching, multilevel and cross-sectoral climate mitigation and addressing barriers. Such systemic change would need to be linked to complementary adaptation actions, including transformational adaptation, especially for pathways that temporarily overshoot 1.5°C (*medium evidence, high agreement*) {Chapter 2, Chapter 3, 4.2.1, 4.4.5, 4.5}. Current national pledges on mitigation and adaptation are not enough to stay below the Paris Agreement temperature limits and achieve its adaptation goals. While transitions in energy efficiency, carbon intensity of fuels, electrification and land-use change are underway in various countries, limiting warming to 1.5°C will require a greater scale and pace of change to transform energy, land, urban and industrial systems globally. {4.3, 4.4, Cross-Chapter Box 9 in this Chapter}

Although multiple communities around the world are demonstrating the possibility of implementation consistent with 1.5°C pathways {Boxes 4.1-4.10}, very few countries, regions, cities, communities or businesses can currently make such a claim (*high confidence*). To strengthen the global response, almost all countries would need to significantly raise their level of ambition. Implementation of this raised ambition would require enhanced institutional capabilities in all countries, including building the capability to utilize indigenous and local knowledge (*medium evidence, high agreement*). In developing countries and for poor and vulnerable people, implementing the response would require financial, technological and other forms of support to build capacity, for which additional local, national and international resources would need to be mobilized (*high confidence*). However, public, financial, institutional and innovation capabilities currently fall short of implementing far-reaching measures at scale in all countries (*high confidence*). Transnational networks that support multilevel climate action are growing, but challenges in their scale-up remain. {4.4.1, 4.4.2, 4.4.4, 4.4.5, Box 4.1, Box 4.2, Box 4.7}

Adaptation needs will be lower in a 1.5°C world compared to a 2°C world (*high confidence*) {Chapter 3; Cross-Chapter Box 11 in this chapter}. Learning from current adaptation practices and strengthening them through adaptive governance {4.4.1}, lifestyle and behavioural change {4.4.3} and innovative financing mechanisms {4.4.5} can help their mainstreaming within sustainable development practices. Preventing maladaptation, drawing on bottom-up approaches {Box 4.6} and using indigenous knowledge {Box 4.3} would effectively engage and protect vulnerable people and communities. While adaptation finance has increased quantitatively, significant further expansion would be needed to adapt to 1.5°C. Qualitative gaps in the distribution of adaptation finance, readiness to absorb resources, and monitoring mechanisms undermine the potential of adaptation finance to reduce impacts. {Chapter 3, 4.4.2, 4.4.5, 4.6}

System Transitions

The energy system transition that would be required to limit global warming to 1.5°C above pre-industrial conditions is underway in many sectors and regions around the world (*medium evidence, high agreement*). The political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years, while that of nuclear energy and carbon dioxide capture and storage (CCS) in the electricity sector have not shown similar improvements. {4.3.1}

Electrification, hydrogen, bio-based feedstocks and substitution, and, in several cases, carbon dioxide capture, utilization and storage (CCUS) would lead to the deep emissions reductions required in energy-intensive industries to limit warming to 1.5°C. However, those options are limited by institutional, economic and technical constraints, which increase financial risks to many incumbent firms (*medium evidence, high agreement*). Energy efficiency in industry is more economically feasible and helps enable industrial system transitions but would have to be complemented with greenhouse gas (GHG)-neutral processes or carbon dioxide removal (CDR) to make energy-intensive industries consistent with 1.5°C (*high confidence*). {4.3.1, 4.3.4}

Global and regional land-use and ecosystems transitions and associated changes in behaviour that would be required to limit warming to 1.5°C can enhance future adaptation and land-based agricultural and forestry mitigation potential. Such transitions could, however, carry consequences for livelihoods that depend on agriculture and natural resources {4.3.2, Cross-Chapter Box 6 in Chapter 3}. Alterations of agriculture and forest systems to achieve mitigation goals could affect current ecosystems and their services and potentially threaten food, water and livelihood security. While this could limit the social and environmental feasibility of land-based mitigation options, careful design and implementation could enhance their acceptability and support sustainable development objectives (*medium evidence, medium agreement*). {4.3.2, 4.5.3}

Changing agricultural practices can be an effective climate adaptation strategy. A diversity of adaptation options exists, including mixed crop-livestock production systems which can be a cost-effective adaptation strategy in many global agriculture systems (*robust evidence, medium agreement*). Improving irrigation efficiency could effectively deal with changing global water endowments, especially if achieved via farmers adopting new behaviours and water-efficient practices rather than through large-scale infrastructural interventions (*medium evidence, medium agreement*). Well-designed adaptation processes such as community-based adaptation can be effective depending upon context and levels of vulnerability. {4.3.2, 4.5.3}

Improving the efficiency of food production and closing yield gaps have the potential to reduce emissions from agriculture, reduce pressure on land, and enhance food security and future

mitigation potential (*high confidence*). Improving productivity of existing agricultural systems generally reduces the emissions intensity of food production and offers strong synergies with rural development, poverty reduction and food security objectives, but options to reduce absolute emissions are limited unless paired with demand-side measures. Technological innovation including biotechnology, with adequate safeguards, could contribute to resolving current feasibility constraints and expand the future mitigation potential of agriculture. {4.3.2, 4.4.4}

Shifts in dietary choices towards foods with lower emissions and requirements for land, along with reduced food loss and waste, could reduce emissions and increase adaptation options (*high confidence*). Decreasing food loss and waste and changing dietary behaviour could result in mitigation and adaptation (*high confidence*) by reducing both emissions and pressure on land, with significant co-benefits for food security, human health and sustainable development {4.3.2, 4.4.5, 4.5.2, 4.5.3, 5.4.2}, but evidence of successful policies to modify dietary choices remains limited.

Mitigation and Adaptation Options and Other Measures

A mix of mitigation and adaptation options implemented in a participatory and integrated manner can enable rapid, systemic transitions – in urban and rural areas – that are necessary elements of an accelerated transition consistent with limiting warming to 1.5°C. Such options and changes are most effective when aligned with economic and sustainable development, and when local and regional governments are supported by national governments {4.3.3, 4.4.1, 4.4.3}. Various mitigation options are expanding rapidly across many geographies. Although many have development synergies, not all income groups have so far benefited from them. Electrification, end-use energy efficiency and increased share of renewables, amongst other options, are lowering energy use and decarbonizing energy supply in the built environment, especially in buildings. Other rapid changes needed in urban environments include demotorization and decarbonization of transport, including the expansion of electric vehicles, and greater use of energy-efficient appliances (*medium evidence, high agreement*). Technological and social innovations can contribute to limiting warming to 1.5°C, for example, by enabling the use of smart grids, energy storage technologies and general-purpose technologies, such as information and communication technology (ICT) that can be deployed to help reduce emissions. Feasible adaptation options include green infrastructure, resilient water and urban ecosystem services, urban and peri-urban agriculture, and adapting buildings and land use through regulation and planning (*medium evidence, medium to high agreement*). {4.3.3, 4.4.3, 4.4.4}

Synergies can be achieved across systemic transitions through several overarching adaptation options in rural and urban areas. Investments in health, social security and risk sharing and spreading are cost-effective adaptation measures with high potential for scaling up (*medium evidence, medium to high agreement*). Disaster risk management and education-based adaptation have lower prospects of scalability and cost-effectiveness (*medium evidence, high agreement*) but are critical for building adaptive capacity. {4.3.5, 4.5.3}

Converging adaptation and mitigation options can lead to synergies and potentially increase cost-effectiveness, but multiple trade-offs can limit the speed of and potential for scaling up. Many examples of synergies and trade-offs exist in all sectors and system transitions. For instance, sustainable water management (*high evidence, medium agreement*) and investment in green infrastructure (*medium evidence, high agreement*) to deliver sustainable water and environmental services and to support urban agriculture are less cost-effective than other adaptation options but can help build climate resilience. Achieving the governance, finance and social support required to enable these synergies and to avoid trade-offs is often challenging, especially when addressing multiple objectives, and attempting appropriate sequencing and timing of interventions. {4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

Though CO_2 dominates long-term warming, the reduction of warming short-lived climate forcers (SLCFs), such as methane and black carbon, can in the short term contribute significantly to limiting warming to 1.5°C above pre-industrial levels. Reductions of black carbon and methane would have substantial co-benefits (*high confidence*), including improved health due to reduced air pollution. This, in turn, enhances the institutional and socio-cultural feasibility of such actions. Reductions of several warming SLCFs are constrained by economic and social feasibility (*low evidence, high agreement*). As they are often co-emitted with CO_2, achieving the energy, land and urban transitions necessary to limit warming to 1.5°C would see emissions of warming SLCFs greatly reduced. {2.3.3.2, 4.3.6}

Most CDR options face multiple feasibility constraints, which differ between options, limiting the potential for any single option to sustainably achieve the large-scale deployment required in the 1.5°C-consistent pathways described in Chapter 2 (*high confidence*). Those 1.5°C pathways typically rely on bioenergy with carbon capture and storage (BECCS), afforestation and reforestation (AR), or both, to neutralize emissions that are expensive to avoid, or to draw down CO_2 emissions in excess of the carbon budget {Chapter 2}. Though BECCS and AR may be technically and geophysically feasible, they face partially overlapping yet different constraints related to land use. The land footprint per tonne of CO_2 removed is higher for AR than for BECCS, but given the low levels of current deployment, the speed and scales required for limiting warming to 1.5°C pose a considerable implementation challenge, even if the issues of public acceptance and absence of economic incentives were to be resolved (*high agreement, medium evidence*). The large potential of afforestation and the co-benefits if implemented appropriately (e.g., on biodiversity and soil quality) will diminish over time, as forests saturate (*high confidence*). The energy requirements and economic costs of direct air carbon capture and storage (DACCS) and enhanced weathering remain high (*medium evidence, medium agreement*). At the local scale, soil carbon sequestration has co-benefits with agriculture and is cost-effective even without climate policy (*high confidence*). Its potential feasibility and cost-effectiveness at the global scale appears to be more limited. {4.3.7}

Uncertainties surrounding solar radiation modification (SRM) measures constrain their potential deployment. These uncertainties include: technological immaturity; limited physical

understanding about their effectiveness to limit global warming; and a weak capacity to govern, legitimize, and scale such measures. Some recent model-based analysis suggests SRM would be effective but that it is too early to evaluate its feasibility. Even in the uncertain case that the most adverse side-effects of SRM can be avoided, public resistance, ethical concerns and potential impacts on sustainable development could render SRM economically, socially and institutionally undesirable (*low agreement, medium evidence*). {4.3.8, Cross-Chapter Box 10 in this chapter}

Enabling Rapid and Far-Reaching Change

The speed of transitions and of technological change required to limit warming to 1.5°C above pre-industrial levels has been observed in the past within specific sectors and technologies {4.2.2.1}. But the geographical and economic scales at which the required rates of change in the energy, land, urban, infrastructure and industrial systems would need to take place are larger and have no documented historic precedent (*limited evidence, medium agreement*). To reduce inequality and alleviate poverty, such transformations would require more planning and stronger institutions (including inclusive markets) than observed in the past, as well as stronger coordination and disruptive innovation across actors and scales of governance. {4.3, 4.4}

Governance consistent with limiting warming to 1.5°C and the political economy of adaptation and mitigation can enable and accelerate systems transitions, behavioural change, innovation and technology deployment (*medium evidence, medium agreement*). For 1.5°C-consistent actions, an effective governance framework would include: accountable multilevel governance that includes non-state actors, such as industry, civil society and scientific institutions; coordinated sectoral and cross-sectoral policies that enable collaborative multi-stakeholder partnerships; strengthened global-to-local financial architecture that enables greater access to finance and technology; addressing climate-related trade barriers; improved climate education and greater public awareness; arrangements to enable accelerated behaviour change; strengthened climate monitoring and evaluation systems; and reciprocal international agreements that are sensitive to equity and the Sustainable Development Goals (SDGs). System transitions can be enabled by enhancing the capacities of public, private and financial institutions to accelerate climate change policy planning and implementation, along with accelerated technological innovation, deployment and upkeep. {4.4.1, 4.4.2, 4.4.3, 4.4.4}

Behaviour change and demand-side management can significantly reduce emissions, substantially limiting the reliance on CDR to limit warming to 1.5°C {Chapter 2, 4.4.3}. Political and financial stakeholders may find climate actions more cost-effective and socially acceptable if multiple factors affecting behaviour are considered, including aligning these actions with people's core values (*medium evidence, high agreement*). Behaviour- and lifestyle-related measures and demand-side management have already led to emission reductions around the world and can enable significant future reductions (*high confidence*). Social innovation through bottom-up initiatives can result in greater participation in the governance of systems transitions and increase support for technologies, practices and policies that are part of the global response to limit warming to 1.5°C . {Chapter 2, 4.4.1, 4.4.3, Figure 4.3}

This rapid and far-reaching response required to keep warming below 1.5°C and enhance the capacity to adapt to climate risks would require large increases of investments in low-emission infrastructure and buildings, along with a redirection of financial flows towards low-emission investments (*robust evidence, high agreement*). An estimated mean annual incremental investment of around 1.5% of global gross fixed capital formation (GFCF) for the energy sector is indicated between 2016 and 2035, as well as about 2.5% of global GFCF for other development infrastructure that could also address SDG implementation. Though quality policy design and effective implementation may enhance efficiency, they cannot fully substitute for these investments. {2.5.2, 4.2.1, 4.4.5}

Enabling this investment requires the mobilization and better integration of a range of policy instruments that include the reduction of socially inefficient fossil fuel subsidy regimes and innovative price and non-price national and international policy instruments. These would need to be complemented by de-risking financial instruments and the emergence of long-term low-emission assets. These instruments would aim to reduce the demand for carbon-intensive services and shift market preferences away from fossil fuel-based technology. Evidence and theory suggest that carbon pricing alone, in the absence of sufficient transfers to compensate their unintended distributional cross-sector, cross-nation effects, cannot reach the incentive levels needed to trigger system transitions (*robust evidence, medium agreement*). But, embedded in consistent policy packages, they can help mobilize incremental resources and provide flexible mechanisms that help reduce the social and economic costs of the triggering phase of the transition (*robust evidence, medium agreement*). {4.4.3, 4.4.4, 4.4.5}

Increasing evidence suggests that a climate-sensitive realignment of savings and expenditure towards low-emission, climate-resilient infrastructure and services requires an evolution of global and national financial systems. Estimates suggest that, in addition to climate-friendly allocation of public investments, a potential redirection of 5% to 10% of the annual capital revenues[1] is necessary for limiting warming to 1.5°C {4.4.5, Table 1 in Box 4.8}. This could be facilitated by a change of incentives for private day-to-day expenditure and the redirection of savings from speculative and precautionary investments towards long-term productive low-emission assets and services. This implies the mobilization of institutional investors and mainstreaming of climate finance within financial and banking system regulation. Access by developing countries to low-risk and low-interest finance through multilateral and national development banks would have to be facilitated (*medium evidence, high agreement*). New forms of public–private partnerships may be needed with multilateral, sovereign and sub-sovereign guarantees to de-risk climate-friendly investments, support new business models for small-scale enterprises and help households with limited access to capital. Ultimately, the aim is to

[1] Annual capital revenues are paid interests plus an increase of asset value.

promote a portfolio shift towards long-term low-emission assets that would help redirect capital away from potentially stranded assets (*medium evidence, medium agreement*). {4.4.5}

Knowledge Gaps

Knowledge gaps around implementing and strengthening the global response to climate change would need to be urgently resolved if the transition to a 1.5°C world is to become reality. Remaining questions include: how much can be realistically expected from innovation and behavioural and systemic political and economic changes in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organised within a global governance framework and financial system, based on principles of justice and ethics (including 'common but differentiated responsibilities and respective capabilities' (CBDR-RC)), reciprocity and partnership? To what extent would limiting warming to 1.5°C require a harmonization of macro-financial and fiscal policies, which could include financial regulators such as central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives? {4.1, 4.3.7, 4.4.1, 4.4.5, 4.6}

4.1 Accelerating the Global Response to Climate Change

This chapter discusses how the global economy and socio-technical and socio-ecological systems can transition to 1.5°C-consistent pathways and adapt to warming of 1.5°C above pre-industrial levels. In the context of systemic transitions, the chapter assesses adaptation and mitigation options, including carbon dioxide removal (CDR), and potential solar radiation modification (SRM) remediative measures (Section 4.3), as well as the enabling conditions that would be required for implementing the rapid and far-reaching global response of limiting warming to 1.5°C (Section 4.4), and render the options more or less feasible (Section 4.5).

The impacts of a 1.5°C-warmer world, while less than in a 2°C-warmer world, would require complementary adaptation and development action, typically at local and national scale. From a mitigation perspective, 1.5°C-consistent pathways require immediate action on a greater and global scale so as to achieve net zero emissions by mid-century, or earlier (Chapter 2). This chapter and Chapter 5 highlight the potential that combined mitigation, development and poverty reduction offer for accelerated decarbonization.

The global context is an increasingly interconnected world, with the human population growing from the current 7.6 billion to over 9 billion by mid-century (UN DESA, 2017). There has been a consistent growth of global economic output, wealth and trade with a significant reduction in extreme poverty. These trends could continue for the next few decades (Burt et al., 2014), potentially supported by new and disruptive information and communication, and nano- and bio-technologies. However, these trends co-exist with rising inequality (Piketty, 2014), exclusion and social stratification, and regions locked in poverty traps (Deaton, 2013) that could fuel social and political tensions.

The aftermath of the 2008 financial crisis generated a challenging environment in which leading economists have issued repeated alerts about the 'discontents of globalisation' (Stiglitz, 2002), 'depression economics' (Krugman, 2009), an excessive reliance of export-led development strategies (Rajan, 2011), and risks of 'secular stagnation' due to the 'saving glut' that slows down the flow of global savings towards productive 1.5°C-consistent investments (Summers, 2016). Each of these affects the implementation of both 1.5°C-consistent pathways and sustainable development (Chapter 5).

The range of mitigation and adaptation actions that can be deployed in the short run are well-known: for example, low-emission technologies, new infrastructure, and energy efficiency measures in buildings, industry and transport; transformation of fiscal structures; reallocation of investments and human resources towards low-emission assets; sustainable land and water management; ecosystem restoration; enhancement of adaptive capacities to climate risks and impacts; disaster risk management; research and development; and mobilization of new, traditional and indigenous knowledge.

The convergence of short-term development co-benefits from mitigation and adaptation to address 'everyday development failures' (e.g., institutions, market structures and political processes) (Hallegatte et al., 2016; Pelling et al., 2018) could enhance the adaptive capacity of key systems at risk (e.g., water, energy, food, biodiversity, urban, regional and coastal systems) to 1.5°C climate impacts (Chapter 3). The issue is whether aligning 1.5°C-consistent pathways with the Sustainable Development Goals (SDGs) will secure support for accelerated change and a new growth cycle (Stern, 2013, 2015). It is difficult to imagine how a 1.5°C world would be attained unless the SDG on cities and sustainable urbanization is achieved in developing countries (Revi, 2016), or without reforms in the global financial intermediation system.

Unless affordable and environmentally and socially acceptable CDR becomes feasible and available at scale well before 2050, 1.5°C-consistent pathways will be difficult to realize, especially in overshoot scenarios. The social costs and benefits of 1.5°C-consistent pathways depend on the depth and timing of policy responses and their alignment with short term and long-term development objectives, through policy packages that bring together a diversity of policy instruments, including public investment (Grubb et al., 2014; Winkler and Dubash, 2015; Campiglio, 2016).

Whatever its potential long-term benefits, a transition to a 1.5°C world may suffer from a lack of broad political and public support, if it exacerbates existing short-term economic and social tensions, including unemployment, poverty, inequality, financial tensions, competitiveness issues and the loss of economic value of carbon-intensive assets (Mercure et al., 2018). The challenge is therefore how to strengthen climate policies without inducing economic collapse or hardship, and to make them contribute to reducing some of the 'fault lines' of the world economy (Rajan, 2011).

This chapter reviews literature addressing the alignment of climate with other public policies (e.g., fiscal, trade, industrial, monetary, urban planning, infrastructure, and innovation) and with a greater access to basic needs and services, defined by the SDGs. It also reviews how de-risking low-emission investments and the evolution of the financial intermediation system can help reduce the 'savings glut' (Arezki et al., 2016) and the gap between cash balances and long-term assets (Aglietta et al., 2015b) to support more sustainable and inclusive growth.

As the transitions associated with 1.5°C-consistent pathways require accelerated and coordinated action, in multiple systems across all world regions, they are inherently exposed to risks of freeriding and moral hazards. A key governance challenge is how the convergence of voluntary domestic policies can be organized via aligned global, national and sub-national governance, based on reciprocity (Ostrom and Walker, 2005) and partnership (UN, 2016), and how different actors and processes in climate governance can reinforce each other to enable this (Gupta, 2014; Andonova et al., 2017). The emergence of polycentric sources of climate action and transnational and subnational networks that link these efforts (Abbott, 2012) offer the opportunity to experiment and learn from different approaches, thereby accelerating approaches led by national governments (Cole, 2015; Jordan et al., 2015).

Section 4.2 of this chapter outlines existing rates of change and attributes of accelerated change. Section 4.3 identifies global systems, and their components, that offer options for this change. Section 4.4 documents the enabling conditions that influence the feasibility of those options, including economic, financial and policy instruments that could trigger the transition to 1.5°C-consistent pathways. Section 4.5 assesses mitigation and adaptation options for feasibility, strategies for implementation and synergies and trade-offs between mitigation and adaptation.

4.2 Pathways Compatible with 1.5°C: Starting Points for Strengthening Implementation

4.2.1 Implications for Implementation of 1.5°C-Consistent Pathways

The 1.5°C-consistent pathways assessed in Chapter 2 form the basis for the feasibility assessment in section 4.5. A wide range of 1.5°C-consistent pathways from integrated assessment modelling (IAM), supplemented by other literature, are assessed in Chapter 2 (Sections 2.1, 2.3, 2.4, and 2.5). The most common feature shared by these pathways is their requirement for faster and more radical changes compared to 2°C and higher warming pathways.

A variety of 1.5°C-consistent technological options and policy targets is identified in the assessed modelling literature (Sections 2.3, 2.4, 2.5). These technology and policy options include energy demand reduction, greater penetration of low-emission and carbon-free technologies as well as electrification of transport and industry, and reduction of land-use change. Both the detailed integrated modelling pathway literature and a number of broader sectoral and bottom-up studies provide examples of how these sectoral technological and policy characteristics can be broken down sectorally for 1.5°C-consistent pathways (see Table 4.1).

Both the integrated pathway literature and the sectoral studies agree on the need for rapid transitions in the production and use of energy across various sectors, to be consistent with limiting global warming to 1.5°C. The pace of these transitions is particularly significant for the supply mix and electrification (Table 4.1). Individual, sectoral studies may show higher rates of change compared to IAMs (Figueres et al., 2017; Rockström et al., 2017; WBCSD, 2017; Kuramochi et al., 2018). These trends and transformation patterns create opportunities and challenges for both mitigation and adaptation (Sections 4.2.1.1 and 4.2.1.2) and have significant implications for the assessment of feasibility and enablers, including governance, institutions, and policy instruments addressed in Sections 4.3 and 4.4.

Table 4.1 | Sectoral indicators of the pace of transformation in 1.5°C-consistent pathways, based on selected integrated pathways assessed in Chapter 2 (from the scenario database) and several other studies reviewed in Chapter 2 that assess mitigation transitions consistent with limiting warming to 1.5°C. Values for '1.5°C-no or -low-OS' and '1.5C-high-OS' indicate the median and the interquartile ranges for 1.5°C scenarios. If a number in square brackets is indicated, this is the number of scenarios for this indicator. S1, S2, S5 and LED represent the four illustrative pathway archetypes selected for this assessment (see Chapter 2, Section 2.1 and Supplementary Material 4.SM.1 for detailed description).

Pathways		Number of scenarios	Energy		Buildings	Transport		Industry
			Share of renewables in primary energy [%]	Share of renewables in electricity [%]	Change in energy demand for buildings (2010 baseline) [%]	Share of low-carbon fuels (electricity, hydrogen and biofuel) in transport [%]	Share of electricity in transport [%]	Industrial emissions reductions (2010 baseline) [%]
IAM Pathways 2030	1.5°C-no or low-OS	50	29 (37; 26)	54 (65; 47)	0 (7; –7) [42]	12 (18; 9) [29]	5 (7; 3) [49]	42 (55; 34) [42]
	1.5°C-high-OS	35	24 (27; 20)	43 (54; 37)	–17 (–12; –20) [29]	7 (8; 6) [23]	3 (5; 3)	18 (28; –13) [29]
	S1		29	58	–8		4	49
	S2		29	48	–14	5	4	19
	S5		14	25		3	1	
	LED		37	60	30		21	42
Other Studies 2030	Löffler et al. (2017)		46	79				
	IEA (2017c) (ETP)		31	47	2	14	5	22
	IEA (2017g) (WEM)		27	50	–6	17	6	15
IAM Pathways 2050	1.5°C-no or low-OS	50	60 (67; 52)	77 (86; 69)	–17 (3; –36) [42]	55 (66; 35) [29]	23 (29; 17) [49]	79 (91; 67) [42]
	1.5°C-high-OS	35	62 (68; 47)	82 (88; 64)	–37 (–13; –51) [29]	38 (44; 27) [23]	18 (23; 14)	68 (81; 54) [29]
	S1		58	81	–21		34	74
	S2		53	63	–25	26	23	73
	S5		67	70		53	10	
	LED		73	77	45		59	91
Other Studies 2050	Löffler et al. (2017)		100	100				
	IEA (2017c) (ETP)		58	74	5	55	30	57
	IEA (2017g) (WEM)		47	69	–5	58	32	55

4.2.1.1 Challenges and Opportunities for Mitigation Along the Reviewed Pathways

Greater scale, speed and change in investment patterns. There is agreement in the literature reviewed by Chapter 2 that staying below 1.5°C would entail significantly greater transformation in terms of energy systems, lifestyles and investments patterns compared to 2°C-consistent pathways. Yet there is *limited evidence* and *low agreement* regarding the magnitudes and costs of the investments (Sections 2.5.1, 2.5.2 and 4.4.5). Based on the IAM literature reviewed in Chapter 2, climate policies in line with limiting warming to 1.5°C would require a marked upscaling of supply-side energy system investments between now and mid-century, reaching levels of between 1.6–3.8 trillion USD yr^{-1} globally with an average of about 3.5 trillion USD yr^{-1} over 2016–2050 (see Figure 2.27). This can be compared to an average of about 3.0 trillion USD yr^{-1} over the same period for 2°C-consistent pathways (also in Figure 2.27).

Not only the level of investment but also the type and speed of sectoral transformation would be impacted by the transitions associated with 1.5°C-consistent pathways. IAM literature projects that investments in low-emission energy would overtake fossil fuel investments globally by 2025 in 1.5°C-consistent pathways (Chapter 2, Section 2.5.2). The projected low-emission investments in electricity generation allocations over the period 2016–2050 are: solar (0.09–1.0 trillion USD yr^{-1}), wind (0.1–0.35 trillion USD yr^{-1}), nuclear (0.1–0.25 trillion USD yr^{-1}), and transmission, distribution, and storage (0.3–1.3 trillion USD yr^{-1}). In contrast, investments in fossil fuel extraction and unabated fossil electricity generation along a 1.5°C-consistent pathway are projected to drop by 0.3–0.85 trillion USD yr^{-1} over the period 2016–2050, with investments in unabated coal generation projected to halt by 2030 in most 1.5°C-consistent pathways (Chapter 2, Section 2.5.2). Estimates of investments in other infrastructure are currently unavailable, but they could be considerably larger in volume than solely those in the energy sector (Section 4.4.5).

Greater policy design and decision-making implications. The 1.5°C-consistent pathways raise multiple challenges for effective policy design and responses to address the scale, speed, and pace of mitigation technology, finance and capacity building needs. These policies and responses would also need to deal with their distributional implications while addressing adaptation to residual climate impacts (see Chapter 5). The available literature indicates that 1.5°C-consistent pathways would require robust, stringent and urgent transformative policy interventions targeting the decarbonization of energy supply, electrification, fuel switching, energy efficiency, land-use change, and lifestyles (Chapter 2, Section 2.5, 4.4.2, 4.4.3). Examples of effective approaches to integrate mitigation with adaptation in the context of sustainable development and to deal with distributional implications proposed in the literature include the utilization of dynamic adaptive policy pathways (Haasnoot et al., 2013; Mathy et al., 2016) and transdisciplinary knowledge systems (Bendito and Barrios, 2016).
Yet, even with good policy design and effective implementation, 1.5°C-consistent pathways would incur higher costs. Projections of the magnitudes of global economic costs associated with 1.5°C-consistent pathways and their sectoral and regional distributions from the currently assessed literature are scant, yet suggestive. For example, IAM simulations assessed in Chapter 2 project (with a probability greater than 50%) that marginal abatement costs, typically represented in IAMs through a carbon price, would increase by about 3–4 times by 2050 under a 1.5°C-consistent pathway compared to a 2°C-consistent pathway (Chapter 2, Section 2.5.2, Figure 2.26). Managing these costs and distributional effects would require an approach that takes account of unintended cross-sector, cross-nation, and cross-policy trade-offs during the transition (Droste et al., 2016; Stiglitz et al., 2017; Pollitt, 2018; Sands, 2018; Siegmeier et al., 2018).

Greater sustainable development implications. Few studies address the relations between the Shared Socio-Economic Pathways (SSPs) and the Sustainable Developments Goals (SDGs) (O'Neill et al., 2015; Riahi et al., 2017). Nonetheless, literature on potential synergies and trade-offs between 1.5°C-consistent mitigation pathways and sustainable development dimensions is emerging (Chapter 2, Section 2.5.3, Chapter 5, Section 5.4). Areas of potential trade-offs include reduction in final energy demand in relation to SDG 7 (the universal clean energy access goal) and increase of biomass production in relation to land use, water resources, food production, biodiversity and air quality (Chapter 2, Sections 2.4.3, 2.5.3). Strengthening the institutional and policy responses to deal with these challenges is discussed in Section 4.4 together with the linkage between disruptive changes in the energy sector and structural changes in other infrastructure (transport, building, water and telecommunication) sectors. A more in-depth assessment of the complexity and interfaces between 1.5°C-consistent pathways and sustainable development is presented in Chapter 5.

4.2.1.2 Implications for Adaptation Along the Reviewed Pathways

Climate variability and uncertainties in the underlying assumptions in Chapter 2's IAMs as well as in model comparisons complicate discerning the implications for climate impacts, adaptation options and avoided adaptation investments at the global level of 2°C compared to 1.5°C warming (James et al., 2017; Mitchell et al., 2017).

Incremental warming from 1.5°C to 2°C would lead to significant increases in temperature and precipitation extremes in many regions (Chapter 3, Section 3.3.2, 3.3.3). Those projected changes in climate extremes under both warming levels, however, depend on the emissions pathways, as they have different greenhouse gas (GHG)/aerosol forcing ratios. Impacts are sector-, system- and region-specific, as described in Chapter 3. For example, precipitation-related impacts reveal distinct regional differences (Chapter 3, Sections 3.3.3, 3.3.4, 3.3.5, 3.4.2). Similarly, regional reduction in water availability and the lengthening of regional dry spells have negative implications for agricultural yields depending on crop types and world regions (see for example Chapter 3, Sections 3.3.4, 3.4.2, 3.4.6).

Adaptation helps reduce impacts and risks. However, adaptation has limits. Not all systems can adapt, and not all impacts can be reversed (Cross-Chapter Box 12 in Chapter 5). For example, tropical coral reefs are projected to be at risk of severe degradation due to temperature-induced bleaching (Chapter 3, Box 3.4).

4.2.2 System Transitions and Rates of Change

Society-wide transformation involves socio-technical transitions and social-ecological resilience (Gillard et al., 2016). Transitional adaptation pathways would need to respond to low-emission energy and economic systems, and the socio-technical transitions for mitigation involve removing barriers in social and institutional processes that could also benefit adaptation (Pant et al., 2015; Geels et al., 2017; Ickowitz et al., 2017). In this chapter, transformative change is framed in mitigation around socio-technical transitions, and in adaptation around socio-ecological transitions. In both instances, emphasis is placed on the enabling role of institutions (including markets, and formal and informal regulation). 1.5°C-consistent pathways and adaptation needs associated with warming of 1.5°C imply both incremental and rapid, disruptive and transformative changes.

4.2.2.1 Mitigation: historical rates of change and state of decoupling

Realizing 1.5°C-consistent pathways would require rapid and systemic changes on unprecedented scales (see Chapter 2 and Section 4.2.1). This section examines whether the needed rates of change have historical precedents and are underway.

Some studies conduct a de-facto validation of IAM projections. For CO_2 emission intensity over 1990–2010, this resulted in the IAMs projecting declining emission intensities while actual observations showed an increase. For individual technologies (in particular solar energy), IAM projections have been conservative regarding deployment rates and cost reductions (Creutzig et al., 2017), suggesting that IAMs do not always impute actual rates of technological change resulting from influence of shocks, broader changes and mutually reinforcing factors in society and politics (Geels and Schot, 2007; Daron et al., 2015; Sovacool, 2016; Battiston et al., 2017).

Other studies extrapolate historical trends into the future (Höök et al., 2011; Fouquet, 2016), or contrast the rates of change associated with specific temperature limits in IAMs (such as those in Chapter 2) with historical trends to investigate plausibility of emission pathways and associated temperature limits (Wilson et al., 2013; Gambhir et al., 2017; Napp et al., 2017). When metrics are normalized to gross domestic product (GDP; as opposed to other normalization metrics such as primary energy), low-emission technology deployment rates used by IAMs over the course of the coming century are shown to be broadly consistent with past trends, but rates of change in emission intensity are typically overestimated (Wilson et al., 2013; Loftus et al., 2014; van Sluisveld et al., 2015). This bias is consistent with the findings from the 'validation' studies cited above, suggesting that IAMs may under-report the potential for supply-side technological change assumed in 1.5°-consistent pathways, but may be more optimistic about the systemic ability to realize incremental changes in reduction of emission intensity as a consequence of favourable energy efficiency payback times (Wilson et al., 2013). This finding suggests that barriers and enablers other than costs and climate limits play a role in technological change, as also found in the innovation literature (Hekkert et al., 2007; Bergek et al., 2008; Geels et al., 2016b).

One barrier to a greater rate of change in energy systems is that economic growth in the past has been coupled to the use of fossil fuels. Disruptive innovation and socio-technical changes could enable the decoupling of economic growth from a range of environmental drivers, including the consumption of fossil fuels, as represented by 1.5°C-consistent pathways (UNEP, 2014; Newman, 2017). This may be relative decoupling due to rebound effects that see financial savings generated by renewable energy used in the consumption of new products and services (Jackson and Senker, 2011; Gillingham et al., 2013), but in 2015 and 2016 total global GHG emissions have decoupled absolutely from economic growth (IEA, 2017g; Peters et al., 2017). A longer data trend would be needed before stable decoupling can be established. The observed decoupling in 2015 and 2016 was driven by absolute declines in both coal and oil use since the early 2000s in Europe, in the past seven years in the United States and Australia, and more recently in China (Newman, 2017). In 2017, decoupling in China reversed by 2% due to a drought and subsequent replacement of hydropower with coal-fired power (Tollefson, 2017), but this reversal is expected to be temporary (IEA, 2017c). Oil consumption in China is still rising slowly, but absolute decoupling is ongoing in megacities like Beijing (Gao and Newman, 2018) (see Box 4.9).

4.2.2.2 Transformational adaptation

In some regions and places, incremental adaptation would not be sufficient to mitigate the impacts of climate change on social-ecological systems (see Chapter 3). Transformational adaptation would then be required (Bahadur and Tanner, 2014; Pant et al., 2015; Gillard, 2016; Gillard et al., 2016; Colloff et al., 2017; Termeer et al., 2017). Transformational adaptation refers to actions aiming at adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices (Dowd et al., 2014; IPCC, 2014a; Few et al., 2017), including approaches that enable new ways of decision-making on adaptation (Colloff et al., 2017). Few studies have assessed the potentially transformative character of adaptation options (Pelling et al., 2015; Rippke et al., 2016; Solecki et al., 2017), especially in the context of warming of 1.5°C.

Transformational adaptation can be adopted at a large scale, can lead to new strategies in a region or resource system, transform places and potentially shift locations (Kates et al., 2012). Some systems might require transformational adaptation at 1.5°C. Implementing adaptation policies in anticipation of 1.5°C would require transformation and flexible planning of adaptation (sometimes called adaptation pathways) (Rothman et al., 2014; Smucker et al., 2015; Holland, 2017; Gajjar et al., 2018), an understanding of the varied stakeholders involved and their motives, and knowledge of less visible aspects of vulnerability based on social, cultural, political, and economic factors (Holland, 2017). Transformational adaptation would seek deep and long-term societal changes that influence sustainable development (Chung Tiam Fook, 2017; Few et al., 2017).

Adaptation requires multidisciplinary approaches integrating scientific, technological and social dimensions. For example, a

framework for transformational adaptation and the integration of mitigation and adaptation pathways can transform rural indigenous communities to address risks of climate change and other stressors (Thornton and Comberti, 2017). In villages in rural Nepal, transformational adaptation has taken place, with villagers changing their agricultural and pastoralist livelihood strategies after years of lost crops due to changing rain patterns and degradation of natural resources (Thornton and Comberti, 2017). Instead, they are now opening stores, hotels, and tea shops. In another case, the arrival of an oil pipeline altered traditional Alaskan communities' livelihoods. With growth of oil production, investments were made for rural development. A later drop in oil production decreased these investments. Alaskan indigenous populations are also dealing with impacts of climate change, such as sea level rise, which is altering their livelihood sources. Transformational adaptation is taking place by changing the energy matrix to renewable energy, in which indigenous people apply their knowledge to achieve environmental, economic, and social benefits (Thornton and Comberti, 2017).

4.2.2.3 Disruptive innovation

Demand-driven disruptive innovations that emerge as the product of political and social changes across multiple scales can be transformative (Seba, 2014; Christensen et al., 2015; Green and Newman, 2017a). Such innovations would lead to simultaneous, profound changes in behaviour, economies and societies (Seba, 2014; Christensen et al. 2015), but are difficult to predict in supply-focused economic models (Geels et al., 2016a; Pindyck, 2017). Rapid socio-technical change has been observed in the solar industry (Creutzig et al. (2017). Similar changes to socio-ecological systems can stimulate adaptation and mitigation options that lead to more climate-resilient systems (Adger et al., 2005; Ostrom, 2009; Gillard et al., 2016) (see the Alaska and Nepal examples in Section 4.2.2.2). The increase in roof-top solar and energy storage technology as well as the increase in passive housing and net zero-emissions buildings are further examples of such disruptions (Green and Newman, 2017b). Both roof-top solar and energy storage have benefitted from countries' economic growth strategies and associated price declines in photovoltaic technologies, particularly in China (Shrivastava and Persson, 2018), as well as from new information and communication technologies (Koomey et al., 2013), rising demand for electricity in urban areas, and global concern regarding greenhouse gas emissions (Azeiteiro and Leal Filho, 2017; Lutz and Muttarak, 2017; Wamsler, 2017).

System co-benefits can create the potential for mutually enforcing and demand-driven climate responses (Jordan et al., 2015; Hallegatte and Mach, 2016; Pelling et al., 2018), and for rapid and transformational change (Cole, 2015; Geels et al., 2016b; Hallegatte and Mach, 2016). Examples of co-benefits include gender equality, agricultural productivity (Nyantakyi-Frimpong and Bezner-Kerr, 2015), reduced indoor air pollution (Satterthwaite and Bartlett, 2017), flood buffering (Colenbrander et al., 2017), livelihood support (Shaw et al., 2014; Ürge-Vorsatz et al., 2014), economic growth (GCEC, 2014; Stiglitz et al., 2017), social progress (Steg et al., 2015; Hallegatte and Mach, 2016) and social justice (Ziervogel et al., 2017; Patterson et al., 2018).

Innovations that disrupt entire systems may leave firms and utilities with stranded assets, as the transition can happen very quickly (IPCC, 2014b; Kossoy et al., 2015). This may have consequences for fossil fuels that are rendered 'unburnable' (McGlade and Ekins, 2015) and fossil fuel-fired power and industry assets that would become obsolete (Caldecott, 2017; Farfan and Breyer, 2017). The presence of multiple barriers and enablers operating in a system implies that rapid change, whether the product of many small changes (Termeer et al., 2017) or large-scale disruptions, is seldom an insular or discrete process (Sterling et al., 2017). This finding informs the multidimensional nature of feasibility in Cross-Chapter Box 3 in Chapter 1 which is applied in Section 4.5. Climate responses that are aligned with multiple feasibility dimensions and combine adaptation and mitigation interventions with non-climate benefits can accelerate change and reduce risks and costs (Fazey et al., 2018). Also political, social and technological influences on energy transitions, for example, can accelerate them faster than narrow techno-economic analysis suggests is possible (Kern and Rogge, 2016), but could also introduce new constraints and risks (Geels et al., 2016b; Sovacool, 2016; Eyre et al., 2018).

Disruptive innovation and technological change may play a role in mitigation and in adaptation. The next section assesses mitigation and adaptation options in energy, land and ecosystem, urban and infrastructure and industrial systems.

4.3 Systemic Changes for 1.5°C-Consistent Pathways

Section 4.2 emphasizes the importance of systemic change for 1.5°C-consistent pathways. This section translates this into four main system transitions: energy, land and ecosystem, urban and infrastructure, and industrial system transitions. This section assesses the mitigation, adaptation and carbon dioxide removal options that offer the potential for such change within those systems, based on options identified by Chapter 2 and risks and impacts in Chapter 3.

The section puts more emphasis on those adaptation options (Sections 4.3.1–4.3.5) and mitigation options (Sections 4.3.1–4.3.4, 4.3.6 and 4.3.7) that are 1.5°C-relevant and have developed considerably since AR5. They also form the basis for the mitigation and adaptation feasibility assessments in Section 4.5. Section 4.3.8 discusses solar radiation modification methods.

This section emphasizes that no single solution or option can enable a global transition to 1.5°C-consistent pathways or adapting to projected impacts. Rather, accelerating change, much of which is already starting or underway, in multiple global systems, simultaneously and at different scales, could provide the impetus for these system transitions. The feasibility of individual options as well as the potential for synergies and reducing trade-offs will vary according to context and the local enabling conditions. These are explored at a high level in Section 4.5. Policy packages that bring together multiple enabling conditions can provide building blocks for a strategy to scale up implementation and intervention impacts.

4.3.1 Energy System Transitions

This section discusses the feasibility of mitigation and adaptation options related to the energy system transition. Only options relevant to 1.5°C and with significant changes since AR5 are discussed, which means that for options like hydropower and geothermal energy, the chapter refers to AR5 and does not provide a discussion. Socio-technical inertia of energy options for 1.5°C-consistent pathways are increasingly being surmounted as fossil fuels start to be phased out. Supply-side mitigation and adaptation options and energy demand-side options, including energy efficiency in buildings and transportation, are discussed in Section 4.3.3; options around energy use in industry are discussed in Section 4.3.4.

Section 4.5 assesses the feasibility in a systematic manner based on the approach outlined in Cross-Chapter Box 3 in Chapter 1.

4.3.1.1 Renewable electricity: solar and wind

All renewable energy options have seen considerable advances over the years since AR5, but solar energy and both onshore and offshore wind energy have had dramatic growth trajectories. They appear well underway to contribute to 1.5°C-consistent pathways (IEA, 2017c; IRENA, 2017b; REN21, 2017).

The largest growth driver for renewable energy since AR5 has been the dramatic reduction in the cost of solar photovoltaics (PV) (REN21, 2017). This has made rooftop solar competitive in sunny areas between 45° north and south latitude (Green and Newman, 2017b), though IRENA (2018) suggests it is cost effective in many other places too. Solar PV with batteries has been cost effective in many rural and developing areas (Pueyo and Hanna, 2015; Szabó et al., 2016; Jimenez, 2017), for example 19 million people in Bangladesh now have solar-battery electricity in remote villages and are reporting positive experiences on safety and ease of use (Kabir et al., 2017). Small-scale distributed energy projects are being implemented in developed and developing cities where residential and commercial rooftops offer potential for consumers becoming producers (called prosumers) (ACOLA, 2017; Kotilainen and Saari, 2018). Such prosumers could contribute significantly to electricity generation in sun-rich areas like California (Kurdgelashvili et al., 2016) or sub-Saharan Africa in combination with micro-grids and mini-grids (Bertheau et al., 2017). It could also contribute to universal energy access (SDG 7) as shown by (IEA, 2017c).

The feasibility of renewable energy options depends to a large extent on geophysical characteristics of the area where the option is implemented. However, technological advances and policy instruments make renewable energy options increasingly attractive in other areas. For example, solar PV is deployed commercially in areas with low solar insolation, like northwest Europe (Nyholm et al., 2017). Feasibility also depends on grid adaptations (e.g., storage, see below) as renewables grow (IEA, 2017c). For regions with high energy needs, such as industrial areas (see Section 4.3.4), high-voltage DC transmission across long distances would be needed (MacDonald et al., 2016).

Another important factor affecting feasibility is public acceptance, in particular for wind energy and other large-scale renewable facilities (Yenneti and Day, 2016; Rand and Hoen, 2017; Gorayeb et al., 2018) that raise landscape management (Nadaï and Labussière, 2017) and distributional justice (Yenneti and Day, 2016) challenges. Research indicates that financial participation and community engagement can be effective in mitigating resistance (Brunes and Ohlhorst, 2011; Rand and Hoen, 2017) (see Section 4.4.3).

Bottom-up studies estimating the use of renewable energy in the future, either at the global or at the national level, are plentiful, especially in the grey literature. It is hotly debated whether a fully renewable energy or electricity system, with or without biomass, is possible (Jacobson et al., 2015, 2017) or not (Clack et al., 2017; Heard et al., 2017), and by what year. Scale-up estimates vary with assumptions about costs and technological maturity, as well as local geographical circumstances and the extent of storage used (Ghorbani et al., 2017; REN21, 2017). Several countries have adopted targets of 100% renewable electricity (IEA, 2017c) as this meets multiple social, economic and environmental goals and contributes to mitigation of climate change (REN21, 2017).

4.3.1.2 Bioenergy and biofuels

Bioenergy is renewable energy from biomass. Biofuel is biomass-based energy used in transport. Chapter 2 suggests that pathways limiting warming to 1.5°C would enable supply of 67–310 (median 150) EJ yr^{-1} (see Table 2.8) from biomass. Most scenarios find that bioenergy is combined with carbon dioxide capture and storage (CCS, BECCS) if it is available but also find robust deployment of bioenergy independent of the availability of CCS (see Chapter 2, Section 2.3.4.2 and Section 4.3.7 for a discussion of BECCS). Detailed assessments indicate that deployment is similar for pathways limiting global warming to below 2°C (Chum et al., 2011; P. Smith et al., 2014; Creutzig et al., 2015b). There is however *high agreement* that the sustainable bioenergy potential in 2050 would be restricted to around 100 EJ yr^{-1} (Slade et al., 2014; Creutzig et al., 2015b). Sustainable deployment at such or higher levels envisioned by 1.5°C-consistent pathways may put significant pressure on available land, food production and prices (Popp et al., 2014b; Persson, 2015; Kline et al., 2017; Searchinger et al., 2017), preservation of ecosystems and biodiversity (Creutzig et al., 2015b; Holland et al., 2015; Santangeli et al., 2016), and potential water and nutrient constraints (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Bows and Smith, 2012; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouratiadou et al., 2016; Smith et al., 2016b; Wei et al., 2016; Mathioudakis et al., 2017); but there is still *low agreement* on these interactions (Robledo-Abad et al., 2017). Some of the disagreement on the sustainable capacity for bioenergy stems from global versus local assessments. Global assessments may mask local dynamics that exacerbate negative impacts and shortages while at the same time niche contexts for deployment may avoid trade-offs and exploit co-benefits more effectively. In some regions of the world (e.g., the case of Brazilian ethanol, see Box 4.7, where land may be less of a constraint, the use of bioenergy is mature and the industry is well developed), land transitions could be balanced with food production and biodiversity to enable a global impact on CO_2 emissions (Jaiswal et al., 2017).

The carbon intensity of bioenergy, key for both bioenergy as an emission-neutral energy option and BECCS as a CDR measure, is

still a matter of debate (Buchholz et al., 2016; Liu et al., 2018) and depends on management (Pyörälä et al., 2014; Torssonen et al., 2016; Baul et al., 2017; Kilpeläinen et al., 2017); direct and indirect land-use change emissions (Plevin et al., 2010; Schulze et al., 2012; Harris et al., 2015; Repo et al., 2015; DeCicco et al., 2016; Qin et al., 2016)[2]; the feedstock considered; and time frame (Zanchi et al., 2012; Daioglou et al., 2017; Booth, 2018; Sterman et al., 2018), as well as the availability of coordinated policies and management to minimize negative side effects and trade-offs, particularly those around food security (Stevanović et al., 2017) and livelihood and equity considerations (Creutzig et al., 2013; Calvin et al., 2014) .

Biofuels are a part of the transport sector in some cities and countries, and may be deployed as a mitigation option for aviation, shipping and freight transport (see Section 4.3.3.5) as well as industrial decarbonization (IEA, 2017g) (Section 4.3.4), though only Brazil has mainstreamed ethanol as a substantial, commercial option. Lower emissions and reduced urban air pollution have been achieved there by use of ethanol and biodiesel as fuels (Hill et al., 2006; Salvo et al., 2017) (see Box 4.7).

4.3.1.3 Nuclear energy

Many scenarios in Chapter 2 and in AR5 (Bruckner et al., 2014) project an increase in the use of nuclear power, while others project a decrease. The increase can be realized through existing mature nuclear technologies or new options (generation III/IV reactors, breeder reactors, new uranium and thorium fuel cycles, small reactors or nuclear cogeneration).

Even though scalability and speed of scaling of nuclear plants have historically been high in many nations, such rates are currently not achieved anymore. In the 1960s and 1970s, France implemented a programme to rapidly get 80% of its power from nuclear in about 25 years (IAEA, 2018), but the current time lag between the decision date and the commissioning of plants is observed to be 10-19 years (Lovins et al., 2018). The current deployment pace of nuclear energy is constrained by social acceptability in many countries due to concerns over risks of accidents and radioactive waste management (Bruckner et al., 2014). Though comparative risk assessment shows health risks are low per unit of electricity production (Hirschberg et al., 2016), and land requirement is lower than that of other power sources (Cheng and Hammond, 2017), the political processes triggered by societal concerns depend on the country-specific means of managing the political debates around technological choices and their environmental impacts (Gregory et al., 1993). Such differences in perception explain why the 2011 Fukushima incident resulted in a confirmation or acceleration of phasing out nuclear energy in five countries (Roh, 2017) while 30 other countries have continued using nuclear energy, amongst which 13 are building new nuclear capacity, including China, India and the United Kingdom (IAEA, 2017; Yuan et al., 2017).

Costs of nuclear power have increased over time in some developed nations, principally due to market conditions where increased investment risks of high-capital expenditure technologies have become significant. 'Learning by doing' processes often failed to compensate for this trend because they were slowed down by the absence of standardization and series effects (Grubler, 2010). What the costs of nuclear power are and have been is debated in the literature (Lovering et al., 2016; Koomey et al., 2017). Countries with liberalized markets that continue to develop nuclear employ de-risking instruments through long-term contracts with guaranteed sale prices (Finon and Roques, 2013). For instance, the United Kingdom works with public guarantees covering part of the upfront investment costs of newly planned nuclear capacity. This dynamic differs in countries such as China and South Korea, where monopolistic conditions in the electric system allow for reducing investment risks, deploying series effects and enhancing the engineering capacities of users due to stable relations between the security authorities and builders (Schneider et al., 2017).

The safety of nuclear plants depends upon the public authorities of each country. However, because accidents affect worldwide public acceptance of this industry, questions have been raised about the risk of economic and political pressures weakening the safety of the plants (Finon, 2013; Budnitz, 2016). This raises the issue of international governance of civil nuclear risks and reinforced international cooperation involving governments, companies and engineering (Walker and Lönnroth, 1983; Thomas, 1988; Finon, 2013), based on the experience of the International Atomic Energy Agency.

4.3.1.4 Energy storage

The growth in electricity storage for renewables has been around grid flexibility resources (GFR) that would enable several places to source more than half their power from non-hydro renewables (Komarnicki, 2016). Ten types of GFRs within smart grids have been developed (largely since AR5)(Blaabjerg et al., 2004; IRENA, 2013; IEA, 2017d; Majzoobi and Khodaei, 2017), though how variable renewables can be balanced without hydro or natural gas-based power back-up at a larger scale would still need demonstration. Pumped hydro comprised 150 GW of storage capacity in 2016, and grid-connected battery storage just 1.7 GW, but the latter grew between 2015 to 2016 by 50% (REN21, 2017). Battery storage has been the main growth feature in energy storage since AR5 (Breyer et al., 2017). This appears to the result of significant cost reductions due to mass production for electric vehicles (EVs) (Nykvist and Nilsson, 2015; Dhar et al., 2017). Although costs and technical maturity look increasingly positive, the feasibility of battery storage is challenged by concerns over the availability of resources and the environmental impacts of its production (Peters et al., 2017). Lithium, a common element in the earth's crust, does not appear to be restricted and large increases in production have happened in recent years with eight new mines in Western Australia where most lithium is produced (GWA, 2016). Emerging battery technologies may provide greater efficiency and recharge rates (Belmonte et al., 2016) but remain significantly more expensive due to speed and scale issues compared to lithium ion batteries (Dhar et al., 2017; IRENA, 2017a).

[2] While there is *high agreement* that indirect land use change (iLUC) could occur, there is *low agreement* about the actual extent of iLUC (P. Smith et al., 2014; Verstegen et al., 2015; Zilberman, 2017)

Research and demonstration of energy storage in the form of thermal and chemical systems continues, but large-scale commercial systems are rare (Pardo et al., 2014). Renewably derived synthetic liquid (like methanol and ammonia) and gas (like methane and hydrogen) are increasingly being seen as a feasible storage options for renewable energy (producing fuel for use in industry during times when solar and wind are abundant) (Bruce et al., 2010; Jiang et al., 2010; Ezeji, 2017) but, in the case of carbonaceous storage media, would need a renewable source of carbon to make a positive contribution to GHG reduction (von der Assen et al., 2013; Abanades et al., 2017) (see also Section 4.3.4.5). The use of electric vehicles as a form of storage has been modelled and evaluated as an opportunity, and demonstrations are emerging (Dhar et al., 2017; Green and Newman, 2017a), but challenges to upscaling remain.

4.3.1.5 Options for adapting electricity systems to 1.5°C

Climate change has started to disrupt electricity generation and, if climate change adaptation options are not considered, it is predicted that these disruptions will be lengthier and more frequent (Jahandideh-Tehrani et al., 2014; Bartos and Chester, 2015; Kraucunas et al., 2015; van Vliet et al., 2016). Adaptation would both secure vulnerable infrastructure and ensure the necessary generation capacity (Minville et al., 2009; Eisenack and Stecker, 2012; Schaeffer et al., 2012; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Goytia et al., 2016). The literature shows *high agreement* that climate change impacts need to be planned for in the design of any kind of infrastructure, especially in the energy sector (Nierop, 2014), including interdependencies with other sectors that require electricity to function, including water, data, telecommunications and transport (Fryer, 2017).

Recent research has developed new frameworks and models that aim to assess and identify vulnerabilities in energy infrastructure and create more proactive responses (Francis and Bekera, 2014; Ouyang and Dueñas-Osorio, 2014; Arab et al., 2015; Bekera and Francis, 2015; Knight et al., 2015; Jeong and An, 2016; Panteli et al., 2016; Perrier, 2016; Erker et al., 2017; Fu et al., 2017). Assessments of energy infrastructure adaptation, while limited, emphasize the need for redundancy (Liu et al., 2017). The implementation of controllable and islandable microgrids, including the use of residential batteries, can increase resiliency, especially after extreme weather events (Qazi and Young Jr., 2014; Liu et al., 2017). Hybrid renewables-based power systems with non-hydro capacity, such as with high-penetration wind generation, could provide the required system flexibility (Canales et al., 2015). Overall, there is *high agreement* that hybrid systems, taking advantage of an array of sources and time of use strategies, can help make electricity generation more resilient (Parkinson and Djilali, 2015), given that energy security standards are in place (Almeida Prado et al., 2016).

Interactions between water and energy are complex (IEA, 2017g). Water scarcity patterns and electricity disruptions will differ across regions. There is *high agreement* that mitigation and adaptation options for thermal electricity generation (if that remains fitted with CCS) need to consider increasing water shortages, taking into account other factors such as ambient water resources and demand changes in irrigation water (Hayashi et al., 2018). Increasing the efficiency of power plants can reduce emissions and water needs (Eisenack and Stecker, 2012; van Vliet et al., 2016), but applying CCS would increase water consumption (Koornneef et al., 2012). The technological, economic, social and institutional feasibility of efficiency improvements is high, but insufficient to limit temperature rise to 1.5°C (van Vliet et al., 2016).

In addition, a number of options for water cooling management systems have been proposed, such as hydraulic measures (Eisenack and Stecker, 2012) and alternative cooling technologies (Chandel et al., 2011; Eisenack and Stecker, 2012; Bartos and Chester, 2015; Murrant et al., 2015; Bustamante et al., 2016; van Vliet et al., 2016; Huang et al., 2017b). There is *high agreement* on the technological and economic feasibility of these technologies, as their absence can severely impact the functioning of the power plant as well as safety and security standards.

4.3.1.6 Carbon dioxide capture and storage in the power sector

The AR5 (IPCC, 2014b) as well as Chapter 2, Section 2.4.2, assign significant emission reductions over the course of this century to CO_2 capture and storage (CCS) in the power sector. This section focuses on CCS in the fossil-fuelled power sector; Section 4.3.4 discusses CCS in non-power industry, and Section 4.3.7 discusses bioenergy with CCS (BECCS). Section 2.4.2 puts the cumulative CO_2 stored from fossil-fuelled power at 410 (199–470 interquartile range) $GtCO_2$ over this century. Such modelling suggests that CCS in the power sector can contribute to cost-effective achievement of emission reduction requirements for limiting warming to 1.5°C. CCS may also offer employment and political advantages for fossil fuel-dependent economies (Kern et al., 2016), but may entail more limited co-benefits than other mitigation options (that, e.g., generate power) and therefore relies on climate policy incentives for its business case and economic feasibility. Since 2017, two CCS projects in the power sector capture 2.4 $MtCO_2$ annually, while 30 $MtCO_2$ is captured annually in all CCS projects (Global CCS Institute, 2017).

The technological maturity of CO_2 capture options in the power sectors has improved considerably (Abanades et al., 2015; Bui et al., 2018), but costs have not come down between 2005 and 2015 due to limited learning in commercial settings and increased energy and resources costs (Rubin et al., 2015). Storage capacity estimates vary greatly, but Section 2.4.2 as well as literature (V. Scott et al., 2015) indicate that perhaps 10,000 $GtCO_2$ could be stored in underground reservoirs. Regional availability of this may not be sufficient, and it requires efforts to have this storage and the corresponding infrastructure available at the necessary rates and times (de Coninck and Benson, 2014). CO_2 retention in the storage reservoir was recently assessed as 98% over 10,000 years for well-managed reservoirs, and 78% for poorly regulated ones (Alcalde et al., 2018). A paper reviewing 42 studies on public perception of CCS (Seigo et al., 2014) found that social acceptance of CCS is predicted by trust, perceived risks and benefits. The technology itself mattered less than the social context of the project. Though insights on communication of CCS projects to the general public and inhabitants of the area around the CO_2 storage sites have been documented over the years, project stakeholders are not consistently implementing these lessons, although some projects have observed good practices (Ashworth et al., 2015).

CCS in the power sector is hardly being realized at scale, mainly because the incremental costs of capture, and the development of transport and storage infrastructures are not sufficiently compensated by market or government incentives (IEA, 2017c). In the two full-scale projects in the power sector mentioned above, part of the capture costs are compensated for by revenues from enhanced oil recovery (EOR) (Global CCS Institute, 2017), demonstrating that EOR helps developing CCS further. EOR is a technique that uses CO_2 to mobilize more oil out of depleting oil fields, leading to additional CO_2 emissions by combusting the additionally recovered oil (Cooney et al., 2015).

4.3.2 Land and Ecosystem Transitions

This section assesses the feasibility of mitigation and adaptation options related to land use and ecosystems. Land transitions are grouped around agriculture and food, ecosystems and forests, and coastal systems.

4.3.2.1 Agriculture and food

In a 1.5°C world, local yields are projected to decrease in tropical regions that are major food producing areas of the world (West Africa, Southeast Asia, South Asia, and Central and northern South America) (Schleussner et al., 2016). Some high-latitude regions may benefit from the combined effects of elevated CO_2 and temperature because their average temperatures are below optimal temperature for crops. In both cases there are consequences for food production and quality (Cross-Chapter Box 6 in Chapter 3 on Food Security), conservation agriculture, irrigation, food wastage, bioenergy and the use of novel technologies.

Food production and quality. Increased temperatures, including 1.5°C warming, would affect the production of cereals such as wheat and rice, impacting food security (Schleussner et al., 2016). There is *medium agreement* that elevated CO_2 concentrations can change food composition, with implications for nutritional security (Taub et al., 2008; Högy et al., 2009; DaMatta et al., 2010; Loladze, 2014; De Souza et al., 2015), with the effects being different depending on the region (Medek et al., 2017).

Meta-analyses of the effects of drought, elevated CO_2, and temperature conclude that at 2°C local warming and above, aggregate production of wheat, maize, and rice are expected to decrease in both temperate and tropical areas (Challinor et al., 2014). These production losses could be lowered if adaptation measures are taken (Challinor et al., 2014), such as developing varieties better adapted to changing climate conditions.

Adaptation options can help ensure access to sufficient, quality food. Such options include conservation agriculture, improved livestock management, increasing irrigation efficiency, agroforestry and management of food loss and waste. Complementary adaptation and mitigation options, for example, the use of climate services (Section 4.3.5), bioenergy (Section 4.3.1) and biotechnology (Section 4.4.4) can also serve to reduce emissions intensity and the carbon footprint of food production.

Conservation agriculture (CA) is a soil management approach that reduces the disruption of soil structure and biotic processes by minimising tillage. A recent meta-analysis showed that no-till practices work well in water-limited agroecosystems when implemented jointly with residue retention and crop rotation, but when used independently, may decrease yields in other situations (Pittelkow et al., 2014). Additional climate adaptations include adjusting planting times and crop varietal selection and improving irrigation efficiency. Adaptations such as these may increase wheat and maize yields by 7–12% under climate change (Challinor et al., 2014). CA can also help build adaptive capacity (*medium evidence, medium agreement*) (H. Smith et al., 2017; Pradhan et al., 2018) and have mitigation co-benefits through improved fertiliser use or efficient use of machinery and fossil fuels (Harvey et al., 2014; Cui et al., 2018; Pradhan et al., 2018). CA practices can also raise soil carbon and therefore remove CO_2 from the atmosphere (Aguilera et al., 2013; Poeplau and Don, 2015; Vicente-Vicente et al., 2016). However, CA adoption can be constrained by inadequate institutional arrangements and funding mechanisms (Harvey et al., 2014; Baudron et al., 2015; Li et al., 2016; Dougill et al., 2017; H. Smith et al., 2017).

Sustainable intensification of agriculture consists of agricultural systems with increased production per unit area but with management of the range of potentially adverse impacts on the environment (Pretty and Bharucha, 2014). Sustainable intensification can increase the efficiency of inputs and enhance health and food security (Ramankutty et al., 2018).

Livestock management. Livestock are responsible for more GHG emissions than all other food sources. Emissions are caused by feed production, enteric fermentation, animal waste, land-use change and livestock transport and processing. Some estimates indicate that livestock supply chains could account for 7.1 $GtCO_2$ per year, equivalent to 14.5% of global anthropogenic greenhouse gas emissions (Gerber et al., 2013). Cattle (beef, milk) are responsible for about two-thirds of that total, largely due to methane emissions resulting from rumen fermentation (Gerber et al., 2013; Opio et al., 2013).

Despite ongoing gains in livestock productivity and volumes, the increase of animal products in global diets is restricting overall agricultural efficiency gains because of inefficiencies in the conversion of agricultural primary production (e.g., crops) in the feed-animal products pathway (Alexander et al., 2017), offsetting the benefits of improvements in livestock production systems (Clark and Tilman, 2017).

There is increasing agreement that overall emissions from food systems could be reduced by targeting the demand for meat and other livestock products, particularly where consumption is higher than suggested by human health guidelines. Adjusting diets to meet nutritional targets could bring large co-benefits, through GHG mitigation and improvements in the overall efficiency of food systems (Erb et al., 2009; Tukker et al., 2011; Tilman and Clark, 2014; van Dooren et al., 2014; Ranganathan et al., 2016). Dietary shifts could contribute one-fifth of the mitigation needed to hold warming below 2°C, with one-quarter of low-cost options (Griscom et al., 2017). There, however, remains *limited evidence* of effective policy interventions to achieve such large-scale shifts in dietary choices, and prevailing trends are for increasing rather than decreasing demand for livestock products at the global scale (Alexandratos and Bruinsma, 2012; OECD/FAO, 2017). How the role of dietary shift could change in 1.5°C-consistent pathways is also not clear (see Chapter 2).

Adaptation of livestock systems can include a suite of strategies such as using different breeds and their wild relatives to develop a genetic pool resilient to climatic shocks and longer-term temperature shifts (Thornton and Herrero, 2014), improving fodder and feed management (Bell et al., 2014; Havet et al., 2014) and disease prevention and control (Skuce et al., 2013; Nguyen et al., 2016). Most interventions that improve the productivity of livestock systems and enhance adaptation to climate changes would also reduce the emissions intensity of food production, with significant co-benefits for rural livelihoods and the security of food supplies (Gerber et al., 2013; FAO and NZAGRC, 2017a, b, c). Whether such reductions in emission intensity result in lower or higher absolute GHG emissions depends on overall demand for livestock products, indicating the relevance of integrating supply-side with demand-side measures within food security objectives (Gerber et al., 2013; Bajželj et al., 2014). Transitions in livestock production systems (e.g., from extensive to intensive) can also result in significant emission reductions as part of broader land-based mitigation strategies (Havlik et al., 2014).

Overall, there is *high agreement* that farm strategies that integrate mixed crop–livestock systems can improve farm productivity and have positive sustainability outcomes (Havet et al., 2014; Thornton and Herrero, 2014; Herrero et al., 2015; Weindl et al., 2015). Shifting towards mixed crop–livestock systems is estimated to reduce agricultural adaptation costs to 0.3% of total production costs while abating deforestation by 76 Mha globally, making it a highly cost-effective adaptation option with mitigation co-benefits (Weindl et al., 2015). Evidence from various regions supports this (Thornton and Herrero, 2015), although the feasible scale varies between regions and systems, as well as being moderated by overall demand in specific food products. In Australia, some farmers have successfully shifted to crop–livestock systems where, each year, they allocate land and forage resources in response to climate and price trends (Bell et al., 2014) . However, there can be some unintended negative impacts of such integration, including increased burdens on women, higher requirements of capital, competing uses of crop residues (e.g., feed vs. mulching vs. carbon sequestration) and higher requirements of management skills, which can be a challenge across several low income countries (Thornton and Herrero, 2015; Thornton et al., 2018). Finally, the feasibility of improving livestock efficiency is dependent on socio-cultural context and acceptability: there remain significant issues around widespread adoption of crossbred animals, especially by smallholders (Thornton et al., 2018).

Irrigation efficiency. Irrigation efficiency is especially critical since water endowments are expected to change, with 20–60 Mha of global cropland being projected to revert from irrigated to rain-fed land, while other areas will receive higher precipitation in shorter time spans, thus affecting irrigation demand (Elliott et al., 2014). While increasing irrigation system efficiency is necessary, there is mixed evidence on how to enact efficiency improvements (Fader et al., 2016; Herwehe and Scott, 2018). Physical and technical strategies include building large-scale reservoirs or dams, renovating or deepening irrigation channels, building on-farm rainwater harvesting structures, lining ponds, channels and tanks to reduce losses through percolation and evaporation, and investing in small infrastructure such as sprinkler or drip irrigation sets (Varela-Ortega et al., 2016; Sikka et al., 2018). Each strategy has differing costs and benefits relating to unique biophysical, social, and economic contexts. Also, increasing irrigation efficiency may foster higher dependency on irrigation, resulting in a heightened sensitivity to climate that may be maladaptive in the long term (Lindoso et al., 2014).

Improvements in irrigation efficiency would need to be supplemented with ancillary activities, such as shifting to crops that require less water and improving soil and moisture conservation (Fader et al., 2016; Hong and Yabe, 2017; Sikka et al., 2018). Currently, the feasibility of improving irrigation efficiency is constrained by issues of replicability across scale and sustainability over time (Burney and Naylor, 2012), institutional barriers and inadequate market linkages (Pittock et al., 2017).

Growing evidence suggests that investing in behavioural shifts towards using irrigation technology such as micro-sprinklers or drip irrigation, is an effective and quick adaptation strategy (Varela-Ortega et al., 2016; Herwehe and Scott, 2018; Sikka et al., 2018) as opposed to large dams which have high financial, ecological and social costs (Varela-Ortega et al., 2016). While improving irrigation efficiency is technically feasible (R. Fishman et al., 2015) and has clear benefits for environmental values (Pfeiffer and Lin, 2014; R. Fishman et al., 2015), feasibility is regionally differentiated as shown by examples as diverse as Kansas (Jägermeyr et al., 2015), India (R. Fishman et al., 2015) and Africa (Pittock et al., 2017).

Agroforestry. The integration of trees and shrubs into crop and livestock systems, when properly managed, can potentially restrict soil erosion, facilitate water infiltration, improve soil physical properties and buffer against extreme events (Lasco et al., 2014; Mbow et al., 2014; Quandt et al., 2017; Sida et al., 2018). There is *medium evidence* and *high agreement* on the feasibility of agroforestry practices that enhance productivity, livelihoods and carbon storage (Lusiana et al., 2012; Murthy, 2013; Coulibaly et al., 2017; Sida et al., 2018), including from indigenous production systems (Coq-Huelva et al., 2017), with variation by region, agroforestry type, and climatic conditions (Place et al., 2012; Coe et al., 2014; Mbow et al., 2014; Iiyama et al., 2017; Abdulai et al., 2018). Long-term studies examining the success of agroforestry, however, are rare (Coe et al., 2014; Meijer et al., 2015; Brockington et al., 2016; Zomer et al., 2016).

The extent to which agroforestry practices employed at the farm level could be scaled up globally while satisfying growing food demand is relatively unknown. Agroforestry adoption has been relatively low and uneven (Jacobi et al., 2017; Hernández-Morcillo et al., 2018), with constraints including the expense of establishment and lack of reliable financial support, insecure land tenure, landowner's lack of experience with trees, complexity of management practices, fluctuating market demand and prices for different food and fibre products, the time and knowledge required for management, low intermediate benefits to offset revenue lags, and inadequate market access (Pattanayak et al., 2003; Mercer, 2004; Sendzimir et al., 2011; Valdivia et al., 2012; Coe et al., 2014; Meijer et al., 2015; Coulibaly et al., 2017; Jacobi et al., 2017).

Managing food loss and waste. The way food is produced, processed and transported strongly influences GHG emissions. Around

one-third of the food produced on the planet is not consumed (FAO, 2013), affecting food security and livelihoods (See Cross-Chapter Box 6 on Food Security in Chapter 3). Food wastage is a combination of food loss – the decrease in mass and nutritional value of food due to poor infrastructure, logistics, and lack of storage technologies and management – and food waste that derives from inappropriate human consumption that leads to food spoilage associated with inferior quality or overproduction. Food wastage could lead to an increase in emissions estimated to 1.9–2.5 $GtCO_2$-eq yr^{-1} (Hiç et al., 2016).

Decreasing food wastage has high mitigation and adaptation potential and could play an important role in land transitions towards 1.5°C, provided that reduced food waste results in lower production-side emissions rather than increased consumption (Foley et al., 2011). There is *medium agreement* that a combination of individual–institutional behaviour (Refsgaard and Magnussen, 2009; Thornton and Herrero, 2014), and improved technologies and management (Lin et al., 2013; Papargyropoulou et al., 2014) can transform food waste into products with marketable value. Institutional behaviour depends on investment and policies, which if adequately addressed could enable mitigation and adaptation co-benefits in a relatively short time.

Novel technologies. New molecular biology tools have been developed that can lead to fast and precise genome modification (De Souza et al., 2016; Scheben et al., 2016) (e.g., CRISPR Cas9; Ran et al., 2013; Schaeffer and Nakata, 2015). Such genome editing tools may moderately assist in mitigation and adaptation of agriculture in relation to climate changes, elevated CO_2, drought and flooding (DaMatta et al., 2010; De Souza et al., 2015, 2016). These tools could contribute to developing new plant varieties that can adapt to warming of 1.5°C and overshoot, potentially avoiding some of the costs of crop shifting (Schlenker and Roberts, 2009; De Souza et al., 2016). However, biosafety concerns and government regulatory systems can be a major barrier to the use of these tools as this increases the time and cost of turning scientific discoveries into ready applicable technologies (Andow and Zwahlen, 2006; Maghari and Ardekani, 2011).

The strategy of reducing enteric methane emissions by ruminants through the development of inhibitors or vaccines has already been attempted with some successes, although the potential for application at scale and in different situations remains uncertain. A methane inhibitor has been demonstrated to reduce methane from feedlot systems by 30% over a 12-week period (Hristov et al., 2015) with some productivity benefits, but the ability to apply it in grazing systems will depend on further technological developments as well as costs and incentives. A vaccine could potentially modify the microbiota of the rumen and be applicable even in extensive grazing systems by reducing the presence of methanogenic micro-organisms (Wedlock et al., 2013) but has not yet been successfully demonstrated to reduce emissions in live animals. Selective breeding for lower-emitting ruminants is becoming rapidly feasible, offering small but cumulative emissions reductions without requiring substantial changes in farm systems (Pickering et al., 2015).

Technological innovation in culturing marine and freshwater micro and macro flora has significant potential to expand food, fuel and fibre resources, and could reduce impacts on land and conventional agriculture (Greene et al., 2017).

Technological innovation could assist in increased agricultural efficiency (e.g., via precision agriculture), decrease food wastage and genetics that enhance plant adaptation traits (Section 4.4.4). Technological and associated management improvements may be ways to increase the efficiency of contemporary agriculture to help produce enough food to cope with population increases in a 1.5°C warmer world, and help reduce the pressure on natural ecosystems and biodiversity.

4.3.2.2 Forests and other ecosystems

Ecosystem restoration. Biomass stocks in tropical, subtropical, temperate and boreal biomes currently hold 1085, 194, 176, 190 Gt CO_2, respectively. Conservation and restoration can enhance these natural carbon sinks (Erb et al., 2017).

Recent studies explore options for conservation, restoration and improved land management estimating up to 23 $GtCO_2$ (Griscom et al., 2017). Mitigation potentials are dominated by reduced rates of deforestation, reforestation and forest management, and concentrated in tropical regions (Houghton, 2013; Canadell and Schulze, 2014; Grace et al., 2014; Houghton et al., 2015; Griscom et al., 2017). Much of the literature focuses on REDD+ (reducing emissions from deforestation and forest degradation) as an institutional mechanism. However, restoration and management activities need not be limited to REDD+, and locally adapted implementation may keep costs low, capitalize on co-benefits and ensure consideration of competing for socio-economic goals (Jantke et al., 2016; Ellison et al., 2017; Perugini et al., 2017; Spencer et al., 2017).

Half of the estimated potential can be achieved at <100 USD/tCO_2; and a third of the cost-effective potential at <10 USD/tCO_2 (Griscom et al., 2017). Variation of costs in projects aiming to reduce emissions from deforestation is high when considering opportunity and transaction costs (Dang Phan et al., 2014; Overmars et al., 2014; Ickowitz et al., 2017; Rakatama et al., 2017).

However, the focus on forests raises concerns of cross-biome leakage (*medium evidence, low agreement*) (Popp et al., 2014a; Strassburg et al., 2014; Jayachandran et al., 2017) and encroachment on other ecosystems (Veldman et al., 2015). Reducing rates of deforestation constrains the land available for agriculture and grazing, with trade-offs between diets, higher yields and food prices (Erb et al., 2016a; Kreidenweis et al., 2016). Forest restoration and conservation are compatible with biodiversity (Rey Benayas et al., 2009; Jantke et al., 2016) and available water resources; in the tropics, reducing rates of deforestation maintains cooler surface temperatures (Perugini et al., 2017) and rainfall (Ellison et al., 2017).

Its multiple potential co-benefits have made REDD+ important for local communities, biodiversity and sustainable landscapes (Ngendakumana et al., 2017; Turnhout et al., 2017). There is *low agreement* on whether climate impacts will reverse mitigation benefits of restoration (Le Page et al., 2013) by increasing the likelihood of disturbance (Anderegg et al., 2015), or reinforce them through carbon fertilization (P. Smith et al., 2014).

Emerging regional assessments offer new perspectives for upscaling. Strengthening coordination, additional funding sources, and access and disbursement points increase the potential of REDD+ in working towards 2°C and 1.5°C limits (Well and Carrapatoso, 2017). While there are indications that land tenure has a positive impact (Sunderlin et al., 2014), a meta-analysis by Wehkamp et al. (2018a) shows that there is *medium evidence* and *low agreement* on which aspects of governance improvements are supportive of conservation. Local benefits, especially for indigenous communities, will only be accrued if land tenure is respected and legally protected, which is not often the case (Sunderlin et al., 2014; Brugnach et al., 2017). Although payments for reduced rates of deforestation may benefit the poor, the most vulnerable populations could have limited, uneven access (Atela et al., 2014) and face lower opportunity costs from deforestation (Ickowitz et al., 2017).

Community-based adaptation (CbA). There is *medium evidence* and *high agreement* for the use of CbA. The specific actions to take will depend upon the location, context, and vulnerability of the specific community. CbA is defined as 'a community-led process, based on communities' priorities, needs, knowledge, and capacities, which aim to empower people to plan for and cope with the impacts of climate change' (Reid et al., 2009). The integration of CbA with ecosystems-based adaptation (EbA) has been increasingly promoted, especially in efforts to alleviate poverty (Mannke, 2011; Reid, 2016).

Despite the potential and advantages of both CbA and EbA, including knowledge exchange, information access and increased social capital and equity; institutional and governance barriers still constitute a challenge for local adaptation efforts (Wright et al., 2014; Fernández-Giménez et al., 2015).

Wetland management. In wetland ecosystems, temperature rise has direct and irreversible impacts on species functioning and distribution, ecosystem equilibrium and services, and second-order impacts on local livelihoods (see Chapter 3, Section 3.4.3). The structure and function of wetland systems are changing due to climate change. Wetland management strategies, including adjustments in infrastructural, behavioural, and institutional practices have clear implications for adaptation (Colloff et al., 2016b; Finlayson et al., 2017; Wigand et al., 2017)

Despite international initiatives on wetland restoration and management through the Ramsar Convention on Wetlands, policies have not been effective (Finlayson, 2012; Finlayson et al., 2017). Institutional reform, such as flexible, locally relevant governance, drawing on principles of adaptive co-management, and multi-stakeholder participation becomes increasingly necessary for effective wetland management (Capon et al., 2013; Finlayson et al., 2017).

4.3.2.3 Coastal systems

Managing coastal stress. Particularly to allow for the landward relocation of coastal ecosystems under a transition to a 1.5°C warmer world, planning for climate change would need to be integrated with the use of coastlines by humans (Saunders et al., 2014; Kelleway et al., 2017). Adaptation options for managing coastal stress include coastal hardening through the building of seawalls and the re-establishment of coastal ecosystems such as mangroves (André et al., 2016; Cooper et al., 2016). While the feasibility of the solutions is high, they are expensive to scale (*robust evidence, medium agreement*).

There is *low evidence* and *high agreement* that reducing the impact of local stresses (Halpern et al., 2015) will improve the resilience of marine ecosystems as they transition to a 1.5°C world (O'Leary et al., 2017). Approaches to reducing local stresses are considered feasible, cost-effective and highly scalable. Ecosystem resilience may be increased through alternative livelihoods (e.g., sustainable aquaculture), which are among a suite of options for building resilience in coastal ecosystems. These options enjoy high levels of feasibility yet are expensive, which stands in the way of scalability (*robust evidence, medium agreement*) (Hiwasaki et al., 2015; Brugnach et al., 2017).

Working with coastal communities has the potential for improving the resilience of coastal ecosystems. Combined with the advantages of using indigenous knowledge to guide transitions, solutions can be more effective when undertaken in partnership with local communities, cultures, and knowledge (See Box 4.3).

Restoration of coastal ecosystems and fisheries. Marine restoration is expensive compared to terrestrial restoration, and the survival of projects is currently low, with success depending on the ecosystem and site, rather than the size of the financial investment (Bayraktarov et al., 2016). Mangrove replanting shows evidence of success globally, with numerous examples of projects that have established forests (Kimball et al., 2015; Bayraktarov et al., 2016).

Efforts with reef-building corals have been attempted with a low level of success (Bayraktarov et al., 2016). Technologies to help re-establish coral communities are limited (Rinkevich, 2014), as are largely untested disruptive technologies (e.g., genetic manipulation, assisted evolution) (van Oppen et al., 2015). Current technologies also have trouble scaling given the substantial costs and investment required (Bayraktarov et al., 2016).

Johannessen and Macdonald (2016) report the 'blue carbon' sink to be 0.4–0.8% of global anthropogenic emissions. However, this does not adequately account for post-depositional processes and could overestimate removal potentials, subject to a risk of reversal. Seagrass beds will thus not contribute significantly to enabling 1.5°C-consistent pathways.

4.3.3 Urban and Infrastructure System Transitions

There will be approximately 70 million additional urban residents every year through to the middle part of this century (UN DESA, 2014). The majority of these new urban citizens will reside in small and medium-sized cities in low- and middle-income countries (Cross-Chapter Box 13 in Chapter 5). The combination of urbanization and economic and infrastructure development could account for an additional 226 $GtCO_2$ by 2050 (Bai et al. 2018). However, urban systems can harness the mega-trends of urbanization, digitalization, financialization and growing sub-national commitment to smart cities, green cities, resilient cities, sustainable cities and adaptive cities, for the type of

transformative change required by 1.5°C-consistent pathways (SDSN, 2013; Parag and Sovacool, 2016; Roberts, 2016; Wachsmuth et al., 2016; Revi, 2017; Solecki et al., 2018). There is a growing number of urban climate responses driven by cost-effectiveness, development, work creation and inclusivity considerations (Solecki et al., 2013; Ahern et al., 2014; Floater et al., 2014; Revi et al., 2014a; Villarroel Walker et al., 2014; Kennedy et al., 2015; Rodríguez, 2015; McGranahan et al., 2016; Dodman et al., 2017a; Newman et al., 2017; UN-Habitat, 2017; Westphal et al., 2017).

In addition, low-carbon cities could reduce the need to deploy carbon dioxide removal (CDR) and solar radiation modification (SRM) (Fink, 2013; Thomson and Newman, 2016).

Cities are also places in which the risks associated with warming of 1.5°C, such as heat stress, terrestrial and coastal flooding, new disease vectors, air pollution and water scarcity, will coalesce (see Chapter 3, Section 3.3) (Dodman et al., 2017a; Satterthwaite and Bartlett, 2017). Unless adaptation and mitigation efforts are designed around the need to decarbonize urban societies in the developed world and provide low-carbon solutions to the needs of growing urban populations in developing countries, they will struggle to deliver the pace or scale of change required by 1.5°C-consistent pathways (Hallegatte et al., 2013; Villarroel Walker et al., 2014; Roberts, 2016; Solecki et al., 2018). The pace and scale of urban climate responses can be enhanced by attention to social equity (including gender equity), urban ecology (Brown and McGranahan, 2016; Wachsmuth et al., 2016; Ziervogel et al., 2016a) and participation in sub-national networks for climate action (Cole, 2015; Jordan et al., 2015).

The long-lived urban transport, water and energy systems that will be constructed in the next three decades to support urban populations in developing countries and to retrofit cities in developed countries will have to be different to those built in Europe and North America in the 20th century, if they are to support the required transitions (Freire et al., 2014; Cartwright, 2015; McPhearson et al., 2016; Roberts, 2016; Lwasa, 2017). Recent literature identifies energy, infrastructure, appliances, urban planning, transport and adaptation options as capable of facilitating systemic change. It is these aspects of the urban system that are discussed below and from which options in Section 4.5 are selected.

4.3.3.1 Urban energy systems

Urban economies tend to be more energy intensive than national economies due to higher levels of per capita income, mobility and consumption (Kennedy et al., 2015; Broto, 2017; Gota et al., 2018). However, some urban systems have begun decoupling development from the consumption of fossil fuel-powered energy through energy efficiency, renewable energy and locally managed smart grids (Dodman, 2009; Freire et al., 2014; Eyre et al., 2018; Glazebrook and Newman, 2018).

The rapidly expanding cities of Africa and Asia, where energy poverty currently undermines adaptive capacity (Westphal et al., 2017; Satterthwaite et al., 2018), have the opportunity to benefit from recent price changes in renewable energy technologies to enable clean energy access to citizens (SDG 7) (Cartwright, 2015; Watkins, 2015; Lwasa, 2017; Kennedy et al., 2018; Teferi and Newman, 2018). This will require strengthened energy governance in these countries (Eberhard et al., 2017). Where renewable energy displaces paraffin, wood fuel or charcoal feedstocks in informal urban settlements, it provides the co-benefits of improved indoor air quality, reduced fire risk and reduced deforestation, all of which can enhance adaptive capacity and strengthen demand for this energy (Newham and Conradie, 2013; Winkler, 2017; Kennedy et al., 2018; Teferi and Newman, 2018).

4.3.3.2 Urban infrastructure, buildings and appliances

Buildings are responsible for 32% of global energy consumption (IEA, 2016c) and have a large energy saving potential with available and demonstrated technologies such as energy efficiency improvements in technical installations and in thermal insulation (Toleikyte et al., 2018) and energy sufficiency (Thomas et al., 2017). Kuramochi et al. (2018) show that 1.5°C-consistent pathways require building emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020, and an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD (Organisation for Economic Co-operation and Development) countries (see also Section 4.2.1).

Based on the IEA-ETP (IEA, 2017g), Chapter 2 identifies large saving potential in heating and cooling through improved building design, efficient equipment, lighting and appliances. Several examples of net zero energy in buildings are now available (Wells et al., 2018). In existing buildings, refurbishment enables energy saving (Semprini et al., 2017; Brambilla et al., 2018; D'Agostino and Parker, 2018; Sun et al., 2018) and cost savings (Toleikyte et al., 2018; Zangheri et al., 2018).

Reducing the energy embodied in building materials provides further energy and GHG savings (Cabeza et al., 2013; Oliver and Morecroft, 2014; Koezjakov et al., 2018), in particular through increased use of bio-based materials (Lupíšek et al., 2015) and wood construction (Ramage et al., 2017). The United Nations Environment Programme (UNEP[3]) estimates that improving embodied energy, thermal performance, and direct energy use of buildings can reduce emissions by 1.9 $GtCO_2e\ yr^{-1}$ (UNEP, 2017b), with an additional reduction of 3 $GtCO_2e\ yr^{-1}$ through energy efficient appliances and lighting (UNEP, 2017b). Further increasing the energy efficiency of appliances and lighting, heating and cooling offers the potential for further savings (Parikh and Parikh, 2016; Garg et al., 2017).

Smart technology, drawing on the internet of things (IoT) and building information modelling, offers opportunities to accelerate energy efficiency in buildings and cities (Moreno-Cruz and Keith, 2013; Hoy, 2016) (see also Section 4.4.4). Some cities in developing countries are drawing on these technologies to adopt 'leapfrog' infrastructure, buildings and appliances to pursue low-carbon development (Newman et al., 2017; Teferi and Newman, 2017) (Cross-Chapter Box 13 in Chapter 5).

[3] Currently called UN Environment.

4.3.3.3 Urban transport and urban planning

Urban form impacts demand for energy (Sims et al., 2014) and other welfare related factors: a meta-analysis of 300 papers reported energy savings of 26 USD per person per year attributable to a 10% increase in urban population density (Ahlfeldt and Pietrostefani, 2017). Significant reductions in car use are associated with dense, pedestrianized cities and towns and medium-density transit corridors (Newman and Kenworthy, 2015; Newman et al., 2017) relative to low-density cities in which car dependency is high (Schiller and Kenworthy, 2018). Combined dense urban forms and new mass transit systems in Shanghai and Beijing have yielded less car use (Gao and Newman, 2018) (see Box 4.9). Compact cities also create the passenger density required to make public transport more financially viable (Rode et al., 2017; Ahlfeldt and Pietrostefani, 2017) and enable combinations of cleaner fuel feedstocks and urban smart grids, in which vehicles form part of the storage capacity (Oldenbroek et al., 2017). Similarly, the spatial organization of urban energy influenced the trajectories of urban development in cities as diverse as Hong Kong, Bengaluru and Maputo (Broto, 2017).

The informal settlements of middle- and low-income cities, where urban density is more typically associated with a range of water- and vector-borne health risks, may provide a notable exception to the adaptive advantages of urban density (Mitlin and Satterthwaite, 2013; Lilford et al., 2017) unless new approaches and technologies are harnessed to accelerate slum upgrading (Teferi and Newman, 2017).

Scenarios consistent with 1.5°C depend on a roughly 15% reduction in final energy use by the transport sector by 2050 relative to 2015 (Chapter 2, Figure 2.12). In one analysis the phasing out of fossil fuel passenger vehicle sales by 2035–2050 was identified as a benchmark for aligning with 1.5°C-consistent pathways (Kuramochi et al., 2018). Reducing emissions from transport has lagged the power sector (Sims et al., 2014; Creutzig et al., 2015a), but evidence since AR5 suggests that cities are urbanizing and re-urbanizing in ways that coordinate transport sector adaptation and mitigation (Colenbrander et al., 2017; Newman et al., 2017; Salvo et al., 2017; Gota et al., 2018). The global transport sector could reduce 4.7 $GtCO_2e\ yr^{-1}$ (4.1–5.3) by 2030. This is significantly more than is predicted by integrated assessment models (UNEP, 2017b). Such a transition depends on cities that enable modal shifts and avoided journeys and that provide incentives for uptake of improved fuel efficiency and changes in urban design that encourage walkable cities, non-motorized transport and shorter commuter distances (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In at least 4 African cities, 43 Asian cities and 54 Latin American cities, transit-oriented development (TOD), has emerged as an organizing principle for urban growth and spatial planning (Colenbrander et al., 2017; Lwasa, 2017; BRTData, 2018). This trend is important to counter the rising demand for private cars in developing-country cities (AfDB/OECD/UNDP, 2016). In India, TOD has been combined with localized solar PV installations and new ways of financing rail expansion (Sharma, 2018).

Cities pursuing sustainable transport benefit from reduced air pollution, congestion and road fatalities and are able to harness the relationship between transport systems, urban form, urban energy intensity and social cohesion (Goodwin and Van Dender, 2013; Newman and Kenworthy, 2015; Wee, 2015).

Technology and electrification trends since AR5 make carbon-efficient urban transport easier (Newman et al., 2016), but realizing urban transport's contribution to a 1.5°C-consistent pathways will require the type of governance that can overcome the financial, institutional, behavioural and legal barriers to change (Geels, 2014; Bakker et al., 2017).

Adaptation to a 1.5°C world is enabled by urban design and spatial planning policies that consider extreme weather conditions and reduce displacement by climate related disasters (UNISDR, 2009; UN-Habitat, 2011; Mitlin and Satterthwaite, 2013).

Building codes and technology standards for public lighting, including traffic lights (Beccali et al., 2015), play a critical role in reducing carbon emissions, enhancing urban climate resilience and managing climate risk (Steenhof and Sparling, 2011; Parnell, 2015; Shapiro, 2016; Evans et al., 2017). Building codes can support the convergence to zero emissions from buildings (Wells et al., 2018) and can be used retrofit the existing building stock for energy efficiency (Ruparathna et al., 2016).

The application of building codes and standards for 1.5°C-consistent pathways will require improved enforcement, which can be a challenge in developing countries where inspection resources are often limited and codes are poorly tailored to local conditions (Ford et al., 2015c; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Hess and Kelman, 2017; Mavhura et al., 2017). In all countries, building codes can be undermined by industry interests and can be maladaptive if they prevent buildings or land use from evolving to reduce climate impacts (Eisenberg, 2016; Shapiro, 2016).

The deficit in building codes and standards in middle-income and developing-country cities need not be a constraint to more energy-efficient and resilient buildings (Tait and Euston-Brown, 2017). For example, the relatively high price that poor households pay for unreliable and at times dangerous household energy in African cities has driven the uptake of renewable energy and energy efficiency technologies in the absence of regulations or fiscal incentives (Eberhard et al., 2011, 2016; Cartwright, 2015; Watkins, 2015). The Kuyasa Housing Project in Khayelitsha, one of Cape Town's poorest suburbs, created significant mitigation and adaptation benefits by installing ceilings, solar water heaters and energy-efficient lightbulbs in houses independent of the formal housing or electrification programme (Winkler, 2017).

4.3.3.4 Electrification of cities and transport

The electrification of urban systems, including transport, has shown global progress since AR5 (IEA, 2016a; Kennedy et al., 2018; Schiller and Kenworthy, 2018). High growth rates are now appearing in electric vehicles (Figure 4.1), electric bikes and electric transit (IEA, 2018), which would need to displace fossil fuel-powered passenger vehicles by 2035–2050 to remain in line with 1.5°C-consistent pathways. China's 2017 Road Map calls for 20% of new vehicle

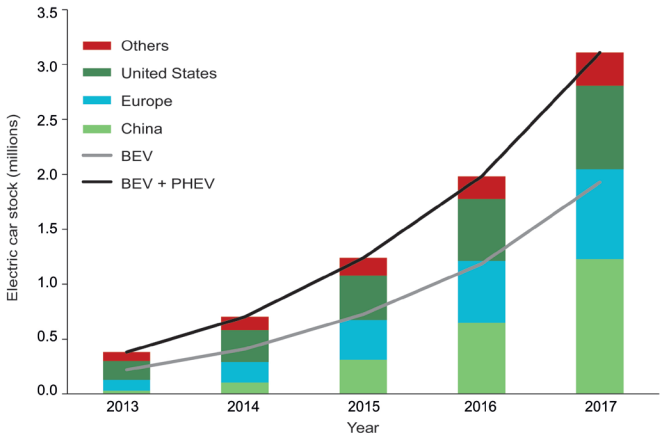

Figure 4.1 | Increase of the global electric car stock by country (2013–2017). The grey line is battery electric vehicles (BEV) only while the black line includes both BEV and plug-in hybrid vehicles (PHEV). Source: (IEA, 2018). Based on IEA data from Global EV Outlook 2018 © OECD/IEA 2018, IEA Publishing.

sales to be electric. India is aiming for exclusively electric vehicles (EVs) by 2032 (NITI Aayog and RMI, 2017). Globally, EV sales were up 42% in 2016 relative to 2015, and in the United States EV sales were up 36% over the same period (Johnson and Walker, 2016).

The extent of electric railways in and between cities has expanded since AR5 (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In high-income cities there is *medium evidence* for the decoupling of car use and wealth since AR5 (Newman, 2017). In cities where private vehicle ownership is expected to increase, less carbon-intensive fuel sources and reduced car journeys will be necessary as well as electrification of all modes of transport (Mittal et al., 2016; van Vuuren et al., 2017). Some recent urban data show a decoupling of urban growth and GHG emissions (Newman and Kenworthy, 2015) and that 'peak car' has been reached in Shanghai and Beijing (Gao and Kenworthy, 2017) and beyond (Manville et al., 2017) (also see Box 4.9).

An estimated 800 cities globally have operational bike-share schemes (E. Fishman et al., 2015), and China had 250 million electric bicycles in 2017 (Newman et al., 2017). Advances in information and communication technologies (ICT) offer cities the chance to reduce urban transport congestion and fuel consumption by making better use of the urban vehicle fleet through car sharing, driverless cars and coordinated public transport, especially when electrified (Wee, 2015; Glazebrook and Newman, 2018). Advances in 'big-data' can assist in creating a better understanding of the connections between cities, green infrastructure, environmental services and health (Jennings et al., 2016) and improve decision-making in urban development (Lin et al., 2017).

4.3.3.5 Shipping, freight and aviation

International transport hubs, including airports and ports, and the associated mobility of people are major economic contributors to most large cities even while under the governance of national authorities and international legislation. Shipping, freight and aviation systems have grown rapidly, and little progress has been made since AR5 on replacing fossil fuels, though some trials are continuing (Zhang, 2016; Bouman et al., 2017; EEA, 2017). Aviation emissions do not yet feature in IAMs (Bows-Larkin, 2015), but could be reduced by between a third and two-thirds through energy efficiency measures and operational changes (Dahlmann et al., 2016). On shorter intercity trips, aviation could be replaced by high-speed electric trains drawing on renewable energy (Åkerman, 2011). Some progress has been made on the use of electricity in planes and shipping (Grewe et al., 2017) though no commercial applications have arisen. Studies indicate that biofuels are the most viable means of decarbonizing intercontinental travel, given their technical characteristics, energy content and affordability (Wise et al., 2017). The lifecycle emissions of bio-based jet fuels and marine fuels can be considerable (Cox et al., 2014; IEA, 2017g) depending on their location (Elshout et al., 2014), but can be reduced by feedstock and conversion technology choices (de Jong et al., 2017).

In recent years the potential for transport to use synfuels, such as ethanol, methanol, methane, ammonia and hydrogen, created from renewable electricity and CO_2, has gained momentum but has not yet demonstrated benefits on a scale consistent with 1.5°C pathways (Ezeji, 2017; Fasihi et al., 2017). Decarbonizing the fuel used by the world's 60,000 large ocean vessels faces governance barriers and the need for a global policy (Bows and Smith, 2012; IRENA, 2015; Rehmatulla and Smith, 2015). Low-emission marine fuels could simultaneously address sulphur and black carbon issues in ports and around waterways and accelerate the electrification of all large ports (Bouman et al., 2017; IEA, 2017g).

4.3.3.6 Climate-resilient land use

Urban land use influences energy intensity, risk exposure and adaptive capacity (Carter et al., 2015; Araos et al., 2016a; Ewing et al., 2016; Newman et al., 2016; Broto, 2017). Accordingly, urban land-use planning can contribute to climate mitigation and adaptation (Parnell, 2015; Francesch-Huidobro et al., 2017) and the growing number of urban climate adaptation plans provide instruments to do this (Carter et al., 2015; Dhar and Khirfan, 2017; Siders, 2017; Stults and Woodruff, 2017). Adaptation plans can reduce exposure to urban flood risk (which, in a 1.5°C world, could double relative to 1976–2005; Alfieri et al., 2017), heat stress (Chapter 3, Section 3.5.5.8), fire risk (Chapter 3, Section 3.4.3.4) and sea level rise (Chapter 3, Section 3.4.5.1) (Schleussner et al., 2016).

Cities can reduce their risk exposure by considering investment in infrastructure and buildings that are more resilient to warming of 1.5°C or beyond. Where adaptation planning and urban planning generate the type of local participation that enhances capacity to cope with risks, they can be mutually supportive processes (Archer et al., 2014; Kettle et al., 2014; Campos et al., 2016; Chu et al., 2017; Siders, 2017; Underwood et al., 2017). Not all adaptation plans are reported as effective (Measham et al., 2011; Hetz, 2016; Woodruff and Stults, 2016; Mahlkow and Donner, 2017), especially in developing-country cities (Kiunsi, 2013). In cases where adaptation planning may further marginalize poor citizens, either through limited local control over adaptation priorities or by displacing impacts onto poorer communities, successful urban risk management would need to consider factors such as justice, equity, and inclusive participation, as well as recognize the political economy of adaptation (Archer, 2016; Shi et al., 2016; Ziervogel et al., 2016a, 2017; Chu et al., 2017).

4.3.3.7 Green urban infrastructure and ecosystem services

Integrating and promoting green urban infrastructure (including street trees, parks, green roofs and facades, and water features) into city planning can be difficult (Leck et al., 2015) but increases urban resilience to impacts of 1.5°C warming (Table 4.2) in ways that can be more cost-effective than conventional infrastructure (Cartwright et al., 2013; Culwick and Bobbins, 2016).

Realizing climate benefits from urban green infrastructure sometimes requires a city-region perspective (Wachsmuth et al., 2016). Where the urban impact on ecological systems in and beyond the city is appreciated, the potential for transformative change exists (Soderlund and Newman, 2015; Ziervogel et al., 2016a), and a locally appropriate combination of green space, ecosystem goods and services and the built environment can increase the set of urban adaptation options (Puppim de Oliveira et al., 2013).

Milan, Italy, a city with deliberate urban greening policies, planted 10,000 hectares of new forest and green areas over the last two decades (Sanesi et al., 2017). The accelerated growth of urban trees, relative to rural trees, in several regions of the world is expected to decrease tree longevity (Pretzsch et al., 2017), requiring monitoring and additional management of urban trees if their contribution to urban ecosystem-based adaptation and mitigation is to be maintained in a 1.5°C world (Buckeridge, 2015; Pretzsch et al., 2017).

4.3.3.8 Sustainable urban water and environmental services

Urban water supply and wastewater treatment is energy intensive and currently accounts for significant GHG emissions (Nair et al., 2014). Cities can integrate sustainable water resource management and the supply of water services in ways that support mitigation, adaptation and development through waste water recycling and storm water diversion (Xue et al., 2015; Poff et al., 2016). Governance and finance challenges complicate balancing sustainable water supply and rising urban demand, particularly in low-income cities (Bettini et al., 2015; Deng and Zhao, 2015; Hill Clarvis and Engle, 2015; Lemos, 2015; Margerum and Robinson, 2015).

Urban surface-sealing with impervious materials affects the volume and velocity of runoff and flooding during intense rainfall (Skougaard Kaspersen et al., 2015), but urban design in many cities now seeks to mediate runoff, encourage groundwater recharge and enhance water quality (Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017). Challenges remain for managing intense rainfall events that are reported to be increasing in frequency and intensity in some locations (Ziervogel et al., 2016b), and urban flooding is expected to increase at 1.5°C of warming (Alfieri et al., 2017). This risk falls disproportionately on women and poor people in cities (Mitlin, 2005; Chu et al., 2016; Ziervogel et al., 2016b; Chant et al., 2017; Dodman et al., 2017a, b).

Nexus approaches that highlight urban areas as socio-ecological systems can support policy coherence (Rasul and Sharma, 2016) and sustainable urban livelihoods (Biggs et al., 2015). The water–energy–food (WEF) nexus is especially important to growing urban populations (Tacoli et al., 2013; Lwasa et al., 2014; Villarroel Walker et al., 2014).

4.3.4 Industrial Systems Transitions

Industry consumes about one-third of global final energy and contributes, directly and indirectly, about one-third of global GHG emissions (IPCC, 2014b). If the increase in global mean temperature is to remain under 1.5°C, modelling indicates that industry cannot emit more than 2 $GtCO_2$ in 2050, corresponding to a reduction of between 67 and 91% (interquartile range) in GHG emissions compared to 2010 (see Chapter 2, Figures 2.20 and 2.21, and Table 4.1). Moreover, the consequences of warming of 1.5°C or more pose substantial challenges for industrial diversity. This section will first briefly discuss the limited literature on adaptation options for industry. Subsequently, new literature since AR5 on the feasibility of industrial mitigation options will be discussed.

Research assessing adaptation actions by industry indicates that only a small fraction of corporations has developed adaptation measures. Studies of adaptation in the private sector remain limited (Agrawala et al., 2011; Linnenluecke et al., 2015; Averchenkova et al., 2016; Bremer and Linnenluecke, 2016; Pauw et al., 2016a) and for 1.5°C are largely

Table 4.2 | Green urban infrastructure and benefits

Green Infrastructure	Adaptation Benefits	Mitigation Benefits	References
Urban tree planting, urban parks	Reduced heat island effect, psychological benefits	Less cement, reduced air-conditioning use	Demuzere et al., 2014; Mullaney et al., 2015; Soderlund and Newman, 2015; Beaudoin and Gosselin, 2016; Green et al., 2016; Lin et al., 2017
Permeable surfaces	Water recharge	Less cement in city, some bio-sequestration, less water pumping	Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017
Forest retention, urban agricultural land	Flood mediation, healthy lifestyles	Reduced air pollution	Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; R. White et al., 2017
Wetland restoration, riparian buffer zones	Reduced urban flooding, low-skilled local work, sense of place	Some bio-sequestration, less energy spent on water treatment	Cartwright et al., 2013; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Culwick and Bobbins, 2016; McPhearson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; F. Li et al., 2017
Biodiverse urban habitat	Psychological benefits, inner-city recreation	Carbon sequestration	Beatley, 2011; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; McPhearson et al., 2016; Collas et al., 2017; F. Li et al., 2017

absent. This knowledge gap is particularly evident for medium-sized enterprises and in low- and middle-income nations (Surminski, 2013).

Depending on the industrial sector, mitigation consistent with 1.5°C would mean, across industries, a reduction of final energy demand by one-third, an increase of the rate of recycling of materials and the development of a circular economy in industry (Lewandowski, 2016; Linder and Williander, 2017), the substitution of materials in high-carbon products with those made up of renewable materials (e.g., wood instead of steel or cement in the construction sector, natural textile fibres instead of plastics), and a range of deep emission reduction options, including use of bio-based feedstocks, low-emission heat sources, electrification of production processes, and/or capture and storage of all CO_2 emissions by 2050 (Åhman et al., 2016). Some of the choices for mitigation options and routes for GHG-intensive industry are discrete and potentially subject to path dependency: if an industry goes one way (e.g., in keeping existing processes), it will be harder to transition to process change (e.g., electrification) (Bataille et al., 2018). In the context of rising demand for construction, an increasing share of industrial production may be based in developing countries (N. Li et al., 2017), where current efficiencies may be lower than in developed countries, and technical and institutional feasibility may differ (Ma et al., 2015).

Except for energy efficiency, costs of disruptive change associated with hydrogen- or electricity-based production, bio-based feedstocks and carbon dioxide capture, (utilization) and storage (CC(U)S) for trade-sensitive industrial sectors (in particular the iron and steel, petrochemical and refining industries) make policy action by individual countries challenging because of competitiveness concerns (Åhman et al., 2016; Nabernegg et al., 2017).

Table 4.3 provides an overview of applicable mitigation options for key industrial sectors.

4.3.4.1 Energy efficiency

Isolated efficiency implementation in energy-intensive industries is a necessary but insufficient condition for deep emission reductions (Napp et al., 2014; Aden, 2018). Various options specific to different industries are available. In general, their feasibility depends on lowering capital costs and raising awareness and expertise (Wesseling et al., 2017). General-purpose technologies, such as ICT, and energy management tools can improve the prospects of energy efficiency in industry (see Section 4.4.4).

Cross-sector technologies and practices, which play a role in all industrial sectors including small- and medium-sized enterprises (SMEs) and non-energy intensive industry, also offer potential for considerable energy efficiency improvements. They include: (i) motor systems (for example electric motors, variable speed drives, pumps, compressors and fans), responsible for about 10% of worldwide industrial energy consumption, with a global energy efficiency improvement potential of around 20–25% (Napp et al., 2014); and (ii) steam systems, responsible for about 30% of industrial energy consumption and energy saving potentials of about 10% (Hasanbeigi et al., 2014; Napp et al., 2014). Waste heat recovery from industry has substantial potential for energy efficiency and emission reduction (Forman et al., 2016). Low awareness and competition from other investments limit the feasibility of such options (Napp et al., 2014).

4.3.4.2 Substitution and circularity

Recycling materials and developing a circular economy can be institutionally challenging, as it requires advanced capabilities (Henry et al., 2006) and organizational changes (Cooper-Searle et al., 2018), but has advantages in terms of cost, health, governance and environment (Ali et al., 2017). An assessment of the impacts on energy use and environmental issues is not available, but substitution could play a large role in reducing emissions (Åhman et al., 2016) although its potential depends on the demand for material and the turnover rate of, for example, buildings (Haas et al., 2015). Material substitution and CO_2 storage options are under development, for example, the use of algae and renewable energy for carbon fibre production, which could become a net sink of CO_2 (Arnold et al., 2018).

4.3.4.3 Bio-based feedstocks

Bio-based feedstock processes could be seen as part of the circular materials economy (see section above). In several sectors, bio-based

Table 4.3 | Overview of different mitigation options potentially consistent with limiting warming to 1.5°C and applicable to main industrial sectors, including examples of application (Napp et al., 2014; Boulamanti and Moya, 2017; Wesseling et al., 2017).

Industrial mitigation option	Iron/Steel	Cement	Refineries and Petrochemicals	Chemicals
Process and Energy Efficiency	Can make a difference of between 10% and 50%, depending on the plant. Relevant but not enough for 1.5°C			
Bio-based	Coke can be made from biomass instead of coal	Partial (only energy-related emissions)	Biomass can replace fossil feedstocks	
Circularity & Substitution	More recycling and replacement by low-emission materials, including alternative chemistries for cement		Limited potential	
Electrification & Hydrogen	Direct reduction with hydrogen Heat generation through electricity	Partial (only electrified heat generation)	Electrified heat and hydrogen generation	
Carbon dioxide capture, utilization and storage	Possible for process emissions and energy. Reduces emissions by 80–95%, and net emissions can become negative when combined with biofuel		Can be applied to energy emissions and different stacks but not on emissions of products in the use phase (e.g., gasoline)	

feedstocks would leave the production process of materials relatively untouched, and a switch would not affect the product quality, making the option more attractive. However, energy requirements for processing bio-based feedstocks are often high, costs are also still higher, and the emissions over the full life cycle, both upstream and downstream, could be significant (Wesseling et al., 2017). Bio-based feedstocks may put pressure on natural resources by increasing land demand by biodiversity impacts beyond bioenergy demand for electricity, transport and buildings (Slade et al., 2014), and, partly as a result, face barriers in public acceptance (Sleenhoff et al., 2015).

4.3.4.4 Electrification and hydrogen

Electrification of manufacturing processes would constitute a significant technological challenge and would entail a more disruptive innovation in industry than bio-based or CCS options to get to very low or zero emissions, except potentially in steel-making (Philibert, 2017). The disruptive characteristics could potentially lead to stranded assets, and could reduce political feasibility and industry support (Åhman et al., 2016). Electrification of manufacturing would require further technological development in industry, as well as an ample supply of cost-effective low-emission electricity (Philibert, 2017).

Low-emission hydrogen can be produced by natural gas with CCS, by electrolysis of water powered by zero-emission electricity, or potentially in the future by generation IV nuclear reactors. Feasibility of electrification and use of hydrogen in production processes or fuel cells is affected by technical development (in terms of efficient hydrogen production and electrification of processes), by geophysical factors related to the availability of low-emission electricity (MacKay, 2013), by associated public perception and by economic feasibility, except in areas with ample solar and/or wind resources (Philibert, 2017; Wesseling et al., 2017).

4.3.4.5 CO_2 capture, utilization and storage in industry

CO_2 capture in industry is generally considered more feasible than CCS in the power sector (Section 4.3.1) or from bioenergy sources (Section 4.3.7), although CCS in industry faces similar barriers. Almost all of the current full-scale (>1MtCO_2 yr^{-1}) CCS projects capture CO_2 from industrial sources, including the Sleipner project in Norway, which has been injecting CO_2 from a gas facility in an offshore saline formation since 1996 (Global CCS Institute, 2017). Compared to the power sector, retrofitting CCS on existing industrial plants would leave the production process of materials relatively untouched (Åhman et al., 2016), though significant investments and modifications still have to be made. Some industries, in particular cement, emit CO_2 as inherent process emissions and can therefore not reduce emissions to zero without CC(U)S. CO_2 stacks in some industries have a high economic and technical feasibility for CO_2 capture as the CO_2 concentration in the exhaust gases is relatively high (IPCC, 2005b; Leeson et al., 2017), but others require strong modifications in the production process, limiting technical and economic feasibility, though costs remain lower than other deep GHG reduction options (Rubin et al., 2015). There are indications that the energy use in CO_2 capture through amine solvents (for solvent regeneration) can decrease by around 60%, from 5 GJ tCO_2^{-1} in 2005 to 2 GJ tCO_2^{-1} in the best-performing current pilot plants (Idem et al., 2015), increasing both technical and economic potential for this option. The heterogeneity of industrial production processes might point to the need for specific institutional arrangements to incentivize industrial CCS (Mikunda et al., 2014), and may decrease institutional feasibility.

Whether carbon dioxide utilization (CCU) can contribute to limiting warming to 1.5°C depends on the origin of the CO_2 (fossil, biogenic or atmospheric), the source of electricity for converting the CO_2 or regenerating catalysts, and the lifetime of the product. Review studies indicate that CO_2 utilization in industry has a small role to play in limiting warming to 1.5°C because of the limited potential of reusing CO_2 with currently available technologies and the re-emission of CO_2 when used as a fuel (IPCC, 2005b; Mac Dowell et al., 2017). However, new developments could make CCU more feasible, in particular in CO_2 use as a feedstock for carbon-based materials that would isolate CO_2 from the atmosphere for a long time, and in low-cost, low-emission electricity that would make the energy use of CO_2 capture more sustainable. The conversion of CO_2 to fuels using zero-emission electricity has a lower technical, economic and environmental feasibility than direct CO_2 capture and storage from industry (Abanades et al., 2017), although the economic prospects have improved recently (Philibert, 2017).

4.3.5 Overarching Adaptation Options Supporting Adaptation Transitions

This section assesses overarching adaptation options –specific solutions from which actors can choose and make decisions to reduce climate vulnerability and build resilience. We examine their feasibility in the context of transitions of energy, land and ecosystem, urban and infrastructure, and industrial systems here, and further in Section 4.5. These options can contribute to creating an enabling environment for adaptation (see Table 4.4 and Section 4.4).

4.3.5.1 Disaster risk management (DRM)

DRM is a process for designing, implementing and evaluating strategies, policies and measures to improve the understanding of disaster risk, and promoting improvement in disaster preparedness, response and recovery (IPCC, 2012). There is increased demand to integrate DRM and adaptation (Howes et al., 2015; Kelman et al., 2015; Serrao-Neumann et al., 2015; Archer, 2016; Rose, 2016; van der Keur et al., 2016; Kelman, 2017; Wallace, 2017) to reduce vulnerability, but institutional, technical and financial capacity challenges in frontline agencies constitute constraints (*medium evidence, high agreement*) (Eakin et al., 2015; Kita, 2017; Wallace, 2017).

4.3.5.2 Risk sharing and spreading

Risks associated with 1.5°C warming (Chapter 3, Section 3.4) may increase the demand for options that share and spread financial burdens. Formal, market-based (re)insurance spreads risk and provides a financial buffer against the impacts of climate hazards (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Patel et al., 2017). As an alternative to traditional indemnity-based insurance, index-

based micro-crop and livestock insurance programmes have been rolled out in regions with less developed insurance markets (Akter et al., 2016, 2017; Jensen and Barrett, 2017). There is *medium evidence* and *medium agreement* on the feasibility of insurance for adaptation, with financial, social, and institutional barriers to implementation and uptake, especially in low-income nations (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016). Social protection programmes include cash and in-kind transfers to protect poor and vulnerable households from the impact of economic shocks, natural disasters and other crises (World Bank, 2017b), and can build generic adaptive capacity and reduce vulnerability when combined with a comprehensive climate risk management approach (*medium evidence, medium agreement*) (Devereux, 2016; Lemos et al., 2016).

4.3.5.3 Education and learning

Educational adaptation options motivate adaptation through building awareness (Butler et al., 2016; Myers et al., 2017), leveraging multiple knowledge systems (Pearce et al., 2015; Janif et al., 2016), developing participatory action research and social learning processes (Butler and Adamowski, 2015; Ensor and Harvey, 2015; Butler et al., 2016; Thi Hong Phuong et al., 2017; Ford et al., 2018), strengthening extension services, and building mechanisms for learning and knowledge sharing through community-based platforms, international conferences and knowledge networks (Vinke-de Kruijf and Pahl-Wostl, 2016) (*medium evidence, high agreement*).

4.3.5.4 Population health and health system adaptation options

Climate change will exacerbate existing health challenges (Chapter 3, Section 3.4.7). Options for enhancing current health services include providing access to safe water and improved sanitation, enhancing access to essential services such as vaccination, and developing or strengthening integrated surveillance systems (WHO, 2015). Combining these with iterative management can facilitate effective adaptation (*medium evidence, high agreement*).

4.3.5.5 Indigenous knowledge

There is *medium evidence* and *high agreement* that indigenous knowledge is critical for adaptation, underpinning adaptive capacity through the diversity of indigenous agro-ecological and forest management systems, collective social memory, repository of accumulated experience and social networks (Hiwasaki et al., 2015; Pearce et al., 2015; Mapfumo et al., 2016; Sherman et al., 2016; Ingty, 2017) (Box 4.3). Indigenous knowledge is threatened by acculturation, dispossession of land rights and land grabbing, rapid environmental changes, colonization and social change, resulting in increasing vulnerability to climate change – which climate policy can exacerbate if based on limited understanding of indigenous worldviews (Thornton and Manasfi, 2010; Ford, 2012; Nakashima et al., 2012; McNamara and Prasad, 2014). Many scholars argue that recognition of indigenous rights, governance systems and laws is central to adaptation, mitigation and sustainable development (Magni, 2017; Thornton and Comberti, 2017; Pearce, 2018).

4.3.5.6 Human migration

Human migration, whether planned, forced or voluntary, is increasingly gaining attention as a response, particularly where climatic risks are becoming severe (Chapter 3, Section 3.4.10.2). There is *medium evidence* and *low agreement* as to whether migration is adaptive, in relation to cost effectiveness concerns (Grecequet et al., 2017) and scalability (Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017). Migrating can have mixed outcomes on reducing socio-economic vulnerability (Birk and Rasmussen, 2014; Kothari, 2014; Adger et al., 2015; Betzold, 2015; Kelman, 2015; Grecequet et al., 2017; Melde et al., 2017; World Bank, 2017a; Kumari Rigaud et al., 2018) and its feasibility is constrained by low political and legal acceptability and inadequate institutional capacity (Betzold, 2015; Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017; Yamamoto et al., 2017).

4.3.5.7 Climate services

There is *medium evidence* and *high agreement* that climate services can play a critical role in aiding adaptation decision-making (Vaughan and Dessai, 2014; Wood et al., 2014; Lourenço et al., 2016; Trenberth et al., 2016; Singh et al., 2017; Vaughan et al., 2018). The higher uptake of short-term climate information such as weather advisories and daily forecasts contrast with lesser use of longer-term information such as seasonal forecasts and multi-decadal projections (Singh et al., 2017; Vaughan et al., 2018). Climate service interventions have met challenges with scaling up due to low capacity, inadequate institutions, and difficulties in maintaining systems beyond pilot project stage (Sivakumar et al., 2014; Tall et al., 2014; Gebru et al., 2015; Singh et al., 2016b), and technical, institutional, design, financial and capacity barriers to the application of climate information for better decision-making remain (Briley et al., 2015; WMO, 2015; L. Jones et al., 2016; Lourenço et al., 2016; Snow et al., 2016; Harjanne, 2017; Singh et al., 2017; C.J. White et al., 2017).

Table 4.4 | Assessment of overarching adaptation options in relation to enabling conditions. For more details, see Supplementary Material 4.SM.2.

Option	Enabling Conditions	Examples
Disaster risk management (DRM)	Governance and institutional capacity: supports post-disaster recovery and reconstruction (Kelman et al., 2015; Kull et al., 2016).	Early warning systems (Anacona et al., 2015), and monitoring of dangerous lakes and surrounding slopes (including using remote sensing) offer DRM opportunities (Emmer et al., 2016; Milner et al., 2017).
Risk sharing and spreading: insurance	Institutional capacity and finance: buffers climate risk (Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017).	In 2007, the Caribbean Catastrophe Risk Insurance Facility was formed to pool risk from tropical cyclones, earthquakes, and excess rainfalls (Murphy et al., 2012; CCRIF, 2017).
Social safety nets	Institutional capacity and finance: builds generic adaptive capacity and reduces social vulnerability (Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017).	In sub-Saharan Africa, cash transfer programmes targeting poor communities have proven successful in smoothing household welfare and food security during droughts, strengthening community ties, and reducing debt levels (del Ninno et al., 2016; Asfaw et al., 2017; Asfaw and Davis, 2018).
Education and learning	Behavioural change and institutional capacity: social learning strengthens adaptation and affects longer-term change (Clemens et al., 2015; Ensor and Harvey, 2015; Henly-Shepard et al., 2015).	Participatory scenario planning is a process by which multiple stakeholders work together to envision future scenarios under a range of climatic conditions (Oteros-Rozas et al., 2015; Butler et al., 2016; Flynn et al., 2018).
Population health and health system	Institutional capacity: 1.5°C warming will primarily exacerbate existing health challenges (K.R. Smith et al., 2014), which can be targeted by enhancing health services.	Heatwave early warning and response systems coordinate the implementation of multiple measures in response to predicted extreme temperatures (e.g., public announcements, opening public cooling shelters, distributing information on heat stress symptoms) (Knowlton et al., 2014; Takahashi et al., 2015; Nitschke et al., 2016, 2017).
Indigenous knowledge	Institutional capacity and behavioural change: knowledge of environmental conditions helps communities detect and monitor change (Johnson et al., 2015; Mistry and Berardi, 2016; Williams et al., 2017).	Options such as integration of indigenous knowledge into resource management systems and school curricula, are identified as potential adaptations (Cunsolo Willox et al., 2013; McNamara and Prasad, 2014; MacDonald et al., 2015; Pearce et al., 2015; Chambers et al., 2017; Inamara and Thomas, 2017).
Human migration	Governance: revising and adopting migration issues in national disaster risk management policies, National Adaptation Plans and NDCs (Kuruppu and Willie, 2015; Yamamoto et al., 2017).	In dryland India, populations in rural regions already experiencing 1.5°C warming are migrating to cities (Gajjar et al., 2018) but are inadequately covered by existing policies (Bhagat, 2017).
Climate services	Technological innovation: rapid technical development (due to increased financial inputs and growing demand) is improving quality of climate information provided (Rogers and Tsirkunov, 2010; Clements et al., 2013; Perrels et al., 2013; Gasc et al., 2014; WMO, 2015; Roudier et al., 2016).	Climate services are seeing wide application in sectors such as agriculture, health, disaster management and insurance (Lourenço et al., 2016; Vaughan et al., 2018), with implications for adaptation decision-making (Singh et al., 2017).

4

Cross-Chapter Box 9 | Risks, Adaptation Interventions, and Implications for Sustainable Development and Equity Across Four Social-Ecological Systems: Arctic, Caribbean, Amazon, and Urban

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This box presents four case studies from different social-ecological systems as examples of risks of 1.5°C warming and higher (Chapter 3); adaptation options that respond to these risks (Chapter 4); and their implications for poverty, livelihoods and sustainability (Chapter 5). It is not yet possible to generalize adaptation effectiveness across regions due to a lack of empirical studies and monitoring and evaluation of current efforts.

Arctic

The Arctic is undergoing the most rapid climate change globally (Larsen et al., 2014), warming by 1.9°C over the last 30 years (Walsh, 2014; Grosse et al., 2016). For 2°C of global warming relative to pre-industrial levels, chances of an ice-free Arctic during summer are substantially higher than at 1.5°C (see Chapter 3, Sections 3.3.5 and 3.3.8), with permafrost melt, increased instances of storm surge, and extreme weather events anticipated along with later ice freeze up, earlier break up, and a longer ice-free open water season (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Chadburn et al., 2017; Melvin et al., 2017). Negative impacts on health, infrastructure, and economic sectors (AMAP, 2017a, b, 2018) are projected, although the extension of the summer ocean-shipping season has potential economic opportunities (Ford et al., 2015b; Dawson et al., 2016; Ng et al., 2018).

Cross Chapter Box 9 (continued)

Communities, many with indigenous roots, have adapted to environmental change, developing or shifting harvesting activities and patterns of travel and transitioning economic systems (Forbes et al., 2009; Wenzel, 2009; Ford et al., 2015b; Pearce et al., 2015), although emotional and psychological effects have been documented (Cunsolo Willox et al., 2012; Cunsolo and Ellis, 2018). Besides climate change (Keskitalo et al., 2011; Loring et al., 2016), economic and social conditions can constrain the capacity to adapt unless resources and cooperation are available from public and private sector actors (AMAP, 2017a, 2018) (see Chapter 5, Box 5.3). In Alaska, the cumulative economic impacts of climate change on public infrastructure are projected at 4.2 billion USD to 5.5 billion USD from 2015 to 2099, with adaptation efforts halving these estimates (Melvin et al., 2017). Marginalization, colonization, and land dispossession provide broader underlying challenges facing many communities across the circumpolar north in adapting to change (Ford et al., 2015a; Sejersen, 2015) (see Section 4.3.5).

Adaptation opportunities include alterations to building codes and infrastructure design, disaster risk management, and surveillance (Ford et al., 2014a; AMAP, 2017a, b; Labbé et al., 2017). Most adaptation initiatives are currently occurring at local levels in response to both observed and projected environmental changes as well as social and economic stresses (Ford et al., 2015a). In a recent study of Canada, most adaptations were found to be in the planning stages (Labbé et al., 2017). Studies have suggested that a number of the adaptation actions are not sustainable, lack evaluation frameworks, and hold potential for maladaptation (Loboda, 2014; Ford et al., 2015a; Larsson et al., 2016). Utilizing indigenous and local knowledge and stakeholder engagement can aid the development of adaptation policies and broader sustainable development, along with more proactive and regionally coherent adaptation plans and actions, and regional cooperation (e.g., through the Arctic Council) (Larsson et al., 2016; AMAP, 2017a; Melvin et al., 2017; Forbis Jr and Hayhoe, 2018) (see Section 4.3.5).

Caribbean Small Island Developing States (SIDS) and Territories

Extreme weather, linked to tropical storms and hurricanes, represent one of the largest risks facing Caribbean island nations (Chapter 3, Section 3.4.5.3). Non-economic damages include detrimental health impacts, forced displacement and destruction of cultural heritages. Projections of increased frequency of the most intense storms at 1.5°C and higher warming levels (Wehner et al., 2018; Chapter 3, Section 3.3.6; Box 3.5) are a significant cause for concern, making adaptation a matter of survival (Mycoo and Donovan, 2017).

Despite a shared vulnerability arising from commonalities in location, circumstance and size (Bishop and Payne, 2012; Nurse et al., 2014), adaptation approaches are nuanced by differences in climate governance, affecting vulnerability and adaptive capacity (see Section 4.4.1). Three cases exemplify differences in disaster risk management.

Cuba: Together with a robust physical infrastructure and human-resource base (Kirk, 2017), Cuba has implemented an effective civil defence system for emergency preparedness and disaster response, centred around community mobilization and preparedness (Kirk, 2017). Legislation to manage disasters, an efficient and robust early warning system, emergency stockpiles, adequate shelter system and continuous training and education of the population help create a 'culture of risk' (Isayama and Ono, 2015; Lizarralde et al., 2015) which reduces vulnerability to extreme events (Pichler and Striessnig, 2013). Cuba's infrastructure is still susceptible to devastation, as seen in the aftermath of the 2017 hurricane season.

United Kingdom Overseas Territories (UKOT): All UKOT have developed National Disaster Preparedness Plans (PAHO/WHO, 2016) and are part of the Caribbean Disaster Risk Management Program which aims to improve disaster risk management within the health sector. Different vulnerability levels across the UKOT (Lam et al., 2015) indicate the benefits of greater regional cooperation and capacity-building, not only within UKOT, but throughout the Caribbean (Forster et al., 2011). While sovereign states in the region can directly access climate funds and international support, Dependent Territories are reliant on their controlling states (Bishop and Payne, 2012). There tends to be low-scale management for environmental issues in UKOT, which increases UKOT's vulnerability. Institutional limitations, lack of human and financial resources, and limited long-term planning are identified as barriers to adaptation (Forster et al., 2011).

Jamaica: Disaster management is coordinated through a hierarchy of national, parish and community disaster committees under the leadership of the Office of Disaster Preparedness and Emergency Management (ODPEM). ODPEM coordinates disaster preparedness and risk-reduction efforts among key state and non-state agencies (Grove, 2013). A National Disaster Committee provides technical and policy oversight to the ODPEM and is composed of representatives from multiple stakeholders (Osei, 2007). Most initiatives are primarily funded through a mix of multilateral and bilateral loan and grant funding focusing on strengthening technical and institutional capacities of state- and research-based institutions and supporting integration of climate change considerations into national and sectoral development plans (Robinson, 2017).

Cross Chapter Box 9 (continued)

To improve climate change governance in the region, Pittman et al. (2015) suggest incorporating holistic and integrated management systems, improving flexibility in collaborative processes, implementing monitoring programs, and increasing the capacity of local authorities. Implementation of the 2030 Sustainable Development Agenda and the Sustainable Development Goals (SDGs) can contribute to addressing the risks related with extreme events (Chapter 5, Box 5.3).

The Amazon

Terrestrial forests, such as the Amazon, are sensitive to changes in the climate, particularly drought (Laurance and Williamson, 2001) which might intensify through the 21st century (Marengo and Espinoza, 2016) (Chapter 3, Section 3.5.5.6).

The poorest communities in the region face substantial risks with climate change, and barriers and limits to adaptive capacity (Maru et al., 2014; Pinho et al., 2014, 2015; Brondízio et al., 2016). The Amazon is considered a hotspot, with interconnections between increasing temperature, decreased precipitation and hydrological flow (Betts et al., 2018) (Sections 3.3.2.2, 3.3.3.2 and 3.3.5); low levels of socio-economic development (Pinho et al., 2014); and high levels of climate vulnerability (Darela et al., 2016). Limiting global warming to 1.5°C could increase food and water security in the region compared to 2°C (Betts et al., 2018), reduce the impact on poor people and sustainable development, and make adaptation easier (O'Neill et al., 2017), particularly in the Amazon (Bathiany et al., 2018) (Chapter 5, Section 5.2.2).

Climate policy in many Amazonian nations has focused on forests as carbon sinks (Soares-Filho et al., 2010). In 2009, the Brazilian National Policy on Climate Change acknowledged adaptation as a concern, and the government sought to mainstream adaptation into public administration. Brazil's National Adaptation Plan sets guidelines for sectoral adaptation measures, primarily by developing capacity building, plans, assessments and tools to support adaptive decision-making. Adaptation is increasingly being presented as having mitigation co-benefits in the Brazilian Amazon (Gregorio et al., 2016), especially within ecosystem-based adaptation (Locatelli et al., 2011). In Peru's Framework Law for Climate Change, every governmental sector will consider climatic conditions as potential risks and/or opportunities to promote economic development and to plan adaptation.

Drought and flood policies have had limited effectiveness in reducing vulnerability (Marengo et al., 2013). In the absence of effective adaptation, achieving the SDGs will be challenging, mainly in poverty, health, water and sanitation, inequality and gender equality (Chapter 5, Section 5.2.3).

Urban systems

Around 360 million people reside in urban coastal areas where precipitation variability is exposing inadequacies of urban infrastructure and governance, with the poor being especially vulnerable (Reckien et al., 2017) (Cross-Chapter Box 13 in Chapter 5). Urban systems have seen growing adaptation action (Revi et al., 2014b; Araos et al., 2016b; Amundsen et al., 2018). Developing cities spend more on health and agriculture-related adaptation options while developed cities spend more on energy and water (Georgeson et al., 2016). Current adaptation activities are lagging in emerging economies, which are major centres of population growth facing complex interrelated pressures on investment in health, housing and education (Georgeson et al., 2016; Reckien et al., 2017).

New York, United States: Adaptation plans are undertaken across government levels, sectors and departments (NYC Parks, 2010; Vision 2020 Project Team, 2011; PlaNYC, 2013), and have been advanced by an expert science panel that is obligated by local city law to provide regular updates on policy-relevant climate science (NPCC, 2015). Federal initiatives include 2013's Rebuild By Design competition to promote resilience through infrastructural projects (HSRTF, 2013). In 2013 the Mayor's office, in response to Hurricane Sandy, published the city's adaptation strategy (PlaNYC, 2013). In 2015, the OneNYC Plan for a Strong and Just City (OneNYC Team, 2015) laid out a strategy for urban planning through a justice and equity lens. In 2017, new climate resiliency guidelines proposed that new construction must include sea level rise projections into planning and development (ORR, 2018). Although this attention to climate-resilient development may help reduce income inequality, its full effect could be constrained if a policy focus on resilience obscures analysis of income redistribution for the poor (Fainstein, 2018).

Kampala, Uganda: Kampala Capital City Authority (KCCA) has the statutory responsibility for managing the city. The Kampala Climate Change Action Strategy (KCCAS) is responding to climatic impacts of elevated temperature and more intense, erratic rain. KCCAS has considered multi-scale and temporal aspects of response (Chelleri et al., 2015; Douglas, 2017; Fraser et al., 2017), strengthened community adaptation (Lwasa, 2010; Dobson, 2017), responded to differential adaptive capacities (Waters and Adger, 2017) and believes in participatory processes and bridging of citywide linkages (KCCA, 2016). Analysis of the implications of uniquely adapted local solutions (e.g., motorcycle taxis) suggests sustainability can be enhanced when planning recognizes the need to adapt to uniquely local solutions (Evans et al., 2018).

Cross Chapter Box 9 (continued)

Rotterdam, The Netherlands: The Rotterdam Climate Initiative (RCI) was launched to reduce greenhouse gas emissions and climate-proof Rotterdam (RCI, 2017). Rotterdam has an integrated adaptation strategy, built on flood management, accessibility, adaptive building, urban water systems and urban climate, defined through the Rotterdam Climate Proof programme and the Rotterdam Climate Change Adaptation Strategy (RCI, 2008, 2013). Governance mechanisms that enabled integration of flood risk management plans with other policies, citizen participation, institutional eco-innovation, and focusing on green infrastructure (Albers et al., 2015; Dircke and Molenaar, 2015; de Boer et al., 2016a; Huang-Lachmann and Lovett, 2016) have contributed to effective adaptation (Ward et al., 2013). Entrenched institutional characteristics constrain the response framework (Francesch-Huidobro et al., 2017), but emerging evidence suggests that new governance arrangements and structures can potentially overcome these barriers in Rotterdam (Hölscher et al., 2018).

4.3.6 Short-Lived Climate Forcers

The main short-lived climate forcer (SLCF) emissions that cause warming are methane (CH_4), other precursors of tropospheric ozone (i.e., carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), black carbon (BC) and hydrofluorocarbons (HFCs); Myhre et al., 2013). SLCFs also include emissions that lead to cooling, such as sulphur dioxide (SO_2) and organic carbon (OC). Nitrogen oxides (NOx) can have both warming and cooling effects, by affecting ozone (O_3) and CH_4, depending on time scale and location (Myhre et al., 2013).

Cross-Chapter Box 2 in Chapter 1 provides a discussion of role of SLCFs in comparison to long-lived GHGs. Chapter 2 shows that 1.5°C-consistent pathways require stringent reductions in CO_2 and CH_4, and that non-CO_2 climate forcers reduce carbon budgets by about 2200 $GtCO_2$ per degree of warming attributed to them (see the Supplementary Material to Chapter 2).

Reducing non-CO_2 emissions is part of most mitigation pathways (IPCC, 2014c). All current GHG emissions and other forcing agents affect the rate and magnitude of climate change over the next few decades, while long-term warming is mainly driven by CO_2 emissions. CO_2 emissions result in a virtually permanent warming, while temperature change from SLCFs disappears within decades after emissions of SLCFs are ceased. Any scenario that fails to reduce CO_2 emissions to net zero would not limit global warming, even if SLCFs are reduced, due to accumulating CO_2-induced warming that overwhelms SLCFs' mitigation benefits in a couple of decades (Shindell et al., 2012; Schmale et al., 2014) (and see Chapter 2, Section 2.3.3.2).

Mitigation options for warming SLCFs often overlap with other mitigation options, especially since many warming SLCFs are co-emitted with CO_2. SLCFs are generally mitigated in 1.5°C- or 2°C-consistent pathways as an integral part of an overall mitigation strategy (Chapter 2). For example, Section 2.3 indicates that most very-low-emissions pathways include a transition away from the use of coal and natural gas in the energy sector and oil in transportation, which coincides with emission-reduction strategies related to methane from the fossil fuel sector and BC from the transportation sector. Much SLCF emission reduction aims at BC-rich sectors and considers the impacts of several co-emitted SLCFs (Bond et al., 2013; Sand et al., 2015; Stohl et al., 2015). The benefits of such strategies depend greatly upon the assumed level of progression of access to modern energy for the poorest populations who still rely on biomass fuels, as this affects the reference level of BC emissions (Rogelj et al., 2014).

Some studies have evaluated the focus on SLCFs in mitigation strategies and point towards trade-offs between short-term SLCF benefits and lock-in of long-term CO_2 warming (Smith and Mizrahi, 2013; Pierrehumbert, 2014). Reducing fossil fuel combustion will reduce aerosols levels, and thereby cause warming from removal of aerosol cooling effects (Myhre et al., 2013; Xu and Ramanathan, 2017; Samset et al., 2018). While some studies have found a lower temperature effect from BC mitigation, thus questioning the effectiveness of targeted BC mitigation for climate change mitigation (Myhre et al., 2013; Baker et al., 2015; Stjern et al., 2017; Samset et al., 2018), other models and observationally constrained estimates suggest that these widely-used models do not fully capture observed effects of BC and co-emissions on climate (e.g., Bond et al., 2013; Cui et al., 2016; Peng et al., 2016).

Table 4.5 provides an overview of three warming SLCFs and their emission sources, with examples of options for emission reductions and associated co-benefits.

A wide range of options to reduce SLCF emissions was extensively discussed in AR5 (IPCC, 2014b). Fossil fuel and waste sector methane mitigation options have high cost-effectiveness, producing a net profit over a few years, considering market costs only. Moreover, reducing roughly one-third to one-half of all human-caused emissions has societal benefits greater than mitigation costs when considering environmental impacts only (UNEP, 2011; Höglund-Isaksson, 2012; IEA, 2017b; Shindell et al., 2017a). Since AR5, new options for methane, such as those related to shale gas, have been included in mitigation portfolios (e.g., Shindell et al., 2017a).

Reducing BC emissions and co-emissions has sustainable development co-benefits, especially around human health (Stohl et al., 2015; Haines et al., 2017; Aakre et al., 2018), avoiding premature deaths and increasing crop yields (Scovronick et al., 2015; Peng et al., 2016). Additional benefits include lower likelihood of non-linear climate changes and feedbacks (Shindell et al., 2017b) and temporarily slowing down the rate of sea level rise (Hu et al., 2013). Interventions to reduce BC offer tangible local air quality benefits, increasing the likelihood of local public support (Eliasson, 2014; Venkataraman et al., 2016) (see Chapter 5, Section 5.4.2.1). Limited interagency co-ordination, poor science-policy interactions (Zusman et al., 2015), and weak policy and

Table 4.5 | Overview of main characteristics of three warming short-lived climate forcers (SLCFs) (core information based on Pierrehumbert, 2014 and Schmale et al., 2014; rest of the details as referenced).

SLCF Compound	Atmospheric Lifetime	Annual Global Emission	Main Anthropogenic Emission Sources	Examples of Options to Reduce Emissions Consistent with 1.5°C	Examples of Co-Benefits Based on Haines et al. (2017) Unless Specified Otherwise
Methane	On the order of 10 years	0.3 $GtCH_4$ (2010) (Pierrehumbert, 2014)	Fossil fuel extraction and transportation; Land-use change; Livestock and rice cultivation; Waste and wastewater	Managing manure from livestock; Intermittent irrigation of rice; Capture and usage of fugitive methane; Dietary change; For more: see Section 4.3.2	Reduction of tropospheric ozone (Shindell et al., 2017a); Health benefits of dietary changes; Increased crop yields; Improved access to drinking water
HFCs	Months to decades, depending on the gas	0.35 $GtCO_2$-eq (2010) (Velders et al., 2015)	Air conditioning; Refrigeration; Construction material	Alternatives to HFCs in air-conditioning and refrigeration applications	Greater energy efficiency (Mota-Babiloni et al., 2017)
Black Carbon	Days	~7 Mt (2010) (Klimont et al., 2017)	Incomplete combustion of fossil fuels or biomass in vehicles (esp. diesel), cook stoves or kerosene lamps; Field and biomass burning	Fewer and cleaner vehicles; Reducing agricultural biomass burning; Cleaner cook stoves, gas-based or electric cooking; Replacing brick and coke ovens; Solar lamps; For more see Section 4.3.3	Health benefits of better air quality; Increased education opportunities; Reduced coal consumption for modern brick kilns; Reduced deforestation

absence of inspections and enforcement (Kholod and Evans, 2016) are among barriers that reduce the institutional feasibility of options to reduce vehicle-induced BC emissions. A case study for India shows that switching from biomass cook stoves to cleaner gas stoves (based on liquefied petroleum gas or natural gas) or to electric cooking stoves is technically and economically feasible in most areas, but faces barriers in user preferences, costs and the organization of supply chains (Jeuland et al., 2015). Similar feasibility considerations emerge in switching from kerosene wick lamps for lighting to solar lanterns, from current low-efficiency brick kilns and coke ovens to cleaner production technologies; and from field burning of crop residues to agricultural practices using deep-sowing and mulching technologies (Williams et al., 2011; Wong, 2012).

The radiative forcing from HFCs are currently small but have been growing rapidly (Myhre et al., 2013). The Kigali Amendment (from 2016) to the Montreal Protocol set out a global accord for phasing out these compounds (Höglund-Isaksson et al., 2017). HFC mitigation options include alternatives with reduced warming effects, ideally combined with improved energy efficiency so as to simultaneously reduce CO_2 and co-emissions (Shah et al., 2015). Costs for most of HFC's mitigation potential are estimated to be below USD_{2010} 60 tCO_2-eq^{-1}, and the remainder below roughly double that number (Höglund-Isaksson et al., 2017).

Reductions in SLCFs can provide large benefits towards sustainable development, beneficial for social, institutional and economic feasibility. Strategies that reduce SLCFs can provide benefits that include improved air quality (e.g., Anenberg et al., 2012) and crop yields (e.g., Shindell et al., 2012), energy access, gender equality and poverty eradication (e.g.,Shindell et al., 2012; Haines et al., 2017). Institutional feasibility can be negatively affected by an information deficit, with the absence of international frameworks for integrating SLCFs into emissions accounting and reporting mechanisms being a barrier to developing policies for addressing SLCF emissions (Venkataraman et al., 2016). The incentives for reducing SLCFs are particularly strong for small groups of countries, and such collaborations could increase the feasibility and effectiveness of SLCF mitigation options (Aakre et al., 2018).

4.3.7 Carbon Dioxide Removal (CDR)

CDR methods refer to a set of techniques for removing CO_2 from the atmosphere. In the context of 1.5°C-consistent pathways (Chapter 2), they serve to offset residual emissions and, in most cases, achieve net negative emissions to return to 1.5°C from an overshoot. See Cross-Chapter Box 7 in Chapter 3 for a synthesis of land-based CDR options. Cross-cutting issues and uncertainties are summarized in Table 4.6.

4.3.7.1 Bioenergy with carbon capture and storage (BECCS)

BECCS has been assessed in previous IPCC reports (IPCC, 2005b, 2014b; P. Smith et al., 2014; Minx et al., 2017) and has been incorporated into integrated assessment models (Clarke et al., 2014), but also 1.5°C-consistent pathways without BECCS have emerged (Bauer et al., 2018; Grubler et al., 2018; Mousavi and Blesl, 2018; van Vuuren et al., 2018). Still, the overall set of pathways limiting global warming to 1.5°C with limited or no overshoot indicates that 0–1, 0–8, and 0–16 $GtCO_2$ yr^{-1} would be removed by BECCS by 2030, 2050 and 2100, respectively (Chapter 2, Section 2.3.4). BECCS is constrained by sustainable bioenergy potentials (Section 4.3.1.2, Chapter 5, Section 5.4.1.3 and Cross-Chapter Box 6 in Chapter 3), and availability of safe storage for CO_2 (Section 4.3.1.6). Literature estimates for BECCS mitigation potentials in 2050 range from 1–85 $GtCO_2$[4]. Fuss et al.

[4] As more bottom-up literature exists on bioenergy potentials, this exercise explored the bioenergy literature and converted those estimates to BECCS potential with 1EJ of bioenergy yielding 0.02–0.05 $GtCO_2$ emission reduction. For the bottom-up literature references for the potentials range, please refer to Supplementary Material 4.SM.3 Table 1.

(2018) narrow this range to 0.5–5 $GtCO_2$ yr^{-1} (*medium agreement, high evidence*) (Figure 4.3), meaning that BECCS mitigation potentials are not necessarily sufficient for 1.5°C-consistent pathways. This is, among other things, related to sustainability concerns (Boysen et al., 2017; Heck et al., 2018; Henry et al., 2018).

Assessing BECCS deployment in 2°C pathways (of about 12 $GtCO_2$-eq yr^{-1} by 2100, considered as a conservative deployment estimate for BECCS-accepting pathways consistent with 1.5°C), Smith et al. (2016b) estimate a land-use intensity of 0.3–0.5 ha tCO_2-eq^{-1} yr^{-1} using forest residues, 0.16 ha CO_2-eq^{-1} yr^{-1} for agricultural residues, and 0.03–0.1 ha tCO_2-eq^{-1} yr^{-1} for purpose-grown energy crops. The average amount of BECCS in these pathways requires 25–46% of arable and permanent crop area in 2100. Land area estimates differ in scale and are not necessarily a good indicator of competition with, for example, food production, because requiring a smaller land area for the same potential could indicate that high-productivity agricultural land is used. In general, the literature shows *low agreement* on the availability of land (Fritz et al., 2011; see Erb et al., 2016b for recent advances). Productivity, food production and competition with other ecosystem services and land use by local communities are important factors for designing regulation. These potentials and trade-offs are not homogenously distributed across regions. However, Robledo-Abad et al. (2017) find that regions with higher potentials are understudied, given their potential contribution. Researchers have expressed the need to complement global assessments with regional, geographically explicit bottom-up studies of biomass potentials and socio-economic impacts (e.g., de Wit and Faaij, 2010; Kraxner et al., 2014; Baik et al., 2018).

Energy production and land and water footprints show wide ranges in bottom-up assessments due to differences in technology, feedstock and other parameters (–1–150 EJ yr^{-1} of energy, 109–990 Mha, 6–79 MtN, 218–4758 km^3 yr^{-1} of water per $GtCO_2$ yr^{-1}; Smith and Torn, 2013; Smith et al., 2016b; Fajardy and Mac Dowell, 2017) and are not comparable to IAM pathways which consider system effects (Bauer et al., 2018). Global impacts on nutrients and albedo are difficult to quantify (Smith et al., 2016b). BECCS competes with other land-based CDR and mitigation measures for resources (Chapter 2).

There is uncertainty about the feasibility of timely upscaling (Nemet et al., 2018). CCS (see Section 4.3.1) is largely absent from the Nationally Determined Contributions (Spencer et al., 2015) and lowly ranked in investment priorities (Fridahl, 2017). Although there are dozens of small-scale BECCS demonstrations (Kemper, 2015) and a full-scale project capturing 1 $MtCO_2$ exists (Finley, 2014), this is well below the numbers associated with 1.5°C or 2°C-compatible pathways (IEA, 2016a; Peters et al., 2017). Although the majority of BECCS cost estimates are below 200 USD tCO_2^{-1} (Figure 4.2), estimates vary widely. Economic incentives for ramping up large CCS or BECCS infrastructure are weak (Bhave et al., 2017). The 2050 average investment costs for such a BECCS infrastructure for bio-electricity and biofuels are estimated at 138 and 123 billion USD yr^{-1}, respectively (Smith et al., 2016b).

BECCS deployment is further constrained by bioenergy's carbon accounting, land, water and nutrient requirements (Section 4.3.1), its compatibility with other policy goals and limited public acceptance of both bioenergy and CCS (Section 4.3.1). Current pathways are believed to have inadequate assumptions on the development of societal support and governance structures (Vaughan and Gough, 2016). However, removing BECCS and CCS from the portfolio of available options significantly raises modelled mitigation costs (Kriegler et al., 2013; Bauer et al., 2018).

4.3.7.2 Afforestation and reforestation (AR)

Afforestation implies planting trees on land not forested for a long time (e.g., over the last 50 years in the context of the Kyoto Protocol), while reforestation implies re-establishment of forest formations after a temporary condition with less than 10% canopy cover due to human-induced or natural perturbations. Houghton et al. (2015) estimate about 500 Mha could be available for the re-establishment of forests on lands previously forested, but not currently used productively. This could sequester at least 3.7 $GtCO_2$ yr^{-1} for decades. The full literature range gives 2050 potentials of 1–7 $GtCO_2$ yr^{-1} (*low evidence, medium agreement*), narrowed down to 0.5–3.6 $GtCO_2$ yr^{-1} based on a number of constraints (Fuss et al., 2018). Abatement costs are estimated to be low compared to other CDR options, 5–50 USD tCO_2-eq^{-1} (*robust evidence, high agreement*). Yet, realizing such large potentials comes at higher land and water footprints than BECCS, although there would be a positive impact on nutrients and the energy requirement would be negligible (Smith et al., 2016b; Cross-Chapter Box 7 in Chapter 3). The 2030 estimate by Griscom et al. (2017) is up to 17.9 $GtCO_2$ yr^{-1} for reforestation with significant co-benefits (Cross-Chapter Box 7 in Chapter 3).

Biogenic storage is not as permanent as emission reductions by geological storage. In addition, forest sinks saturate, a process which typically occurs in decades to centuries compared to the thousands of years of residence time of CO_2 stored geologically (Smith et al., 2016a) and is subject to disturbances that can be exacerbated by climate change (e.g., drought, forest fires and pests) (Seidl et al., 2017). Handling these challenges requires careful forest management. There is much practical experience with AR, facilitating upscaling but with two caveats: AR potentials are heterogeneously distributed (Bala et al., 2007), partly because the planting of less reflective forests results in higher net absorbed radiation and localised surface warming in higher latitudes (Bright et al., 2015; Jones et al., 2015), and forest governance structures and monitoring capacities can be bottlenecks and are usually not considered in models (Wang et al., 2016; Wehkamp et al., 2018b). There is *medium agreement* on the positive impacts of AR on ecosystems and biodiversity due to different forms of afforestation discussed in the literature: afforestation of grassland ecosystems or diversified agricultural landscapes with monocultures or invasive alien species can have significant negative impacts on biodiversity, water resources, etc. (P. Smith et al., 2014), while forest ecosystem restoration (forestry and agroforestry) with native species can have positive social and environmental impacts (Cunningham et al., 2015; Locatelli et al., 2015; Paul et al., 2016; See Section 4.3.2).

Synergies with other policy goals are possible (see also Section 4.5.4); for example, land spared by diet shifts could be afforested (Röös et al., 2017) or used for energy crops (Grubler et al., 2018). Such land-sparing strategies could also benefit other land-based CDR options.

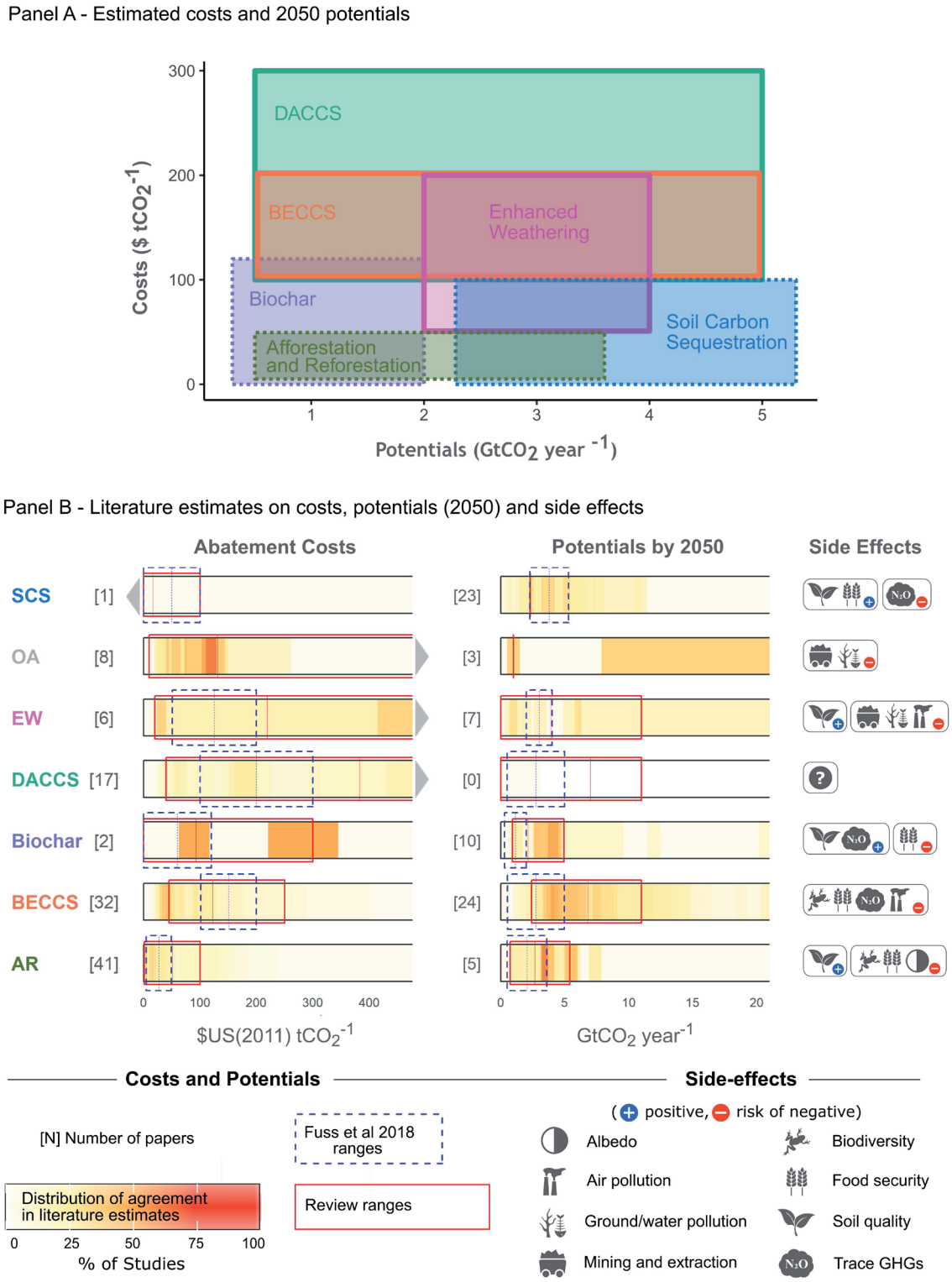

Figure 4.2 | Evidence on carbon dioxide removal (CDR) abatement costs, 2050 deployment potentials, and key side effects. Panel A presents estimates based on a systematic review of the bottom up literature (Fuss et al., 2018), corresponding to dashed blue boxes in Panel B. Dashed lines represent saturation limits for the corresponding technology. Panel B shows the percentage of papers at a given cost or potential estimate. Reference year for all potential estimates is 2050, while all cost estimates preceding 2050 have been included (as early as 2030, older estimates are excluded if they lack a base year and thus cannot be made comparable). Ranges have been trimmed to show detail (see Fuss et al., 2018 for the full range). Costs refer only to abatement costs. Icons for side-effects are allocated only if a critical mass of papers corroborates their occurrence

Notes: For references please see Supplementary Material Table 4.SM.3. Direct air carbon dioxide capture and storage (DACCS) is theoretically only constrained by geological storage capacity, estimates presented are considering upscaling and cost challenges (Nemet et al., 2018). *BECCS potential estimates are based on bioenergy estimates in the literature (EJ yr^{-1}), converted to $GtCO_2$ following footnote 4. Potentials cannot be added up, as CDR options would compete for resources (e.g., land). SCS - soil carbon sequestration; OA - ocean alkalinization; EW- enhanced weathering; DACCS - direct air carbon dioxide capture and storage; BECCS - bioenergy with carbon capture and storage; AR - afforestation.*

4.3.7.3 Soil carbon sequestration and biochar

At local scales there is *robust evidence* that soil carbon sequestration (SCS, e.g., agroforestry, De Stefano and Jacobson, 2018), restoration of degraded land (Griscom et al., 2017), or conservation agriculture management practices (Aguilera et al., 2013; Poeplau and Don, 2015; Vicente-Vicente et al., 2016) have co-benefits in agriculture and that many measures are cost-effective even without supportive climate policy. Evidence at global scale for potentials and especially costs is much lower. The literature spans cost ranges of –45–100 USD tCO_2^{-1} (negative costs relating to the multiple co-benefits of SCS, such as increased productivity and resilience of soils; P. Smith et al., 2014), and 2050 potentials are estimated at between 0.5 and 11 $GtCO_2$ yr^{-1}, narrowed down to 2.3–5.3 $GtCO_2$ yr^{-1} considering that studies above 5 $GtCO_2$ yr^{-1} often do not apply constraints, while estimates lower than 2 $GtCO_2$ yr^{-1} mostly focus on single practices (Fuss et al., 2018).

SCS has negligible water and energy requirements (Smith, 2016), affects nutrients and food security favourably (*high agreement, robust evidence*) and can be applied without changing current land use, thus making it socially more acceptable than CDR options with a high land footprint. However, soil sinks saturate after 10–100 years, depending on the SCS option, soil type and climate zone (Smith, 2016).

Biochar is formed by recalcitrant (i.e., very stable) organic carbon obtained from pyrolysis, which, applied to soil, can increase soil carbon sequestration leading to improved soil fertility properties.[5] Looking at the full literature range, the global potential in 2050 lies between 1 and 35 Gt CO_2 yr^{-1} (*low agreement, low evidence*), but considering limitations in biomass availability and uncertainties due to a lack of large-scale trials of biochar application to agricultural soils under field conditions, Fuss et al. (2018) lower the 2050 range to 0.3–2 $GtCO_2$ yr^{-1}. This potential is below previous estimates (e.g., Woolf et al., 2010), which additionally consider the displacement of fossil fuels through biochar. Permanence depends on soil type and biochar production temperatures, varying between a few decades and several centuries (Fang et al., 2014). Costs are 30– 120 USD tCO_2^{-1} (*medium agreement, medium evidence*) (McCarl et al., 2009; McGlashan et al., 2012; McLaren, 2012; Smith, 2016).

Water requirements are low and at full theoretical deployment, up to 65 EJ yr^{-1} of energy could be generated as a side product (Smith, 2016). Positive side effects include a favourable effect on nutrients and reduced N_2O emissions (Cayuela et al., 2014; Kammann et al., 2017). However, 40–260 Mha are needed to grow the biomass for biochar for implementation at 0.3 $GtCO_2$-eq yr^{-1} (Smith, 2016), even though it is also possible to use residues (e.g., Windeatt et al., 2014). Biochar is further constrained by the maximum safe holding capacity of soils (Lenton, 2010) and the labile nature of carbon sequestrated in plants and soil at higher temperatures (Wang et al., 2013).

4.3.7.4 Enhanced weathering (EW) and ocean alkalinization

Weathering is the natural process of rock decomposition via chemical and physical processes in which CO_2 is spontaneously consumed and converted to solid or dissolved alkaline bicarbonates and/or carbonates (IPCC, 2005a). The process is controlled by temperature, reactive surface area, interactions with biota and, in particular, water solution composition. CDR can be achieved by accelerating mineral weathering through the distribution of ground-up rock material over land (Hartmann and Kempe, 2008; Wilson et al., 2009; Köhler et al., 2010; Renforth, 2012; ten Berge et al., 2012; Manning and Renforth, 2013; Taylor et al., 2016), shorelines (Hangx and Spiers, 2009; Montserrat et al., 2017) or the open ocean (House et al., 2007; Harvey, 2008; Köhler et al., 2013; Hauck et al., 2016). Ocean alkalinization adds alkalinity to marine areas to locally increase the CO_2 buffering capacity of the ocean (González and Ilyina, 2016; Renforth and Henderson, 2017).

In the case of land application of ground minerals, the estimated CDR potential range is 0.72–95 $GtCO_2$ yr^{-1} (*low evidence, low agreement*) (Hartmann and Kempe, 2008; Köhler et al., 2010; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018a). Marine application of ground minerals is limited by feasible rates of mineral extraction, grinding and delivery, with estimates of 1–6 $GtCO_2$ yr^{-1} (*low evidence, low agreement*) (Köhler et al., 2013; Hauck et al., 2016; Renforth and Henderson, 2017). Agreement is low due to a variety of assumptions and unknown parameter ranges in the applied modelling procedures that would need to be verified by field experiments (Fuss et al., 2018). As with other CDR options, scaling and maturity are challenges, with deployment at scale potentially requiring decades (NRC, 2015a), considerable costs in transport and disposal (Hangx and Spiers, 2009; Strefler et al., 2018a) and mining (NRC, 2015a; Strefler et al., 2018a)[6].

Site-specific cost estimates vary depending on the chosen technology for rock grinding (an energy-intensive process; Köhler et al., 2013; Hauck et al., 2016), material transport, and rock source (Renforth, 2012; Hartmann et al., 2013), and range from 15–40 USD tCO_2^{-1} to 3,460 USD tCO_2^{-1} (*limited evidence, low agreement*; Figure 4.2) (Schuiling and Krijgsman, 2006; Köhler et al., 2010; Taylor et al., 2016). The evidence base for costs of ocean alkalinization and marine enhanced weathering is sparser than the land applications. The ocean alkalinization potential is assessed to be 0.1–10 $GtCO_2$ yr^{-1} with costs of 14– >500 USD tCO_2^{-1} (Renforth and Henderson, 2017).

The main side effects of terrestrial EW are an increase in water pH (Taylor et al., 2016), the release of heavy metals like Ni and Cr and plant nutrients like K, Ca, Mg, P and Si (Hartmann et al., 2013), and changes in hydrological soil properties. Respirable particle sizes, though resulting in higher potentials, can have impacts on health (Schuiling and Krijgsman, 2006; Taylor et al., 2016); utilization of wave-assisted decomposition through deployment on coasts could avert the need for fine grinding (Hangx and Spiers, 2009; Schuiling and de Boer, 2010). Side effects

[5] Other pyrolysis products that can achieve net CO_2 removals are bio-oil (pumped into geological storages) and permanent-pyrogas (capture and storage of CO_2 from gas combustion) (Werner et al., 2018)

[6] It has also been suggested that ocean alkalinity can be increased through accelerated weathering of limestone (Rau and Caldeira, 1999; Rau, 2011; Chou et al., 2015) or electrochemical processes (House et al., 2007; Rau, 2008; Rau et al., 2013; Lu et al., 2015). However, these techniques have not been proven at large scale either (Renforth and Henderson, 2017).

of marine EW and ocean alkalinization are the potential release of heavy metals like Ni and Cr (Montserrat et al., 2017). Increasing ocean alkalinity helps counter ocean acidification (Albright et al., 2016; Feng et al., 2016). Ocean alkalinization could affect ocean biogeochemical functioning (González and Ilyina, 2016). A further caveat of relates to saturation state and the potential to trigger spontaneous carbonate precipitation.[7] While the geochemical potential to remove and store CO_2 is quite large, *limited evidence* on the preceding topics makes it difficult to assess the true capacity, net benefits and desirability of EW and ocean alkalinity addition in the context of CDR.

4.3.7.5 Direct air carbon dioxide capture and storage (DACCS)

Capturing CO_2 from ambient air through chemical processes with subsequent storage of the CO_2 in geological formations is independent of source and timing of emissions and can avoid competition for land. Yet, this is also the main challenge: while the theoretical potential for DACCS is mainly limited by the availability of safe and accessible geological storage, the CO_2 concentration in ambient air is 100–300 times lower than at gas- or coal-fired power plants (Sanz-Pérez et al., 2016) thus requiring more energy than flue gas CO_2 capture (Pritchard et al., 2015). This appears to be the main challenge to DACCS (Sanz-Pérez et al., 2016; Barkakaty et al., 2017).

Studies explore alternative techniques to reduce the energy penalty of DACCS (van der Giesen et al., 2017). Energy consumption could be up to 12.9 GJ tCO_2-eq^{-1}; translating into an average of 156 EJ yr^{-1} by 2100 (current annual global primary energy supply is 600 EJ); water requirements are estimated to average 0.8–24.8 km^3 $GtCO_2$-eq^{-1} yr^{-1} (Smith et al., 2016b, based on Socolow et al., 2011).

However, the literature shows *low agreement* and is fragmented (Broehm et al., 2015). This fragmentation is reflected in a large range of cost estimates: from 20–1,000 USD tCO_2^{-1} (Keith et al., 2006; Pielke, 2009; House et al., 2011; Ranjan and Herzog, 2011; Simon et al., 2011; Goeppert et al., 2012; Holmes and Keith, 2012; Zeman, 2014; Sanz-Pérez et al., 2016; Sinha et al., 2017). There is lower agreement and a smaller evidence base at the lower end of the cost range. Fuss et al. (2018) narrow this range to 100–300 USD tCO_2^{-1}.

Research and efforts by small-scale commercialization projects focus on utilization of captured CO_2 (Wilcox et al., 2017). Given that only a few IAM scenarios incorporate DACCS (e.g., Chen and Tavoni, 2013; Strefler et al., 2018b) its possible role in cost-optimized 1.5°C scenarios is not yet fully explored. Given the technology's early stage of development (McLaren, 2012; NRC, 2015a; Nemet et al., 2018) and few demonstrations (Holmes et al., 2013; Rau et al., 2013; Agee et al., 2016), deploying the technology at scale is still a considerable challenge, though both optimistic (Lackner et al., 2012) and pessimistic outlooks exist (Pritchard et al., 2015).

4.3.7.6 Ocean fertilization

Nutrients can be added to the ocean resulting in increased biologic production, leading to carbon fixation in the sunlit ocean and subsequent sequestration in the deep ocean or sea floor sediments. The added nutrients can be either micronutrients (such as iron) or macronutrients (such as nitrogen and/or phosphorous) (Harrison, 2017). There is *limited evidence* and *low agreement* on the readiness of this technology to contribute to rapid decarbonization (Williamson et al., 2012). Only small-scale field experiments and theoretical modelling have been conducted (e.g., McLaren, 2012). The full range of CDR potential estimates is from 15.2 $ktCO_2$ yr^{-1} (Bakker et al., 2001) for a spatially constrained field experiment up to 44 $GtCO_2$ yr^{-1} (Sarmiento and Orr, 1991) following a modelling approach, but Fuss et al. (2018) consider the potential to be extremely limited given the evidence and existing barriers. Due to scavenging of iron, the iron addition only leads to inefficient use of the nitrogen in exporting carbon (Zeebe, 2005; Aumont and Bopp, 2006; Zahariev et al., 2008).

Cost estimates range from 2 USD tCO_2^{-1} (for iron fertilization) (Boyd and Denman, 2008) to 457 USD tCO_2^{-1} (Harrison, 2013). Jones (2014) proposed values greater than 20 USD tCO_2^{-1} for nitrogen fertilization. Fertilization is expected to impact food webs by stimulating its base organisms (Matear, 2004), and extensive algal blooms may cause anoxia (Sarmiento and Orr, 1991; Matear, 2004; Russell et al., 2012) and deep water oxygen decline (Matear, 2004), with negative impacts on biodiversity. Nutrient inputs can shift ecosystem production from an iron-limited system to a P, N-, or Si-limited system depending on the location (Matear, 2004; Bertram, 2010) and non-CO_2 GHGs may increase (Sarmiento and Orr, 1991; Matear, 2004; Bertram, 2010). The greatest theoretical potential for this practice is the Southern Ocean, posing challenges for monitoring and governance (Robinson et al., 2014). The London Protocol of the International Maritime Organization has asserted authority for regulation of ocean fertilization (Strong et al., 2009), which is widely viewed as a de facto moratorium on commercial ocean fertilization activities.

There is *low agreement* in the technical literature on the permanence of CO_2 in the ocean, with estimated residence times of 1,600 years to millennia, especially if injected or buried in or below the sea floor (Williams and Druffel, 1987; Jones, 2014). Storage at the surface would mean that the carbon would be rapidly released after cessation (Zeebe, 2005; Aumont and Bopp, 2006).

[7] This analysis relies on the assessment in Fuss et al. (2018), which provides more detail on saturation and permanence.

Table 4.6 | Cross-cutting issues and uncertainties across carbon dioxide removal (CDR) options, aspects and uncertainties

Area of Uncertainty	Cross-Cutting Issues and Uncertainties
Technology upscaling	• CDR options are at different stages of technological readiness (McLaren, 2012) and differ with respect to scalability. • Nemet et al. (2018) find >50% of the CDR innovation literature concerned with the earliest stages of the innovation process (R&D), identifying a dissonance between the large CO_2 removals needed in 1.5°C pathways and the long -time periods involved in scaling up novel technologies. • Lack of post-R&D literature, including incentives for early deployment, niche markets, scale up, demand, and public acceptance.
Emerging and niche technologies	• For BECCS, there are niche opportunities with high efficiencies and fewer trade-offs, for example, sugar and paper processing facilities (Möllersten et al., 2003), district heating (Kärki et al., 2013; Ericsson and Werner, 2016), and industrial and municipal waste (Sanna et al., 2012). Turner et al. (2018) constrain potential using sustainability considerations and overlap with storage basins to avoid the CO_2 transportation challenge, providing a possible, though limited entry point for BECCS. • The impacts on land use, water, nutrients and albedo of BECCS could be alleviated using marine sources of biomass that could include aquacultured micro and macro flora (Hughes et al., 2012; Lenton, 2014). • Regarding captured CO_2 as a resource is discussed as an entry point for CDR. However, this does not necessarily lead to carbon removals, particularly if the CO_2 is sourced from fossil fuels and/or if the products do not store the CO_2 for climate-relevant horizons (von der Assen et al., 2013) (see also Section 4.3.4.5). • Methane[8] is a much more potent GHG than CO_2 (Montzka et al., 2011), associated with difficult-to-abate emissions in industry and agriculture and with outgassing from lakes, wetlands, and oceans (Lockley, 2012; Stolaroff et al., 2012). Enhancing processes that naturally remove methane, either by chemical or biological decomposition (Sundqvist et al., 2012), has been proposed to remove CH_4. There is *low confidence* that existing technologies for CH_4 removal are economically or energetically suitable for large-scale air capture (Boucher and Folberth, 2010). Methane removal potentials are limited due to its low atmospheric concentration and its low chemical reactivity at ambient conditions.
Ethical aspects	• Preston (2013) identifies distributive and procedural justice, permissibility, moral hazard (Shue, 2018), and hubris as ethical aspects that could apply to large-scale CDR deployment. • There is a lack of reflection on the climate futures produced by recent modelling and implying very different ethical costs/risks and benefits (Minx et al., 2018).
Governance	• Existing governance mechanisms are scarce and either targeted at particular CDR options (e.g., ocean-based) or aspects (e.g., concerning indirect land-use change (iLUC)) associated with bioenergy upscaling, and often the mechanisms are at national or regional scale (e.g., EU). Regulation accounting for iLUC by formulating sustainability criteria (e.g., the EU Renewable Energy Directive) has been assessed as insufficient in avoiding leakage (e.g., Frank et al., 2013). • An international governance mechanism is only in place for R&D of ocean fertilization within the Convention on Biological Diversity (IMO, 1972, 1996; CBD, 2008, 2010). • Burns and Nicholson (2017) propose a human rights-based approach to protect those potentially adversely impacted by CDR options.
Policy	• The CDR potentials that can be realized are constrained by the lack of policy portfolios incentivising large-scale CDR (Peters and Geden, 2017). • Near-term opportunities could be supported through modifying existing policy mechanisms (Lomax et al., 2015). • Scott and Geden (2018) sketch three possible routes for limited progress, (i) at EU-level, (ii) at EU Member State level, and (iii) at private sector level, noting the implied paradigm shift this would entail. • EU may struggle to adopt policies for CDR deployment on the scale or time-frame envisioned by IAMs (Geden et al., 2018). • Social impacts of large-scale CDR deployment (Buck, 2016) require policies taking these into account.
Carbon cycle	• On long time scales, natural sinks could reverse (C.D. Jones et al., 2016) • No robust assessments yet of the effectiveness of CDR in reverting climate change (Tokarska and Zickfeld, 2015; Wu et al., 2015; Keller et al., 2018), see also Chapter 2, Section 2.2.2.2.

4.3.8 Solar Radiation Modification (SRM)

This report refrains from using the term 'geoengineering' and separates SRM from CDR and other mitigation options (see Chapter 1, Section 1.4.1 and Glossary).

Table 4.7 gives an overview of SRM methods and characteristics. For a more comprehensive discussion of currently proposed SRM methods, and their implications for geophysical quantities and sustainable development, see also Cross-Chapter Box 10 in this Chapter. This section assesses the feasibility, from an institutional, technological, economic and social-cultural viewpoint, focusing on stratospheric aerosol injection (SAI) unless otherwise indicated, as most available literature is about SAI.

Some of the literature on SRM appears in the forms of commentaries, policy briefs, viewpoints and opinions (e.g., (Horton et al., 2016; Keith et al., 2017; Parson, 2017). This assessment covers original research rather than viewpoints, even if the latter appear in peer-reviewed journals.

SRM could reduce some of the global risks of climate change related to temperature rise (Izrael et al., 2014; MacMartin et al., 2014), rate of sea level rise (Moore et al., 2010), sea-ice loss (Berdahl et al., 2014) and frequency of extreme storms in the North Atlantic and heatwaves in Europe (Jones et al., 2018). SRM also holds risks of changing precipitation and ozone concentrations and potentially reductions in biodiversity (Pitari et al., 2014; Visioni et al., 2017a; Trisos et al., 2018). Literature only supports SRM as a supplement to deep mitigation, for example in overshoot scenarios (Smith and Rasch, 2013; MacMartin et al., 2018).

4.3.8.1 Governance and institutional feasibility

There is *robust evidence* but *medium agreement* for unilateral action potentially becoming a serious SRM governance issue (Weitzman, 2015; Rabitz, 2016), as some argue that enhanced collaboration might emerge around SRM (Horton, 2011). An equitable institutional or governance arrangement around SRM would have to reflect views of different countries (Heyen et al., 2015) and be multilateral because of the risk of termination, and risks that implementation or unilateral action by one country or organization will produce negative precipitation or extreme weather effects across borders (Lempert and

[8] Current work (e.g., de Richter et al., 2017) examines other technologies considering non-CO_2 GHGs like N_2O.

Table 4.7 | Overview of the main characteristics of the most-studied SRM methods.

SRM indicator	Stratospheric Aerosol injection (SAI)	Marine Cloud Brightening (MCB)	Cirrus Cloud Thinning (CCT)	Ground-Based Albedo Modification (GBAM)
Description of SRM method	Injection of a gas in the stratosphere, which then converts to aerosols. Injection of other particles also considered.	Spraying sea salt or other particles into marine clouds, making them more reflective.	Seeding to promote nucleation, reducing optical thickness and cloud lifetime, to allow more outgoing longwave radiation to escape into space.	Whitening roofs, changes in land use management (e.g., no-till farming), change of albedo at a larger scale (covering glaciers or deserts with reflective sheeting and changes in ocean albedo).
Radiative forcing efficiencies	1–4 TgS W^{-1} m^2 yr^{-1}	100–295 Tg dry sea salt W^{-1} m^2 yr^{-1}	Not known	Small on global scale, up to 1°C–3°C on regional scale
Amount needed for 1°C overshoot	2–8 TgS yr^{-1}	70 Tg dry sea salt yr^{-1}	Not known	0.04–0.1 albedo change in agricultural and urban areas
SRM specific impacts on climate variables	Changes in precipitation patterns and circulation regimes; in case of SO_2 injection, disruption to stratospheric chemistry (for instance NOx depletion and changes in methane lifetime); increase in stratospheric water vapour and tropospheric-stratospheric ice formation affecting cloud microphysics	Regional rainfall responses; reduction in hurricane intensity	Low-level cloud changes; tropospheric drying; intensification of the hydrological cycle	Impacts on precipitation in monsoon areas; could target hot extremes
SRM specific impacts on human/ natural systems	In case of SO_2 injection, stratospheric ozone loss (which could also have a positive effect – a net reduction in global mortality due to competing health impact pathways) and significant increase of surface UV	Reduction in the number of mild crop failures	Not known	Not known
Maturity of science	Volcanic analogues; *high agreement* amongst simulations; *robust evidence* on ethical, governance and sustainable development limitations	Observed in ships tracks; several simulations confirm mechanism; regionally limited	No clear physical mechanism; *limited evidence* and *low agreement*; several simulations	Natural and land-use analogues; several simulations confirm mechanism; *high agreement* to influence on regional temperature; land use costly
Key references	Robock et al., 2008; Heckendorn et al., 2009; Tilmes et al., 2012, 2016; Pitari et al., 2014; Crook et al., 2015; C.J. Smith et al., 2017; Visioni et al., 2017a, b; Eastham et al., 2018; Plazzotta et al., 2018	Salter et al., 2008; Alterskjær et al., 2012; Jones and Haywood, 2012; Latham et al., 2012, 2013; Kravitz et al., 2013; Crook et al., 2015; Parkes et al., 2015; Ahlm et al., 2017	Storelvmo et al., 2014; Kristjánsson et al., 2015; Jackson et al., 2016; Kärcher, 2017; Lohmann and Gasparini, 2017	Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Seneviratne et al., 2018

Prosnitz, 2011; Dilling and Hauser, 2013; NRC, 2015b). Some have suggested that the governance of research and field experimentation can help clarify uncertainties surrounding deployment of SRM (Long and Shepherd, 2014; Parker, 2014; NRC, 2015c; Caldeira and Bala, 2017; Lawrence and Crutzen, 2017), and that SRM is compatible with democratic processes (Horton et al., 2018) or not (Szerszynski et al., 2013; Owen, 2014).

Several possible institutional arrangements have been considered for SRM governance: under the UNFCCC (in particular under the Subsidiary Body on Scientific and Technological Advice (SBSTA)) or the United Nations Convention on Biological Diversity (UNCBD) (Honegger et al., 2013; Nicholson et al., 2018), or through a consortium of states (Bodansky, 2013; Sandler, 2017). Reasons for states to join an international governance framework for SRM include having a voice in SRM diplomacy, prevention of unilateral action by others and benefits from research collaboration (Lloyd and Oppenheimer, 2014).

Alongside SBSTA, the WMO, UNESCO and UN Environment could play a role in governance of SRM (Nicholson et al., 2018). Each of these organizations has relevance with respect to the regulatory framework (Bodle et al., 2012; Williamson and Bodle, 2016). The UNCBD gives guidance that 'that no climate-related geo-engineering activities that may affect biodiversity take place' (CBD, 2010).

4.3.8.2 Economic and technological feasibility

The literature on the engineering costs of SRM is limited and may be unreliable in the absence of testing or deployment. There is *high agreement* that costs of SAI (not taking into account indirect and social costs, research and development costs and monitoring expenses) may be in the range of 1–10 billion USD yr^{-1} for injection of 1–5 MtS to achieve cooling of 1–2 W m^{-2} (Robock et al., 2009; McClellan et al., 2012; Ryaboshapko and Revokatova, 2015; Moriyama et al., 2016), suggesting that cost-effectiveness may be high if side-effects are low

or neglected (McClellan et al., 2012). The overall economic feasibility of SRM also depends on externalities and social costs (Moreno-Cruz and Keith, 2013; Mackerron, 2014), climate sensitivity (Kosugi, 2013), option value (Arino et al., 2016), presence of climate tipping points (Eric Bickel, 2013) and damage costs as a function of the level of SRM (Bahn et al., 2015; Heutel et al., 2018). Modelling of game-theoretic, strategic interactions of states under heterogeneous climatic impacts shows *low agreement* on the outcome and viability of a cost-benefit analysis for SRM (Ricke et al., 2015; Weitzman, 2015).

For SAI, there is *high agreement* that aircrafts could, after some modifications, inject millions of tons of SO_2 in the lower stratosphere (at approximately 20 km; (Davidson et al., 2012; McClellan et al., 2012; Irvine et al., 2016).

4.3.8.3 Social acceptability and ethics

Ethical questions around SRM include those of international responsibilities for implementation, financing, compensation for negative effects, the procedural justice questions of who is involved in decisions, privatization and patenting, welfare, informed consent by affected publics, intergenerational ethics (because SRM requires sustained action in order to avoid termination hazards), and the so-called 'moral hazard' (Burns, 2011; Whyte, 2012; Gardiner, 2013; Lin, 2013; Buck et al., 2014; Klepper and Rickels, 2014; Morrow, 2014; Wong, 2014; Reynolds, 2015; Lockley and Coffman, 2016; McLaren, 2016; Suarez and van Aalst, 2017; Reynolds et al., 2018). The literature shows *low agreement* on whether SRM research and deployment may lead policy-makers to reduce mitigation efforts and thus imply a moral hazard (Linnér and Wibeck, 2015). SRM might motivate individuals (as opposed to policymakers) to reduce their GHG emissions, but even a subtle difference in the articulation of information about SRM can influence subsequent judgements of favourability (Merk et al., 2016). The argument that SRM research increases the likelihood of deployment (the 'slippery slope' argument), is also made (Quaas et al., 2017), but some also found an opposite effect (Bellamy and Healey, 2018).

Unequal representation and deliberate exclusion are plausible in decision-making on SRM, given diverging regional interests and the anticipated low resource requirements to deploy SRM (Ricke et al., 2013). Whyte (2012) argues that the concerns, sovereignties, and experiences of indigenous peoples may particularly be at risk.

The general public can be characterized as oblivious to and worried about SRM (Carr et al., 2013; Parkhill et al., 2013; Wibeck et al., 2017). An emerging literature discusses public perception of SRM, showing a lack of knowledge and unstable opinions (Scheer and Renn, 2014). The perception of controllability affects legitimacy and public acceptability of SRM experiments (Bellamy et al., 2017). In Germany, laboratory work on SRM is generally approved of, field research much less so, and immediate deployment is largely rejected (Merk et al., 2015; Braun et al., 2017). Various factors could explain variations in the degree of rejection of SRM between Canada, China, Germany, Switzerland, the United Kingdom, and the United States (Visschers et al., 2017).

Cross-Chapter Box 10 | Solar Radiation Modification in the Context of 1.5°C Mitigation Pathways

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Solar radiation modification (SRM) refers to a range of radiation modification measures not related to greenhouse gas (GHG) mitigation that seek to limit global warming (see Chapter 1, Section 1.4.1). Most methods involve reducing the amount of incoming solar radiation reaching the surface, but others also act on the longwave radiation budget by reducing optical thickness and cloud lifetime (see Table 4.7). In the context of this report, SRM is assessed in terms of its potential to limit warming below 1.5°C in temporary overshoot scenarios as a way to reduce elevated temperatures and associated impacts (Irvine et al., 2016; Keith and Irvine, 2016; Chen and Xin, 2017; Sugiyama et al., 2017a; Visioni et al., 2017a; MacMartin et al., 2018). The inherent variability of the climate system would make it difficult to detect the efficacy or side-effects of SRM intervention when deployed in such a temporary scenario (Jackson et al., 2015).

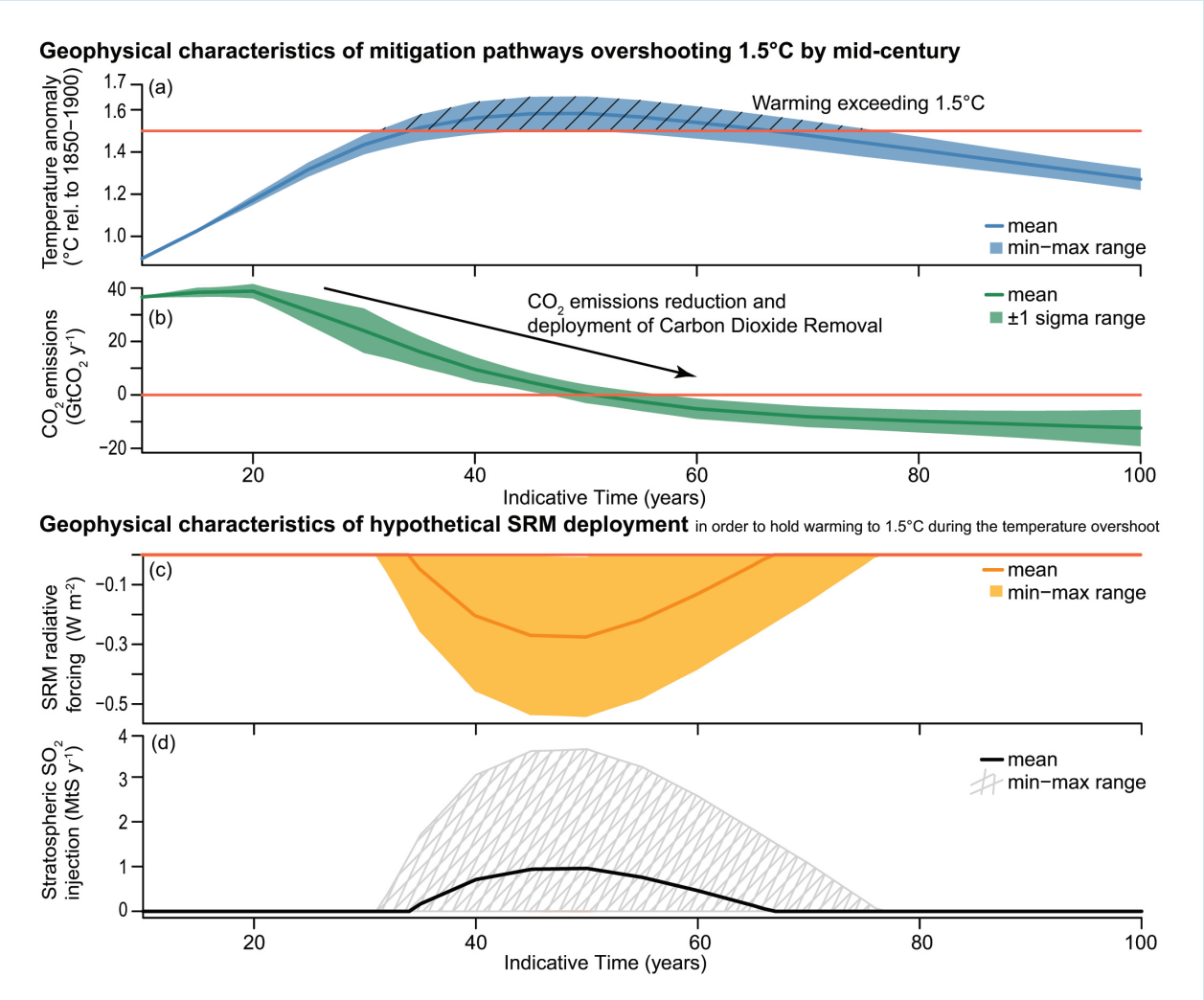
A. Potential SRM timing and magnitude

Published SRM approaches are summarized in Table 4.7. The timing and magnitude of potential SRM deployment depends on the temperature overshoot associated with mitigation pathways. All overshooting pathways make use of carbon dioxide removal. Therefore, if considered, SRM would only be deployed as a supplemental measure to large-scale carbon dioxide removal (Chapter 2, Section 2.3).

Cross-Chapter Box 10, Figure 1 below illustrates an example of how a hypothetical SRM deployment based on stratospheric aerosols injection (SAI) could be used to limit warming below 1.5°C using an 'adaptive SRM' approach (e.g., Kravitz et al., 2011; Tilmes et al., 2016), where global mean temperature rise exceeds 1.5°C compared to pre-industrial level by mid-century and returns below 1.5°C before 2100 with a 66% likelihood (see Chapter 2). In all such limited adaptive deployment scenarios, deployment of SRM only

Cross Chapter Box 10 (continued)

commences under conditions in which CO_2 emissions have already fallen substantially below their peak level and are continuing to fall. In order to hold warming to 1.5°C, a hypothetical SRM deployment could span from one to several decades, with the earliest possible threshold exceedance occurring before mid-century. Over this duration, SRM has to compensate for warming that exceeds 1.5°C (displayed with hatching on panel a) with a decrease in radiative forcing (panel b) which could be achieved with a rate of SAI varying between 0–5.9 $MtSO_2$ yr^{-1} (panel c) (Robock et al., 2008; Heckendorn et al., 2009).



Cross-Chapter Box 10, Figure 1 | Evolution of hypothetical SRM deployment (based on stratospheric aerosols injection, or SAI) in the context of 1.5°C-consistent pathways. (a) Range of median temperature outcomes as simulated by MAGICC (see in Chapter 2, Section 2.2) given the range of CO_2 emissions and (b) other climate forcers for mitigation pathways exceeding 1.5°C at mid-century and returning below by 2100 with a 66% likelihood. Geophysical characteristics are represented by (c) the magnitude of radiative forcing and (d) the amount of stratospheric SO_2 injection that are required to keep the global median temperature below 1.5°C during the temperature overshoot (given by the blue hatching on panel a). SRM surface radiative forcing has been diagnosed using a mean cooling efficiency of 0.3°C (W– m^2) of Plazzotta et al. (2018). Magnitude and timing of SO_2 injection have been derived from published estimates of Heckendorn et al. (2009) and Robock et al. (2008).

SAI is the most-researched SRM method, with *high agreement* that it could limit warming to below 1.5°C (Tilmes et al., 2016; Jones et al., 2018). The response of global temperature to SO_2 injection, however, is uncertain and varies depending on the model parametrization and emission scenarios (Jones et al., 2011; Kravitz et al., 2011; Izrael et al., 2014; Crook et al., 2015; Niemeier and Timmreck, 2015; Tilmes et al., 2016; Kashimura et al., 2017). Uncertainty also arises due to the nature and the optical properties of injected aerosols.

Cross Chapter Box 10 (continued)

Other approaches are less well researched, but the literature suggests that ground-based albedo modification (GBAM), marine cloud brightening (MCB) or cirrus cloud thinning (CCT) are not assessed to be able to substantially reduce overall global temperature (Irvine et al., 2011; Seneviratne et al., 2018). However, these SRM approaches are known to create spatially heterogeneous forcing and potentially more spatially heterogeneous climate effects, which may be used to mitigate regional climate impacts. This may be of most relevance in the case of GBAM when applied to crop and urban areas (Seneviratne et al., 2018). Most of the literature on regional mitigation has focused on GBAM in relationship with land-use and land-cover change scenarios. Both models and observations suggest that there is a *high agreement* that GBAM would result in cooling over the region of changed albedo, and in particular would reduce hot extremes (Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Alkama and Cescatti, 2016; Seneviratne et al., 2018). In comparison, there is a *limited evidence* on the ability of MCB or CCT to mitigate regional climate impacts of 1.5°C warming because the magnitude of the climate response to MCB or CCT remains uncertain and the processes are not fully understood (Lohmann and Gasparini, 2017).

B. General consequences and impacts of solar radiation modification

It has been proposed that deploying SRM as a supplement to mitigation may reduce increases in global temperature-related extremes and rainfall intensity, and lessen the loss of coral reefs from increasing sea-surface temperatures (Keith and Irvine, 2016), but it would not address, or could even worsen (Tjiputra et al., 2016), negative effects from continued ocean acidification.

Another concern with SRM is the risk of a 'termination shock' or 'termination effect' when suddenly stopping SRM, which might cause rapid temperature rise and associated impacts (Jones et al., 2013; Izrael et al., 2014; McCusker et al., 2014), most noticeably biodiversity loss (Trisos et al., 2018). The severity of the termination effect has recently been debated (Parker and Irvine, 2018) and depends on the degree of SRM cooling. This report only considers limited SRM in the context of mitigation pathways to 1.5°C. Other risks of SRM deployment could be associated with the lack of testing of the proposed deployment schemes (e.g., Schäfer et al., 2013). Ethical aspects and issues related to the governance and economics are discussed in Section 4.3.8.

C. Consequences and impacts of SRM on the carbon budget

Because of its effects on surface temperature, precipitation and surface shortwave radiation, SRM would also alter the carbon budget pathways to 1.5°C or 2°C (Eliseev, 2012; Keller et al., 2014; Keith et al., 2017; Lauvset et al., 2017).

Despite the large uncertainties in the simulated climate response to SRM, current model simulations suggest that SRM would lead to altered carbon budgets compatible with 1.5°C or 2°C. The 6 CMIP5 models investigated simulated an increase of natural carbon uptake by land biosphere and, to a smaller extent, by the oceans (*high agreement*). The multimodel mean of this response suggests an increase of the RCP4.5 carbon budget of about 150 $GtCO_2$ after 50 years of SO_2 injection with a rate of 4 TgS yr^{-1}, which represents about 4 years of CO_2 emissions at the current rate (36 $GtCO_2$ yr^{-1}). However, there is uncertainty around quantitative determination of the effects that SRM or its cessation has on the carbon budget due to a lack of understanding of the radiative processes driving the global carbon cycle response to SRM (Ramachandran et al., 2000; Mercado et al., 2009; Eliseev, 2012; Xia et al., 2016), uncertainties about how the carbon cycle will respond to termination effects of SRM, and uncertainties in climate–carbon cycle feedbacks (Friedlingstein et al., 2014).

D. Sustainable development and SRM

There are few studies investigating potential implications of SRM for sustainable development. These are based on a limited number of scenarios and hypothetical considerations, mainly referring to benefits from lower temperatures (Irvine et al., 2011; Nicholson, 2013; Anshelm and Hansson, 2014; Harding and Moreno-Cruz, 2016). Other studies suggest negative impacts from SRM implementation concerning issues related to regional disparities (Heyen et al., 2015), equity (Buck, 2012), fisheries, ecosystems, agriculture, and termination effects (Robock, 2012; Morrow, 2014; Wong, 2014). If SRM is initiated by the richer nations, there might be issues with local agency, and possibly worsening conditions for those suffering most under climate change (Buck et al., 2014). In addition, ethical issues related to testing SRM have been raised (e.g., Lenferna et al., 2017). Overall, there is *high agreement* that SRM would affect many development issues but *limited evidence* on the degree of influence, and how it manifests itself across regions and different levels of society.

E. Overall feasibility of SRM

If mitigation efforts do not keep global mean temperature below 1.5°C, SRM can potentially reduce the climate impacts of a temporary temperature overshoot, in particular extreme temperatures, rate of sea level rise and intensity of tropical cyclones, alongside intense mitigation and adaptation efforts. While theoretical developments show that SRM is technically feasible (see Section 4.3.8.2), global field experiments have not been conducted and most of the knowledge about SRM is based on imperfect

Cross Chapter Box 10 (continued)

model simulations and some natural analogues. There are also considerable challenges to the implementation of SRM associated with disagreements over the governance, ethics, public perception, and distributional development impacts (see Section 4.3.8) (Boyd, 2016; Preston, 2016; Asayama et al., 2017; Sugiyama et al., 2017b; Svoboda, 2017; McKinnon, 2018; Talberg et al., 2018). Overall, the combined uncertainties surrounding the various SRM approaches, including technological maturity, physical understanding, potential impacts, and challenges of governance, constrain the ability to implement SRM in the near future.

4.4 Implementing Far-Reaching and Rapid Change

The feasibility of 1.5°C-compatible pathways is contingent upon enabling conditions for systemic change (see Cross Chapter Box 3 in Chapter 1). Section 4.3 identifies the major systems, and options within those systems, that offer the potential for change to align with 1.5°C pathways.

AR5 identifies enabling conditions as influencing the feasibility of climate responses (Kolstad et al., 2014). This section draws on 1.5°C-specific and related literature on rapid and scaled up change to identify the enabling conditions that influence the feasibility of adaptation and mitigation options assessed in Section 4.5. Examples from diverse regions and sectors are provided in Boxes 4.1 to 4.10 to illustrate how these conditions could enable or constrain the implementation of incremental, rapid, disruptive and transformative mitigation and adaptation consistent with 1.5°C pathways.

Coherence between the enabling conditions holds potential to enhance the feasibility of 1.5°C-consistent pathways and adapting to the consequences. This includes better alignment across governance scales (OECD, 2015a; Geels et al., 2017), enabling multilevel governance (Cheshmehzangi, 2016; Revi, 2017; Tait and Euston-Brown, 2017) and nested institutions (Abbott, 2012). It also includes interdisciplinary actions, combined adaptation and mitigation action (Göpfert et al., 2018), and science–policy partnerships (Vogel et al., 2007; Hering et al., 2014; Roberts, 2016; Figueres et al., 2017; Leal Filho et al., 2018). These partnerships are difficult to establish and sustain, but can generate trust (Cole, 2015; Jordan et al., 2015) and inclusivity that ultimately can provide durability and the realization of co-benefits for sustained rapid change (Blanchet, 2015; Ziervogel et al., 2016a).

4.4.1 Enhancing Multilevel Governance

Addressing climate change and implementing responses to 1.5°C-consistent pathways would require engagement between various levels and types of governance (Betsill and Bulkeley, 2006; Kern and Alber, 2009; Christoforidis et al., 2013; Romero-Lankao et al., 2018). AR5 highlighted the significance of governance as a means of strengthening adaptation and mitigation and advancing sustainable development (Fleurbaey et al., 2014). Governance is defined in the broadest sense as the 'processes of interaction and decision-making among actors involved in a common problem' (Kooiman, 2003; Hufty, 2011; Fleurbaey et al., 2014). This definition goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions and communities.

4.4.1.1 Institutions and their capacity to invoke far-reaching and rapid change

Institutions – the rules and norms that guide human interactions (Section 4.4.2) – enable or impede the structures, mechanisms and measures that guide mitigation and adaptation. Institutions, understood as the 'rules of the game' (North, 1990), exert direct and indirect influence over the viability of 1.5°C-consistent pathways (Munck et al., 2014; Willis, 2017). Governance would be needed to support wide-scale and effective adoption of mitigation and adaptation options. Institutions and governance structures are strengthened when the principle of the 'commons' is explored as a way of sharing management and responsibilities (Ostrom et al., 1999; Chaffin et al., 2014; Young, 2016). Institutions would need to be strengthened to interact amongst themselves, and to share responsibilities for the development and implementation of rules, regulations and policies (Ostrom et al., 1999; Wejs et al., 2014; Craig et al., 2017), with the goal of ensuring that these embrace equity, justice, poverty alleviation and sustainable development, enabling a 1.5°C world (Reckien et al., 2017; Wood et al., 2017).

Several authors have identified different modes of cross-stakeholder interaction in climate policy, including the role played by large multinational corporations, small enterprises, civil society and non-state actors. Ciplet et al. (2015) argue that civil society is to a great extent the only reliable motor for driving institutions to change at the pace required. Kern and Alber (2009) recognize different forms of collaboration relevant to successful climate policies beyond the local level. Horizontal collaboration (e.g., transnational city networks) and vertical collaboration within nation-states can play an enabling role (Ringel, 2017). Vertical and horizontal collaboration requires synergistic relationships between stakeholders (Ingold and Fischer, 2014; Hsu et al., 2017). The importance of community participation is emphasized in literature, and in particular the need to take into account equity and gender considerations (Chapter 5) (Graham et al., 2015; Bryan et al., 2017; Wangui and Smucker, 2017). Participation often faces implementation challenges and may not always result in better policy outcomes. Stakeholders, for example, may not view climate change as a priority and may not share the same preferences, potentially creating a policy deadlock (Preston et al., 2013, 2015; Ford et al., 2016).

4.4.1.2 International governance

International treaties help strengthen policy implementation, providing a medium- and long-term vision (Obergassel et al., 2016). International climate governance is organized via many mechanisms, including international organizations, treaties and conventions, for example,

UNFCCC, the Paris Agreement and the Montreal Protocol. Other multilateral and bilateral agreements, such as trade agreements, also have a bearing on climate change.

There are significant differences between global mitigation and adaptation governance frames. Mitigation tends to be global by its nature and based on the principle of the climate system as a global commons (Ostrom et al., 1999). Adaptation has traditionally been viewed as a local process, involving local authorities, communities, and stakeholders (Khan, 2013; Preston et al., 2015), although it is now recognized to be a multi-scaled, multi-actor process that transcends scales from local and sub-national to national and international (Mimura et al., 2014; UNEP, 2017a). National governments provide a central pivot for coordination, planning, determining policy priorities and distributing resources. National governments are accountable to the international community through international agreements. Yet, many of the impacts of climate change are transboundary, so that bilateral and multilateral cooperation are needed (Nalau et al., 2015; Donner et al., 2016; Magnan and Ribera, 2016; Tilleard and Ford, 2016; Lesnikowski et al., 2017). The Kigali Amendment to the Montreal Protocol demonstrates that a global environmental agreement facilitating common but differentiated responsibilities is possible (Sharadin, 2018). This was operationalized by developed countries acting first, with developing countries following and benefiting from leap-frogging the trial-and-error stages of innovative technology development.

Work on international climate governance has focused on the nature of 'climate regimes' and coordinating the action of nation-states (Aykut, 2016) organized around a diverse set of instruments: (i) binding limits allocated by principles of historical responsibility and equity, (ii) carbon prices, emissions quotas, (iii) pledges and review of policies and measures or (iv) a combination of these options (Stavins, 1988; Grubb, 1990; Pizer, 2002; Newell and Pizer, 2003).

Literature on the Kyoto Protocol provides two important insights for the 1.5°C transition: the challenge of agreeing on rules to allocate emissions quotas (Shukla, 2005; Caney, 2012; Winkler et al., 2013; Gupta, 2014; Méjean et al., 2015) and a climate-centric vision (Shukla, 2005; BASIC experts, 2011), separated from development issues which drove resistance from many developing nations (Roberts and Parks, 2006). For the former, a burden-sharing approach led to an adversarial process among nations to decide who should be allocated 'how much' of the remainder of the emissions budget (Caney, 2014; Ohndorf et al., 2015; Roser et al., 2015; Giménez-Gómez et al., 2016). Industry group lobbying further contributed to reducing space for manoeuvre of some major emitting nations (Newell and Paterson, 1998; Levy and Egan, 2003; Dunlap and McCright, 2011; Michaelowa, 2013; Geels, 2014).

Given the political unwillingness to continue with the Kyoto Protocol approach a new approach was introduced in the Copenhagen Accord, the Cancun Agreements, and finally in the Paris Agreement. The transition to 1.5°C requires carbon neutrality and thus going beyond the traditional framing of climate as a 'tragedy of the commons' to be addressed via cost-optimal allocation rules, which demonstrated a low probability of enabling a transition to 1.5°C-consistent pathways (Patt, 2017). The Paris Agreement, built on a 'pledge and review' system, is thought be more effective in securing trust (Dagnet et al., 2016) and enables effective monitoring and timely reporting on national actions (including adaptation), allowing for international scrutiny and persistent efforts of civil society and non-state actors to encourage action in both national and international contexts (Allan and Hadden, 2017; Bäckstrand and Kuyper, 2017; Höhne et al., 2017; Lesnikowski et al., 2017; Maor et al., 2017; UNEP, 2017a), with some limitations (Nieto et al., 2018).

The paradigm shift enabled at Cancun succeeded by focusing on the objective of 'equitable access to sustainable development' (Hourcade et al., 2015). The use of 'pledge and review' now underpins the Paris Agreement. This consolidates multiple attempts to define a governance approach that relies on Nationally Determined Contributions (NDCs) and on means for a 'facilitative model' (Bodansky and Diringer, 2014) to reinforce them. This enables a regular, iterative, review of NDCs allowing countries to set their own ambitions after a global stocktake and more flexible, experimental forms of climate governance, which may provide room for higher ambition and be consistent with the needs of governing for a rapid transition to close the emission gap (Clémençon, 2016; Falkner, 2016) (Cross-Chapter Box 11 in this chapter). Beyond a general consensus on the necessity of measurement, reporting and verification (MRV) mechanisms as a key element of a climate regime (Ford et al., 2015b; van Asselt et al., 2015), some authors emphasize different governance approaches to implement the Paris Agreement. Through the new proposed sustainable development mechanism in Article 6, the Paris Agreement allows the space to harness the lowest cost mitigation options worldwide. This may incentivize policymakers to enhance mitigation ambition by speeding up climate action as part of a 'climate regime complex' (Keohane and Victor, 2011) of loosely interrelated global governance institutions. In the Paris Agreement, the 'common but differentiated responsibilities and respective capabilities' (CBDR-RC) principle could be expanded and revisited under a 'sharing the pie' paradigm (Ji and Sha, 2015) as a tool to open innovation processes towards alternative development pathways (Chapter 5).

COP 16 in Cancun was also the first time in the UNFCCC that adaptation was recognized to have similar priority as mitigation. The Paris Agreement recognizes the importance of adaptation action and cooperation to enhance such action. Chung Tiam Fook (2017) and Lesnikowski et al. (2017) suggest that the Paris Agreement is explicit about multilevel adaptation governance, outlines stronger transparency mechanisms, links adaptation to development and climate justice, and is therefore suggestive of greater inclusiveness of non-state voices and the broader contexts of social change.

1.5°C-consistent pathways require further exploration of conditions of trust and reciprocity amongst nation states (Schelling, 1991; Ostrom and Walker, 2005). Some authors (Colman et al., 2011; Courtois et al., 2015) suggest a departure from the vision of actors acting individually in the pursuit of self-interest to that of iterated games with actors interacting over time showing that reciprocity, with occasional forgiveness and initial good faith, can lead to win-win outcomes and to cooperation as a stable strategy (Axelrod and Hamilton, 1981).

Regional cooperation plays an important role in the context of global governance. Literature on climate regimes has only started

exploring innovative governance arrangements, including coalitions of transnational actors including state, market and non-state actors (Bulkeley et al., 2012; Hovi et al., 2016; Hagen et al., 2017; Hermwille et al., 2017; Roelfsema et al., 2018) and groupings of countries, as a complement to the UNFCCC (Abbott and Snidal, 2009; Biermann, 2010; Zelli, 2011; Nordhaus, 2015). Climate action requires multilevel governance from the local and community level to national, regional and international levels. Box 4.1 shows the role of sub-national authorities (e.g., regions and provinces) in facilitating urban climate action, while Box 4.2 shows that climate governance can be organized across hydrological as well as political units.

4.4.1.3 Sub-national governance

Local governments can play a key role (Melica et al., 2018; Romero-Lankao et al., 2018) in influencing mitigation and adaptation strategies. It is important to understand how rural and urban areas, small islands, informal settlements and communities might intervene to reduce climate impacts (Bulkeley et al., 2011), either by implementing climate objectives defined at higher government levels or by taking initiative autonomously or collectively (Aall et al., 2007; Reckien et al., 2014; Araos et al., 2016a; Heidrich et al., 2016). Local governance faces the challenge of reconciling local concerns with global objectives. Local governments could coordinate and develop effective local responses, and could pursue procedural justice in ensuring community engagement and more effective policies around energy and vulnerability reduction (Moss et al., 2013; Fudge et al., 2016). They can enable more participative decision-making (Barrett, 2015; Hesse, 2016). Fudge et al. (2016) argue that local authorities are well-positioned to involve the wider community in: designing and implementing climate policies, engaging with sustainable energy generation (e.g., by supporting energy communities) (Slee, 2015), and the delivery of demand-side measures and adaptation implementation.

By 2050, it is estimated three billion people will be living in slums and informal settlements: neighbourhoods without formal governance, on un-zoned land developments and in places that are exposed to climate-related hazards (Bai et al., 2018). Emerging research is examining how citizens can contribute informally to governance with rapid urbanization and weaker government regulation (Sarmiento and Tilly, 2018). It remains to be seen how the possibilities and consequences of alternative urban governance models will be managed for large, complex problems and for addressing inequality and urban adaptation (Amin and Cirolia, 2018; Bai et al., 2018; Sarmiento and Tilly, 2018).

Expanding networks of cities are sharing experiences on coping with climate change and drawing economic and development benefits from climate change responses – a recent institutional innovation. This could be complemented by efforts of national governments to enhance local climate action through national urban policies (Broekhoff et al., 2018). Over the years, non-state actors have set up several transnational climate governance initiatives to accelerate the climate response, for example, ICLEI (1990), C–40 (2005), the Global Island Partnership (2006) and the Covenant of Mayors (2008) (Gordon and Johnson, 2017; Hsu et al., 2017; Ringel, 2017; Kona et al., 2018; Melica et al., 2018) and to exert influence on national governments and the UNFCCC (Bulkeley, 2005). However, Michaelowa and Michaelowa (2017) find low effectiveness for over 100 of such mitigation initiatives.

4.4.1.4 Interactions and processes for multilevel governance

Literature has proposed multilevel governance in climate change as an enabler for systemic transformation and effective governance, as the concept is thought to allow for combining decisions across levels and sectors and across institutional types at the same level (Romero-Lankao et al., 2018), with multilevel reinforcement and the mobilization of economic interests at different levels of governance (Jänicke and Quitzow, 2017). These governance mechanisms are based on accountability and transparency rules and participation and coordination across and within these levels.

A study of 29 European countries showed that the rapid adoption and diffusion of adaptation policymaking is largely driven by internal factors, at the national and sub-national levels (Massey et al., 2014). An assessment of national-level adaptation in 117 countries (Berrang-Ford et al., 2014) found good governance to be the one of the strongest predictors of national adaptation policy. An analysis of the climate responses of 200 large and medium-sized cities across eleven European countries found that factors such as membership of climate networks, population size, gross domestic product (GDP) per capita and adaptive capacity act as drivers of mitigation and adaptation plans (Reckien et al., 2015).

Adaptation policy has seen growth in some areas (Massey et al., 2014; Lesnikowski et al., 2016), although efforts to track adaptation progress are constrained by an absence of data sources on adaptation (Berrang-Ford et al., 2011; Ford and Berrang-Ford, 2016; Magnan, 2016; Magnan and Ribera, 2016). Many developing countries have made progress in formulating national policies, plans and strategies on responding to climate change. The NDCs have been identified as one such institutional mechanism (Cross-Chapter Box 11 in this Chapter) (Magnan et al., 2015; Kato and Ellis, 2016; Peters et al., 2017).

To overcome barriers to policy implementation, local conflicts of interest or vested interests, strong leadership and agency is needed by political leaders. As shown by the Covenant of Mayors initiative (Box 4.1), political leaders with a vision for the future of the local community can succeed in reducing GHG emissions, when they are supported by civil society (Rivas et al., 2015; Croci et al., 2017; Kona et al., 2018). Any political vision would need to be translated into an action plan, which could include elements describing policies and measures needed to achieve transition, the human and financial resources needed, milestones, and appropriate measurement and verification processes (Azevedo and Leal, 2017). Discussing the plan with stakeholders and civil society, including citizens and allowing for participation for minorities, and having them provide input and endorse it, has been found to increase the likelihood of success (Rivas et al., 2015; Wamsler, 2017). However, as described by Nightingale (2017) and Green (2016), struggles over natural resources and adaptation governance both at the national and community levels would also need to be addressed 'in politically unstable contexts, where power and politics shape adaptation outcomes'.

Multilevel governance includes adaptation across local, regional, and national scales (Adger et al., 2005). The whole-of-government approach to understanding and influencing climate change policy design and implementation puts analytical emphasis on how different levels of government and different types of actors (e.g., public and private) can constrain or support local adaptive capacity (Corfee-Morlot et al., 2011), including the role of the civil society. National governments, for example, have been associated with enhancing adaptive capacity through building awareness of climate impacts, encouraging economic growth, providing incentives, establishing legislative frameworks conducive to adaptation, and communicating climate change information (Berrang-Ford et al., 2014; Massey et al., 2014; Austin et al., 2015; Henstra, 2016; Massey and Huitema, 2016). Local governments, on the other hand, are responsible for delivering basic services and utilities to the urban population, and protecting their integrity from the impacts of extreme weather (Austin et al., 2015; Cloutier et al., 2015; Nalau et al., 2015; Araos et al., 2016b). National policies and transnational governance could be seen as complementary, rather than competitors, and strong national policies favour transnational engagement of sub- and non-state actors (Andonova et al., 2017). Local initiatives are complementary with higher level policies and can be integrated in the multilevel governance system (Fuhr et al., 2018).

A multilevel approach considers that adaptation planning is affected by scale mismatches between the local manifestation of climate impacts and the diverse scales at which the problem is driven (Shi et al., 2016). Multilevel approaches may be relevant in low-income countries where limited financial resources and human capabilities within local governments often lead to greater dependency on national governments and other (donor) organizations, to strengthen adaptation responses (Donner et al., 2016; Adenle et al., 2017). National governments or international organizations may motivate urban adaptation externally through broad policy directives or projects by international donors. Municipal governments on the other hand work within the city to spur progress on adaptation. Individual political leadership in municipal government, for example, has been cited as a factor driving the adaptation policies of early adapters in Quito, Ecuador, and Durban, and South Africa (Anguelovski et al., 2014), and for adaptation more generally (Smith et al., 2009). Adaptation pathways can help identify maladaptive actions (Juhola et al., 2016; Magnan et al., 2016; Gajjar et al., 2018) and encourage social learning approaches across multiple levels of stakeholders in sectors such as marine biodiversity and water supply (Bosomworth et al., 2015; Butler et al., 2015; van der Brugge and Roosjen, 2015).

Box 4.1 | Multilevel Governance in the EU Covenant of Mayors: Example of the Provincia di Foggia

Since 2005, cities have emerged as a locus of institutional and governance climate innovation (Melica et al., 2018) and are driving responses to climate change (Roberts, 2016). Many cities have adopted more ambitious greenhouse gas (GHG) emission reduction targets than countries (Kona et al., 2018), with an overall commitment of GHG emission reduction targets by 2020 of 27%, almost 7 percentage points higher than the minimum target for 2020 (Kona et al., 2018). The Covenant of Mayors (CoM) is an initiative in which municipalities voluntarily commit to CO_2 emission reduction. The participation of small municipalities has been facilitated by the development and testing of a new multilevel governance model involving Covenant Territorial Coordinators (CTCs), i.e., provinces and regions, which commit to providing strategic guidance and financial and technical support to municipalities in their territories. Results from the 315 monitoring inventories submitted show an achievement of 23% reduction in emissions (compared to an average year 2005) for more than half of the cities under a CTC schema (Kona et al., 2018).

The Province of Foggia, acting as a CTC, gave support to 36 municipalities to participate in the CoM and to prepare Sustainable Energy Action Plans (SEAPs). The Province developed a common approach to prepare SEAPs, provided data to compile municipal emission inventories (Bertoldi et al., 2018) and guided the signatory to identify an appropriate combination of measures to curb GHG emissions. The local Chamber of Commerce also had a key role in the implementation of these projects by the municipalities (Lombardi et al., 2016). The joint action by the province and the municipalities in collaboration with the local business community could be seen as an example of multilevel governance (Lombardi et al., 2016).

Researchers have investigated local forms of collaboration within local government, with the active involvement of citizens and stakeholders, and acknowledge that public acceptance is key to the successful implementation of policies (Larsen and Gunnarsson-Östling, 2009; Musall and Kuik, 2011; Pollak et al., 2011; Christoforidis et al., 2013; Pasimeni et al., 2014; Lee and Painter, 2015). Achieving ambitious targets would need leadership, enhanced multilevel governance, vision and widespread participation in transformative change (Castán Broto and Bulkeley, 2013; Rosenzweig et al., 2015; Castán Broto, 2017; Fazey et al., 2017; Wamsler, 2017; Romero-Lankao et al., 2018). The Chapter 5, Section 5.6.4 case studies of climate-resilient development pathways, at state and community scales, show that participation, social learning and iterative decision-making are governance features of strategies that deliver mitigation, adaptation, and sustainable development in a fair and equitable manner. Another insight is the finding that incremental voluntary changes are amplified through community networking, polycentric governance (Dorsch and Flachsland, 2017), partnerships, and long-term change to governance systems at multiple levels (Stevenson and Dryzek, 2014; Lövbrand et al., 2017; Pichler et al., 2017; Termeer et al., 2017).

Box 4.2 | Watershed Management in a 1.5°C World

Water management is necessary in order for the global community to adapt to 1.5°C-consistent pathways. Cohesive planning that includes numerous stakeholders would be required to improve access, utilization and efficiency of water use and to ensure hydrologic viability.

Response to drought and El Niño–Southern Oscillation (ENSO) in southern Guatemala

Hydro-meteorological events, including ENSO, have impacted Central America (Steinhoff et al., 2014; Chang et al., 2015; Maggioni et al., 2016) and are projected to increase in frequency during a 1.5°C transition (Wang et al., 2017). The 2014–2016 ENSO damaged agriculture, seriously impacting rural communities.

In 2016, the Climate Change Institute, in conjunction with local governments, the private sector, communities and human rights organizations, established dialogue tables for different watersheds to discuss water usage amongst stakeholders and plans to mitigate the effects of drought, alleviate social tension, and map water use of watersheds at risk. The goal was to encourage better water resource management and to enhance ecological flow through improved communication, transparency, and coordination amongst users. These goals were achieved in 2017 when each previously affected river reached the Pacific Ocean with at least its minimum ecological flow (Guerra, 2017).

Drought management through the Limpopo Watercourse Commission

The governments sharing the Limpopo river basin (Botswana, Mozambique, South Africa and Zimbabwe) formed the Limpopo Watercourse Commission in 2003 (Nyagwambo et al., 2008; Mitchell, 2013). It has an advisory body composed of working groups that assess water use and sustainability, decide national level distribution of water access, and support disaster and emergency planning. The Limpopo basin delta is highly vulnerable (Tessler et al., 2015), and is associated with a lack of infrastructure and investment capacity, requiring increased economic development together with plans for vulnerability reduction (Tessler et al., 2015) and water rights (Swatuk, 2015). The high vulnerability is influenced by gender inequality, limited stakeholder participation and limited institutional capacity to address unequal water access (Mehta et al., 2014). The implementation of integrated water resources management (IWRM) would need to consider pre-existing social, economic, historical and cultural contexts (Merrey, 2009; Mehta et al., 2014). The Commission therefore could play a role in improving participation and in providing an adaptable and equitable strategy for cross-border water sharing (Ekblom et al., 2017).

Flood management in the Danube

The Danube River Protection Convention is the official instrument for cooperation on transboundary water governance between the countries that share the Danube Basin. The International Commission for the Protection of the Danube River (ICPDR) provides a strong science–policy link through expert working groups dealing with issues including governance, monitoring and assessment, and flood protection (Schmeier, 2014). The Trans-National Monitoring Network (TNMN) was developed to undertake comprehensive monitoring of water quality (Schmeier, 2014). Monitoring of water quality constitutes almost 50% of ICPDR's scientific publications, although ICPDR also works on governance, basin planning, monitoring, and IWRM, indicating its importance. The ICPDR is an example of IWRM 'coordinating groundwater, surface water abstractions, flood management, energy production, navigation, and water quality' (Hering et al., 2014).

Box 4.2 exemplifies how multilevel governance has been used for watershed management in different basins, given the impacts on water sources (Chapter 3, Section 3.4.2).

Cross-Chapter Box 11 | Consistency Between Nationally Determined Contributions and 1.5°C Scenarios

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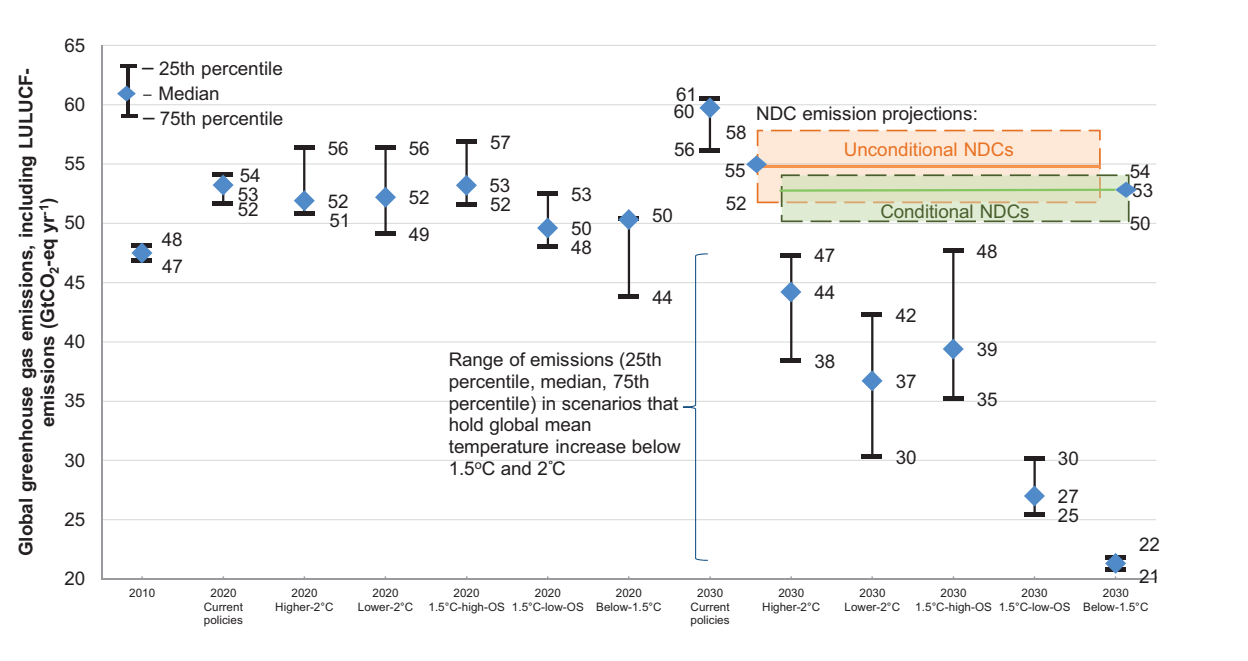
Mitigation

1. Introduction

There is *high agreement* that Nationally Determined Contributions (NDCs) are important for the global response to climate change and represent an innovative bottom-up instrument in climate change governance (Section 4.4.1), with contributions from all signatory countries (den Elzen et al., 2016; Rogelj et al., 2016; Vandyck et al., 2016; Luderer et al., 2018; Vrontisi et al., 2018). The global emission projections resulting from full implementation of the NDCs represent an improvement compared to business as usual (Rogelj et al., 2016) and current policies scenarios to 2030 (den Elzen et al., 2016; Vrontisi et al., 2018). Most G20 economies would require new policies and actions to achieve their NDC targets (den Elzen et al., 2016; Vandyck et al., 2016; UNEP, 2017b; Kuramochi et al., 2018).

2. The effect of NDCs on global greenhouse gas (GHG) emissions

Several studies estimate global emission levels that would be achieved under the NDCs (e.g., den Elzen et al., 2016; Luderer et al., 2016; Rogelj et al., 2016, 2017; Vandyck et al., 2016; Rose et al., 2017; Vrontisi et al., 2018). Rogelj et al. (2016) and UNEP (2017b) concluded that the full implementation of the unconditional and conditional NDCs are expected to result in global GHG emissions of about 55 (52–58) and 53 (50–54) $GtCO_2$-eq yr^{-1}, respectively (Cross-Chapter Box 11, Figure 1 below).



Cross-Chapter Box 11, Figure 1 | GHG emissions are all expressed in units of CO_2-equivalence computed with 100-year global warming potentials (GWPs) reported in IPCC SAR, while the emissions for the 1.5°C and 2°C scenarios in Table 2.4 are reported using the 100-year GWPs reported in IPCC AR4, and are hence about 3% higher. Using IPCC AR4 instead of SAR GWP values is estimated to result in a 2–3% increase in estimated 1.5°C and 2°C emissions levels in 2030. Source: based on Rogelj et al. (2016) and UNEP (2017b).

3. The effect of NDCs on temperature increase and carbon budget

Estimates of global average temperature increase are 2.9°C–3.4°C above preindustrial levels with a greater than 66% probability by 2100 (Rogelj et al., 2016; UNEP, 2017b), under a full implementation of unconditional NDCs and a continuation of climate action similar to that of the NDCs. Full implementation of the conditional NDCs would lower the estimates by about 0.2°C by 2100. As an indication of the carbon budget implications of NDC scenarios, Rogelj et al. (2016) estimated cumulative emissions in the range

Cross Chapter Box 11 (continued)

of 690 to 850 $GtCO_2$ for the period 2011–2030 if the NDCs are successfully implemented. The carbon budget for post-2010 till 2100 compatible with staying below 1.5°C with a 50–66% probability was estimated at 550–600 $GtCO_2$ (Clarke et al., 2014; Rogelj et al., 2016), which will be well exceeded by 2030 at full implementation of the NDCs (Chapter 2, Section 2.2 and Section 2.3.1).

4. The 2030 emissions gap with 1.5°C and urgency of action

As the 1.5°C pathways require reaching carbon neutrality by mid-century, the NDCs alone are not sufficient, as they have a time horizon until 2030. Rogelj et al. (2016) and Hof et al. (2017) have used results or compared NDC pathways with emissions pathways produced by integrated assessment models (IAMs) assessing the contribution of NDCs to achieve the 1.5°C targets. There is *high agreement* that current NDC emissions levels are not in line with pathways that limit warming to 1.5°C by the end of the century (Rogelj et al., 2016, 2017; Hof et al., 2017; UNEP, 2017b; Vrontisi et al., 2018). The median 1.5°C emissions gap (>66% chance) for the full implementation of both the conditional and unconditional NDCs for 2030 is 26 (19–29) to 28 (22–33) $GtCO_2$-eq (Cross-Chapter Box 11, Figure 1 above).

Studies indicate important trade-offs of delaying global emissions reductions (Chapter 2, Sections 2.3.5 and 2.5.1). AR5 identified flexibility in 2030 emission levels when pursuing a 2°C objective (Clarke et al., 2014) indicating that strongest trade-offs for 2°C pathways could be avoided if emissions are limited to below 50 $GtCO_2$-eq yr^{-1} in 2030 (here computed with the GWP–100 metric of the IPCC SAR). New scenario studies show that full implementation of the NDCs by 2030 would imply the need for deeper and faster emission reductions beyond 2030 in order to meet 2°C, and also higher costs and efforts of negative emissions (Fujimori et al., 2016; Sanderson et al., 2016; Rose et al., 2017; van Soest et al., 2017; Luderer et al., 2018). However, no flexibility has been found for 1.5°C-consistent pathways (Luderer et al., 2016; Rogelj et al., 2017), indicating that if emissions through 2030 are at NDC levels, the resulting post-2030 reductions required to remain within a 1.5°C-consistent carbon budget during the 21st century (Chapter 2, Section 2.2) are not within the feasible operating space of IAMs. This indicates that the chances of failing to reach a 1.5°C pathway are significantly increased (Riahi et al., 2015), if near-term ambition is not strengthened beyond the level implied by current NDCs.

Accelerated and stronger short-term action and enhanced longer-term national ambition going beyond the NDCs would be needed for 1.5°C-consistent pathways. Implementing deeper emissions reductions than current NDCs would imply action towards levels identified in Chapter 2, Section 2.3.3, either as part of or over-delivering on NDCs.

5. The impact of uncertainties on NDC emission levels

The measures proposed in NDCs are not legally binding (Nemet et al., 2017), further impacting estimates of anticipated 2030 emission levels. The aggregation of targets results in high uncertainty (Rogelj et al., 2017), which could be reduced with clearer guidelines for compiling future NDCs focused more on energy accounting (Rogelj et al., 2017) and increased transparency and comparability (Pauw et al., 2018).

Many factors would influence NDCs global aggregated effects, including: (1) variations in socio-economic conditions (GDP and population growth), (2) uncertainties in historical emission inventories, (3) conditionality of certain NDCs, (4) definition of NDC targets as ranges instead of single values, (5) the way in which renewable energy targets are expressed, and (6) the way in which traditional biomass use is accounted for. Additionally, there are land-use mitigation uncertainties (Forsell et al., 2016; Grassi et al., 2017). Land-use options play a key role in many country NDCs; however, many analyses on NDCs do not use country estimates on land-use emissions, but use model estimates, mainly because of the large difference in estimating the 'anthropogenic' forest sink between countries and models (Grassi et al., 2017).

6. Comparing countries' NDC ambition (equity, cost optimal allocation and other indicators)

Various assessment frameworks have been proposed to analyse, benchmark and compare NDCs, and indicate possible strengthening, based on equity and other indicators (Aldy et al., 2016; den Elzen et al., 2016; Höhne et al., 2017; Jiang et al., 2017; Holz et al., 2018).There is large variation in conformity/fulfilment with equity principles across NDCs and countries. Studies use assessment frameworks based on six effort sharing categories in the AR5 (Clarke et al., 2014) with the principles of 'responsibility', 'capability' and 'equity' (Höhne et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017). There is an important methodological gap in the assessment of the NDCs' fairness and equity implications, partly due to lack of information on countries' own assessments (Winkler et al., 2017). Implementation of Article 2.2 of the Paris Agreement could reflect equity and the principle of 'common but differentiated responsibilities and respective capabilities', due to different national circumstances and different interpretations of equity principles (Lahn and Sundqvist, 2017; Lahn, 2018).

Cross Chapter Box 11 (continued)

Adaptation

The Paris Agreement recognizes adaptation by establishing a global goal for adaptation (Kato and Ellis, 2016; Rajamani, 2016; Kinley, 2017; Lesnikowski et al., 2017; UNEP, 2017a). This is assessed qualitatively, as achieving a temperature goal would determine the level of adaptation ambition required to deal with the consequent risks and impacts (Rajamani, 2016). Countries can include domestic adaptation goals in their NDCs, which together with national adaptation plans (NAPs) give countries flexibility to design and adjust their adaptation trajectories as their needs evolve and as progress is evaluated over time. A challenge for assessing progress on adaptation globally is the aggregation of many national adaptation actions and approaches. Knowledge gaps still remain about how to design measurement frameworks that generate and integrate national adaptation data without placing undue burdens on countries (UNEP, 2017a).

The Paris Agreement stipulates that adaptation communications shall be submitted as a component of or in conjunction with other communications, such as an NDC, a NAP, or a national communication. Of the 197 Parties to the UNFCCC, 140 NDCs have an adaptation component, almost exclusively from developing countries. NDC adaptation components could be an opportunity for enhancing adaptation planning and implementation by highlighting priorities and goals (Kato and Ellis, 2016). At the national level they provide momentum for the development of NAPs and raise the profile of adaptation (Pauw et al., 2016b, 2018). The Paris Agreement's transparency framework includes adaptation, through which 'adaptation communication' and accelerated adaptation actions are submitted and reviewed every five years (Hermwille, 2016; Kato and Ellis, 2016). This framework, unlike others used in the past, is applicable to all countries taking into account differing capacities amongst Parties (Rajamani, 2016).

Adaptation measures presented in qualitative terms include sectors, risks and vulnerabilities that are seen as priorities by the Parties. Sectoral coverage of adaptation actions identified in NDCs is uneven, with adaptation primarily reported to focus on the water sector (71% of NDCs with adaptation component), agriculture (63%), health (54%), and biodiversity/ecosystems (50%) (Pauw et al., 2016b, 2018).

4.4.2 Enhancing Institutional Capacities

The implementation of sound responses and strategies to enable a transition to 1.5°C world would require strengthening governance and scaling up institutional capacities, particularly in developing countries (Adenle et al., 2017; Rosenbloom, 2017). Building on the characterization of governance in Section 4.4.1, this section examines the necessary institutional capacity to implement actions to limit warming to 1.5°C and adapt to the consequences. This takes into account a plurality of regional and local responses, as institutional capacity is highly context-dependent (North, 1990; Lustick et al., 2011).

Institutions would need to interact with one another and align across scales to ensure that rules and regulations are followed (Chaffin and Gunderson, 2016; Young, 2016). The institutional architecture required for a 1.5°C world would include the growing proportion of the world's population that live in peri-urban and informal settlements and engage in informal economic activity (Simone and Pieterse, 2017). This population, amongst the most exposed to perturbed climates in the world (Hallegatte et al., 2017), is also beyond the direct reach of some policy instruments (Jaglin, 2014; Thieme, 2018). Strategies that accommodate the informal rules of the game adopted by these populations have large chances of success (McGranahan et al., 2016; Kaika, 2017).

The goal for strengthening implementation is to ensure that these rules and regulations embrace equity, equality and poverty alleviation along 1.5°C-consistent pathways (mitigation) and enables the building of adaptive capacity that together, will enable sustainable development and poverty reduction.

Rising to the challenge of a transition to a 1.5°C world would require enhancing institutional climate change capacities along multiple dimensions presented below.

4.4.2.1 Capacity for policy design and implementation

The enhancement of institutional capacity for integrated policy design and implementation has long been among the top items on the UN agenda of addressing global environmental problems and sustainable development (see Chapter 5, Section 5.5) (UNEP, 2005).

Political stability, an effective regulatory and enforcement framework (e.g., institutions to impose sanctions, collect taxes and to verify building codes), access to a knowledge base and the availability of resources, would be needed at various governance levels to address a wide range of stakeholders and their concerns. The strengthening of the global response would need to support these with different interventions, in the context of sustainable development (Chapter 5, Section 5.5.1) (Pasquini et al., 2015).

Given the scale of change needed to limit warming to 1.5°C, strengthening the response capacity of relevant institutions is best addressed in ways that take advantage of existing decision-making processes in local and regional governments and within cities and

communities (Romero-Lankao et al., 2013), and draws upon diverse knowledge sources including indigenous and local knowledge (Nakashima et al., 2012; Smith and Sharp, 2012; Mistry and Berardi, 2016; Tschakert et al., 2017). Examples of successful local institutional processes and the integration of local knowledge in climate-related decision-making are provided in Box 4.3 and Box 4.4.

Implementing 1.5°C-consistent strategies would require well-functioning legal frameworks to be in place, in conjunction with clearly defined mandates, rights and responsibilities to enable the institutional capacity to deliver (Romero-Lankao et al., 2013). As an example, current rates of urbanization occurring in cities with a lack of institutional capacity for effective land-use planning, zoning and infrastructure development result in unplanned, informal urban settlements which are vulnerable to climate impacts. It is common for 30–50% of urban populations in low-income nations to live in informal settlements with no regulatory infrastructure (Revi et al., 2014b). For example, in Huambo (Angola), a classified 'urban' area extends 20 km west of the city and is predominantly made up of 'unplanned' urban settlements (Smith and Jenkins, 2015).

Internationally, the Paris Agreement process has aimed at enhancing the capacity of decision-making institutions in developing countries to support effective implementation. These efforts are particularly reflected in Article 11 of the Paris Agreement on capacity building (the creation of the Paris Committee on Capacity Building), Article 13 (the creation of the Capacity Building Initiative on Transparency), and Article 15 on compliance (UNFCCC, 2016).

Box 4.3 | Indigenous Knowledge and Community Adaptation

Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (UNESCO, 2017). This knowledge can underpin the development of adaptation and mitigation strategies (Ford et al., 2014b; Green and Minchin, 2014; Pearce et al., 2015; Savo et al., 2016).

Climate change is an important concern for the Maya, who depend on climate knowledge for their livelihood. In Guatemala, the collaboration between the Mayan K'iché population of the Nahualate river basin and the Climate Change Institute has resulted in a catalogue of indigenous knowledge, used to identify indicators for watershed meteorological forecasts (López and Álvarez, 2016). These indicators are relevant but would need continuous assessment if their continued reliability is to be confirmed (Nyong et al., 2007; Alexander et al., 2011; Mistry and Berardi, 2016). For more than ten years, Guatemala has maintained an 'Indigenous Table for Climate Change', to enable the consideration of indigenous knowledge in disaster management and adaptation development.

In Tanzania, increased variability of rainfall is challenging indigenous and local communities (Mahoo et al., 2015; Sewando et al., 2016). The majority of agro-pastoralists use indigenous knowledge to forecast seasonal rainfall, relying on observations of plant phenology, bird, animal, and insect behaviour, the sun and moon, and wind (Chang'a et al., 2010; Elia et al., 2014; Shaffer, 2014). Increased climate variability has raised concerns about the reliability of these indicators (Shaffer, 2014); therefore, initiatives have focused on the co-production of knowledge by involving local communities in monitoring and discussing the implications of indigenous knowledge and meteorological forecasts (Shaffer, 2014), and creating local forecasts by utilizing the two sources of knowledge (Mahoo et al., 2013). This has resulted in increased documentation of indigenous knowledge, understanding of relevant climate information amongst stakeholders, and adaptive capacity at the community level (Mahoo et al., 2013, 2015; Shaffer, 2014).

The Pacific Islands and small island developing states (SIDS) are vulnerable to the effects of climate change, but the cultural resilience of Pacific Island inhabitants is also recognized (Nunn et al., 2017). In Fiji and Vanuatu, strategies used to prepare for cyclones include building reserve emergency supplies and utilizing farming techniques to ensure adequate crop yield to combat potential losses from a cyclone or drought (McNamara and Prasad, 2014; Granderson, 2017; Pearce et al., 2017). Social cohesion and kinship are important in responding and preparing for climate-related hazards, including the role of resource sharing, communal labour, and remittances (McMillen et al., 2014; Gawith et al., 2016; Granderson, 2017). There is a concern that indigenous knowledge will weaken, a process driven by westernization and disruptions in established bioclimatic indicators and traditional planning calendars (Granderson, 2017). In some urban settlements, it has been noted that cultural practices (e.g., prioritizing the quantity of food over the quality of food) can lower food security through dispersing limited resources and by encouraging the consumption of cheap but nutrient-poor foods (Mccubbin et al., 2017) (See Cross-Chapter Box 6 on Food Security in Chapter 3). Indigenous practices also encounter limitations, particularly in relation to sea level rise (Nunn et al., 2017).

Box 4.4 | Manizales, Colombia: Supportive National Government and Localized Planning and Integration as an Enabling Condition for Managing Climate and Development Risks

Institutional reform in the city of Manizales, Colombia, helps identify three important features of an enabling environment: integrating climate change adaptation, mitigation and disaster risk management at the city-scale; the importance of decentralized planning and policy formulation within a supportive national policy environment; and the role of a multi-sectoral framework in mainstreaming climate action in development activities.

Manizales is exposed to risks caused by rapid development and expansion in a mountainous terrain exposed to seismic activity and periodic wet and dry spells. Local assessments expect climate change to amplify the risk of disasters (Carreño et al., 2017). The city is widely recognized for its longstanding urban environmental policy (Biomanizales) and local environmental action plan (Bioplan), and has been integrating environmental planning in its development agenda for nearly two decades (Velásquez Barrero, 1998; Hardoy and Velásquez Barrero, 2014). When the city's environmental agenda was updated in 2014 to reflect climate change risks, assessments were conducted in a participatory manner at the street and neighbourhood level (Hardoy and Velásquez Barrero, 2016).

The creation of a new Environmental Secretariat assisted in coordination and integration of environmental policies, disaster risk management, development and climate change (Leck and Roberts, 2015). Planning in Manizales remains mindful of steep gradients through its longstanding Slope Guardian programme that trains women and keeps records of vulnerable households. Planning also looks to include mitigation opportunities and enhance local capacity through participatory engagement (Hardoy and Velásquez Barrero, 2016).

Manizales' mayors were identified as important champions for much of these early integration and innovation efforts. Their role may have been enabled by Colombia's history of decentralized approaches to planning and policy formulation, including establishing environmental observatories (for continuous environmental assessment) and participatory tracking of environmental indicators. Multi-stakeholder involvement has both enabled and driven progress, and has enabled the integration of climate risks in development planning (Hardoy and Velásquez Barrero, 2016).

4.4.2.2 Monitoring, reporting, and review institutions

One of the novel features of the new climate governance architecture emerging from the 2015 Paris Agreement is the transparency framework in Article 13 committing countries, based on capacity, to provide regular progress reports on national pledges to address climate change (UNFCCC, 2016). Many countries will rely on public policies and existing national reporting channels to deliver on their NDCs under the Paris Agreement. Scaling up the mitigation and adaptation efforts in these countries to be consistent with 1.5°C would put significant pressure on the need to develop, enhance and streamline local, national and international climate change reporting and monitoring methodologies and institutional capacity in relation to mitigation, adaptation, finance, and GHG inventories (Ford et al., 2015b; Lesnikowski et al., 2015; Schoenefeld et al., 2016). Consistent with this direction, the provision of the information to the stocktake under Article 14 of the Paris Agreement would contribute to enhancing reporting and transparency (UNFCCC, 2016). Nonetheless, approaches, reporting procedures, reference points, and data sources to assess progress on implementation across and within nations are still largely underdeveloped (Ford et al., 2015b; Araos et al., 2016b; Magnan and Ribera, 2016; Lesnikowski et al., 2017). The availability of independent private and public reporting and statistical institutions are integral to oversight, effective monitoring, reporting and review. The creation and enhancement of these institutions would be an important contribution to an effective transition to a low-emission world.

4.4.2.3 Financial institutions

IPCC AR5 assessed that in order to enable a transition to a 2°C pathway, the volume of climate investments would need to be transformed along with changes in the pattern of general investment behaviour towards low emissions. The report argued that, compared to 2012, annually up to a trillion dollars in additional investment in low-emission energy and energy efficiency measures may be required until 2050 (Blanco et al., 2014; IEA, 2014a). Financing of 1.5°C would present an even greater challenge, addressing financing of both existing and new assets, which would require significant transitions to the type and structure of financial institutions as well as to the method of financing (Cochrani et al., 2014; Ma, 2014). Both public and private financial institutions would be needed to contribute to the large resource mobilization needed for 1.5°C, yet, in the ordinary course of business, these transitions may not be expected. On the one hand, private financial institutions could face scale-up risk, for example, the risks associated with commercialization and scaling up of renewable technologies to accelerate mitigation (Wilson, 2012; Hartley and Medlock, 2013) and/or price risk, such as carbon price volatility that carbon markets could face. In contrast, traditional public financial institutions are limited by both structure and instruments, while concessional financing would require taxpayer support for subsidization. Special efforts and innovative approaches would be needed to address these challenges, for example the creation of special institutions that underwrite the value of emission reductions using auctioned price floors (Bodnar et al., 2018) to deal with price volatility.

Financial institutions are equally important for adaptation. Linnerooth-Bayer and Hochrainer-Stigler (2015) discussed the benefits of financial instruments in adaptation, including the provision of post-disaster finances for recovery and pre-disaster security necessary for climate adaptation and poverty reduction. Pre-disaster financial instruments and options include insurance, such as index-based weather insurance schemes, catastrophe bonds, and laws to encourage insurance purchasing. The development and enhancement of microfinance institutions to ensure social resilience and smooth transitions in the adaptation to climate change impacts could be an important local institutional innovation (Hammill et al., 2008).

4.4.2.4 Co-operative institutions and social safety nets

Effective cooperative institutions and social safety nets may help address energy access and adaptation, as well as distributional impacts during the transition to 1.5°C-consistent pathways and enabling sustainable development. Not all countries have the institutional capabilities to design and manage these. Social capital for adaptation in the form of bonding, bridging, and linking social institutions has proved to be effective in dealing with climate crises at the local, regional and national levels (Aldrich et al., 2016).

The shift towards sustainable energy systems in transitioning economies could impact the livelihoods of large populations in traditional and legacy employment sectors. The transition of selected EU Member States to biofuels, for example, caused anxiety among farmers, who lacked confidence in the biofuel crop market. Enabling contracts between farmers and energy companies, involving local governments, helped create an atmosphere of confidence during the transition (McCormick and Kåberger, 2007).

How do broader socio-economic processes influence urban vulnerabilities and thereby underpin climate change adaptation? This is a systemic challenge originating from a lack of collective societal ownership of the responsibility for climate risk management. Explanations for this situation include competing time-horizons due to self-interest of stakeholders to a more 'rational' conception of risk assessment, measured across a risk-tolerance spectrum (Moffatt, 2014).

Self-governing and self-organ¬ised institutional settings, where equipment and resource systems are commonly owned and managed, can poten¬tially generate a much higher diversity of administration solutions, than other institutional arrangements, where energy technology and resource systems are either owned and administered individually in market settings or via a central authority (e.g., the state). They can also increase the adaptability of technological systems while reducing their burden on the environment (Labanca, 2017). Educational, learning and awareness-building institutions can help strengthen the societal response to climate change (Butler et al., 2016; Thi Hong Phuong et al., 2017).

4.4.3 Enabling Lifestyle and Behavioural Change

Humans are at the centre of global climate change: their actions cause anthropogenic climate change, and social change is key to effectively responding to climate change (Vlek and Steg, 2007; Dietz et al., 2013; ISSC and UNESCO, 2013; Hackmann et al., 2014). Chapter 2 shows that 1.5°C-consistent pathways assume substantial changes in behaviour. This section assesses the potential of behaviour change, as the integrated assessment models (IAMs) applied in Chapter 2 do not comprehensively asses this potential.

Table 4.8 shows examples of mitigation and adaption actions relevant for 1.5°C-consistent pathways. Reductions in population growth can reduce overall carbon demand and mitigate climate change (Bridgeman, 2017), particularly when population growth is accompanied by increases in affluence and carbon-intensive consumption (Rosa and Dietz, 2012; Clayton et al., 2017). Mitigation actions with a substantial carbon emission reduction potential (see Figure 4.3) that individuals may readily adopt would have the most climate impact (Dietz et al., 2009).

Various policy approaches and strategies can encourage and enable climate actions by individuals and organizations. Policy approaches would be more effective when they address key contextual and psycho-

Table 4.8 | Examples of mitigation and adaptation behaviours relevant for 1.5°C (Dietz et al., 2009; Jabeen, 2014; Taylor et al., 2014; Araos et al., 2016b; Steg, 2016; Stern et al., 2016b; Creutzig et al., 2018)

Climate action	Type of action	Examples
Mitigation	Implementing resource efficiency in buildings	Insulation Low-carbon building materials
	Adopting low-emission innovations	Electric vehicles Heat pumps, district heating and cooling
	Adopting energy efficient appliances	Energy-efficient heating or cooling Energy-efficient appliances
	Energy-saving behaviour	Walking or cycling rather than drive short distances Using mass transit rather than flying Lower temperature for space heating Line drying of laundry Reducing food waste
	Buying products and materials with low GHG emissions during production and transport	Reducing meat and dairy consumption Buying local, seasonal food Replacing aluminium products by low-GHG alternatives
	Organisational behaviour	Designing low-emission products and procedures Replacing business travel by videoconferencing

Table 4.8 (continued)

Climate action	Type of action	Examples
Adaptation	Growing different crops and raising different animal varieties	Using crops with higher tolerance for higher temperatures or CO_2 elevation
	Flood protective behaviour	Elevating barriers between rooms Building elevated storage spaces Building drainage channels outside the home
	Heat protective behaviour	Staying hydrated Moving to cooler places Installing green roofs
	Efficient water use during water shortage crisis	Rationing water Constructing wells or rainwater tanks
Mitigation & adaptation	Adoption of renewable energy sources	Solar PV Solar water heaters
	Citizenship behaviour	Engage through civic channels to encourage or support planning for low-carbon climate-resilient development

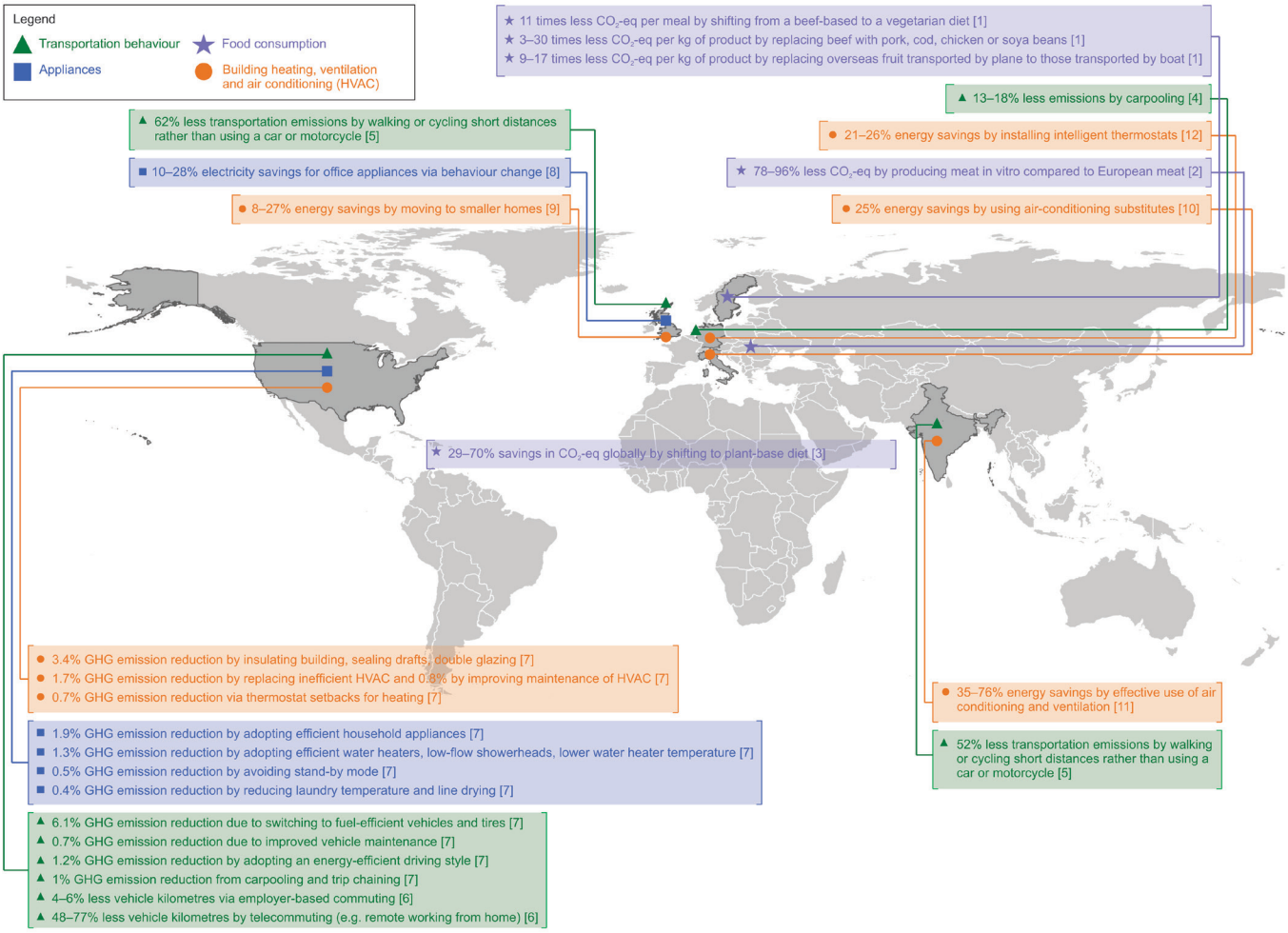


Figure 4.3 | Examples of mitigation behaviour and their GHG emission reduction potential. Mitigation potential assessments are printed in different units. Based on [1] Carlsson-Kanyama and González (2009); [2] Tuomisto and Teixeira de Mattos (2011); [3] Springmann et al. (2016); [4] Nijland and Meerkerk (2017); [5] Woodcock et al. (2009); [6] Salon et al. (2012); [7] Dietz et al. (2009); [8] Mulville et al. (2017); [9] Huebner and Shipworth (2017); [10] Jaboyedoff et al. (2004); [11] Pellegrino et al. (2016); [12] Nägele et al. (2017).

social factors influencing climate actions, which differ across contexts and individuals (Steg and Vlek, 2009; Stern, 2011). This suggests that diverse policy approaches would be needed in 1.5°C-consistent pathways in different contexts and regions. Combinations of policies that target multiple barriers and enabling factors simultaneously can be more effective (Nissinen et al., 2015).

In the United States and Europe, GHG emissions are lower when legislators have strong environmental records (Jensen and Spoon, 2011; Dietz et al., 2015). Political elites affect public concern about climate change: pro-climate action statements increased concern, while anti-climate action statements and anti-environment voting reduced public concern about climate change (Brulle et al., 2012). In the European

Union (EU), individuals worry more about climate change and engage more in climate actions in countries where political party elites are united rather than divided in their support for environmental issues (Sohlberg, 2017).

This section discusses how to enable and encourage behaviour and lifestyle changes that strengthen implementation of 1.5°C-consistent pathways by assessing psycho-social factors related to climate action, as well as the effects and acceptability of policy approaches targeting climate actions that are consistent with 1.5°C. Box 4.5 and Box 4.6 illustrate how these have worked in practice.

4.4.3.1 Factors related to climate actions

Mitigation and adaptation behaviour is affected by many factors that shape which options are feasible and considered by individuals. Besides contextual factors (see other sub-sections in Section 4.4), these include abilities and different types of motivation to engage in behaviour.

Ability to engage in climate action. Individuals more often engage in adaptation (Gebrehiwot and van der Veen, 2015; Koerth et al., 2017) and mitigation behaviour (Pisano and Lubell, 2017) when they are or feel more capable to do so. Hence, it is important to enhance ability to act on climate change, which depends on income and knowledge, among other things. A higher income is related to higher CO_2 emissions; higher income groups can afford more carbon-intensive lifestyles (Lamb et al., 2014; Dietz et al., 2015; Wang et al., 2015). Yet low-income groups may lack resources to invest in energy-efficient technology and refurbishments (Andrews-Speed and Ma, 2016) and adaptation options (Wamsler, 2007; Fleming et al., 2015b; Takahashi et al., 2016). Adaptive capacity further depends on gender roles (Jabeen, 2014; Bunce and Ford, 2015), technical capacities and knowledge (Feola et al., 2015; Eakin et al., 2016; Singh et al., 2016b).

Knowledge of the causes and consequences of climate change and of ways to reduce GHG emissions is not always accurate (Bord et al., 2000; Whitmarsh et al., 2011; Tobler et al., 2012), which can inhibit climate actions, even when people would be motivated to act. For example, people overestimate savings from low-energy activities, and underestimate savings from high-energy activities (Attari et al., 2010). They know little about 'embodied' energy (i.e., energy needed to produce products; Tobler et al., 2011), including meat (de Boer et al., 2016b). Some people mistake weather for climate (Reynolds et al., 2010), or conflate climate risks with other hazards, which can inhibit adequate adaptation (Taylor et al., 2014).

More knowledge on adaptation is related to higher engagement in adaptation actions in some circumstances (Bates et al., 2009; van Kasteren, 2014; Hagen et al., 2016). How adaptation is framed in the media can influence the types of options viewed as important in different contexts (Boykoff et al., 2013; Moser, 2014; Ford and King, 2015).

Knowledge is important, but is often not sufficient to motivate action (Trenberth et al., 2016). Climate change knowledge and perceptions are not strongly related to mitigation actions (Hornsey et al., 2016). Direct experience of events related to climate change influences climate concerns and actions (Blennow et al., 2012; Taylor et al., 2014), more so than second-hand information (Spence et al., 2011; Myers et al., 2012; Demski et al., 2017); high impact events with low frequency are remembered more than low impact regular events (Meze-Hausken, 2004; Singh et al., 2016b; Sullivan-Wiley and Short Gianotti, 2017). Personal experience with climate hazards strengthens motivation to protect oneself (Jabeen, 2014) and enhances adaptation actions (Bryan et al., 2009; Berrang-Ford et al., 2011; Demski et al., 2017), although this does not always translate into proactive adaptation (Taylor et al., 2014). Collectively constructed notions of risk and expectations of future climate variability shape risk perception and adaptation behaviour (Singh et al., 2016b). People with particular political views and those who emphasize individual autonomy may reject climate science knowledge and believe that there is widespread scientific disagreement about climate change (Kahan, 2010; O'Neill et al., 2013), inhibiting support for climate policy (Ding et al., 2011; McCright et al., 2013). This may explain why extreme weather experiences enhances preparedness to reduce energy use among left- but not right-leaning voters (Ogunbode et al., 2017).

Motivation to engage in climate action. Climate actions are more strongly related to motivational factors than to knowledge, reflecting individuals' reasons for actions, such as values, ideology and worldviews (Hornsey et al., 2016). People consider various types of costs and benefits of actions (Gölz and Hahnel, 2016) and focus on consequences that have implications for the values they find most important (Dietz et al., 2013; Hahnel et al., 2015; Steg, 2016). This implies that different individuals consider different consequences when making choices. People who strongly value protecting the environment and other people generally more strongly consider climate impacts and act more on climate change than those who strongly endorse hedonic and egoistic values (Taylor et al., 2014; Steg, 2016). People are more prone to adopt sustainable innovations when they are more open to new ideas (Jansson, 2011; Wolske et al., 2017). Further, a free-market ideology is associated with weaker climate change beliefs (McCright and Dunlap, 2011; Hornsey et al., 2016), and a capital-oriented culture tends to promote activity associated with GHG emissions (Kasser et al., 2007).

Some indigenous populations believe it is arrogant to predict the future, and some cultures have belief systems that interpret natural phenomena as sentient, where thoughts and words are believed to influence the future, with people reluctant to talk about negative future possibilities (Natcher et al., 2007; Flynn et al., 2018). Integrating these considerations into the design of adaptation and mitigation policy is important (Cochran et al., 2013; Chapin et al., 2016; Brugnach et al., 2017; Flynn et al., 2018).

People are more prone to act on climate change when individual benefits of actions exceed costs (Steg and Vlek, 2009; Kardooni et al., 2016; Wolske et al., 2017). For this reason, people generally prefer adoption of energy-efficient appliances above energy-consumption reductions; the latter is perceived as more costly (Poortinga et al., 2003; Steg et al., 2006), although transaction costs can inhibit the uptake of mitigation technology (Mundaca, 2007). Decentralized renewable energy systems are evaluated most favourably when they guarantee independence, autonomy, control and supply security (Ecker et al., 2017).

Besides, social costs and benefits affect climate action (Farrow et al., 2017). People engage more in climate actions when they think others expect them to do so and when others act as well (Nolan et al., 2008; Le Dang et al., 2014; Truelove et al., 2015; Rai et al., 2016), and when they experience social support (Singh et al., 2016a; Burnham and Ma, 2017; Wolske et al., 2017). Discussing effective actions with peers also encourages climate action (Esham and Garforth, 2013), particularly when individuals strongly identify with their peers (Biddau et al., 2012; Fielding and Hornsey, 2016). Further, individuals may engage in mitigation actions when they think doing so would enhance their reputation (Milinski et al., 2006; Noppers et al., 2014; Kastner and Stern, 2015). Such social costs and benefits can be addressed in climate policy (see Section 4.4.3.2).

Feelings affect climate action (Brosch et al., 2014). Negative feelings related to climate change can encourage adaptation action (Kerstholt et al., 2017; Zhang et al., 2017), while positive feelings associated with climate risks may inhibit protective behaviour (Lefevre et al., 2015). Individuals are more prone to engage in mitigation actions when they worry about climate change (Verplanken and Roy, 2013) and when they expect to derive positive feelings from such actions (Pelletier et al., 1998; Taufik et al., 2016).

Furthermore, collective consequences affect climate actions (Balcombe et al., 2013; Dóci and Vasileiadou, 2015; Kastner and Stern, 2015). People are motivated to see themselves as morally right, which encourages mitigation actions (Steg et al., 2015), particularly when long-term goals are salient (Zaval et al., 2015) and behavioural costs are not too high (Diekmann and Preisendörfer, 2003). Individuals are more prone to engage in climate actions when they believe climate change is occurring, when they are aware of threats caused by climate change and by their inaction, and when they think they can engage in actions that will reduce these threats (Esham and Garforth, 2013; Arunrat et al., 2017; Chatrchyan et al., 2017). The more individuals are concerned about climate change and aware of the negative climate impact of their behaviour, the more they feel responsible for their actions and think that their actions can help reduce such negative impacts, which can strengthen their moral norms to act accordingly (Steg and de Groot, 2010; Jakovcevic and Steg, 2013; Chen, 2015; Ray et al., 2017; Wolske et al., 2017; Woods et al., 2017). Individuals may engage in mitigation actions when they see themselves as supportive of the environment (i.e., strong environmental self-identity) (Fielding et al., 2008; van der Werff et al., 2013b; Kashima et al., 2014; Barbarossa et al., 2017); a strong environmental identity strengthens intrinsic motivation to engage in mitigation actions both at home (van der Werff et al., 2013a) and at work (Ruepert et al., 2016). Environmental self-identity is strengthened when people realize they have engaged in mitigation actions, which can in turn promote further mitigation actions (van der Werff et al., 2014b).

Individuals are less prone to engage in adaptation behaviour themselves when they rely on external measures such as government interventions (Grothmann and Reusswig, 2006; Wamsler and Brink, 2014a; Armah et al., 2015; Burnham and Ma, 2017) or perceive themselves as protected by god (Gandure et al., 2013; Dang et al., 2014; Cannon, 2015).

Habits, heuristics and biases. Decisions are often not based on weighing costs and benefits, but on habit or automaticity, both of individuals (Aarts and Dijksterhuis, 2000; Kloeckner et al., 2003) and within organizations (Dooley, 2017) and institutions (Munck et al., 2014). When habits are strong, individuals are less perceptive of information (Verplanken et al., 1997; Aarts et al., 1998) and may not consider alternatives as long as outcomes are good enough (Maréchal, 2010). Habits are mostly only reconsidered when the situation changed significantly (Fujii and Kitamura, 2003; Maréchal, 2010; Verplanken and Roy, 2016). Hence, strategies that create the opportunity for reflection and encourage active decisions can break habits (Steg et al., 2018).

Individuals can follow heuristics, or 'rules of thumb', in making inferences, which demand less cognitive resources, knowledge and time than thinking through all implications of actions (Preston et al., 2013; Frederiks et al., 2015; Gillingham and Palmer, 2017). For example, people tend to think that larger and more visible appliances use more energy, which is not always accurate (Cowen and Gatersleben, 2017). They underestimate energy used for water heating and overestimate energy used for lighting (Stern, 2014). When facing choice overload, people may choose the easiest or first available option, which can inhibit energy-saving behaviour (Stern and Gardner, 1981; Frederiks et al., 2015). As a result, individuals and firms often strive for satisficing ('good enough') outcomes with regard to energy decisions (Wilson and Dowlatabadi, 2007; Klotz, 2011), which can inhibit investments in energy efficiency (Decanio, 1993; Frederiks et al., 2015).

Biases also play a role. In Mozambique, farmers displayed omission biases (unwillingness to take adaptation actions with potentially negative consequences to avoid personal responsibility for losses), while policymakers displayed action biases (wanting to demonstrate positive action despite potential negative consequences; Patt and Schröter, 2008). People tend to place greater value on relative losses than gains (Kahneman, 2003). Perceived gains and losses depend on the reference point or status-quo (Kahneman, 2003). Loss aversion and the status-quo bias prevent consumers from switching electricity suppliers (Ek and Söderholm, 2008), to time-of-use electricity tariffs (Nicolson et al., 2017), and to accept new energy systems (Leijten et al., 2014).

Owned inefficient appliances and fossil fuel-based electricity can act as endowments, increasing their value compared to alternatives (Pichert and Katsikopoulos, 2008; Dinner et al., 2011). Uncertainty and loss aversion lead consumers to undervalue future energy savings (Greene, 2011) and savings from energy efficient technologies (Kolstad et al., 2014). Uncertainties about the performance of products and illiquidity of investments can drive consumers to postpone (profitable) energy-efficient investments (Sutherland, 1991; van Soest and Bulte, 2001). People with a higher tendency to delay decisions may engage less in energy saving actions (Lillemo, 2014). Training energy auditors in loss-aversion increased their clients' investments in energy efficiency improvements (Gonzales et al., 1988). Engagement in energy saving and renewable energy programmes can be enhanced if participation is set as a default option (Pichert and Katsikopoulos, 2008; Ölander and Thøgersen, 2014; Ebeling and Lotz, 2015).

4.4.3.2 Strategies and policies to promote actions on climate change

Policy can enable and strengthen motivation to act on climate change via top-down or bottom-up approaches, through informational campaigns, regulatory measures, financial (dis)incentives, and infrastructural and technological changes (Adger et al., 2003; Steg and Vlek, 2009; Henstra, 2016).

Adaptation efforts tend to focus on infrastructural and technological solutions (Ford and King, 2015) with lower emphasis on socio-cognitive and finance aspects of adaptation. For example, flooding policies in cities focus on infrastructure projects and regulation such as building codes, and hardly target individual or household behaviour (Araos et al., 2016b; Georgeson et al., 2016).

Current mitigation policies emphasize infrastructural and technology development, regulation, financial incentives and information provision (Mundaca and Markandya, 2016) that can create conditions enabling climate action, but target only some of the many factors influencing climate actions (see Section 4.4.5.1). They fall short of their true potential if their social and psychological implications are overlooked (Stern et al., 2016a). For example, promising energy-saving or low-carbon technology may not be adopted or not be used as intended (Pritoni et al., 2015) when people lack resources and trustworthy information (Stern, 2011; Balcombe et al., 2013).

Financial incentives or feedback on financial savings can encourage climate action (Santos, 2008; Bolderdijk et al., 2011; Maki et al., 2016) (see Box 4.5), but are not always effective (Delmas et al., 2013) and can be less effective than social rewards (Handgraaf et al., 2013) or emphasising benefits for people and the environment (Bolderdijk et al., 2013b; Asensio and Delmas, 2015; Schwartz et al., 2015). The latter can happen when financial incentives reduce a focus on environmental considerations and weaken intrinsic motivation to engage in climate action (Evans et al., 2012; Agrawal et al., 2015; Schwartz et al., 2015). In addition, pursuing small financial gains is perceived to be less worth the effort than pursuing equivalent CO_2 emission reductions (Bolderdijk et al., 2013b; Dogan et al., 2014). Also, people may not respond to financial incentives (e.g., to improve energy efficiency) because they do not trust the organization sponsoring incentive programmes (Mundaca, 2007) or when it takes too much effort to receive the incentive (Stern et al., 2016a).

Box 4.5 | How Pricing Policy has Reduced Car Use in Singapore, Stockholm and London

In Singapore, Stockholm and London, car ownership, car use, and GHG emissions have reduced because of pricing and regulatory policies and policies facilitating behaviour change. Notably, acceptability of these policies has increased as people experienced their positive effects.

Singapore implemented electronic road pricing in the central business district and at major expressways, a vehicle quota and registration fee system, and investments in mass transit. In the vehicle quota system introduced in 1990, registration of new vehicles is conditional upon a successful bid (via auctioning) (Chu, 2015), costing about 50,000 USD in 2014 (LTA, 2015). The registration tax incentivizes purchases of low-emission vehicles via a feebate system. As a result, per capita transport emissions (approximately 1.25 tCO_2yr^{-1}) and car ownership (107 vehicles per 1000 capita) (LTA, 2017) are substantially lower than in cities with comparable income levels. Modal share of public transport was 63% during peak hours in 2013 (LTA, 2013).

The Stockholm congestion charge implemented in 2007 (after a trial in 2006) reduced kilometres driven in the inner city by 16%, and outside the city by 5%; traffic volumes reduced by 20% and remained constant over time despite economic and population growth (Eliasson, 2014). CO_2 emissions from traffic reduced by 2–3% in Stockholm county. Vehicles entering or leaving the city centre were charged during weekdays (except for holidays). Charges were 1–2€ (maximum 6€ per day), being higher during peak hours; taxis, emergency vehicles and buses were exempted. Before introducing the charge, public transport and parking places near mass transit stations were extended. The aim and effects of the charge were extensively communicated to the public. Acceptability of the congestion charge was initially low, but the scheme gained support of about two-thirds of the population and all political parties after it was implemented (Eliasson, 2014), which may be related to the fact that the revenues were earmarked for constructing a motorway tunnel. After the trial, people believed that the charge had more positive effects on environmental, congestion and parking problems while costs increased less than they anticipated beforehand (Schuitema et al., 2010a). The initially hostile media eventually declared the scheme to be a success.

In 2003, a congestion charge was implemented in the Greater London area, with an enforcement and compliance scheme and an information campaign on the functioning of the scheme. Vehicles entering, leaving, driving or parking on a public road in the zone at weekdays at daytime pay a congestion charge of 8£ (until 2005, 5£), with some exemptions. Revenues were invested in London's bus network (80%), cycling facilities, and road safety measures (Leape, 2006). The number of cars entering the zone decreased by 18% in 2003 and 2004. In the charging zone, vehicle kilometres driven decreased by 15% in the first year and a further 6% a year later, while CO_2 emissions from road traffic reduced by 20% (Santos, 2008).

While providing information on the causes and consequences of climate change or on effective climate actions generally increases knowledge, it often does not encourage engagement in climate actions by individuals (Abrahamse et al., 2005; Ünal et al., 2017) or organizations (Anderson and Newell, 2004). Similarly, media coverage on the UN Climate Summit slightly increased knowledge about the conference but did not enhance motivation to engage personally in climate protection (Brüggemann et al., 2017). Fear-inducing representations of climate change may inhibit action when they make people feel helpless and overwhelmed (O'Neill and Nicholson-Cole, 2009). Energy-related recommendations and feedback (e.g., via performance contracts, energy audits, smart metering) are more effective for promoting energy conservation, load shifting in electricity use and sustainable travel choices when framed in terms of losses rather than gains (Gonzales et al., 1988; Wolak, 2011; Bradley et al., 2016; Bager and Mundaca, 2017).

Credible and targeted information at the point of decision can promote climate action (Stern et al., 2016a). For example, communicating the impacts of climate change is more effective when provided right before adaptation decisions are taken (e.g., before the agricultural season) and when bundled with information on potential actions to ameliorate impacts, rather than just providing information on climate projections with little meaning to end users (e.g., weather forecasts, seasonal forecasts, decadal climate trends) (Dorward et al., 2015; Singh et al., 2017). Similarly, heat action plans that provide early alerts and advisories combined with emergency public health measures can reduce heat-related morbidity and mortality (Benmarhnia et al., 2016).

Information provision is more effective when tailored to the personal situation of individuals, demonstrating clear impacts, and resonating with individuals' core values (Daamen et al., 2001; Abrahamse et al., 2007; Bolderdijk et al., 2013a; Dorward et al., 2015; Singh et al., 2017). Tailored information prevents information overload, and people are more motivated to consider and act upon information that aligns with their core values and beliefs (Campbell and Kay, 2014; Hornsey et al., 2016). Also, tailored information can remove barriers to receive and interpret information faced by vulnerable groups, such as the elderly during heatwaves (Vandentorren et al., 2006; Keim, 2008). Further, prompts can be effective when they serve as reminders to perform a planned action (Osbaldiston and Schott, 2012).

Feedback provision is generally effective in promoting mitigation behaviour within households (Abrahamse et al., 2005; Delmas et al., 2013; Karlin et al., 2015) and at work (Young et al., 2015), particularly when provided in real-time or immediately after the action (Abrahamse et al., 2005), which makes the implications of one's behaviour more salient (Tiefenbeck et al., 2016). Simple information is more effective than detailed and technical data (Wilson and Dowlatabadi, 2007; Ek and Söderholm, 2010; Frederiks et al., 2015). Energy labels (Banerjee and Solomon, 2003; Stadelmann, 2017), visualization techniques (Pahl et al., 2016), and ambient persuasive technology (Midden and Ham, 2012) can encourage mitigation actions by providing information and feedback in a format that immediately makes sense and hardly requires users' conscious attention.

Social influence approaches that emphasize what other people do or think can encourage climate action (Clayton et al., 2015), particularly when they involve face-to-face interaction (Abrahamse and Steg, 2013). For example, community approaches, where change is initiated from the bottom-up, can promote adaptation (see Box 4.6) and mitigation actions (Middlemiss, 2011; Seyfang and Haxeltine, 2012; Abrahamse and Steg, 2013), especially when community ties are strong (Weenig and Midden, 1991). Furthermore, providing social models of desired actions can encourage mitigation action (Osbaldiston and Schott, 2012; Abrahamse and Steg, 2013). Social influence approaches that do not involve social interaction, such as social norm, social comparison and group feedback, are less effective, but can be easily administered on a large scale at low costs (Allcott, 2011; Abrahamse and Steg, 2013).

Goal setting can promote mitigation action when goals are not set too low or too high (Loock et al., 2013). Commitment strategies where people make a pledge to engage in climate actions can encourage mitigation behaviour (Abrahamse and Steg, 2013; Lokhorst et al., 2013), particularly when individuals also indicate how and when they will perform the relevant action and anticipate how to cope with possible barriers (i.e., implementation intentions) (Bamberg, 2000, 2002). Such strategies take advantage of individuals' desire to be consistent (Steg, 2016). Similarly, hypocrisy-related strategies that make people aware of inconsistencies between their attitudes and behaviour can encourage mitigation actions (Osbaldiston and Schott, 2012).

Actions that reduce climate risks can be rewarded and facilitated, while actions that increase climate risks can be punished and inhibited, and behaviour change can be voluntary (e.g., information provision) or imposed (e.g., by law); voluntary changes that involve rewards are more acceptable than imposed changes that restrict choices (Eriksson et al., 2006, 2008; Steg et al., 2006; Dietz et al., 2007). Policies punishing maladaptive behaviour can increase vulnerability when they reinforce socio-economic inequalities that typically produce the maladaptive behaviour in the first place (Adger et al., 2003). Change can be initiated by governments at various levels, but also by individuals, communities, profit-making organizations, trade organizations, and other non-governmental actors (Lindenberg and Steg, 2013; Robertson and Barling, 2015; Stern et al., 2016b).

Strategies can target intrinsic versus extrinsic motivation. It may be particularly important to enhance intrinsic motivation so that people voluntarily engage in climate action over and again (Steg, 2016). Endorsement of mitigation and adaptation actions are positively related (Brügger et al., 2015; Carrico et al., 2015); both are positively related to concern about climate change (Brügger et al., 2015). Strategies that target general antecedents that affect a wide range of actions, such as values, identities, worldviews, climate change beliefs, awareness of the climate impacts of one's actions, and feelings of responsibility to act on climate change, can encourage consistent actions on climate change (van Der Werff and Steg, 2015; Hornsey et al., 2016; Steg, 2016). Initial climate actions can lead to further commitment to climate action (Juhl et al., 2017), when people learn that such actions are easy and effective (Lauren et al., 2016), when they engaged in the initial behaviour for environmental reasons (Peters et al., 2018), hold strong pro-environmental values and norms (Thøgersen and Ölander, 2003), and when initial actions make them realise they are an environmentally sensitive person, motivating them to act on climate change in subsequent situations so as to be consistent (van der

Box 4.6 | Bottom-up Initiatives: Adaptation Responses Initiated by Individuals and Communities

To effectively adapt to climate change, bottom-up initiatives by individuals and communities are essential, in addition to efforts of governments, organizations, and institutions (Wamsler and Brink, 2014a). This box presents examples of bottom-up adaptation responses and behavioural change.

Fiji increasingly faces a lack of freshwater due to decreasing rainfall and rising temperatures (Deo, 2011; IPCC, 2014a). While some villages have access to boreholes, these are not sufficient to supply the population with freshwater. Villagers are adapting by rationing water, changing diets, and setting up inter-village sharing networks (Pearce et al., 2017). Some villagers take up wage employment to buy food instead of growing it themselves (Pearce et al., 2017). In Kiribati, residents adapt to drought by purchasing rainwater tanks and constructing additional wells (Kuruppu and Liverman, 2011). An important factor that motivated residents of Kiribati to adapt to drought was the perception that they could effectively adapt to the negative consequences of climate change (Kuruppu and Liverman, 2011).

In the Philippines, seismic activity has caused some islands to flood during high tide. While the municipal government offered affected island communities the possibility to relocate to the mainland, residents preferred to stay and implement measures themselves in their local community to reduce flood damage (Laurice Jamero et al., 2017). Migration is perceived as undesirable because island communities have strong place-based identities (Mortreux and Barnett, 2009). Instead, these island communities have adapted to flooding by constructing stilted houses and raising floors, furniture, and roads to prevent water damage (Laurice Jamero et al., 2017). While inundation was in this case caused by seismic activity, this example indicates how island-based communities may respond to rising sea levels caused by climate change.

Adaptation initiatives by individuals may temporarily reduce the impacts of climate change and enable residents to cope with changing environmental circumstances. However, they may not be sufficient to sustain communities' way of life in the long term. For instance, in Fiji and Kiribati, freshwater and food are projected to become even scarcer in the future, rendering individual adaptations ineffective. Moreover, individuals can sometimes engage in behaviour that may be maladaptive over larger spatio-temporal scales. For example, in the Philippines, many islanders adapt to flooding by elevating their floors using coral stone (Laurice Jamero et al., 2017). Over time, this can harm the survivability of their community, as coral reefs are critical for reducing flood vulnerability (Ferrario et al., 2014). In Maharashtra, India, on-farm ponds are promoted as rainwater harvesting structures to adapt to dry spells during the monsoon season. However, some individuals fill these ponds with groundwater, leading to depletion of water tables and potentially maladaptive outcomes in the long run (Kale, 2015).

Integration of individuals' adaptation initiatives with top-down adaptation policy is critical (Butler et al., 2015), as failing to do so may lead individual actors to mistrust authority and can discourage them from undertaking adequate adaptive actions (Wamsler and Brink, 2014a).

Werff et al., 2014a; Lacasse, 2015, 2016). Yet some studies suggest that people may feel licensed not to engage in further mitigation actions when they believe they have already done their part (Truelove et al., 2014).

4.4.3.3 Acceptability of policy and system changes

Public acceptability can shape, enable or prevent policy and system changes. Acceptability reflects the extent to which policy or system changes are evaluated (un)favourably. Acceptability is higher when people expect more positive and less negative effects of policy and system changes (Perlaviciute and Steg, 2014; Demski et al., 2015; Drews and Van den Bergh, 2016), including climate impacts (Schuitema et al., 2010b). Because of this, policy 'rewarding' climate actions is more acceptable than policy 'punishing' actions that increase climate risks (Steg et al., 2006; Eriksson et al., 2008). Pricing policy is more acceptable when revenues are earmarked for environmental purposes (Steg et al., 2006; Sælen and Kallbekken, 2011) or redistributed towards those affected (Schuitema and Steg, 2008). Acceptability can increase when people experience positive effects after a policy has been implemented (Schuitema et al., 2010a; Eliasson, 2014; Weber, 2015); effective policy trials can thus build public support for climate policy (see Box 4.8).

Climate policy and renewable energy systems are more acceptable when people strongly value other people and the environment, or support egalitarian worldviews, left-wing or green political ideologies (Drews and Van den Bergh, 2016), and less acceptable when people strongly endorse self-enhancement values, or support individualistic and hierarchical worldviews (Dietz et al., 2007; Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Solar radiation modification is more acceptable when people strongly endorse self-enhancement values, and less acceptable when they strongly value other people and the environment (Visschers et al., 2017). Climate policy is more acceptable when people believe climate change is real, when they are concerned about climate change (Hornsey et al., 2016), when

they think their actions may reduce climate risks, and when they feel responsible to act on climate change (Steg et al., 2005; Eriksson et al., 2006; Jakovcevic and Steg, 2013; Drews and Van den Bergh, 2016; Kim and Shin, 2017). Stronger environmental awareness is associated with a preference for governmental regulation and behaviour change rather than free-market and technological solutions (Poortinga et al., 2002).

Climate policy is more acceptable when costs and benefits are distributed equally, when nature and future generations are protected (Sjöberg and Drottz-Sjöberg, 2001; Schuitema et al., 2011; Drews and Van den Bergh, 2016), and when fair procedures have been followed, including participation by the public (Dietz, 2013; Bernauer et al., 2016a; Bidwell, 2016) or public society organizations (Bernauer and Gampfer, 2013). Providing benefits to compensate affected communities for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg, 2014), although people may disagree on what would be a worthwhile compensation (Aitken, 2010; Cass et al., 2010), or feel they are being bribed (Cass et al., 2010; Perlaviciute and Steg, 2014).

Public support is higher when individuals trust responsible parties (Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Yet, public support for multilateral climate policy is not higher than for unilateral policy (Bernauer and Gampfer, 2015); public support for unilateral, non-reciprocal climate policy is rather strong and robust (Bernauer et al., 2016b). Public opposition may result from a culturally valued landscape being affected by adaptation or mitigation options, such as renewable energy development (Warren et al., 2005; Devine-wright and Howes, 2010) or coastal protection measures (Kimura, 2016), particularly when people have formed strong emotional bonds with the place (Devine-Wright, 2009, 2013).

Climate actions may reduce human well-being when such actions involve more costs, effort or discomfort. Yet some climate actions enhance well-being, such as technology that improves daily comfort and nature-based solutions for climate adaptation (Wamsler and Brink, 2014b). Further, climate action may enhance well-being (Kasser and Sheldon, 2002; Xiao et al., 2011; Schmitt et al., 2018) because pursuing meaning by acting on climate change can make people feel good (Venhoeven et al., 2013, 2016; Taufik et al., 2015), more so than merely pursuing pleasure.

4.4.4 Enabling Technological Innovation

This section focuses on the role of technological innovation in limiting warming to 1.5°C, and how innovation can contribute to strengthening implementation to move towards or to adapt to 1.5°C worlds. This assessment builds on information of technological innovation and related policy debates in and after AR5 (Somanathan et al., 2014).

4.4.4.1 The nature of technological innovations

Technological systems have their own dynamics. New technologies have been described as emerging as part of a 'socio-technical system' that is integrated with social structures and that itself evolves over time (Geels and Schot, 2007). This progress is cumulative and accelerating (Kauffman, 2002; Arthur, 2009). To illustrate such a process of co-evolution: the progress of computer simulation enables us to better understand climate, agriculture, and material sciences, contributing to upgrading food production and quality, microscale manufacturing techniques, and leading to much faster computing technologies, resulting, for instance, in better performing photovoltaic (PV) cells.

A variety of technological developments have and will contribute to 1.5°C-consistent climate action or the lack of it. They can do this, for example, in the form of applications such as smart lighting systems, more efficient drilling techniques that make fossil fuels cheaper, or precision agriculture. As discussed in Section 4.3.1, costs of PV (IEA, 2017f) and batteries (Nykvist and Nilsson, 2015) have sharply dropped. In addition, costs of fuel cells (Iguma and Kidoshi, 2015; Wei et al., 2017) and shale gas and oil (Wang et al., 2014; Mills, 2015) have come down as a consequence of innovation.

4.4.4.2 Technologies as enablers of climate action

Since AR5, literature has emerged as to how much future GHG emission reductions can be enabled by the rapid progress of general purpose technologies (GPTs), consisting of information and communication technologies (ICT), including artificial intelligence (AI) and the internet of things (IoT), nanotechnologies, biotechnologies, robotics, and so forth (WEF, 2015; OECD, 2017c). Although these may contribute to limiting warming to 1.5°C, the potential environmental, social and economic impacts of new technologies are uncertain.

Rapid improvement of performance and cost reduction is observed for many GPTs. They include AI, sensors, internet, memory storage and microelectromechanical systems. The latter GPTs are not usually categorized as climate technologies, but they can impact GHG emissions.

Progress of GPT could help reduce GHG emissions more cost-effectively. Examples are shown in Table 4.9. It may however, result in more emissions by increasing the volume of economic activities, with unintended negative consequence on sustainable development. While ICT increases electricity consumption (Aebischer and Hilty, 2015), the energy consumption of ICT is usually dwarfed by the energy saving by ICT (Koomey et al., 2013; Malmodin et al., 2014), but rebound effects and other sustainable development impacts may be significant. An appropriate policy framework that accommodates such impacts and their uncertainties could address the potential negative impacts by GPT (Jasanoff, 2007).

GHG emission reduction potentials in relation to GPTs were estimated for passenger cars using a combination of three emerging technologies: electric vehicles, car sharing, and self-driving. GHG emission reduction potential is reported, assuming generation of electricity with low GHG emissions (Greenblatt and Saxena, 2015; ITF, 2015; Viegas et al., 2016; Fulton et al., 2017). It is also possible that GHG emissions increase due to an incentive to car use. Appropriate policies such as urban planning and efficiency regulations could contain such rebound effects (Wadud et al., 2016).

Estimating emission reductions by GPT is difficult due to substantial uncertainties, including projections of future technological performance,

Table 4.9 | Examples of technological innovations relevant to 1.5°C enabled by general purpose technologies (GPT). Note: lists of enabling GPT or adaptation/mitigation options are not exhaustive, and the GPTs by themselves do not reduce emissions or increase climate change resilience.

Sector	Examples of Mitigation/Adaptation Technological Innovation	Enabling GPT
Buildings	Energy and CO_2 efficiency of logistics, warehouse and shops (GeSI, 2015; IEA, 2017a)	IoT, AI
	Smart lighting and air conditioning (IEA, 2016b, 2017a)	IoT, AI
Industry	Energy efficiency improvement by industrial process optimization (IEA, 2017a)	Robots, IoT
	Bio-based plastic production by biorefinery (OECD, 2017c)	Biotechnology
	New materials from biorefineries (Fornell et al., 2013; McKay et al., 2016)	ICT, biotechnology
Transport	Electric vehicles, car sharing, automation (Greenblatt and Saxena, 2015; Fulton et al., 2017)	Biotechnology
	Bio-based diesel fuel by biorefinery (OECD, 2017c)	ICT, biotechnology
	Second generation bioethanol potentially coupled to carbon capture systems (De Souza et al., 2014; Rochedo et al., 2016)	Biotechnology
	Logistical optimization, and electrification of trucks by overhead line (IEA, 2017e)	ICT, biotechnology
	Reduction of transport needs by remote education, health and other services (GeSI, 2015; IEA, 2017a)	Biotechnology
	Energy saving by lightweight aircraft components (Beyer, 2014; Faludi et al., 2015; Verhoef et al., 2018)	Additive manufacturing (3D printing)
Electricity	Solar PV manufacturing (Nemet, 2014)	Nanotechnology
	Smart grids and grid flexibility to accommodate intermittent renewables (Heard et al., 2017)	IoT, AI
	Plasma confinement for nuclear fusion (Baltz et al., 2017)	AI
Agriculture	Precision agriculture (improvement of energy and resource efficiency including reduction of fertilizer use and N_2O emissions) (Pierpaoli et al., 2013; Brown et al., 2016; Schimmelpfennig and Ebel, 2016)	Biotechnology ICT, AI
	Methane inhibitors (and methane-suppressing vaccines) that reduce livestock emissions from enteric fermentation (Wedlock et al. 2013; Hristov et al. 2015; Wollenberg et al. 2016)	Biotechnology
	Engineering C3 into C4 photosynthesis to improve agricultural production and productivity (Schuler et al., 2016)	Biotechnology
	Genome editing using CRISPR to improve/adapt crops to a changing climate (Gao, 2018)	Biotechnology
Disaster Reduction and Adaptation	Weather forecasting and early warning systems, in combination with user knowledge (Hewitt et al., 2012; Lourenço et al., 2016)	ICT
	Climate risk reduction (Upadhyay and Bijalwan, 2015)	ICT
	Rapid assessment of disaster damage (Kryvasheyeu et al., 2016)	ICT

costs, penetration rates, and induced human activity. Even if a technology is available, the establishment of business models might not be feasible (Linder and Williander, 2017). Indeed, studies show a wide range of estimates, ranging from deep emission reductions to possible increases in emissions due to the rebound effect (Larson and Zhao, 2017).

GPT could also enable climate adaptation, in particular through more effective climate disaster risk management and improved weather forecasting.

Government policy usually plays a role in promoting or limiting GPTs, or science and technology in general. It has impacts on climate action, because the performance of further climate technologies will partly depend on the progress of GPTs. Governments have established institutions for achieving many social, and sometimes conflicting goals, including economic growth and addressing climate change (OECD, 2017c), which include investment in basic research and development (R&D) that can help develop game-changing technologies (Shayegh et al., 2017). Governments are also needed to create an enabling environment for the growth of scientific and technological ecosystems necessary for GPT development (Tassey, 2014).

4.4.4.3 The role of government in 1.5°C-consistent climate technology policy

While literature on 1.5°C-specific innovation policy is absent, a growing body of literature indicates that governments aim to achieve social, economic and environmental goals by promoting science and a broad range of technologies through 'mission-driven' innovation policies, based on differentiated national priorities (Edler and Fagerberg, 2017). Governments can play a role in advancing climate technology via a 'technology push' policy on the technology supply side (e.g., R&D subsidies), and by 'demand pull' policy on the demand side (e.g., energy-efficiency regulation), and these policies can be complemented by enabling environments (Somanathan et al., 2014). Governments may also play a role in removing existent support for incumbents (Kivimaa and Kern, 2016). A growing literature indicates that policy mixes, rather than single policy instruments, are more effective in addressing climate innovation challenges ranging from technologies in the R&D phase to those ready for diffusion (Veugelers, 2012; Quitzow, 2015; Rogge et al., 2017; Rosenow et al., 2017). Such innovation policies can help address two kinds of externalities: environmental externalities and proprietary problems (GEA, 2012; IPCC, 2014b; Mazzucato and Semieniuk, 2017). To avoid 'picking winners', governments often maintain a broad portfolio of technological options (Kverndokk and Rosendahl, 2007) and work in

close collaboration with the industrial sector and society in general. Some governments have achieved relative success in supporting innovation policies (Grubler et al., 2012; Mazzucato, 2013) that addressed climate-related R&D (see Box 4.7 on bioethanol in Brazil).

Funding for R&D could come from various sources, including the general budget, energy or resource taxation, or emission trading schemes (see Section 4.4.5). Investing in climate-related R&D has as an additional benefit of building capabilities to implement climate mitigation and adaptation technologies (Ockwell et al., 2015). Countries regard innovation in general and climate technology specifically as a national interests issue and addressing climate change primarily as being in the global interest. Reframing part of climate policy as technology or industrial policy might therefore contribute to resolving the difficulties that continue to plague emission target negotiations (Faehn and Isaksen, 2016; Fischer et al., 2017; Lachapelle et al., 2017).

Climate technology transfer to emerging economies has happened regardless of international treaties, as these countries have been keen to acquire them, and companies have an incentive to access emerging markets to remain competitive (Glachant and Dechezleprêtre, 2016). However, the complexity of these transfer processes is high, and they have to be conducted carefully by governments and institutions (Favretto et al., 2017). It is noticeable that the impact of the EU emission trading scheme (EU ETS) on innovation is contested; recent work (based on lower carbon prices than anticipated for 1.5°C-consistent pathways) indicates that it is limited (Calel and Dechezleprêtre, 2016), but earlier assessments (Blanco et al., 2014) indicate otherwise.

4.4.4.4 Technology transfer in the Paris Agreement

Technology development and transfer is recognized as an enabler of both mitigation and adaptation in Article 10 in the Paris Agreement (UNFCCC, 2016) as well as in Article 4.5 of the original text of the UNFCCC (UNFCCC, 1992). As previous sections have focused on technology development and diffusion, this section focuses on technology transfer. Technology transfer can adapt technologies to local circumstances, reduce financing costs, develop indigenous technology, and build capabilities to operate, maintain, adapt and innovate on technology globally (Ockwell et al., 2015; de Coninck and Sagar, 2017). Technology cooperation could decrease global mitigation cost, and enhance developing countries' mitigation contributions (Huang et al., 2017a).

Box 4.7 | Bioethanol in Brazil: Innovation and Lessons for Technology Transfer

The use of sugarcane as a bioenergy source started in Brazil in the 1970s. Government and multinational car factories modified car engines nationwide so that vehicles running only on ethanol could be produced. As demand grew, production and distribution systems matured and costs came down (Soccol et al., 2010). After a transition period in which both ethanol-only and gasoline-only cars were used, the flex-fuel era started in 2003, when all gasoline was blended with 25% ethanol (de Freitas and Kaneko, 2011). By 2010, around 80% of the car fleet in Brazil had been converted to use flex-fuel (Goldemberg, 2011; Su et al., 2015).

More than forty years of combining technology push and market pull measures led to the deployment of ethanol production, transportation and distribution systems across Brazil, leading to a significant decrease in CO_2 emissions (Macedo et al., 2008). Examples of innovations include: (i) the development of environmentally well-adapted varieties of sugarcane; (ii) the development and scaling up of sugar fermentation in a non-sterile environment, and (iii) the development of adaptations of car engines to use ethanol as a fuel in isolation or in combination with gasoline (Amorim et al., 2011; de Freitas and Kaneko, 2011; De Souza et al., 2014). Public procurement, public investment in R&D and mandated fuel blends accompanying these innovations were also crucial (Hogarth, 2017). In the future, innovation could lead to viable partial CO_2 removal through deployment of BECCS associated with the bioethanol refineries (Fuss et al., 2014; Rochedo et al., 2016) (see Section 4.3.7).

Ethanol appears to reduce urban car emission of health-affecting ultrafine particles by 30% compared to gasoline-based cars, but increases ozone (Salvo et al., 2017). During the 1990s, when sugarcane burning was still prevalent, particulate pollution had negative consequences for human health and the environment (Ribeiro, 2008; Paraiso and Gouveia, 2015). While Jaiswal et al. (2017) report bioethanol's limited impact on food production and forests in Brazil, despite the large scale, and attribute this to specific agro-ecological zoning legislation, various studies report adverse effects of bioenergy production through forest substitution by croplands (Searchinger et al., 2008), as well as impacts on biodiversity, water resources and food security (Rathore et al., 2016). For new generation biofuels, feasibility and life cycle assessment studies can provide information on their impacts on environmental, economic and social factors (Rathore et al., 2016).

Brazil and the European Union have tried to replicate Brazil's bioethanol experience in climatically suitable African countries. Although such technology transfer achieved relative success in Angola and Sudan, the attempts to set up bioethanol value chains did not pass the phase of political deliberations and feasibility studies elsewhere in Africa. Lessons learned include the need for political and economic stability of the donor country (Brazil) and the necessity for market creation to attract investments in first-generation biofuels alongside a safe legal and policy environment for improved technologies (Afionis et al., 2014; Favretto et al., 2017).

The international institutional landscape around technology development and transfer includes the UNFCCC (via its technology framework and Technology Mechanism including the Climate Technology Centre and Network (CTCN)), the United Nations (a technology facilitation mechanism for the SDGs) and a variety of non-UN multilateral and bilateral cooperation initiatives such as the Consultative Group on International Agricultural Research (CGIAR, founded in the 1970s), and numerous initiatives of companies, foundations, governments and non-governmental and academic organizations. Moreover, in 2015, twenty countries launched an initiative called 'Mission Innovation', seeking to double their energy R&D funding. At this point it is difficult to evaluate whether Mission Innovation achieved its objective (Sanchez and Sivaram, 2017). At the same time, the private sector started an innovation initiative called the 'Breakthrough Energy Coalition'.

Most technology transfer is driven by through markets by the interests of technology seekers and technology holders, particularly in regions with well-developed institutional and technological capabilities such as developed and emerging nations (Glachant and Dechezleprêtre, 2016). However, the current international technology transfer landscape has gaps, in particular in reaching out to least-developed countries, where institutional and technology capabilities are limited (de Coninck and Puig, 2015; Ockwell and Byrne, 2016). On the one hand, literature suggests that the management or even monitoring of all these UN, bilateral, private and public initiatives may fail to lead to better results. On the other hand, it is probably more cost-effective to adopt a strategy of 'letting a thousand flowers bloom', by challenging and enticing researchers in the public and the private sector to direct innovation towards low-emission and adaptation options (Haselip et al., 2015). This can be done at the same time as mission-oriented research is adopted in parallel by the scientific community (Mazzucato, 2018).

At COP 21, the UNFCCC requested the Subsidiary Body for Scientific and Technological Advice (SBSTA) to initiate the elaboration of the technology framework established under the Paris Agreement (UNFCCC, 2016). Among other things, the technology framework would 'provide overarching guidance for the work of the Technology Mechanism in promoting and facilitating enhanced action on technology development and transfer in order to support the implementation of this Agreement' (this Agreement being the Paris Agreement). An enhanced guidance issued by the Technology Executive Committee (TEC) for preparing a technology action plan (TAP) supports the new technology framework as well as the Parties' long-term vision on technology development and transfer, reflected in the Paris Agreement (TEC, 2016).

4.4.5 Strengthening Policy Instruments and Enabling Climate Finance

Triggering rapid and far-reaching change in technical choices and institutional arrangements, consumption and lifestyles, infrastructure, land use, and spatial patterns implies the ability to scale up policy signals to enable the decoupling of GHGs emission, and economic growth and development (Section 4.2.2.3). Such a scale-up would also imply that potential short-term negative responses by populations and interest groups, which could block these changes from the outset, would need to be prevented or overcome. This section describes the size and nature of investment needs and the financial challenge over the coming two decades in the context of 1.5°C warmer worlds, assesses the potential and constraints of three categories of policy instruments that respond to the challenge, and explains the conditions for using them synergistically. The policy and finance instruments discussed in this section relate to Section 4.4.1 (on governance) and other Sections in 4.4.

4.4.5.1 The core challenge: cost-efficiency, coordination of expectations and distributive effects

Box 4.8 shows that the average estimate by seven models of annual investment needs in the energy system is around 2.38 trillion USD2010 (1.38 to 3.25) between 2016 and 2035. This represents between 2.53% (1.6–4%) of the world GDP in market exchange rates (MER) and 1.7% of the world GDP in purchasing power parity (PPP). OECD investment assessments for a 2°C-consistent transition suggest that including investments in transportation and in other infrastructure would increase the investment needs by a factor of three. Other studies not included in Box 4.8, in particular by the World Economic Forum (WEF, 2013) and the Global Commission on the Economy and Climate (GCEC, 2014) confirm these orders of magnitude of investment.

The average increase of investment in the energy sector resulting from Box 4.8 represents a mean value of 1.5% of the total world investment compared with the baselines scenario in MER and a little over 1% in PPP. Including infrastructure investments would raise this to 2.5% and 1.7% respectively.[9]

These incremental investments could be funded through a drain on consumption (Bowen et al., 2017), which would necessitate between 0.68% and 0.45% lower global consumption than in the baseline. But, consumption at a constant savings/consumption ratio can alternatively be funded by shifting savings towards productive adaptation and mitigation investments, instead of real-estate sector and liquid financial products. This response depends upon whether it is possible to close the global investment funding gap for infrastructure that potentially inhibits growth, through structural changes in the global economy. In this case, investing more in infrastructure would not be an incremental cost in terms of development and welfare (IMF, 2014; Gurara et al., 2017)

[9] A calculation in MER tends indeed to underestimate the world GDP and its growth by giving a lower weight to fast-growing developing countries, whereas a calculation in PPP tends to overestimate it. The difference between the value of two currencies in PPP and MER should vanish as the gap of the income levels of the two concerned countries decreases. Accounting for this trend in modelling is challenging.

Box 4.8 | Investment Needs and the Financial Challenge of Limiting Warming to 1.5°C

Peer-reviewed literature that estimates the investment needs over the next two decades to scale up the response to limit warming to 1.5°C is very limited (see Section 4.6). This box attempts to bring together available estimates of the order of magnitude of these investments, after consultation with the makers of those estimates, to provide the context for global and national financial mobilization policy and related institutional arrangements.

Table 1 in this box presents mean annual investments up to 2035, based on three studies (after clarifying their scope and harmonizing their metrics): an ensemble of four integrated assessment models (here denoted IAM, see Chapter 2), an Organization for Economic Co-operation and Development (OECD) scenario for a 2°C limit (OECD, 2017a) and scenarios from the International Energy Agency (IEA, 2016c). All three sources provide estimates for the energy sector for various mitigation scenarios. They give a mean value of 2.38 trillion USD of yearly investments in the energy sector over the period, with minimum and maximum values of 1.38 and 3.25 respectively. We also report the OECD estimate for 2°C because it also covers transportation and other infrastructure (water, sanitation, and telecommunication), which are essential to deliver the Sustainable Development Goals (SDGs), including SDG 7 on clean energy access, and enhance the adaptive capacity to climate change.

Box 4.8, Table 1 | Estimated annualized world mitigation investment needed to limit global warming to 2°C or 1.5°C (2015–2035 in trillions of USD at market exchange rates) from different sources. The top four lines indicate the results of Integrated Assessment Models (IAMs) as reported in Chapter 2 for their Baseline, Nationally Determined Contributions (NDC), 2°C- and 1.5°C-consistent pathways. These numbers only cover the energy sector and the second row includes energy efficiency in all sectors. The final two rows indicate the mitigation investment needs for the energy, transport and other infrastructure according to the Organization for Economic Co-operation and Development (OECD) for a Baseline pathway and a 2°C-consistent pathway. Sources: IEA, 2016c; OECD, 2017a.

	Energy Investments	Of which Demand Side	Transport	Other Infra-structures	Total	Ratio to MER GDP
IAM Baseline (mean)	1.96	0.24			1.96	1.8%
IAM NDC (mean)	2.04	0.28			2.04	1.9%
IAM 2°C (mean)	2.19	0.38			2.19	2.1%
IAM 1.5°C (mean)	2.32	0.45			2.32	2.2%
IEA NDC	2.40	0.72			2.40	2.3%
IEA 1.5°C	2.76	1.13			2.76	2.7%
Mean IAM-IEA, 1.5°C	**2.38**	**0.54**			**2.38**	**2.53%**
Min IAM-IEA, 1.5°C	1.38	0.38			1.38	1.6%
Max IAM-IEA, 1.5°C	3.25	1.13			3.25	4.0%
OECD Baseline					5.74	5.4%
OECD 2°C	2.13	0.40	2.73	1.52	6.38	6.0%

The mean incremental share of annual energy investments to stay well below 2°C is 0.36% (between 0.2–1%) of global GDP between 2016 and 2035. Since total world investment (also called gross fixed capital formation (GFCF)) is about 24% of global GDP, the estimated incremental energy investments between a baseline and a 1.5°C transition would be approximately 1.5% (between 0.8–4.2%) of projected total world investments. As the higher ends of these ranges reflect pessimistic assumptions in 1.5°C-consistent pathways on technological change, the implementation of policies to accelerate technical change (see the remainder of Section 4.4.5) could lower the probability of higher incremental investment.

If we assume the amounts of investments given by the OECD for transportation and other infrastructure for warming of 2°C to be a lower limit for an 1.5°C pathway, then total incremental investments for all sectors for a 1.5°C-consistent pathway would be estimated at 2.4% of total world investments. This total incremental investment reaches 2.53% if the investments in transportation are scaled up proportionally with the investments in the energy sector and if all other investments are kept constant. Comparing this 2.4% or 2.53% number for all sectors to the 1.5% number for energy only (see previous paragraph) suggests that the investments in sectors other than energy contribute significantly to incremental world investments, even though a comprehensive study or estimate of these investments for a 1.5°C limit is not available.

The issue, from a macroeconomic perspective, is whether these investments would be funded by higher savings at the costs of lower consumption. This would mean a 0.5% reduction in consumption for the energy sector for 1.5°C. Note that for a 2°C scenario, this

Box 4.8 (continued)

reduction would be 0.8% if we account for the investment needs of all infrastructure sectors. Assuming conversely a constant savings ratio, this would necessitate reallocating existing capital flows towards infrastructure. In addition to these incremental investments, the amount of redirected investments is relevant from a financial perspective. In the reported IAM energy sector scenarios, about three times the incremental investments is redirected. There is no such assessment for the other sectors. The OECD report suggests that these ratios might be higher.

These orders of magnitude of investment can be compared to the available statistics of the global stock of 386 trillion USD of financial capital, which consists of 100 trillion USD in bonds (SIFMA, 2017), around 60 trillion USD in equity (World Bank, 2018b), and 226 trillion USD of loans managed by the banking system (IIF, 2017; World Bank, 2018a). The long-term rate of return (interest plus increase of shareholder value) is about 3% on bonds, 5% on bank lending and 7% on equity, leading to a weighted mean return on capital of 3.4% in real terms (5.4% in nominal terms). Using 3.4% as a lower bound and 5% as a higher bound (following Piketty, 2014) and taking a conservative assumption that global financial capital grows at the same rate as global GDP, the estimated yearly financial capital revenues would be between 16.8 and 25.4 trillion USD.

Assuming that a quarter of these investments comes from public funds (as estimated by the World Bank; World Bank, 2018a), the amount of private resources needed to enable an energy sector transition is between 3.3% and 5.3% of annual capital income and between 5.6% and 8.3% of these revenues for all infrastructure to meet the 2°C limit and the SDGs.

Since the financial system has limited fungibility across budget lines, changing the partitioning of investments is not a zero-sum game. An effective policy regime could encourage investment managers to change their asset allocation. Part of the challenge may lie in increasing the pace of financing of low-emission assets to compensate for a possible 38% decrease, by 2035, in the value of fossil fuel assets (energy sector and indirect holdings in downstream uses like automobiles) (Mercure et al., 2018).

Investments in other (non-energy system) infrastructure to meet development and poverty-reduction goals can strengthen the adaptive capacity to address climate change, and are difficult to separate from overall sustainable development and poverty-alleviation investments (Hallegatte and Rozenberg, 2017). The magnitude of potential climate change damages is related to pre-existing fragility of impacted societies (Hallegatte et al., 2007). Enhancing infrastructure and service provision would lower this fragility, for example, through the provision of universal (water, sanitation, telecommunication) service access (Arezki et al., 2016).

The main challenge is thus not just a lack of mobilization of aggregate resources but of redirection of savings towards infrastructure, and the further redirection of these infrastructure investments towards low-emission options. If emission-free assets emerge fast enough to compensate for the devaluation of high-emission assets, the sum of the required incremental and redirected investments in the energy sector would (up to 2035) be equivalent to between 3.3% and 5.3% of the average annual revenues of the private capital stock (see Box 4.8) and to between 5.6% and 8.3%, including all infrastructure investments.

The interplay between mechanisms of financial intermediation and the private risk-return calculus is a major barrier to realizing these investments (Sirkis et al., 2015). This obstacle is not specific to climate mitigation investments but also affects infrastructure and has been characterised as the gap between the 'propensity to save' and the 'propensity to invest' (Summers, 2016). The issue is whether new financial instruments could close this gap and inject liquidity into the low-emission transition, thereby unlocking new economic opportunities (GCEC, 2014; NCE, 2016). By offsetting the crowding-out of other private and public investments (Pollitt and Mercure, 2017), the ensuing ripple effect could reinforce growth and the sustainability of development (King, 2011; Teulings and Baldwin, 2014) and potentially trigger a new growth cycle (Stern, 2013, 2015). In this case, a massive mobilization of low-emission investments would require a significant effort but may be complementary to sustainable development investments.

This uncertain but potentially positive outcome might be constrained by the higher energy costs of low-emission options in the energy and transportation sectors. The envelope of worldwide marginal abatement costs for 1.5°C-consistent pathways reported in Chapter 2 is 135–5500 USD2010 tCO_2^{-1} in 2030 and 245–13000 USD2010 tCO_2^{-1} in 2050, which is between three to four times higher than for a 2°C limit.

These figures are consistent with the dramatic reduction in the unit costs of some low-emission technical options (for example solar PV, LED lighting) over the past decade (see Section 4.3.1) (OECD, 2017c). Yet there are multiple constraints to a system-wide energy transition. Lower costs of some supply- and demand-side options do not always result in a proportional decrease in energy system costs. The adoption of alternative options can be slowed down by increasing costs of decommissioning existing infrastructure, the inertia of market structures, cultural habits and risk-adverse user behaviour (see Sections 4.4.1 to 4.4.3). Learning-by-doing processes and R&D can accelerate the cost-efficiency of low-emission technology but often imply higher early-phase costs. The German energy transition resulted in high consumer prices for electricity in Germany (Kreuz and Müsgens, 2017) and needed strong accompanying measures to succeed.

One key issue is that energy costs can propagate across sectors and amplify overall production costs. During the early stage of a low-emission transition, an increase in the prices of non-energy goods could reduce consumer purchasing power and final demand. A rise in energy prices has a proportionally greater impact in developing countries that are in a catch-up phase, as they have a stronger dependence on energy-intensive sectors (Crassous et al., 2006; Luderer et al., 2012) and a higher ratio of energy to labour cost (Waisman et al., 2012). This explains why with lower carbon prices, similar emission reductions are reached in South Africa (Altieri et al., 2016) and Brazil (La Rovere et al., 2017a) compared to developed countries. However, three distributional issues emerge.

First, in the absence of countervailing policies, higher energy costs have an adverse effect on the distribution of welfare (see also Chapter 5). The negative impact is inversely correlated with the level of income (Harberger, 1984; Fleurbaey and Hammond, 2004) and positively correlated with the share of energy in the households budget, which is high for low- and middle-income households (Proost and Van Regemorter, 1995; Barker and Kohler, 1998; West and Williams, 2004; Chiroleu-Assouline and Fodha, 2011). Moreover, climatic conditions and the geographical conditions of human settlements matter for heating and mobility needs (see Chapter 5). Medium-income populations in the suburbs, in remote areas, and in low-density regions can be as vulnerable as residents of low-income urban areas. Poor households with low levels of energy consumption are also impacted by price increases of non-energy goods caused by the propagation of energy costs (Combet et al., 2010; Dubois, 2012). These impacts are generally not offset by non-market co-benefits of climate policies for the poor (Baumgärtner et al., 2017).

A second matter of concern is the distortion of international competition and employment implications in the case of uneven carbon constraints, especially for energy-intensive industries (Demailly and Quirion, 2008). Some of these industries are not highly exposed to international competition because of their very high transportation costs per unit value added (Sartor, 2013; Branger et al., 2016), but other industries could suffer severe shocks, generate 'carbon leakage' through cheaper imports from countries with lower carbon constraints (Branger and Quirion, 2014), and weaken the surrounding regional industrial fabric with economy-wide and employment implications.

A third challenge is the depreciation of assets whose value is based on the valuation of fossil energy resources, of which future revenues may decline precipitously with higher carbon prices (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015), and on emission-intensive capital stocks (Guivarch and Hallegatte, 2011; OECD, 2015a; Pfeiffer et al., 2016). This raises issues of changes in industrial structure, adaptation of worker skills, and of stability of financial, insurance and social security systems. These systems are in part based on current holdings of carbon-based assets whose value might decrease by about 38% by the mid-2030s (Mercure et al., 2018). This stranded asset challenge may be exacerbated by a decline of export revenues of fossil fuel producing countries and regions (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015).

These distributional issues, if addressed carefully and expeditiously, could affect popular sensitivity towards climate policies. Addressing them could mitigate adverse macroeconomic effects on economic growth and employment that could undermine the potential benefits of a redirection of savings and investments towards 1.5°C-consistent pathways.

Strengthening policy instruments for a low-emission transition would thus need to reconcile three objectives: (i) handling the short-term frictions inherent to this transition in an equitable way, (ii) minimizing these frictions by lowering the cost of avoided GHGs emissions, and (iii) coordinating expectations of multiple stakeholders at various decision-making levels to accelerate the decline in costs of emission reduction, efficiency and decoupling options and maximizing their co-benefits (see the practical example of lowering car use in cities in Box 4.9).

Three categories of policy tools would be available to meet the distributional challenges: carbon pricing, regulatory instruments and information and financial tools. Each of them has its own strengths and weaknesses, from a 1.5°C perspective, policy tools would have to be both scaled up and better coordinated in packages in a synergistic manner.

4.4.5.2 Carbon pricing: necessity and constraints

Economic literature has long argued that climate and energy policy grounded only in regulation, standards and public funding of R&D is at risk of being influenced by political and administrative arbitrariness, which could raise the costs of implementation. This literature has argued that it may be more efficient to make these costs explicit through carbon taxes and carbon trading, securing the abatement of emissions in places and sectors where it is cheapest (IPCC, 1995, 2001; Gupta et al., 2007; Somanathan et al., 2014).

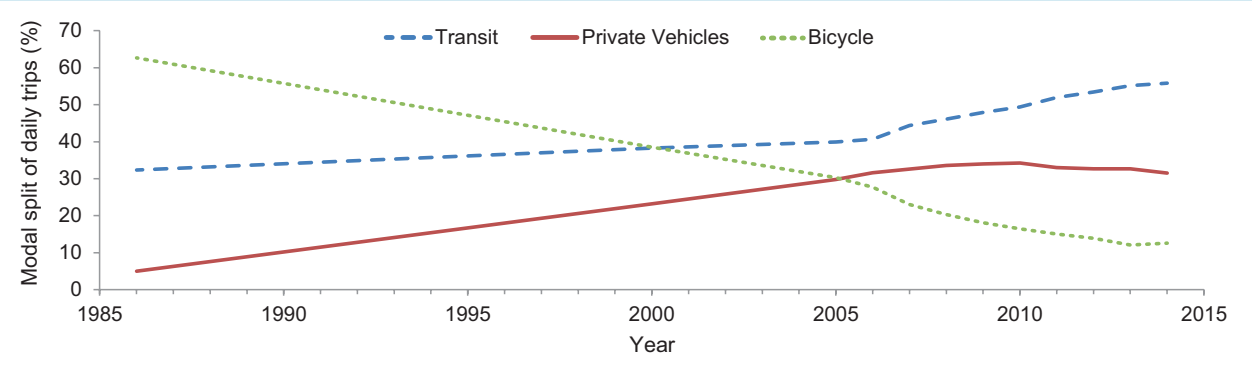
In a frictionless world, a uniform world carbon price could minimize the social costs of the low-carbon transition by equating the marginal costs of abatement across all sources of emissions. This implies that investors will be able to make the right choices under perfect foresight and that domestic and international compensatory transfers offset the adverse distributional impacts of higher energy prices and their consequences on economic activity. In the absence of such transfers, carbon prices would have to be differentiated by jurisdiction (Chichilnisky and Heal, 2000; Sheeran, 2006; Böhringer et al., 2009; Böhringer and Alexeeva-Talebi, 2013). This differentiation could in turn raise concerns of distortions in international competition (Hourcade et al., 2001; Stavins et al., 2014).

Obstacles to enforcing a uniform world carbon price in the short run would not necessarily crowd out explicit national carbon pricing, for three reasons. First, a uniform carbon price would limit an emissions rebound resulting from a higher consumption of energy services enabled by efficiency gains, if energy prices do not change (Greening et al., 2000; Fleurbaey and Hammond, 2004; Sorrell et al., 2009; Guivarch and Hallegatte, 2011; Chitnis and Sorrell, 2015; Freire-González, 2017). Second, it could hedge against the arbitrariness of regulatory policies. Third, 'revenue neutral' recycling, at a constant share of taxes on GDP, into lowering some existing taxes would compensate for at least part of the propagation effect of higher energy costs (Stiglitz et al., 2017). The substitution by carbon taxes of taxes that cause distortions on the

Box 4.9 | Emerging Cities and 'Peak Car Use': Evidence of Decoupling in Beijing

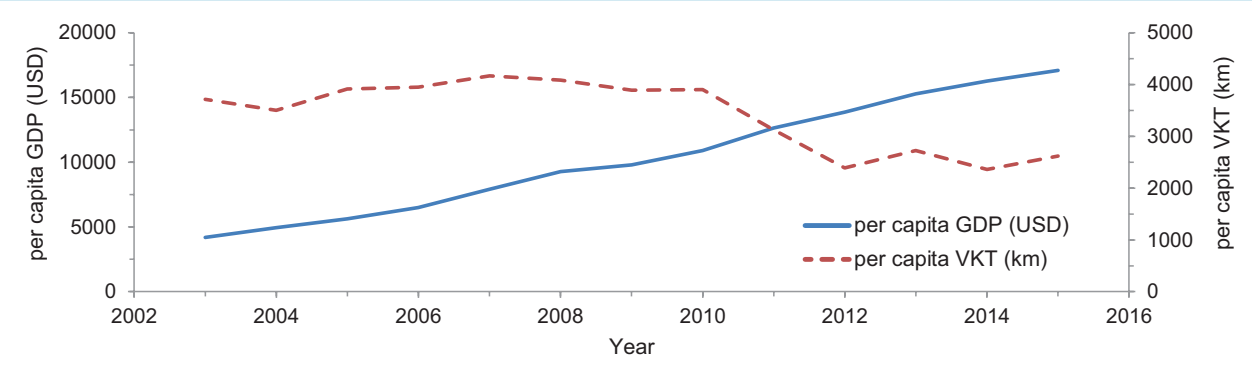
The phenomenon of 'peak car use', or reductions in per capita car use, provides hope for continuing reductions in greenhouse gases from oil consumption (Millard-Ball and Schipper, 2011; Newman and Kenworthy, 2011; Goodwin and Van Dender, 2013). The phenomenon has been mostly associated with developed cities apart from some early signs in Eastern Europe, Latin America and China (Newman and Kenworthy, 2015). New research indicates that peak car is now also underway in China (Gao and Newman, 2018).

China's rapid urban motorization was a result of strong economic growth, fast urban development and the prosperity of the Chinese automobile industry (Gao et al., 2015). However, recent data (Gao and Newman, 2018) (expressed as a percentage of daily trips) suggest the first signs of a break in the growth of car use along with the growth in mass transit, primarily the expansion of Metro systems (see Box 4.9, Figure 1).



Box 4.9, Figure 1 | The modal split data in Beijing between 1986 and 2014. Source: (Gao and Newman, 2018).

Chinese urban fabrics, featuring traditional dense linear forms and mixed land use, favour mass transit systems over automobiles (Gao and Newman, 2018). The data show that the decline in car use did not impede economic development, but the growth in vehicle kilometres of travel (VKT) has decoupled absolutely from GDP as shown in Box 4.9, Figure 2 below.



Box 4.9, Figure 2 | Peak car in Beijing: relationships between economic performance and private automobile use in Beijing from 1986 to 2014. VKT is vehicle kilometres of travel. Source: (Gao and Newman, 2018).

economy can counteract the regressive effect of higher energy prices. For example, offsetting increased carbon prices with lower labour taxes can potentially decrease labour costs (without affecting salaries), enhance employment and reduce the attractiveness of informal economic activity (Goulder, 2013).

The conditions under which an economic gain along with climate benefit (a 'double dividend') can be expected are well documented (Goulder, 1995; Bovenberg, 1999; Mooij, 2000). In the context of OECD countries, the literature examines how carbon taxation could substitute for other taxes to fund the social security system (Combet, 2013). The same general principles apply for countries that are building their social welfare system, such as China (Li and Wang, 2012) or Brazil (La Rovere et al., 2017a), but an optimal recycling scheme could differ based on the structure of the economy (Lefèvre et al., 2018).

In every country the design of carbon pricing policy implies a balance between incentivizing low-carbon behaviour and mitigating the adverse distributional consequences of higher energy prices (Combet et al., 2010). Carbon taxes can offset these effects if their revenues are redistributed through rebates to poor households. Other options include the reduction of value-added taxes for basic products or direct benefit transfers to enable poverty reduction (see Winkler et al. (2017) for South Africa and Grottera et al. (2016) for Brazil). This is possible because higher-income households pay more in absolute terms, even though their carbon tax burden is a relatively smaller share of their income (Arze del Granado et al., 2012).

Ultimately, the pace of increase of carbon prices would depend on the pace at which they can be embedded in a consistent set of fiscal and social policies. This is specifically critical in the context of the 1.5°C limit (Michaelowa et al., 2018). This is why, after a quarter century of academic debate and experimentation (see IPCC WGIII reports since the SAR), a gap persists with respect to 'switching carbon prices' needed to trigger rapid changes. In 2016, only 15% of global emissions are covered by carbon pricing, three-quarters of which with prices below 10 USD tCO_2^{-1} (World Bank, 2016). This is too low to outweigh the 'noise' from the volatility of oil markets (in the range of 100 USD tCO_2^{-1} over the past decade), of other price dynamics (interest rates, currency exchange rates and real estate prices) and of regulatory policies in energy, transportation and industry. For example, the dynamics of mobility depend upon a trade-off between housing prices and transportation costs in which the price of real estate and the inert endowments in public transport play as important a role as liquid fuel prices (Lampin et al., 2013).

These considerations apply to attempts to secure a minimum price in carbon trading systems (Wood and Jotzo, 2011; Fell et al., 2012; Fuss et al., 2018) and to the reduction of fossil fuel subsidies. Estimated at 650 billion USD in 2015 (Coady et al., 2017), these subsidies represent 25–30% of government expenditures in forty (mostly developing) countries (IEA, 2014b). Reducing these subsidies would contribute to reaching 1.5°C-consistent pathways, but raises similar issues as carbon pricing around long-term benefits and short-term costs (Jakob et al., 2015; Zeng and Chen, 2016), as well as social impacts.

Explicit carbon prices remain a necessary condition of ambitious climate policies, and some authors highlight the potential benefit brought by coordination among groups of countries (Weischer et al., 2012; Hermwille et al., 2017; Keohane et al., 2017). They could take the form of carbon pricing corridors (Bhattacharya et al., 2015). They are a necessary 'lubricant' through fiscal reforms or direct compensating transfers to accommodate the general equilibrium effects of higher energy prices but may not suffice to trigger the low-carbon transition because of a persistent 'implementation gap' between the aspirational carbon prices and those that can practically be enforced. When systemic changes, such as those needed for 1.5°C-consistent pathways, are at play on many dimensions of development, price levels 'depend on the path and the path depends on political decisions' (Drèze and Stern, 1990).

4.4.5.3 Regulatory measures and information flows

Regulatory instruments are a common tool for improving energy efficiency and enhancing renewable energy in OECD countries (e.g., the USA, Japan, Korea, Australia, the EU) and, more recently, in developing countries (M.J. Scott et al., 2015; Brown et al., 2017). Such instruments include constraints on the import of products banned in other countries (Knoop and Lechtenböhmer, 2017).

For energy efficiency, these instruments include end-use standards and labelling for domestic appliances, lighting, electric motors, water heaters and air-conditioners. They are often complemented by mandatory efficiency labels to attract consumers' attention and stimulate the manufacture of more efficient products (Girod et al., 2017). Experience shows that these policy instruments are effective only if they are regularly reviewed to follow technological developments, as in the 'Top Runner' programme for domestic appliances in Japan (Sunikka-Blank and Iwafune, 2011).

In four countries, efficiency standards (e.g. miles per gallon or level of CO_2 emission per kilometre) have been used in the transport sector, for light- and heavy-duty vehicles, which have spillovers for the global car industry. In the EU (Ajanovic and Haas, 2017) and the USA (Sen et al., 2017), vehicle manufacturers need to meet an annual CO_2 emission target for their entire new vehicle fleet. This allows them to compensate through the introduction of low-emission vehicles for the high-emission ones in the fleet. This leads to increasingly efficient fleets of vehicles over time but does not necessarily limit the driven distance.

Building codes that prescribe efficiency requirements for new and existing buildings have been adopted in many OECD countries (Evans et al., 2017) and are regularly revised to increase their efficiency per unit of floor space. Building codes can avoid locking rapidly urbanizing countries into poorly performing buildings that remain in use for the next 50–100 years (Ürge-Vorsatz et al., 2014). In OECD countries, however, their main role is to incentivize the retrofit of existing buildings. In addition of the convergence of these codes to net zero energy buildings (D'Agostino, 2015), a new focus should be placed, in the context of 1.5°C-consistent pathways, on public and private coordination to achieve better integration of building policies with the promotion of low-emission transportation modes (Bertoldi, 2017).

The efficacy of regulatory instruments can be reinforced by economic incentives, such as feed-in tariffs based on the quantity of renewable energy produced, subsidies or tax exemptions for energy savings (Bertoldi et al., 2013; Ritzenhofen and Spinler, 2016; García-Álvarez et al., 2017; Pablo-Romero et al., 2017), fee-bates, and 'bonus-malus' that foster the penetration of low-emission options (Butler and Neuhoff, 2008). Economic incentives can also be combined with direct-use market-based instruments, for example combining, in the United States and, in some EU countries, carbon trading schemes with energy savings obligations for energy retailers (Haoqi et al., 2017), or with green certificates for renewable energy portfolio standards (Upton and Snyder, 2017). Scholars have investigated caps on utilities' energy sales (Thomas et al., 2017) and emission caps implemented at a personal level (Fawcett et al., 2010).

In combination with the funding of public research institutes, grants or subsidies also support R&D, where risk and the uncertainty about long-term perspectives can reduce the private sector's willingness to invest in low-emission innovation (see also Section 4.4.4). Subsidies can take the form of rebates on value-added tax (VAT), of direct support to investments (e.g., renewable energy or refurbishment of buildings) or feed-in tariffs (Mir-Artigues and del Río, 2014). They can be provided by the public budget, via consumption levies, or via the revenues of carbon taxes or pricing. Fee-bates, introduced in some countries (e.g., for cars), have had a neutral impact on public budgets by incentivizing low-emission products and penalizing high-emission ones (de Haan et al., 2009).

All policy instruments can benefit from information campaigns (e.g., TV ads) tailored to specific end-users. A vast majority of public campaigns on energy and climate have been delivered through mass-media channels and advertising-based approaches (Corner and Randall, 2011; Doyle, 2011). Although some authors report large savings obtained by such campaigns, most agree that the effects are short-lived and decrease over time (Bertoldi et al., 2016). Recently, focus has been placed on the use of social norms to motivate behavioural changes (Allcott, 2011; Alló and Loureiro, 2014). More on strategies to change behaviour can be found in Section 4.4.3.

4.4.5.4 Scaling up climate finance and de-risking low-emission investments

The redirection of savings towards low-emission investments may be constrained by enforceable carbon prices, implementation of technical standards and the short-term bias of financial systems (Miles, 1993; Bushee, 2001; Black and Fraser, 2002). The many causes of this bias are extensively analysed in economic literature (Tehranian and Waegelein, 1985; Shleifer and Vishny, 1990; Bikhchandani and Sharma, 2000), including their link with prevailing patterns of economic globalization (Krugman, 2009; Rajan, 2011) and the chronic underinvestment in long-term infrastructure (IMF, 2014). Emerging literature explores how to overcome this through reforms targeted to bridge the gap between short-term cash balances and long-term low-emission assets and to reduce the risk-weighted capital costs of climate-resilient investments. This gap, which was qualified by the Governor of the Bank of England as a 'tragedy of the horizon' (Carney, 2016) that constitutes a threat to the stability of the financial system, is confirmed by the literature (Arezki et al., 2016; Christophers, 2017). This potential threat would encompass the impact of climate events on the value of assets (Battiston et al., 2017), liability risks (Heede, 2014) and the transition risk due to devaluation of certain classes of assets (Platinga and Scholtens, 2016).

The financial community's attention to climate change grew after COP 15 (ESRB ASC, 2016). This led to the introduction of climate-related risk disclosure in financial portfolios (UNEP, 2015), placing it on the agenda of G20 Green Finance Study Group and of the Financial Stability Board. This led to the creation of low-carbon financial indices that investors could consider as a 'free option on carbon' to hedge against risks of stranded carbon-intensive assets (Andersson et al., 2016). This could also accelerate the emergence of climate-friendly financial products such as green or climate bonds. The estimated value of the green bonds market in 2017 is 155 billion USD (BNEF, 2018). The bulk of these investments are in renewable energy, energy efficiency and low-emission transport (Lazurko and Venema, 2017), with only 4% for adaptation (OECD, 2017b). One major question is whether individual strategies based on improved climate-related information alone will enable the financial system to allocate capital in an optimal way (Christophers, 2017) since climate change is a systemic risk (CISL, 2015; Schoenmaker and van Tilburg, 2016).

The readiness of financial actors to reduce investments in fossil fuels is a real trend (Platinga and Scholtens, 2016; Ayling and Gunningham, 2017), but they may not resist the attractiveness of carbon-intensive investments in many regions. Hence, decarbonizing an investment portfolio is not synonymous with investing massively in low-emission infrastructure. Scaling up climate-friendly financial products may depend upon a business context conducive to the reduction of the risk-weighted capital costs of low-emission projects. The typical leverage of public funding mechanisms for low-emission investment is low (2 to 4) compared with other sectors (10 to 15) (Maclean et al., 2008; Ward et al., 2009; MDB, 2016). This is due to the interplay of the uncertainty of emerging low-emission technologies in the midst of their learning-by-doing cycle with uncertain future revenues due to volatility of fossil fuel prices (Roques et al., 2008; Gross et al., 2010) as well as uncertainty around regulatory policies. This inhibits low-emission investments by corporations functioning under a 'shareholder value business regime' (Berle and Means, 1932; Roe, 1996; Froud et al., 2000) and actors with restricted access to capital (e.g. cities, local authorities, SMEs and households).

De-risking policy instruments to enable low-emission investment encompasses interest rate subsidies, fee-bates, tax breaks, concessional loans from development banks, and public investment funds, including revolving funds. Given the constraints on public budgets, public guarantees can be used to increase the leverage effect of public financing on private financing. Such de-risking instruments imply indeed a full direct burden on public budgets only in case of default of the project. They could back for example various forms of green infrastructure funds (de Gouvello and Zelenko, 2010; Emin et al., 2014; Studart and Gallagher, 2015).[10]

The risk of defaulting can be mitigated by strong measurement, reporting and verifying (MRV) systems (Bellassen et al., 2015) and by the use of notional prices recommended in public economics (and currently in use in France and the UK) to calibrate public support to the provision of public goods in case of persisting distortions in pricing (Stiglitz et al., 2017). Some suggest linking these notional prices to 'social, economic and environmental value of voluntary mitigation actions' recognized by the COP 21 Decision accompanying the Paris Agreement (paragraph 108) (Hourcade et al., 2015; La Rovere et al., 2017b; Shukla et al., 2017), in order to incorporate the co-benefits of mitigation.

Such public guarantees ultimately amount to money issuance backed by low-emission projects as collateral. This explains the potentially strong link between global climate finance and the evolution of the financial

[10] One prototype is the World Bank's Pilot Auction Facility on Methane and Climate Change

and monetary system. Amongst suggested mechanisms for this evolution are the use of International Monetary Fund's (IMF's) Special Drawing Rights to fund the paid-in capital of the Green Climate Fund (Bredenkamp and Pattillo, 2010) and the creation of carbon remediation assets at a predetermined face value per avoided tonne of emissions (Aglietta et al., 2015a, b). Such a predetermined value could hedge against the fragmentation of climate finance initiatives and support the emergence of financial products backed by a new class of long-term assets.

Combining public guarantees at a predetermined value of avoided emissions, in addition to improving the consistency of non-price measures, could support the emergence of financial products backed by a new class of certified assets to attract savers in search of safe and ethical investments (Aglietta et al., 2015b). It could hedge against the fragmentation of climate finance initiatives and provide a mechanism to compensate for the 'stranded' assets caused by divestment in carbon-based activities and in lowering the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). These new assets could also facilitate a low-carbon transition for fossil fuel producers and help them to overcome the 'resource curse' (Ross, 2015; Venables, 2016).

Blended injection of liquidity has monetary implications. Some argue that this questions the premise that money should remain neutral (Annicchiarico and Di Dio, 2015, 2016; Nikiforos and Zezza, 2017). Central banks or financial regulators could act as a facilitator of last resort for low-emission financing instruments, which could in turn lower the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). This may, in time, lead to the use of carbon-based monetary instruments to diversify reserve currencies (Jaeger et al., 2013) and differentiate reserve requirements (Rozenberg et al., 2013) in the context of a climate-friendly Bretton Woods (Sirkis et al., 2015; Stua, 2017).

4.4.5.5 Financial challenge for basic needs and adaptation finance

Adaptation finance is difficult to quantify for two reasons. The first is that it is very difficult to isolate specific investment needs to enhance climate resilience from the provision of basic infrastructure that are currently underinvested (IMF, 2014; Gurara et al., 2017). The UNEP (2016) estimate of investment needs on adaptation in developing countries between 140–300 billion USD yr^{-1} in 2030, a major part being investment expenditures that are complementary with SDG-related investments focused on universal access to infrastructure and services and meeting basic needs. Many climate-adaptation-centric financial incentives are relevant to non-market services, offering fewer opportunities for market revenues while they contribute to creating resilience to climate impacts.

Hence, adaptation investments and the provision of basic needs would typically have to be supported by national and sub-national government budgets together with support from overseas development assistance and multilateral development banks (Fankhauser and Schmidt-Traub, 2011; Adenle et al., 2017; Robinson and Dornan, 2017), and a slow increase of dedicated NGO and private climate funds (Nakhooda and Watson, 2016). Even though the UNEP estimates of the costs of adaptation might be lower in a 1.5°C world (UNEP/Climate Analytics, 2015) they would be higher than the UNEP estimate of 22.5 billion USD of bilateral and multilateral funding for climate change adaptation in 2014. Currently, 18–25% of climate finance flows to adaptation in developing countries (OECD, 2015b, 2016; Shine and Campillo, 2016). It remains fragmented, with small proportions flowing through UNFCCC channels (AdaptationWatch, 2015; Roberts and Weikmans, 2017).

Means of raising resources for adaptation, achieving the SDGs and meeting basic needs (Durand et al., 2016; Roberts et al., 2017) include the reduction of fossil fuel subsidies (Jakob et al., 2016), increasing revenues from carbon taxes (Jakob et al., 2016), levies on international aviation and maritime transport, and sharing of the proceeds of financial arrangements supporting mitigation activities (Keen et al., 2013). Each have different redistribution implications. Challenges, however, include the efficient use of resources, the emergence of long-term assets using infrastructure as collateral and the capacity to implement small-scale adaptation and the mainstreaming of adaptation in overall development policies. There is thus a need for greater policy coordination (Fankhauser and McDermott, 2014; Morita and Matsumoto, 2015; Sovacool et al., 2015, 2017; Lemos et al., 2016; Adenle et al., 2017; Peake and Ekins, 2017) that includes robust mechanisms for tracking, reporting and ensuring transparency of adaptation finance (Donner et al., 2016; Pauw et al., 2016a; Roberts and Weikmans, 2017; Trabacchi and Buchner, 2017) and its consistency with the provision of basic needs (Hallegatte et al., 2016).

4.4.5.6 Towards integrated policy packages and innovative forms of financial cooperation

Carbon prices, regulation and standards, improved information and appropriate financial instruments can work synergistically to meet the challenge of 'making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development', as in Article 2 in the Paris Agreement.

There is growing attention to the combination of policy instruments that address three domains of action: behavioural changes, economic optimization and long-term strategies (Grubb et al., 2014). For example, de-risking low-emission investments would result in higher volumes of low-emission investments, and would in turn lead to a lower switching price for the same climate ambition (Hirth and Steckel, 2016). In the reverse direction, higher explicit carbon prices may generate more low-emission projects for a given quantum of de-risking. For example, efficiency standards for housing can increase the efficacy of carbon prices and overcome the barriers coming from the high discount rates used by households (Parry et al., 2014), while explicit and notional carbon prices can lower the risk of arbitrary standards. The calibration of innovative financial instruments to notional carbon prices could encourage large multinational companies to increase their level of internal carbon prices (UNEP, 2016). These notional prices could be higher than explicit carbon prices because they redirect new hardware investments without an immediate impact on existing capital stocks and associated interests.

Literature, however, shows that conflicts between poorly articulated policy instruments can undermine their efficiency (Lecuyer and Quirion, 2013; Bhattacharya et al., 2017; García-Álvarez et al., 2017).

As has been illustrated in Europe, commitment uncertainty and lack of credibility of regulation have consistently led to low carbon prices in the case of the EU Emission Trading System (Koch et al., 2014, 2016). A comparative study shows how these conflicts can be avoided by policy packages that integrate many dimensions of public policies and are designed to match institutional and social context of each country and region (Bataille et al., 2015).

Even though policy packages depend upon domestic political processes, they might not reinforce the NDCs at a level consistent with the 1.5°C transition without a conducive international setting where international development finance plays a critical role. Section 4.4.1 explores the means of mainstreaming climate finance in the current evolution of the lending practices of national and multilateral banks (Badré, 2018). This could facilitate the access of developing countries to loans via bond markets at low interest rates, encouragement of the emergence of new business models for infrastructure, and encouragement of financial markets to support small-scale investments (Déau and Touati, 2017).

These financial innovations may involve non-state public actors like cities and regional public authorities that govern infrastructure investment, enable energy and food systems transitions and manage urban dynamics (Cartwright, 2015). They would help, for example, in raising the 4.5–5.4 trillion USD yr^{-1} from 2015 to 2030 announced by the Cities Climate Finance Leadership Alliance (CCFLA, 2016) to achieve the commitments by the Covenant of Mayors of many cities to long-term climate targets (Kona et al., 2018).

The evolution of global climate financial cooperation may involve central banks, financial regulatory authorities, and multilateral and commercial banks. There are still knowledge gaps about the form, structure and potential of these arrangements. They could be viewed as a form of a burden-sharing between high-, medium- and low-income countries to enhance the deployment of ambitious Nationally Determined Contributions (NDCs) and new forms of 'common but differentiated responsibility and respective capabilities' (Edenhofer et al., 2015; Hourcade et al., 2015; Ji and Sha, 2015).

4.5 Integration and Enabling Transformation

4.5.1 Assessing Feasibility of Options for Accelerated Transitions

Chapter 2 shows that 1.5°C-consistent pathways involve rapid, global climate responses to reach net zero emissions by mid-century or earlier. Chapter 3 identifies climate change risks and impacts to which the world would need to adapt during these transitions and additional risks and impacts during potential 1.5°C overshoot pathways. The feasibility of these pathways is contingent upon systemic change (Section 4.3) and enabling conditions (Section 4.4), including policy packages. This section assesses the feasibility of options (technologies, actions and measures) that form part of global systems under transition that make up 1.5°C-consistent pathways.

Following the assessment framework developed in Chapter 1, economic and technological, institutional and socio-cultural, and environmental and geophysical feasibility are considered and applied to system transitions (Sections 4.3.1–4.3.4), overarching adaptation options (Section 4.3.5) and carbon dioxide removal (CDR) options (Section 4.3.7). This is done to assess the multidimensional feasibility of mitigation and adaptation options that have seen considerable development and change since AR5. In the case of adaptation, the assessed AR5 options are typically clustered. For example, all options related to energy infrastructure resilience, independently of the generation source, are categorized as 'resilience of power infrastructure'.

Table 4.10 presents sets of indicators against which the multidimensional feasibility of individual adaptation options relevant to warming of 1.5°C, and mitigation options along 1.5°C-consistent pathways, is assessed.

The feasibility assessment takes the following steps. First, each of the mitigation and adaptation options is assessed along the relevant indicators grouped around six feasibility dimensions: economic, technological, institutional, socio-cultural, environmental/ecological and geophysical. Three types of feasibility groupings were assessed from the underlying literature: first, if the indicator could block the feasibility of this option; second, if the indicator has neither a positive nor a negative effect on the feasibility of the option or the evidence is mixed; and third, if the indicator does not pose any barrier to the feasibility of this option. The full assessment of each option under each indicator, including the literature references on which the assessment is based, can be found in supplementary materials 4.SM.4.2 and 4.SM.4.3. When appropriate, it is indicated that there is no evidence (NE), limited evidence (LE) or that the indicator is not applicable to the option (NA).

Next, for each feasibility dimension and option, the overall feasibility for a given dimension is assessed as the mean of combined scores of the relevant underlying indicators and classified into 'insignificant barriers' (2.5 to 3), 'mixed or moderate but still existent barriers' (1.5 to 2.5) or 'significant barriers' (below 1.5) to feasibility. Indicators assessed as NA, LE or NE are not included in this overall assessment (see supplementary material 4.SM.4.1 for the averaging and weighing guidance).

The results are summarized in Table 4.11 (for mitigation options) and Table 4.12 (for adaptation options) for each of the six feasibility dimensions: where dark shading indicates few feasibility barriers; moderate shading indicates that there are mixed or moderate but still existent barriers, and light shading indicates that multiple barriers, in this dimension, may block implementation.

A three-step process of independent validation and discussion by authors was undertaken to make this assessment as robust as possible within the scope of this Special Report. It must, however, be recognized that this is an indicative assessment at global scale, and both policy and implementation at regional, national and local level would need to adapt and build on this knowledge, within the particular local context and constraints. Some contextual factors are indicated in the rightmost column in Tables 4.11 and 4.12.

Table 4.10 | Sets of indicators against which the feasibility of adaptation and mitigation options are assessed for each feasibility dimension. The options are discussed in Sections 4.3.1-4.3.5 and 4.3.7.

Feasibility Dimensions	Adaptation Indicators	Mitigation Indicators
Economic	Microeconomic viability Macroeconomic viability Socio-economic vulnerability reduction potential Employment & productivity enhancement potential	Cost-effectiveness Absence of distributional effects Employment & productivity enhancement potential
Technological	Technical resource availability Risks mitigation potential	Technical scalability Maturity Simplicity Absence of risk
Institutional	Political acceptability Legal & regulatory feasibility Institutional capacity & administrative feasibility Transparency & accountability potential	Political acceptability Legal & administrative feasibility Institutional capacity Transparency & accountability potential
Socio-cultural	Social co-benefits (health, education) Socio-cultural acceptability Social & regional inclusiveness Intergenerational equity	Social co-benefits (health, education) Public acceptance Social & regional inclusiveness Intergenerational equity Human capabilities
Environmental/Ecological	Ecological capacity Adaptive capacity/ resilience building potential	Reduction of air pollution Reduction of toxic waste Reduction of water use Improved biodiversity
Geophysical	Physical feasibility Land use change enhancement potential Hazard risk reduction potential	Physical feasibility (physical potentials) Limited use of land Limited use of scarce (geo)physical resources Global spread

4.5.2 Implementing Mitigation

This section builds on the insights on mitigation options in Section 4.3, applies the assessment methodology along feasibility dimensions and indicators explained in Section 4.5.1, and synthesizes the assessment of the enabling conditions in Section 4.4.

4.5.2.1 Assessing mitigation options for limiting warming to 1.5˚C against feasibility dimensions

An assessment of the degree to which examples of 1.5°C-relevant mitigation options face barriers to implementation, and on which contexts this depends, is summarized in Table 4.11. An explanation of the approach is given in Section 4.5.1 and in supplementary material 4.SM.4.1. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments. The detailed assessment and the literature underpinning the assessment can be found in supplementary material 4.SM.4.2.

The feasibility framework in Cross-Chapter Box 3 in Chapter 1 highlights that the feasibility of mitigation and adaptation options depends on many factors. Many of those are captured in the indicators in Table 4.10, but many depend on the specific context in which an option features. This Special Report did not have the mandate, space or the literature base to undertake a regionally specific assessment. Hence the assessment is caveated as providing a broad indication of the likely global barriers, ignoring significant regional diversity. Regional and context-specific literature is also just emerging as is noted in the knowledge gaps section (Section 4.6). Nevertheless, in Table 4.11, an indicative attempt has been made to capture relevant contextual information. The 'context' column indicates which contextual factors may affect the feasibility of an option, including regional differences. For instance, solar irradiation in an area impacts the cost-effectiveness of solar photovoltaic energy, so solar irradiation is mentioned in this column.

4.5.2.2 Enabling conditions for implementation of mitigation options towards 1.5˚C

The feasibility assessment highlights six dimensions that could help inform an agenda that could be addressed by the areas discussed in Section 4.4: governance, behaviour and lifestyles, innovation, enhancing institutional capacities, policy and finance. For instance, Section 4.4.3 on behaviour offers strategies for addressing public acceptance problems, and how changes can be more effective when communication and actions relate to people's values. This section synthesizes the findings in Section 4.4 in an attempt to link them to the assessment in Table 4.11. The literature on which the discussion is based is found in Section 4.4.

From Section 4.4, including the case studies presented in the Boxes 4.1 to 4.10, several main messages can be constructed. For instance, governance would have to be multilevel and engaging different actors, while being efficient, and choosing the form of cooperation based on the specific systemic challenge or option at hand. If institutional capacity for financing and governing the various transitions is not urgently built, many countries would lack the ability to change pathways from a high-emission scenario to a low- or zero-emission scenario. In terms of innovation, governments, both national and multilateral, can contribute

Table 4.11 | Feasibility assessment of examples of 1.5°C-relevant mitigation options, with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading indicating that, on average, the dimension does not have a positive or negative effect on the feasibility of the option, or the evidence is mixed, and faint shading the presence of potentially blocking barriers. No shading means that the literature found was not sufficient to make an assessment. Evidence and agreement assessment is undertaken at the option level. The context column on the far right indicates how the assessment might change if contextual factors were different. For the methodology and literature basis, see supplementary material 4.SM.4.1 and 4.SM.4.2.
Abbreviations used: Ec: Economic - Tec: Technological - Inst: Institutional - Soc: Socio-cultural - Env: Environmental/Ecological - Geo: Geophysical

System	Mitigation Option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Energy System Transitions	Wind energy (on-shore & off-shore)	Robust	Medium							Wind regime, economic status, space for wind farms, and the existence of a legal framework for independent power producers affect uptake; cost-effectiveness affected by incentive regime
	Solar PV	Robust	High							Cost-effectiveness affected by solar irradiation and incentive regime. Also enhanced by legal framework for independent power producers, which affects uptake
	Bioenergy	Robust	Medium							Depends on availability of biomass and land and the capability to manage sustainable land use. Distributional effects depend on the agrarian (or other) system used to produce feedstock
	Electricity storage	Robust	High							Batteries universal, but grid-flexible resources vary with area's level of development
	Power sector carbon dioxide capture and storage	Robust	High							Varies with local CO_2 storage capacity, presence of legal framework, level of development and quality of public engagement
	Nuclear energy	Robust	High							Electricity market organization, legal framework, standardization & know-how, country's 'democratic fabric', institutional and technical capacity, and safety culture of public and private institutions
Land & Ecosystem Transitions	Reduced food wastage & efficient food production	Robust	High							Will depend on the combination of individual and institutional behaviour
	Dietary shifts	Medium	High							Depends on individual behaviour, education, cultural factors and institutional support
	Sustainable intensification of agriculture	Medium	High							Depends on development and deployment of new technologies
	Ecosystems restoration	Medium	High							Depends on location and institutional factors
Urban & Infra structure System Transitions	Land-use & urban planning	Robust	Medium							Varies with urban fabric, not geography or economy; requires capacitated local government and legitimate tenure system
	Electric cars and buses	Medium	High							Varies with degree of government intervention; requires capacity to retrofit "fuelling" stations
	Sharing schemes	Limited	Medium							Historic schemes universal, but new ones depend on ICT status; undermined by high crime and low levels of law enforcement
	Public transport	Robust	Medium							Depends on presence of existing 'informal' taxi systems, which may be more cost-effective and affordable than capital-intensive new build schemes, as well as (local) government capabilities
	Non-motorized transport	Robust	High							Viability rests on linkages with public transport, cultural factors, climate and geography
	Aviation & shipping	Medium	Medium							Varies with technology, governance and accountability
	Smart grids	Medium	Medium							Varies with economic status and presence or quality of existing grid
	Efficient appliances	Medium	High							Adoption varies with economic status and policy framework
	Low/zero-energy buildings	Medium	High							Depends on size of existing building stock and growth of building stock

Table 4.11 (continued)

System	Mitigation Option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Industrial System Transitions	Energy efficiency	Robust	High							Potential and adoption depend on existing efficiency, energy prices and interest rates, as well as government incentives
	Bio-based & circularity	Medium	Medium							Faces barriers in terms of pressure on natural resources and biodiversity. Product substitution depends on market organization and government incentivization
	Electrification & hydrogen	Medium	High							Depends on availability of large-scale, cheap, emission-free electricity (electrification, hydrogen) or CO_2 storage nearby (hydrogen). Manufacturers' appetite to embrace disruptive innovations
	Industrial carbon dioxide capture, utilization and storage	Robust	High							High concentration of CO_2 in exhaust gas improve economic and technical feasibility of CCUS in industry. CO_2 storage or reuse possibilities
Carbon Dioxide Removal	Bioenergy and carbon dioxide capture and storage	Robust	Medium							Depends on biomass availability, CO_2 storage capacity, legal framework, economic status and social acceptance
	Direct air carbon dioxide capture and storage	Medium	Medium							Depends on CO_2-free energy, CO_2 storage capacity, legal framework, economic status and social acceptance
	Afforestation & reforestation	Robust	High							Depends on location, mode of implementation, and economic and institutional factors
	Soil carbon sequestration & biochar	Robust	High							Depends on location, soil properties, time span
	Enhanced weathering	Medium	Low							Depends on CO_2-free energy, economic status and social acceptance

to applying general-purpose technologies to mitigation purposes. If this is not managed, some reduction in emissions could happen autonomously, but it may not lead to a 1.5°C-consistent pathway. International cooperation on technology, including technology transfer where this does not happen autonomously, is needed and can help create innovation capabilities in all countries that allow them to operate, maintain, adapt and regulate a portfolio of mitigation technologies. Case studies in the various subsections highlight the opportunities and challenges of doing this in practice. They indicate that it can be done in specific circumstances, which can be created.

A combination of behaviour-oriented pricing policies and financing options can help change technologies and social behaviour as it would challenge the existing, high-emission socio-technical regime on multiple levels across feasibility characteristics. For instance, for dietary change, combining supply-side measures with value-driven communication and economic instruments may help make a lasting transition, while an economic instrument, such as enhanced prices or taxation, on its own may not be as robust.

Governments could benefit from enhanced carbon prices, as a price and innovation incentive and also a source of additional revenue to correct distributional effects and subsidize the development of new, cost-effective negative-emission technology and infrastructure. However, there is *high evidence* and *medium agreement* that pricing alone is insufficient. Even if prices rise significantly, they typically incentivize incremental change, but typically fail to provide the impetus for private actors to take the risk of engaging in the transformational changes that would be needed to limit warming to 1.5°C. Apart from the incentives to change behaviour and technology, financial systems are an indispensable element of a systemic transition. If financial markets do not acknowledge climate risk and the risk of transitions, regulatory financial institutions, such as central banks, could intervene.

Strengthening implementation revolves around more than addressing barriers to feasibility. A system transition, be it in energy, industry, land or a city, requires changing the core parameters of a system. These relate, as introduced in Section 4.2 and further elaborated in Section 4.4, to how actors cooperate, how technologies are embedded, how resources are linked, how cultures relate and what values people associate with the transition and the current regime.

4.5.3 Implementing Adaptation

Article 7 of the Paris Agreement provides an aspirational global goal for adaptation, of 'enhancing adaptive capacity, strengthening resilience, and reducing vulnerability' (UNFCCC, 2016). Adaptation implementation is gathering momentum in many regions, guided by national NDC's and national adaptation plans (see Cross-Chapter Box 11 in this Chapter).

Operationalizing adaptation in a set of regional environments on pathways to a 1.5°C world requires strengthened global and differentiated regional and local capacities. It also needs rapid and decisive adaptation actions to reduce the costs and magnitude of potential climate impacts (Vergara et al., 2015).

This could be facilitated by: (i) enabling conditions, especially improved governance, economic measures and financing (Section 4.4); (ii)

enhanced clarity on adaptation options to help identify strategic priorities, sequencing and timing of implementation (Section 4.3); (iii) robust monitoring and evaluation frameworks; and (iv) political leadership (Magnan et al., 2015; Magnan and Ribera, 2016; Lesnikowski et al., 2017; UNEP, 2017a).

4.5.3.1 Feasible adaptation options

This section summarizes the feasibility (defined in Cross-Chapter Box 3, Table 1 in Chapter 1 and Table 4.4) of select adaptation options using evidence presented across this chapter and in supplementary material 4.SM.4.3 and the expert-judgement of its authors (Table 4.12). The options assessed respond to risks and impacts identified in Chapter 3. They were selected based on options identified in AR5 (Noble et al., 2014), focusing on those relevant to 1.5°C-compatible pathways, where sufficient literature exists. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments.

Besides gaps in the literature around crucial adaptation questions on the transition to a 1.5°C world (Section 4.6), there is inadequate current literature to undertake a spatially differentiated assessment (Cross-Chapter Box 3 in Chapter 1). There are also limited baselines for exposure, vulnerability and risk to help policy and implementation prioritization. Hence, the compiled results can at best provide a broad framework to inform policymaking. Given the bottom-up nature of most adaptation implementation evidence, care needs to be taken in generalizing these findings.

Options are considered as part of a systemic approach, recognizing that no single solution exists to limit warming to 1.5°C and adapting to its impacts. To respond to the local and regional context – and to synergies and trade-offs between adaptation, mitigation and sustainable development – packages of options suited to local enabling conditions can be implemented.

Table 4.12 summarizes the feasibility assessment through its six dimensions with levels of evidence and agreement and indicates how the feasibility of an adaptation option may be differentiated by certain contextual factors (last column).

When considered jointly, the description of adaptation options (Section 4.3), the feasibility assessment (summarized in Table 4.12), and discussion of enabling conditions (Section 4.4) show us how options can be implemented and lead towards transformational adaptation if and when needed.

The adaptation options for energy system transitions focus on existing power infrastructure resilience and water management, when required, for any type of generation source. These options are not sufficient for the far-reaching transformations required in the energy sector, which have tended to focus on technologies to shift from a fossil-based to a renewable energy system (Erlinghagen and Markard, 2012; Muench et al., 2014; Brand and von Gleich, 2015; Monstadt and Wolff, 2015; Child and Breyer, 2017; Hermwille et al., 2017). There is also need for integration of such energy system transitions with social-ecological systems transformations to increase the resilience of the energy sector, for which appropriate enabling conditions, such as for technological innovations, are fundamentally important. Institutional capacities can be enhanced by expanding the role of actors as transformation catalysts (Erlinghagen and Markard, 2012). The integration of ethics and justice within these transformations can help attain SDG7 on clean energy access (Jenkins et al., 2018), while inclusion of the cultural dimension and cultural legitimacy (Amars et al., 2017) can provide a more substantial base for societal transformation. Strengthening policy instruments and regulatory frameworks and enhancing multilevel governance that focuses on resilience components can help secure these transitions (Exner et al., 2016).

For land and ecosystem transitions, the options of conservation agriculture, efficient irrigation, agroforestry, ecosystem restoration and avoided deforestation, and coastal defence and hardening have between *medium and robust evidence* with *medium to high agreement.* The other options assessed have limited or no evidence across one or more of the feasibility dimensions. Community-based adaptation is assessed as having *medium evidence* and *high agreement* to face scaling barriers. Scaling community-based adaptation may require structural changes, implying the need for transformational adaptation in some regions. This would involve enhanced multilevel governance and institutional capacities by enabling anticipatory and flexible decision-making systems that access and develop collaborative networks (Dowd et al., 2014), tackling root causes of vulnerability (Chung Tiam Fook, 2017), and developing synergies between development and climate change (Burch et al., 2017). Case studies show the use of transformational adaptation approaches for fire management (Colloff et al., 2016a), floodplain and wetland management (Colloff et al., 2016b), and forest management (Chung Tiam Fook, 2017), in which the strengthening of policy instruments and climate finance are also required.

There is growing recognition of the need for transformational adaptation within the agricultural sector but limited evidence on how to facilitate processes of deep, systemic change (Dowd et al., 2014). Case studies demonstrate that transformational adaptation in agriculture requires a sequencing and overlap between incremental and transformational adaptation actions (Hadarits et al., 2017; Termeer et al., 2017), e.g., incremental improvements to crop management while new crop varieties are being researched and field-tested (Rippke et al., 2016). Broader considerations include addressing stakeholder values and attitudes (Fleming et al., 2015a), understanding and leveraging the role of social capital, collaborative networks, and information (Dowd et al., 2014), and being inclusive with rural and urban communities, and the social, political, and cultural environment (Rickards and Howden, 2012). Transformational adaptation in agriculture systems could have significant economic and institutional costs (Mushtaq, 2016), along with potential unintended negative consequences (Davidson, 2016; Rippke et al., 2016; Gajjar et al., 2018; Mushtaq, 2018), and a need to focus on the transitional space between incremental and transformational adaptation (Hadarits et al., 2017), as well as the timing of the shift from one to the other (Läderach et al., 2017).

Within urban and infrastructure transitions, green infrastructure and sustainable water management are assessed as the most feasible options, followed by sustainable land-use and urban planning. The

Table 4.12 | Feasibility assessment of examples of 1.5°C-relevant adaptation options, with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading indicating that, on average, the dimension does not have a positive or negative effect on the feasibility of the option, or the evidence is mixed, and light shading indicating the presence of potentially blocking barriers. No shading means that sufficient literature could not be found to make the assessment. NA signifies that the dimension is not applicable to that adaptation option. For methodology and literature basis, see supplementary material 4.SM.4.
Abbreviations used: Ec: Economic - Tec: Technological - Inst: Institutional - Soc: Socio-cultural - Env: Environmental/Ecological - Geo: Geophysical

System	Adaptation Option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Energy System Transitions	Power infrastructure, including water	Medium	High							Depends on existing power infrastructure, all generation sources and those with intensive water requirements
Land & Ecosystem Transitions	Conservation agriculture	Medium	Medium							Depends on irrigated/rainfed system, ecosystem characteristics, crop type, other farming practices
	Efficient irrigation	Medium	Medium							Depends on agricultural system, technology used, regional institutional and biophysical context
	Efficient livestock systems	Limited	High							Dependent on livestock breeds, feed practices, and biophysical context (e.g., carrying capacity)
	Agroforestry	Medium	High							Depends on knowledge, financial support, and market conditions
	Community-based adaptation	Medium	High							Focus on rural areas and combined with ecosystems-based adaptation, does not include urban settings
	Ecosystem restoration & avoided deforestation	Robust	Medium							Mostly focused on existing and evaluated REDD+ projects
	Biodiversity management	Medium	Medium							Focus on hotspots of biodiversity vulnerability and high connectivity
	Coastal defence & hardening	Robust	Medium							Depends on locations that require it as a first adaptation option
	Sustainable aquaculture	Limited	Medium							Depends on locations at risk and socio-cultural context
Urban & Infrastructure System Transitions	Sustainable land-use & urban planning	Medium	Medium							Depends on nature of planning systems and enforcement mechanisms
	Sustainable water management	Robust	Medium							Balancing sustainable water supply and rising demand, especially in low-income countries
	Green infrastructure & ecosystem services	Medium	High							Depends on reconciliation of urban development with green infrastructure
	Building codes & standards	Limited	Medium							Adoption requires legal, educational, and enforcement mechanisms to regulate buildings
Industrial System Transitions	Intensive industry infrastructure resilience and water management	Limited	High							Depends on intensive industry, existing infrastructure and using or requiring high demand of water
Overarching Adaptation Options	Disaster risk management	Medium	High							Requires institutional, technical, and financial capacity in frontline agencies and government
	Risk spreading and sharing: insurance	Medium	Medium							Requires well-developed financial structures and public understanding
	Social safety nets	Medium	Medium							Type and mechanism of safety net, political priorities, institutional transparency
	Climate services	Medium	High							Depends on climate information availability and usability, local infrastructure and institutions, national priorities
	Indigenous knowledge	Medium	High							Dependent on recognition of indigenous rights, laws, and governance systems
	Education and learning	Medium	High							Existing education system, funding
	Population health and health system	Medium	High						NA	Requires basic health services and infrastructure
	Human migration	Medium	Low							Hazard exposure, political and socio-cultural acceptability (in destination), migrant skills and social networks

need for transformational adaptation in urban settings arises from the root causes of poverty, failures in sustainable development, and a lack of focus on social justice (Revi et al., 2014a; Parnell, 2015; Simon and Leck, 2015; Shi et al., 2016; Ziervogel et al., 2016a; Burch et al., 2017), and necessitates a focus on governance structures and the inclusion of equity and justice concerns (Bos et al., 2015; Shi et al., 2016; Hölscher et al., 2018).

Current implementation of urban ecosystems-based adaptation (EbA) lacks a systems perspective of transformations and consideration of the normative and ethical aspects of EbA (Brink et al., 2016). Flexibility within urban planning could help deal with the multiple uncertainties of implementing adaptation (Rosenzweig and Solecki, 2014; Radhakrishnan et al., 2018), for example, urban adaptation pathways were implemented in the aftermath of Superstorm Sandy in New York, which is considered as tipping point that led to the implementation of transformational adaptation practices.

Adaptation options for industry focus on infrastructure resilience and water management. Like with energy system transitions, technological innovation would be required, but also the enhancement of institutional capacities. Recent research illustrates transformational adaptation within industrial transitions focusing on the role of different actors and tools driving innovation, and points to the role of nationally appropriate mitigation actions in avoiding lock-ins and promoting system innovation (Boodoo and Olsen, 2017), the role of private sector in sustainability governance in the socio-political context (Burch et al., 2016), and of green entrepreneurs driving transformative change in the green economy (Gibbs and O'Neill, 2014). Lim-Camacho et al. (2015) suggest an analysis of the complete lifecycle of supply chains as a means of identifying additional adaptation strategies, as opposed to the current focus on a part of the supply chain. Chain-wide strategies can modify the rest of the chain and present a win-win with commercial objectives.

The assessed adaptation options also have mitigation synergies and trade-offs (assessed in Section 4.5.4) that need to be carefully considered, while planning climate action.

4.5.3.2 Monitoring and evaluation

Monitoring and evaluation (M&E) in adaptation implementation can promote accountability and transparency of adaptation financing, facilitate policy learning and sharing good practices, pressure laggards, and guide adaptation planning. The majority of research on M&E focuses on specific policies or programmes, and has typically been driven by the needs of development organizations, donors, and governments to measure the impact and attribution of adaptation initiatives (Ford and Berrang-Ford, 2016). There is growing research examining adaptation progress across nations, sectors, and scales (Reckien et al., 2014; Araos et al., 2016a, b; Austin et al., 2016; Heidrich et al., 2016; Lesnikowski et al., 2016; Robinson, 2017). In response to a need for global, regional and local adaptation, the development of indicators and standardized approaches to evaluate and compare adaptation over time and across regions, countries, and sectors would enhance comparability and learning. A number of constraints continue to hamper progress on adaptation M&E, including a debate on what actually constitutes adaptation for the purposes of assessing progress (Dupuis and Biesbroek, 2013; Biesbroek et al., 2015), an absence of comprehensive and systematically collected data on adaptation to support longitudinal assessment and comparison (Ford et al., 2015b; Lesnikowski et al., 2016), a lack of agreement on indicators to measure (Brooks et al., 2013; Bours et al., 2015; Lesnikowski et al., 2015), and challenges of attributing altered vulnerability to adaptation actions (Ford et al., 2013; Bours et al., 2015; UNEP, 2017a).

4.5.4 Synergies and Trade-Offs between Adaptation and Mitigation

Implementing a particular mitigation or adaptation option may affect the feasibility and effectiveness of other mitigation and adaptation options. Supplementary Material 4.SM.5.1 provides examples of possible positive impacts (synergies) and negative impacts (trade-offs) of mitigation options for adaptation. For example, renewable energy sources such as wind energy and solar PV combined with electricity storage can increase resilience due to distributed grids, thereby enhancing both mitigation and adaptation. Yet, as another example, urban densification may reduce GHG emissions, enhancing mitigation, but can also intensify heat island effects and inhibit restoration of local ecosystems if not accounted for, thereby increasing adaptation challenges.

The table in Supplementary Material 4.SM.5.2 provides examples of synergies and trade-offs of adaptation options for mitigation. It shows, for example, that conservation agriculture can reduce some GHG emissions and thus enhance mitigation, but at the same time can increase other GHG emissions, thereby reducing mitigation potential. As another example, agroforestry can reduce GHG emissions through reduced deforestation and fossil fuel consumption but has a lower carbon sequestration potential compared with natural and secondary forest.

Maladaptive actions could increase the risk of adverse climate-related outcomes. For example, biofuel targets could lead to indirect land use change and influence local food security, through a shift in land use abroad in response to increased domestic biofuel demand, increasing global GHG emissions rather than decreasing them.

Various options enhance both climate change mitigation and adaptation, and would hence serve two 1.5°C-related goals: reducing emissions while adapting to the associated climate change. Examples of such options are reforestation, urban and spatial planning, and land and water management.

Synergies between mitigation and adaptation may be enhanced, and trade-offs reduced, by considering enabling conditions (Section 4.4), while trade-offs can be amplified when enabling conditions are not considered (C.A. Scott et al., 2015). For example, information that is tailored to the personal situation of individuals and communities, including climate services that are credible and targeted at the point of decision-making, can enable and promote both mitigation and adaptation actions (Section 4.4.3). Similarly, multilevel governance and community participation, respectively, can enable and promote both adaptation and mitigation actions (Section 4.4.1). Governance, policies and institutions can facilitate the implementation of the water–

energy–food (WEF) nexus (Rasul and Sharma, 2016). The WEF nexus can enhance food, water and energy security, particularly in cities with agricultural production areas (Biggs et al., 2015), electricity generation with intensive water requirements (Conway et al 2015), and in agriculture (El Gafy et al., 2017) and livelihoods (Biggs et al., 2015). Such a nexus approach can reduce the transport energy that is embedded in food value chains (Villarroel Walker et al., 2014), providing diverse sources of food in the face of changing climates (Tacoli et al., 2013). Urban agriculture, where integrated, can mitigate climate change and support urban flood management (Angotti, 2015; Bell et al., 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lwasa et al., 2015; Yang et al., 2016; Sanesi et al., 2017). In the case of electricity generation, enabling conditions through a combination of carefully selected policy instruments can maximize the synergic benefits between low GHG energy production and water for energy (Shang et al., 2018). Despite the multiple benefits of maximizing synergies between mitigation and adaptations options through the WEF nexus approach (Chen and Chen, 2016), there are implementation challenges given institutional complexity, political economy, and interdependencies between actors (Leck et al., 2015).

Box 4.10 | Bhutan: Synergies and Trade-Offs in Economic Growth, Carbon Neutrality and Happiness

Bhutan has three national goals: improving its gross national happiness index (GNHI), improving its economic growth (gross domestic product, GDP) and maintaining its carbon neutrality. These goals increasingly interact and raise questions about whether they can be sustainably maintained into the future. Interventions in this enabling environment are required to comply with all three goals.

Bhutan is well known for its GNHI, which is based on a variety of indicators covering psychological well-being, health, education, cultural and community vitality, living standards, ecological issues and good governance (RGoB, 2012; Schroeder and Schroeder, 2014; Ura, 2015). The GNHI is a precursor to the Sustainable Development Goals (SDGs) (Allison, 2012; Brooks, 2013) and reflects local enabling environments. The GNHI has been measured twice, in 2010 and 2015, and this showed an increase of 1.8% (CBS & GNH, 2016). Like most emerging countries, Bhutan wants to increase its wealth and become a middle-income country (RGoB, 2013, 2016), while remaining carbon-neutral – a goal which has been in place since 2009 at COP15 and was reiterated in its Intended Nationally Determined Contribution (NEC, 2015). Bhutan achieves its current carbon-neutral status through hydropower and forest cover (Yangka and Diesendorf, 2016), which are part of its resilience and adaptation strategy.

Nevertheless, Bhutan faces rising GHG emissions. Transport and industry are the largest growth areas (NEC, 2011). Bhutan's carbon-neutral status would be threatened by 2044 with business-as-usual approaches to economic growth (Yangka and Newman, 2018). Increases in hydropower are being planned based on climate change scenarios that suggest sufficient water supply will be available (NEC, 2011). Forest cover is expected to remain sufficient to maintain co-benefits. The biggest challenge is to electrify both freight and passenger transport (ADB, 2013). Bhutan wants to be a model for achieving economic growth consistent with limiting climate change to 1.5°C and improving its GNHI (Michaelowa et al., 2018) through synthesizing all three goals and improving its adaptive capacity.

4.6 Knowledge Gaps and Key Uncertainties

The global response to limiting warming to 1.5°C is a new knowledge area, which has emerged after the Paris Agreement. This section presents a number of knowledge gaps that have emerged from the assessment of mitigation, adaptation and carbon dioxide removal (CDR) options and solar radiation modification (SRM) measures; enabling conditions; and synergies and trade-offs. Illustrative questions that emerge synthesizing the more comprehensive Table 4.13 below include: how much can be realistically expected from innovation, behaviour and systemic political and economic change in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organized within a global governance framework and financial system, based on principles of justice and ethics (CBDR-RC), reciprocity and partnership? To what extent would limiting warming to 1.5°C require a harmonization of macro-financial and fiscal policies, which could include central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives?

These knowledge gaps are highlighted in Table 4.13 along with a cross-reference to the respective sections in the last column.

Table 4.13 | Knowledge gaps and uncertainties

Knowledge Area		Mitigation	Adaptation	Reference
1.5°C Pathways and Ensuing Change		• Lack of literature specific to 1.5°C on investment costs with detailed breakdown by technology • Lack of literature specific to 1.5°C on mitigation costs in terms of GDP and welfare • Lack of literature on distributional implications of 1.5°C compared to 2°C or business-as-usual at sectoral and regional levels • Limited 1.5°C-specific case studies for mitigation • Limited knowledge on the systemic and dynamic aspects of transitions to 1.5°C, including how vicious or virtuous circles might work, how self-reinforcing aspects can be actively introduced and managed	• Lack of literature specific to 1.5°C on adaptation costs and need • Lack of literature on what overshoot means for adaptation • Lack of knowledge on avoided adaptation investments associated with limiting warming to 1.5°C, 2°C or business-as-usual • Limited 1.5°C-specific case studies for adaptation • Scant literature examining current or future adaptation options, or examining what different climate pathways mean for adaptation success • Need for transformational adaptation at 1.5°C and beyond remains largely unexplored	4.2
Options to Achieve and Adapt to 1.5°C	Energy Systems	• The shift to variable renewables that many countries are implementing is just reaching a level where large-scale storage systems or other grid flexibility options, e.g., demand response, are required to enable resilient grid systems. Thus, new knowledge on the opportunities and issues associated with scaling up zero-carbon grids would be needed, including knowledge about how zero-carbon electric grids can integrate with the full-scale electrification of transport systems • CCS suffers mostly from uncertainty about the feasibility of timely upscaling, both due to lack of regulatory capacity and concerns about storage safety and cost • There is not much literature on the distributional implications of large-scale bioenergy deployment, the assessment of environmental feasibility is hampered by a diversity of contexts of individual studies (type of feedstock, technology, land availability), which could be improved through emerging meta-studies	• Relatively little literature on individual adaptation options since AR5 • No evidence on socio-cultural acceptability of adaptation options • Lack of regional research on the implementation of adaptation options	4.3.1
	Land & ecosystems	• More knowledge would be needed on how land-based mitigation can be reconciled with land demands for adaptation and development • While there is now more literature on the underlying mechanisms of land transitions, data is often insufficient to draw robust conclusions, and there is uncertainty about land availability • The lack of data on social and institutional information (largest knowledge gap indicated for ecosystems restoration in Table 4.11), which are therefore not widely integrated in land use modelling • Examples of successful policy implementation and institutions related to land-based mitigation leading to co-benefits for adaptation and development are missing from the literature • There is relatively little scientific literature on the effects of dietary shifts and reduction of food wastage on mitigation, especially regarding the institutional, technical and environmental concerns	• Regional information on some options does not exist, especially in the case of land-use transitions • Limited research examining socio-cultural perspectives and impacts of adaptation options, especially for efficient irrigation, coastal defence and hardening, agroforestry and biodiversity management • Lack of longitudinal, regional studies assessing the impacts of certain adaptation options, such as conservation agriculture and shifting to efficient livestock systems • More knowledge is needed on the cost-effectiveness and scalability of various adaptation options. For example, there is no evidence for the macro-economic viability of community-based adaptation (CbA) and biodiversity management, or on employment and productivity enhancement potential for biodiversity management and coastal defence and hardening. • More knowledge is needed on risk mitigation and the potential of biodiversity management • Lack of evidence of the political acceptability of efficient livestock systems • *Limited evidence* on legal and regulatory feasibility of conservation agriculture and no evidence on coastal defence and hardening • For transparency and accountability potential, there is *limited evidence* for conservation agriculture and no evidence for biodiversity management, coastal defence and hardening and sustainable aquaculture • No evidence on hazard risk reduction potential of conservation agriculture and biodiversity management	4.3.2
	Urban & infrastructure systems	• *Limited evidence* of effective land-use planning in low-income cities where tenure and land zoning are contested, and the risks of trying to implement land-use planning under communal tenure • *Limited evidence* on the governance of public transport from an accountability and transparency perspective	• Regional and sectoral adaptation cost assessments are missing, particularly in the context of welfare losses of households, across time and space • More knowledge is needed on the political economy of adaptation, particularly on how to impute different types of cost and benefit in a consistent manner, on adaptation performance indicators that could stimulate investment, and the impact of adaptation interventions on socio-economic and other types of inequality	4.3.3

Table 4.13 (continued)

Knowledge Area		Mitigation	Adaptation	Reference
Options to Achieve and Adapt to 1.5°C	Urban & infrastructure systems	• *Limited evidence* on relationship between toxic waste and public transport • *Limited evidence* on the impacts of electric vehicles and non-motorized urban transport, as most schemes are too new • As changes in shipping and aviation have been limited to date, limited evidence of social impacts • Knowledge about how to facilitate disruptive, demand-based innovations that may be transformative in urban systems, is needed • Understanding of the urban form implications of combined changes from electric, autonomous and shared/public mobility systems, is needed • Considering distributional consequences of climate responses is an on-going need • Knowledge gaps in the application and scale up of combinations of new smart technologies, sustainable design, advanced construction techniques and new insulation materials, renewable energy and behaviour change in urban settlements • The potential for leapfrog technologies to be applied to slums and new urban developments in developing countries is weak.	• More evidence would be needed on hot-spots, for example the growth of peri-urban areas populated by large informal settlements • Major uncertainties emanate from the lack of knowledge on the integration of climate adaptation and mitigation, disaster risk management, and urban poverty alleviation • There is *limited evidence* on the institutional, technological and economic feasibility of green infrastructure and environmental services and for socio-cultural and environmental feasibility of codes and standards • In general, there is no evidence for the employment and productivity enhancement potential of most adaptation options. • There is *limited evidence* on the economic feasibility of sustainable water management	4.3.3
	Industrial systems	• Lack of knowledge on potential for scaling up and global diffusion of zero- and low-emission technologies in industry • Questions remain on the socio-cultural feasibility of industry options, including human capacity and private sector acceptance of new, radically different technologies from current well-developed practices, as well as distributional effects of potential new business models • As the industrial transition unfolds, lack of knowledge on its dynamic interactions with other sectors, in particular with the power sector (and infrastructure) for electrification of industry, with food production and other users of biomass in case of bio-based industry developments, and with CDR technologies in the case of CC(U)S • Life-cycle assessment-based comparative analyses of CCUS options are missing, as well as life-cycle information on electrification and hydrogen • Impacts of industrial system transitions are not well understood, especially on employment, identity and well-being, in particular in the case of substitution of conventional, high-carbon industrial products with lower-carbon alternatives, as well as electrification and use of hydrogen	• *Very limited evidence* on how industry would adapt to the consequences of 1.5°C or 2°C temperature increases, in particular large and immobile industrial clusters in low-lying areas as well as availability of transportation and (cooling) water resources and infrastructure • There is *limited evidence* on the economic, institutional and socio-cultural feasibility of adaptation options available to industry	4.3.4
	Overarching adaptation options	• There is no evidence on technical and institutional feasibility of educational options • There is *limited evidence* on employment and productivity enforcement potential of climate services • There is *limited evidence* on socio-cultural acceptability of social safety nets • There is a small but growing literature on human migration as an adaptation strategy. Scant literature on the cost-effectiveness of migration		4.3.5
	Short-lived climate forcers	• *Limited evidence* of co-benefits and trade-offs of SLCF reduction (e.g., better health outcomes, agricultural productivity improvements) • Integration of SLCFs into emissions accounting and international reporting mechanisms enabling a better understanding of the links between black carbon, air pollution, climate change and agricultural productivity		4.3.6

Table 4.13 (continued)

Knowledge Area		Mitigation	Adaptation	Reference
Options to Achieve and Adapt to 1.5°C	Carbon dioxide removal	• A bottom-up analysis of CDR options indicates that there are still key uncertainties around the individual technologies. Ocean-based options will be assessed in depth in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) • Assessments of environmental aspects are missing, especially for 'newer' options like enhanced weathering or direct air carbon capture • In order to obtain more information on realistically available and sustainable removal potentials, more bottom-up, regional studies, also taking into account also social issues, would be needed. These can better inform the modelling of 1.5°C pathways • Knowledge gaps on issues of governance and public acceptance, the impacts of large-scale removals on the carbon cycle, the potential to accelerate deployment and upscaling, and means of incentivization • Knowledge gaps on integrated systems of renewable energy and CDR technologies such as enhanced weathering and DACCS • Knowledge gaps on under which conditions the use of captured CO_2 is generating negative emissions and would qualify as a mitigation option		4.3.7
Solar radiation modification (SRM)		• In spite of increasing attention to the different SRM measures and their potential to keep global temperature below 1.5°C, knowledge gaps remain, not only with respect to the physical understanding of SRM measures but also concerning ethical issues • We do not know how to govern SRM in order to avoid unilateral action and how to prevent possible reductions in mitigation ('moral hazard')		4.3.8
Enabling Conditions	Governance	• As technological changes have begun to accelerate, there is a lack of knowledge on new mechanisms that can enable private enterprise to mainstream this activity, and reasons for success and failure need to be researched • Research is thin on effective multilevel governance, in particular in developing countries, including participation by civil society, women and minorities • Gaps in knowledge remain pertaining to partnerships within local governance arrangements that may act as mediators and drivers for achieving global ambition and local action • Methods for assessing contribution and aggregation of non-state actors in limiting warming to 1.5°C • Knowledge gap on an enhanced framework for assessment of the ambition of NDCs	• The ability to identify explanatory factors affecting the progress of climate policy is constrained by a lack of data on adaptation actions across nations, regions, and sectors, compounded by an absence of frameworks for assessing progress. Most hypotheses on what drives adaptation remain untested • Limited empirical assessment of how governance affects adaptation across cases • Focus on 'success' stories and leading adaptors overlooks lessons from situations where no or unsuccessful adaptation is taking place	4.4.1
	Institutions	• Lack of 1.5°C-specific literature • Role of regulatory financial institutions and their capacity to guarantee financial stability of economies when investments potentially face risks, both because of climate impacts and because of the systems transitions if lower temperature scenarios are pursued • Knowledge gaps on how to build capabilities across all countries and regions globally to implement, maintain, manage, govern and further develop mitigation options for 1.5°C. • While importance of indigenous and local knowledge is recognized, the ability to scale up beyond the local remains challenging and little examined • There is a lack of monitoring and evaluation (M&E) of adaptation measures, with most studies enumerating M&E challenges and emphasising the importance of context and social learning. Very few studies evaluate whether and why an adaptation initiative has been effective. One of the challenges of M&E for both mitigation and adaptation is a lack of high quality information for modelling. Adaptation M&E is additionally challenged by limited understanding on what indicators to measure and how to attribute altered vulnerability to adaptation actions		4.4.2
	Lifestyle and behavioural change	• Whereas mitigation pathways studies address (implicitly or explicitly) the reduction or elimination of market failures (e.g., external costs, information asymmetries) via climate or energy policies, no study addresses behavioural change strategies in the relationship with mitigation and adaptation actions in the 1.5°C context • Limited knowledge on GHG emissions reduction potential of diverse mitigation behaviour across the world • Most studies on factors enabling lifestyle changes have been conducted in high-income countries, more knowledge needed from low- and middle-income countries, and the focus is typically on enabling individual behaviour change, far less on enabling change in organizations and political systems	• Knowledge gaps on factors enabling adaptation behaviour, except for behaviour in agriculture. • Little is known about cognitive and motivational factors promoting adaptive behaviour. • Little is known about how potential adaptation actions might affect behaviour to influence vulnerability outcomes	4.4.3

Table 4.13 (continued)

Knowledge Area		Mitigation	Adaptation	Reference
Enabling Conditions	Lifestyle and behavioural change	• Limited understanding and treatment of behavioural change and the potential effects of related policies in ambitious mitigation pathways, e.g., in Integrated Assessment Models		4.4.3
		Lack of insight on what can enable changes in adaptation and mitigation behaviour in organizations and political systems		
	Technological innovation	• Quantitative estimates for mitigation and adaptation potentials at economy or sector scale as a result of the combination of general purpose technologies and mitigation technologies have been scarce, except for some evidence in the transport sector • Evidence on the role of international organizations, including the UNFCCC, in building capabilities and enhancing technological innovation for 1.5°C, except for some parts of the transport sector • Technology transfer trials to enable leapfrog applications in developing countries have *limited evidence*		4.4.4
	Policy	• More empirical research would be needed to derive robust conclusions on effectiveness of policies for enabling transitions to 1.5°C and on which factors aid decision-makers seeking to ratchet up their NDCs	• Understanding of what policies work (and do not work) is limited for adaptation in general and for 1.5°C in particular, beyond specific case studies	4.4.5
	Finance	Knowledge gaps persist with respect to the instruments to match finance to its most effective use in mitigation and adaptation		4.4.5
Synergies and Trade-Offs Between Adaptation and Mitigation		• Strong claims are made with respect to synergies and trade-offs, but there is little knowledge to underpin these, especially of co-benefits by region • Water–energy conservation relationships of individual conservation measures in industries other than the water and energy sectors have not been investigated in detail • There is no evidence on synergies with adaptation of CCS in the power sector and of enhanced weathering under carbon dioxide removal • There is no evidence on trade-offs with adaptation of low- and zero-energy buildings, and circularity and substitution and bio-based industrial system transitions • There is no evidence of synergies or trade-offs with mitigation of CbA • There is no evidence of trade-offs with mitigation of the built environment, on adaptation options for industrial energy, and climate services		4.5.4

Frequently Asked Questions

FAQ 4.1 | What Transitions could Enable Limiting Global Warming to 1.5°C?

Summary: *In order to limit warming to 1.5°C above pre-industrial levels, the world would need to transform in a number of complex and connected ways. While transitions towards lower greenhouse gas emissions are underway in some cities, regions, countries, businesses and communities, there are few that are currently consistent with limiting warming to 1.5°C. Meeting this challenge would require a rapid escalation in the current scale and pace of change, particularly in the coming decades. There are many factors that affect the feasibility of different adaptation and mitigation options that could help limit warming to 1.5°C and with adapting to the consequences.*

There are actions across all sectors that can substantially reduce greenhouse gas emissions. This Special Report assesses energy, land and ecosystems, urban and infrastructure, and industry in developed and developing nations to see how they would need to be transformed to limit warming to 1.5°C. Examples of actions include shifting to low- or zero-emission power generation, such as renewables; changing food systems, such as diet changes away from land-intensive animal products; electrifying transport and developing 'green infrastructure', such as building green roofs, or improving energy efficiency by smart urban planning, which will change the layout of many cities.

Because these different actions are connected, a 'whole systems' approach would be needed for the type of transformations that could limit warming to 1.5°C. This means that all relevant companies, industries and stakeholders would need to be involved to increase the support and chance of successful implementation. As an illustration, the deployment of low-emission technology (e.g., renewable energy projects or a bio-based chemical plants) would depend upon economic conditions (e.g., employment generation or capacity to mobilize investment), but also on social/cultural conditions (e.g., awareness and acceptability) and institutional conditions (e.g., political support and understanding).

To limit warming to1.5°C, mitigation would have to be large-scale and rapid. Transitions can be transformative or incremental, and they often, but not always, go hand in hand. Transformative change can arise from growth in demand for a new product or market, such that it displaces an existing one. This is sometimes called 'disruptive innovation'. For example, high demand for LED lighting is now making more energy-intensive, incandescent lighting near-obsolete, with the support of policy action that spurred rapid industry innovation. Similarly, smart phones have become global in use within ten years. But electric cars, which were released around the same time, have not been adopted so quickly because the bigger, more connected transport and energy systems are harder to change. Renewable energy, especially solar and wind, is considered to be disruptive by some as it is rapidly being adopted and is transitioning faster than predicted. But its demand is not yet uniform. Urban systems that are moving towards transformation are coupling solar and wind with battery storage and electric vehicles in a more incremental transition, though this would still require changes in regulations, tax incentives, new standards, demonstration projects and education programmes to enable markets for this system to work.

Transitional changes are already underway in many systems, but limiting warming to 1.5°C would require a rapid escalation in the scale and pace of transition, particularly in the next 10–20 years. While limiting warming to 1.5°C would involve many of the same types of transitions as limiting warming to 2°C, the pace of change would need to be much faster. While the pace of change that would be required to limit warming to 1.5°C can be found in the past, there is no historical precedent for the scale of the necessary transitions, in particular in a socially and economically sustainable way. Resolving such speed and scale issues would require people's support, public-sector interventions and private-sector cooperation.

Different types of transitions carry with them different associated costs and requirements for institutional or governmental support. Some are also easier to scale up than others, and some need more government support than others. Transitions between, and within, these systems are connected and none would be sufficient on its own to limit warming to 1.5°C.

The 'feasibility' of adaptation and mitigation options or actions within each system that together can limit warming to 1.5°C within the context of sustainable development and efforts to eradicate poverty requires careful consideration of multiple different factors. These factors include: (i) whether sufficient natural systems and resources are available to support the various options for transitioning (known as *environmental feasibility*); (ii) the degree to which the required technologies are developed and available (known as *technological feasibility*);

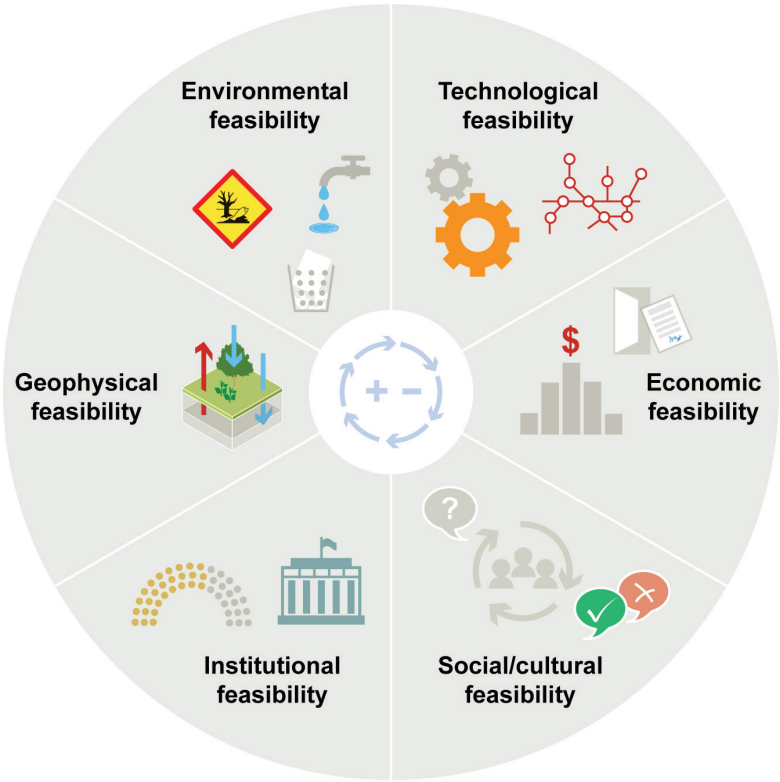
FAQ 4.1 (continued)

(iii) the economic conditions and implications (known as *economic feasibility*); (iv) what are the implications for human behaviour and health (known as *social/cultural feasibility*); and (v) what type of institutional support would be needed, such as governance, institutional capacity and political support (known as *institutional feasibility*). An additional factor (vi – known as the *geophysical feasibility*) addresses the capacity of physical systems to carry the option, for example, whether it is geophysically possible to implement large-scale afforestation consistent with 1.5°C.

Promoting enabling conditions, such as finance, innovation and behaviour change, would reduce barriers to the options, make the required speed and scale of the system transitions more likely, and therefore would increase the overall feasibility limiting warming to 1.5°C.

FAQ4.1: **The different feasibility dimensions towards limiting warming to 1.5°C**

Assessing the feasibility of different adaptation and mitigation options/actions requires consideration across six dimensions.



FAQ 4.1, Figure 1 | The different dimensions to consider when assessing the 'feasibility' of adaptation and mitigation options or actions within each system that can help to limit warming to 1.5°C. These are: (i) the environmental feasibility; (ii) the technological feasibility; (iii) the economic feasibility; (iv) the social/cultural feasibility; (v) the institutional feasibility; and (vi) the geophysical feasibility.

Frequently Asked Questions

FAQ 4.2 | What are Carbon Dioxide Removal and Negative Emissions?

Summary: *Carbon dioxide removal (CDR) refers to the process of removing CO_2 from the atmosphere. Since this is the opposite of emissions, practices or technologies that remove CO_2 are often described as achieving 'negative emissions'. The process is sometimes referred to more broadly as greenhouse gas removal if it involves removing gases other than CO_2. There are two main types of CDR: either enhancing existing natural processes that remove carbon from the atmosphere (e.g., by increasing its uptake by trees, soil, or other 'carbon sinks') or using chemical processes to, for example, capture CO_2 directly from the ambient air and store it elsewhere (e.g., underground). All CDR methods are at different stages of development and some are more conceptual than others, as they have not been tested at scale.*

Limiting warming to 1.5°C above pre-industrial levels would require unprecedented rates of transformation in many areas, including in the energy and industrial sectors, for example. Conceptually, it is possible that techniques to draw CO_2 out of the atmosphere (known as carbon dioxide removal, or CDR) could contribute to limiting warming to 1.5°C. One use of CDR could be to compensate for greenhouse gas emissions from sectors that cannot completely decarbonize, or which may take a long time to do so.

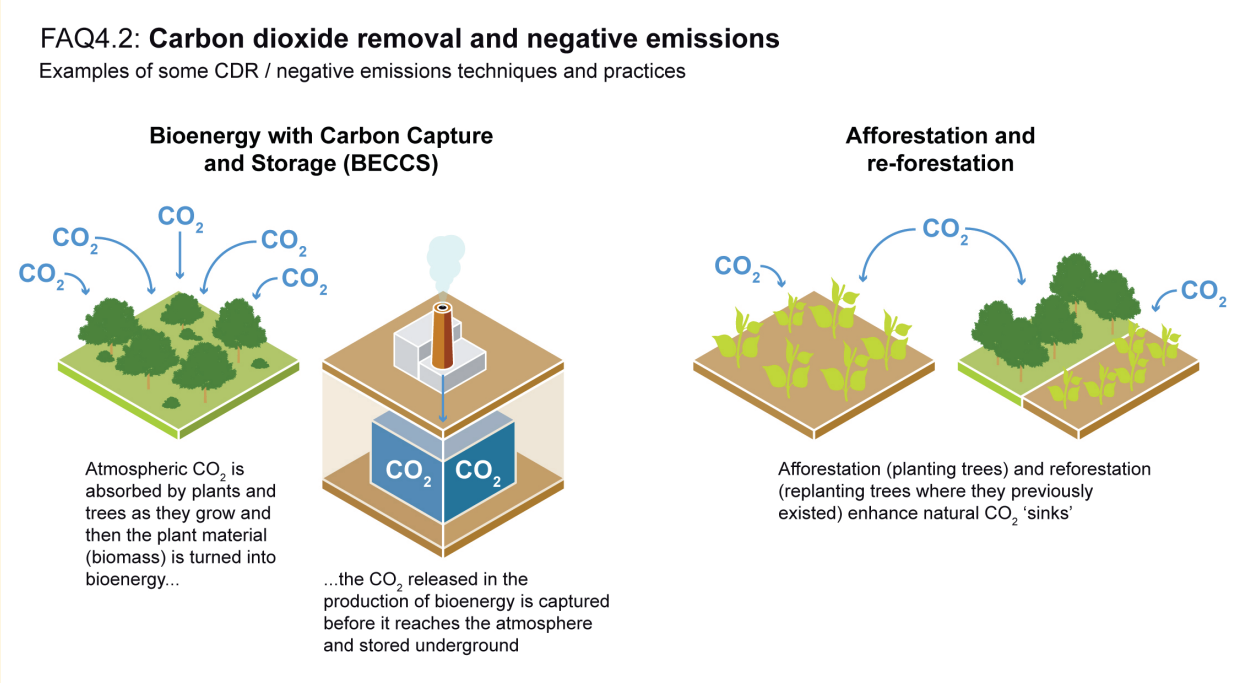
If global temperature temporarily overshoots 1.5°C, CDR would be required to reduce the atmospheric concentration of CO_2 to bring global temperature back down. To achieve this temperature reduction, the amount of CO_2 drawn out of the atmosphere would need to be greater than the amount entering the atmosphere, resulting in 'net negative emissions'. This would involve a greater amount of CDR than stabilizing atmospheric CO_2 concentration – and, therefore, global temperature – at a certain level. The larger and longer an overshoot, the greater the reliance on practices that remove CO_2 from the atmosphere.

There are a number of CDR methods, each with different potentials for achieving negative emissions, as well as different associated costs and side effects. They are also at differing levels of development, with some more conceptual than others. One example of a CDR method in the demonstration phase is a process known as bioenergy with carbon capture and storage (BECCS), in which atmospheric CO_2 is absorbed by plants and trees as they grow, and then the plant material (biomass) is burned to produce bioenergy. The CO_2 released in the production of bioenergy is captured before it reaches the atmosphere and stored in geological formations deep underground on very long time scales. Since the plants absorb CO_2 as they grow and the process does not emit CO_2, the overall effect can be to reduce atmospheric CO_2.

Afforestation (planting new trees) and reforestation (replanting trees where they previously existed) are also considered forms of CDR because they enhance natural CO_2 'sinks'. Another category of CDR techniques uses chemical processes to capture CO_2 from the air and store it away on very long time scales. In a process known as direct air carbon capture and storage (DACCS), CO_2 is extracted directly from the air and stored in geological formations deep underground. Converting waste plant material into a charcoal-like substance called biochar and burying it in soil can also be used to store carbon away from the atmosphere for decades to centuries.

There can be beneficial side effects of some types of CDR, other than removing CO_2 from the atmosphere. For example, restoring forests or mangroves can enhance biodiversity and protect against flooding and storms. But there could also be risks involved with some CDR methods. For example, deploying BECCS at large scale would require a large amount of land to cultivate the biomass required for bioenergy. This could have consequences for sustainable development if the use of land competes with producing food to support a growing population, biodiversity conservation or land rights. There are also other considerations. For example, there are uncertainties about how much it would cost to deploy DACCS as a CDR technique, given that removing CO_2 from the air requires considerable energy.

FAQ 4.2 (continued)



FAQ 4.2, Figure 1 | Carbon dioxide removal (CDR) refers to the process of removing CO_2 from the atmosphere. There are a number of CDR techniques, each with different potential for achieving 'negative emissions', as well as different associated costs and side effects.

Frequently Asked Questions

FAQ 4.3 | Why is Adaptation Important in a 1.5°C-Warmer World?

Summary: *Adaptation is the process of adjusting to current or expected changes in climate and its effects. Even though climate change is a global problem, its impacts are experienced differently across the world. This means that responses are often specific to the local context, and so people in different regions are adapting in different ways. A rise in global temperature from the current 1°C above pre-industrial levels to 1.5°C, and beyond, increases the need for adaptation. Therefore, stabilizing global temperatures at 1.5°C above pre-industrial levels would require a smaller adaptation effort than at 2°C. Despite many successful examples around the world, progress in adaptation is, in many regions, in its infancy and unevenly distributed globally.*

Adaptation refers to the process of adjustment to actual or expected changes in climate and its effects. Since different parts of the world are experiencing the impacts of climate change differently, there is similar diversity in how people in a given region are adapting to those impacts.

The world is already experiencing the impacts from 1°C of global warming above pre-industrial levels, and there are many examples of adaptation to impacts associated with this warming. Examples of adaptation efforts taking place around the world include investing in flood defences such as building sea walls or restoring mangroves, efforts to guide development away from high risk areas, modifying crops to avoid yield reductions, and using social learning (social interactions that change understanding on the community level) to modify agricultural practices, amongst many others. Adaptation also involves building capacity to respond better to climate change impacts, including making governance more flexible and strengthening financing mechanisms, such as by providing different types of insurance.

In general, an increase in global temperature from present day to 1.5°C or 2°C (or higher) above pre-industrial temperatures would increase the need for adaptation. Stabilizing global temperature increase at 1.5°C would require a smaller adaptation effort than for 2°C.

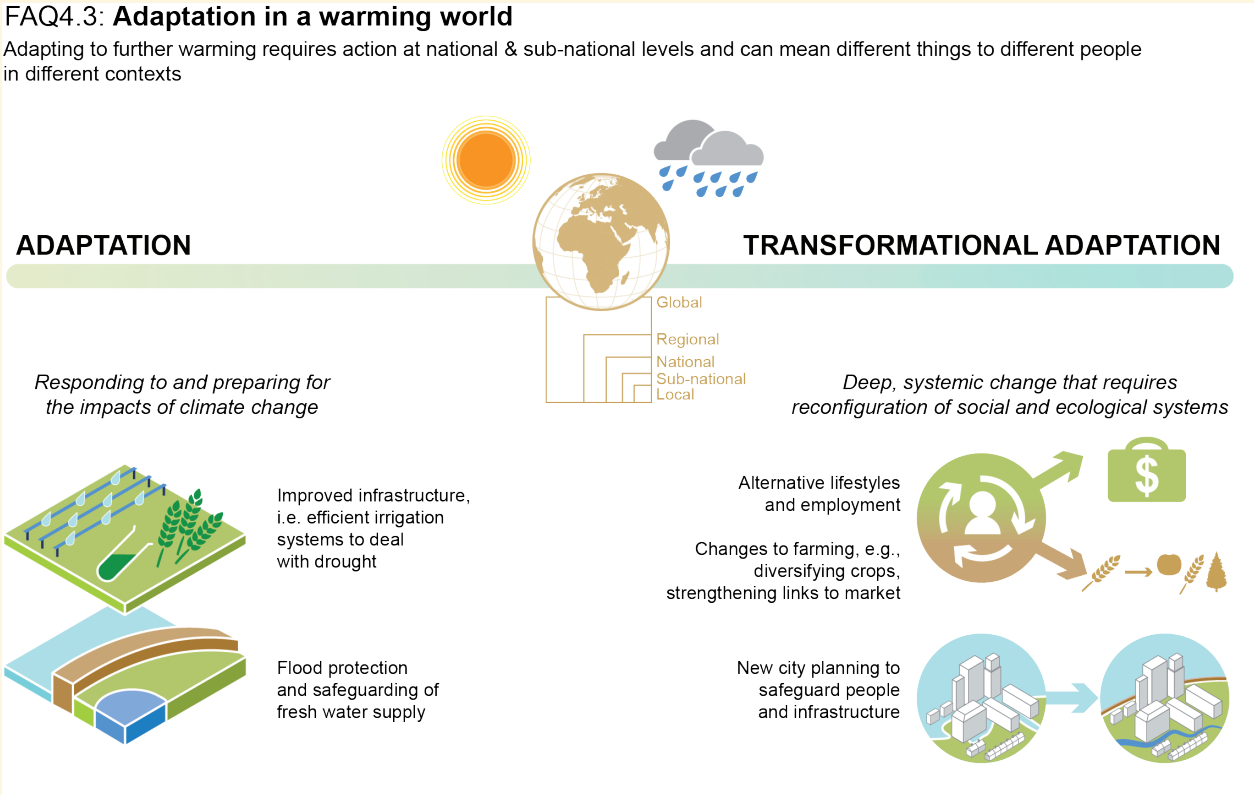
Since adaptation is still in early stages in many regions, there are questions about the capacity of vulnerable communities to cope with any amount of further warming. Successful adaptation can be supported at the national and sub-national levels, with national governments playing an important role in coordination, planning, determining policy priorities, and distributing resources and support. However, given that the need for adaptation can be very different from one community to the next, the kinds of measures that can successfully reduce climate risks will also depend heavily on the local context.

When done successfully, adaptation can allow individuals to adjust to the impacts of climate change in ways that minimize negative consequences and to maintain their livelihoods. This could involve, for example, a farmer switching to drought-tolerant crops to deal with increasing occurrences of heatwaves. In some cases, however, the impacts of climate change could result in entire systems changing significantly, such as moving to an entirely new agricultural system in areas where the climate is no longer suitable for current practices. Constructing sea walls to stop flooding due to sea level rise from climate change is another example of adaptation, but developing city planning to change how flood water is managed throughout the city would be an example of transformational adaptation. These actions require significantly more institutional, structural, and financial support. While this kind of transformational adaptation would not be needed everywhere in a 1.5°C world, the scale of change needed would be challenging to implement, as it requires additional support, such as through financial assistance and behavioural change. Few empirical examples exist to date.

Examples from around the world show that adaptation is an iterative process. Adaptation pathways describe how communities can make decisions about adaptation in an ongoing and flexible way. Such pathways allow for pausing, evaluating the outcomes of specific adaptation actions, and modifying the strategy as appropriate. Due to their flexible nature, adaptation pathways can help to identify the most effective ways to minimise the impacts of present and future climate change for a given local context. This is important since adaptation can sometimes exacerbate vulnerabilities and existing inequalities if poorly designed. The unintended negative consequences of adaptation that can sometimes occur are known as 'maladaptation'. Maladaptation can be seen if a particular adaptation option has negative consequences for some (e.g., rainwater harvesting upstream might reduce water availability downstream) or if an adaptation intervention in the present has trade-offs in the future (e.g., desalination plants may improve water availability in the present but have large energy demands over time).

FAQ 4.3 (continued)

While adaptation is important to reduce the negative impacts from climate change, adaptation measures on their own are not enough to prevent climate change impacts entirely. The more global temperature rises, the more frequent, severe, and erratic the impacts will be, and adaptation may not protect against all risks. Examples of where limits may be reached include substantial loss of coral reefs, massive range losses for terrestrial species, more human deaths from extreme heat, and losses of coastal-dependent livelihoods in low lying islands and coasts.



FAQ 4.3, Figure 1 | Why is adaptation important in a world with global warming of 1.5°C? Examples of adaptation and transformational adaptation. Adapting to further warming requires action at national and sub-national levels and can mean different things to different people in different contexts. While transformational adaptation would not be needed everywhere in a world limited to 1.5°C warming, the scale of change needed would be challenging to implement.

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5

Sustainable Development, Poverty Eradication and Reducing Inequalities

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5

Executive Summary

This chapter takes sustainable development as the starting point and focus for analysis. It considers the broad and multifaceted bi-directional interplay between sustainable development, including its focus on eradicating poverty and reducing inequality in their multidimensional aspects, and climate actions in a 1.5°C warmer world. These fundamental connections are embedded in the Sustainable Development Goals (SDGs). The chapter also examines synergies and trade-offs of adaptation and mitigation options with sustainable development and the SDGs and offers insights into possible pathways, especially climate-resilient development pathways towards a 1.5°C warmer world.

Sustainable Development, Poverty and Inequality in a 1.5°C Warmer World

Limiting global warming to 1.5°C rather than 2°C above pre-industrial levels would make it markedly easier to achieve many aspects of sustainable development, with greater potential to eradicate poverty and reduce inequalities (*medium evidence, high agreement*). Impacts avoided with the lower temperature limit could reduce the number of people exposed to climate risks and vulnerable to poverty by 62 to 457 million, and lessen the risks of poor people to experience food and water insecurity, adverse health impacts, and economic losses, particularly in regions that already face development challenges (*medium evidence, medium agreement*). {5.2.2, 5.2.3} Avoided impacts expected to occur between 1.5°C and 2°C warming would also make it easier to achieve certain SDGs, such as those that relate to poverty, hunger, health, water and sanitation, cities and ecosystems (SDGs 1, 2, 3, 6, 11, 14 and 15) (*medium evidence, high agreement*). {5.2.3, Table 5.2 available at the end of the chapter}

Compared to current conditions, 1.5°C of global warming would nonetheless pose heightened risks to eradicating poverty, reducing inequalities and ensuring human and ecosystem well-being (*medium evidence, high agreement*). Warming of 1.5°C is not considered 'safe' for most nations, communities, ecosystems and sectors and poses significant risks to natural and human systems as compared to the current warming of 1°C (*high confidence*). {Cross-Chapter Box 12 in Chapter 5} The impacts of 1.5°C of warming would disproportionately affect disadvantaged and vulnerable populations through food insecurity, higher food prices, income losses, lost livelihood opportunities, adverse health impacts and population displacements (*medium evidence, high agreement*). {5.2.1} Some of the worst impacts on sustainable development are expected to be felt among agricultural and coastal dependent livelihoods, indigenous people, children and the elderly, poor labourers, poor urban dwellers in African cities, and people and ecosystems in the Arctic and Small Island Developing States (SIDS) (*medium evidence, high agreement*). {5.2.1, Box 5.3, Chapter 3, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

Climate Adaptation and Sustainable Development

Prioritization of sustainable development and meeting the SDGs is consistent with efforts to adapt to climate change (*high confidence*). Many strategies for sustainable development enable transformational adaptation for a 1.5°C warmer world, provided attention is paid to reducing poverty in all its forms and to promoting equity and participation in decision-making (*medium evidence, high agreement*). As such, sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (*high confidence*). {5.3.1}

Synergies between adaptation strategies and the SDGs are expected to hold true in a 1.5°C warmer world, across sectors and contexts (*medium evidence, medium agreement*). Synergies between adaptation and sustainable development are significant for agriculture and health, advancing SDGs 1 (extreme poverty), 2 (hunger), 3 (healthy lives and well-being) and 6 (clean water) (*robust evidence, medium agreement*). {5.3.2} Ecosystem- and community-based adaptation, along with the incorporation of indigenous and local knowledge, advances synergies with SDGs 5 (gender equality), 10 (reducing inequalities) and 16 (inclusive societies), as exemplified in drylands and the Arctic (*high evidence, medium agreement*). {5.3.2, Box 5.1, Cross-Chapter Box 10 in Chapter 4}

Adaptation strategies can result in trade-offs with and among the SDGs (*medium evidence, high agreement*). Strategies that advance one SDG may create negative consequences for other SDGs, for instance SDGs 3 (health) versus 7 (energy consumption) and agricultural adaptation and SDG 2 (food security) versus SDGs 3 (health), 5 (gender equality), 6 (clean water), 10 (reducing inequalities), 14 (life below water) and 15 (life on the land) (*medium evidence, medium agreement*). {5.3.2}

Pursuing place-specific adaptation pathways towards a 1.5°C warmer world has the potential for significant positive outcomes for well-being in countries at all levels of development (*medium evidence, high agreement*). Positive outcomes emerge when adaptation pathways (i) ensure a diversity of adaptation options based on people's values and the trade-offs they consider acceptable, (ii) maximize synergies with sustainable development through inclusive, participatory and deliberative processes, and (iii) facilitate equitable transformation. Yet such pathways would be difficult to achieve without redistributive measures to overcome path dependencies, uneven power structures, and entrenched social inequalities (*medium evidence, high agreement*). {5.3.3}

Mitigation and Sustainable Development

The deployment of mitigation options consistent with 1.5°C pathways leads to multiple synergies across a range of sustainable development dimensions. At the same time, the rapid pace and magnitude of change that would be required to limit warming to 1.5°C, if not carefully managed, would lead to trade-offs with some sustainable development dimensions (*high confidence*). The number of synergies between mitigation response options and sustainable development exceeds the number of trade-offs in energy demand and supply sectors; agriculture, forestry and other land use (AFOLU); and for oceans (*very high confidence*). {Figure 5.2, Table 5.2 available at the end of the chapter} The 1.5°C

pathways indicate robust synergies, particularly for the SDGs 3 (health), 7 (energy), 12 (responsible consumption and production) and 14 (oceans) (*very high confidence*). {5.4.2, Figure 5.3} For SDGs 1 (poverty), 2 (hunger), 6 (water) and 7 (energy), there is a risk of trade-offs or negative side effects from stringent mitigation actions compatible with 1.5°C of warming (*medium evidence, high agreement*). {5.4.2}

Appropriately designed mitigation actions to reduce energy demand can advance multiple SDGs simultaneously. Pathways compatible with 1.5°C that feature low energy demand show the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*very high confidence*). Accelerating energy efficiency in all sectors has synergies with SDGs 7 (energy), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production), 16 (peace, justice and strong institutions), and 17 (partnerships for the goals) (*robust evidence, high agreement*). {5.4.1, Figure 5.2, Table 5.2} Low-demand pathways, which would reduce or completely avoid the reliance on bioenergy with carbon capture and storage (BECCS) in 1.5°C pathways, would result in significantly reduced pressure on food security, lower food prices and fewer people at risk of hunger (*medium evidence, high agreement*). {5.4.2, Figure 5.3}

The impacts of carbon dioxide removal options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, carbon dioxide removal (CDR) options such as bioenergy, BECCS and AFOLU would lead to trade-offs. Appropriate design and implementation requires considering local people's needs, biodiversity and other sustainable development dimensions (*very high confidence*). {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

The design of the mitigation portfolios and policy instruments to limit warming to 1.5°C will largely determine the overall synergies and trade-offs between mitigation and sustainable development (*very high confidence*). Redistributive policies that shield the poor and vulnerable can resolve trade-offs for a range of SDGs (*medium evidence, high agreement*). Individual mitigation options are associated with both positive and negative interactions with the SDGs (*very high confidence*). {5.4.1} However, appropriate choices across the mitigation portfolio can help to maximize positive side effects while minimizing negative side effects (*high confidence*). {5.4.2, 5.5.2} Investment needs for complementary policies resolving trade-offs with a range of SDGs are only a small fraction of the overall mitigation investments in 1.5°C pathways (*medium evidence, high agreement*). {5.4.2, Figure 5.4} Integration of mitigation with adaptation and sustainable development compatible with 1.5°C warming requires a systems perspective (*high confidence*). {5.4.2, 5.5.2}

Mitigation consistent with 1.5°C of warming create high risks for sustainable development in countries with high dependency on fossil fuels for revenue and employment generation (*high confidence*). These risks are caused by the reduction of global demand affecting mining activity and export revenues and challenges to rapidly decrease high carbon intensity of the domestic economy (*robust evidence, high agreement*). {5.4.1.2, Box 5.2} Targeted policies that promote diversification of the economy and the energy sector could ease this transition (*medium evidence, high agreement*). {5.4.1.2, Box 5.2}

Sustainable Development Pathways to 1.5°C

Sustainable development broadly supports and often enables the fundamental societal and systems transformations that would be required for limiting warming to 1.5°C above pre-industrial levels (*high confidence*). Simulated pathways that feature the most sustainable worlds (e.g., Shared Socio-Economic Pathways (SSP) 1) are associated with relatively lower mitigation and adaptation challenges and limit warming to 1.5°C at comparatively lower mitigation costs. In contrast, development pathways with high fragmentation, inequality and poverty (e.g., SSP3) are associated with comparatively higher mitigation and adaptation challenges. In such pathways, it is not possible to limit warming to 1.5°C for the vast majority of the integrated assessment models (*medium evidence, high agreement*). {5.5.2} In all SSPs, mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways. No pathway in the literature integrates or achieves all 17 SDGs (*high confidence*). {5.5.2} Real-world experiences at the project level show that the actual integration between adaptation, mitigation and sustainable development is challenging as it requires reconciling trade-offs across sectors and spatial scales (*very high confidence*). {5.5.1}

Without societal transformation and rapid implementation of ambitious greenhouse gas reduction measures, pathways to limiting warming to 1.5°C and achieving sustainable development will be exceedingly difficult, if not impossible, to achieve (*high confidence*). The potential for pursuing such pathways differs between and within nations and regions, due to different development trajectories, opportunities and challenges (*very high confidence*). {5.5.3.2, Figure 5.1} Limiting warming to 1.5°C would require all countries and non-state actors to strengthen their contributions without delay. This could be achieved through sharing efforts based on bolder and more committed cooperation, with support for those with the least capacity to adapt, mitigate and transform (*medium evidence, high agreement*). {5.5.3.1, 5.5.3.2} Current efforts towards reconciling low-carbon trajectories and reducing inequalities, including those that avoid difficult trade-offs associated with transformation, are partially successful yet demonstrate notable obstacles (*medium evidence, medium agreement*). {5.5.3.3, Box 5.3, Cross-Chapter Box 13 in this chapter}

Social justice and equity are core aspects of climate-resilient development pathways for transformational social change. Addressing challenges and widening opportunities between and within countries and communities would be necessary to achieve sustainable development and limit warming to 1.5°C, without making the poor and disadvantaged worse off (*high confidence*). Identifying and navigating inclusive and socially acceptable pathways towards low-carbon, climate-resilient futures is a challenging yet important endeavour, fraught with moral, practical and political difficulties and inevitable trade-offs (*very high confidence*). {5.5.2, 5.5.3.3, Box 5.3} It entails deliberation and problem-solving

processes to negotiate societal values, well-being, risks and resilience and to determine what is desirable and fair, and to whom (*medium evidence, high agreement*). Pathways that encompass joint, iterative planning and transformative visions, for instance in Pacific SIDS like Vanuatu and in urban contexts, show potential for liveable and sustainable futures (*high confidence*). {5.5.3.1, 5.5.3.3, Figure 5.5, Box 5.3, Cross-Chapter Box 13 in this chapter}

The fundamental societal and systemic changes to achieve sustainable development, eradicate poverty and reduce inequalities while limiting warming to 1.5°C would require meeting a set of institutional, social, cultural, economic and technological conditions (*high confidence*). The coordination and monitoring of policy actions across sectors and spatial scales is essential to support sustainable development in 1.5°C warmer conditions (*very high confidence*). {5.6.2, Box 5.3} External funding and technology transfer better support these efforts when they consider recipients' context-specific needs (*medium evidence, high agreement*). {5.6.1} Inclusive processes can facilitate transformations by ensuring participation, transparency, capacity building and iterative social learning (*high confidence*). {5.5.3.3, Cross-Chapter Box 13, 5.6.3} Attention to power asymmetries and unequal opportunities for development, among and within countries, is key to adopting 1.5°C-compatible development pathways that benefit all populations (*high confidence*). {5.5.3, 5.6.4, Box 5.3} Re-examining individual and collective values could help spur urgent, ambitious and cooperative change (*medium evidence, high agreement*). {5.5.3, 5.6.5}

5.1 Scope and Delineations

This chapter takes sustainable development as the starting point and focus for analysis, considering the broader bi-directional interplay and multifaceted interactions between development patterns and climate actions in a 1.5°C warmer world and in the context of eradicating poverty and reducing inequality. It assesses the impacts of keeping temperatures at or below 1.5°C of global warming above pre-industrial levels on sustainable development and compares the impacts avoided at 1.5°C compared to 2°C (Section 5.2). It then examines the interactions, synergies and trade-offs of adaptation (Section 5.3) and mitigation (Section 5.4) measures with sustainable development and the Sustainable Development Goals (SDGs). The chapter offers insights into possible pathways towards a 1.5°C warmer world, especially through climate-resilient development pathways providing a comprehensive vision across different contexts (Section 5.5). The chapter also identifies the conditions that would be needed to simultaneously achieve sustainable development, poverty eradication, the reduction of inequalities, and the 1.5°C climate objective (Section 5.6).

5.1.1 Sustainable Development, SDGs, Poverty Eradication and Reducing Inequalities

Chapter 1 (see Cross-Chapter Box 4 in Chapter 1) defines sustainable development as 'development that meets the needs of the present and future generations' through balancing economic, social and environmental considerations, and then introduces the United Nations (UN) 2030 Agenda for Sustainable Development, which sets out 17 ambitious goals for sustainable development for all countries by 2030. These SDGs are: no poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), quality education (SDG 4), gender equality (SDG 5), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9), reduced inequalities (SDG 10), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), peace, justice and strong institutions (SDG 16) and partnerships for the goals (SDG 17).

The IPCC Fifth Assessment Report (AR5) included extensive discussion of links between climate and sustainable development, especially in Chapter 13 (Olsson et al., 2014) and Chapter 20 (Denton et al., 2014) in Working Group II and Chapter 4 (Fleurbaey et al., 2014) in Working Group III. However, the AR5 preceded the 2015 adoption of the SDGs and the literature that argues for their fundamental links to climate (Wright et al., 2015; Salleh, 2016; von Stechow et al., 2016; Hammill and Price-Kelly, 2017; ICSU, 2017; Maupin, 2017; Gomez-Echeverri, 2018).

The SDGs build on efforts under the UN Millennium Development Goals to reduce poverty, hunger, and other deprivations. According to the UN, the Millennium Development Goals were successful in reducing poverty and hunger and improving water security (UN, 2015a). However, critics argued that they failed to address within-country disparities, human rights and key environmental concerns, focused only on developing countries, and had numerous measurement and attribution problems (Langford et al., 2013; Fukuda-Parr et al., 2014). While improvements in water security, slums and health may have reduced some aspects of climate vulnerability, increases in incomes were linked to rising greenhouse gas (GHG) emissions and thus to a trade-off between development and climate change (Janetos et al., 2012; UN, 2015a; Hubacek et al., 2017).

While the SDGs capture many important aspects of sustainable development, including the explicit goals of poverty eradication and reducing inequality, there are direct connections from climate to other measures of sustainable development including multidimensional poverty, equity, ethics, human security, well-being and climate-resilient development (Bebbington and Larrinaga, 2014; Robertson, 2014; Redclift and Springett, 2015; Barrington-Leigh, 2016; Helliwell et al., 2018; Kirby and O'Mahony, 2018) (see Glossary). The UN proposes sustainable development as 'eradicating poverty in all its forms and dimensions, combating inequality within and among countries, preserving the planet, creating sustained, inclusive and sustainable economic growth and fostering social inclusion' (UN, 2015b). There is *robust evidence* of the links between climate change and poverty (see Chapter 1, Cross-Chapter Box 4). The AR5 concluded with *high confidence* that disruptive levels of climate change would preclude reducing poverty (Denton et al., 2014; Fleurbaey et al., 2014). International organizations have since stated that climate changes 'undermine the ability of all countries to achieve sustainable development' (UN, 2015b) and can reverse or erase improvements in living conditions and decades of development (Hallegatte et al., 2016).

Climate warming has unequal impacts on different people and places as a result of differences in regional climate changes, vulnerabilities and impacts, and these differences then result in unequal impacts on sustainable development and poverty (Section 5.2). Responses to climate change also interact in complex ways with goals of poverty reduction. The benefits of adaptation and mitigation projects and funding may accrue to some and not others, responses may be costly and unaffordable to some people and countries, and projects may disadvantage some individuals, groups and development initiatives (Sections 5.3 and 5.4, Cross-Chapter Box 11 in Chapter 4).

5.1.2 Pathways to 1.5°C

Pathways to 1.5°C (see Chapter 1, Cross-Chapter Box 1 in Chapter 1, Glossary) include ambitious reductions in emissions and strategies for adaptation that are transformational, as well as complex interactions with sustainable development, poverty eradication and reducing inequalities. The AR5 WGII introduced the concept of climate-resilient development pathways (CRDPs) (see Glossary) which combine adaptation and mitigation to reduce climate change and its impacts, and emphasize the importance of addressing structural and intersecting inequalities, marginalization and multidimensional poverty to 'transform […] the development pathways themselves towards greater social and environmental sustainability, equity, resilience, and justice' (Olsson et al., 2014). This chapter assesses literature on CRDPs relevant to 1.5°C global warming (Section 5.5.3), to understand better the possible societal and systems transformations (see Glossary) that reduce inequality and increase well-being

(Figure 5.1). It also summarizes the knowledge on conditions to achieve such transformations, including changes in technologies, culture, values, financing and institutions that support low-carbon and resilient pathways and sustainable development (Section 5.6).

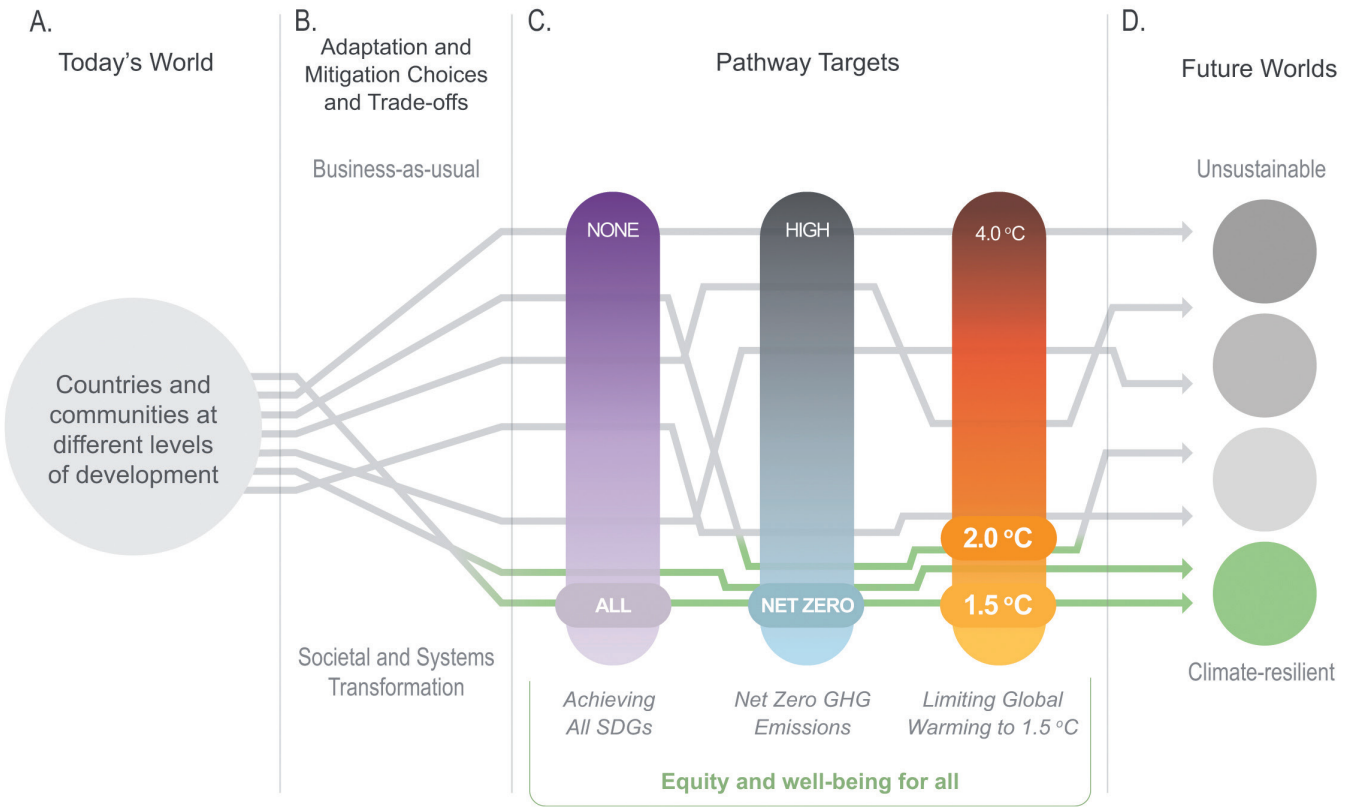

Figure 5.1 | Climate-resilient development pathways (CRDPs) (green arrows) between a current world in which countries and communities exist at different levels of development (A) and future worlds that range from climate-resilient (bottom) to unsustainable (top) (D). CRDPs involve societal transformation rather than business-as-usual approaches, and all pathways involve adaptation and mitigation choices and trade-offs (B). Pathways that achieve the Sustainable Development Goals by 2030 and beyond, strive for net zero emissions around mid-21st century, and stay within the global 1.5°C warming target by the end of the 21st century, while ensuring equity and well-being for all, are best positioned to achieve climate-resilient futures (C). Overshooting on the path to 1.5°C will make achieving CRDPs and other sustainable trajectories more difficult; yet, the limited literature does not allow meaningful estimates.

5.1.3 Types of Evidence

A variety of sources of evidence are used to assess the interactions of sustainable development and the SDGs with the causes, impacts and responses to climate change of 1.5°C warming. This chapter builds on Chapter 3 to assess the sustainable development implications of impacts at 1.5°C and 2°C, and on Chapter 4 to examine the implications of response measures. Scientific and grey literature, with a post-AR5 focus, and data that evaluate, measure and model sustainable development–climate links from various perspectives, quantitatively and qualitatively, across scales, and through well-documented case studies are assessed.

Literature that explicitly links 1.5°C global warming to sustainable development across scales remains scarce; yet we find relevant insights in many recent publications on climate and development that assess impacts across warming levels, the effects of adaptation and mitigation response measures, and interactions with the SDGs. Relevant evidence also stems from emerging literature on possible pathways, overshoot and enabling conditions (see Glossary) for integrating sustainable development, poverty eradication and reducing inequalities in the context of 1.5°C.

5.2 Poverty, Equality and Equity Implications of a 1.5°C Warmer World

Climate change could lead to significant impacts on extreme poverty by 2030 (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). The AR5 concluded, with *very high confidence*, that climate change and climate variability worsen existing poverty and exacerbate inequalities, especially for those disadvantaged by gender, age, race, class, caste, indigeneity and (dis)ability (Olsson et al., 2014). New literature on these links is substantial, showing that the poor will continue to experience climate change severely, and climate change will exacerbate poverty (*very high confidence*) (Fankhauser and Stern, 2016; Hallegatte et al., 2016; O'Neill et al., 2017a; Winsemius et al., 2018). The understanding of regional impacts and risks of 1.5°C global warming and interactions with patterns of societal

vulnerability and poverty remains limited. Yet identifying and addressing poverty and inequality is at the core of staying within a safe and just space for humanity (Raworth, 2017; Bathiany et al., 2018). Building on relevant findings from Chapter 3 (see Section 3.4), this section examines anticipated impacts and risks of 1.5°C and higher warming on sustainable development, poverty, inequality and equity (see Glossary).

5.2.1 Impacts and Risks of a 1.5°C Warmer World: Implications for Poverty and Livelihoods

Global warming of 1.5°C will have consequences for sustainable development, poverty and inequalities. This includes residual risks, limits to adaptation, and losses and damages (Cross-Chapter Box 12 in this chapter; see Glossary). Some regions have already experienced a 1.5°C warming, with impacts on food and water security, health and other components of sustainable development (*medium evidence, medium agreement*) (see Chapter 3, Section 3.4). Climate change is also already affecting poorer subsistence communities through decreases in crop production and quality, increases in crop pests and diseases, and disruption to culture (Savo et al., 2016). It disproportionally affects children and the elderly and can increase gender inequality (Kaijser and Kronsell, 2014; Vinyeta et al., 2015; Carter et al., 2016; Hanna and Oliva, 2016; Li et al., 2016).

At 1.5°C warming, compared to current conditions, further negative consequences are expected for poor people, and inequality and vulnerability (*medium evidence, high agreement*). Hallegatte and Rozenberg (2017) report that by 2030 (roughly approximating a 1.5°C warming), 122 million additional people could experience extreme poverty, based on a 'poverty scenario' of limited socio-economic progress, comparable to the Shared Socio-Economic Pathway (SSP) 4 (inequality), mainly due to higher food prices and declining health, with substantial income losses for the poorest 20% across 92 countries. Pretis et al. (2018) estimate negative impacts on economic growth in lower-income countries at 1.5°C warming, despite uncertainties. Impacts are likely to occur simultaneously across livelihood, food, human, water and ecosystem security (*limited evidence, high agreement*) (Byers et al., 2018), but the literature on interacting and cascading effects remains scarce (Hallegatte et al., 2014; O'Neill et al., 2017b; Reyer et al., 2017a, b).

Chapter 3 outlines future impacts and risks for ecosystems and human systems, many of which could also undermine sustainable development and efforts to eradicate poverty and hunger, and to protect health and ecosystems. Chapter 3 findings (see Section 3.5.2.1) suggest increasing Reasons for Concern from moderate to high at a warming of 1.1° to 1.6°C, including for indigenous people and their livelihoods, and ecosystems in the Arctic (O'Neill et al., 2017b). In 2050, based on the Hadley Centre Climate Prediction Model 3 (HadCM3) and the Special Report on Emission Scenarios A1b scenario (roughly comparable to 1.5°C warming), 450 million more flood-prone people would be exposed to doubling in flood frequency, and global flood risk would increase substantially (Arnell and Gosling, 2016). For droughts, poor people are expected to be more exposed (85% in population terms) in a warming scenario greater than 1.5°C for several countries in Asia and southern and western Africa (Winsemius et al., 2018). In urban Africa, a 1.5°C warming could expose many households to water poverty and increased flooding (Pelling et al., 2018). At 1.5°C warming, fisheries-dependent and coastal livelihoods, of often disadvantaged populations, would suffer from the loss of coral reefs (see Chapter 3, Box 3.4).

Global heat stress is projected to increase in a 1.5°C warmer world, and by 2030, compared to 1961–1990, climate change could be responsible for additional annual deaths of 38,000 people from heat stress, particularly among the elderly, and 48,000 from diarrhoea, 60,000 from malaria, and 95,000 from childhood undernutrition (WHO, 2014). Each 1°C increase could reduce work productivity by 1 to 3% for people working outdoors or without air conditioning, typically the poorer segments of the workforce (Park et al., 2015).

The regional variation in the 'warming experience at 1.5°C' (see Chapter 1, Section 1.3.1) is large (see Chapter 3, Section 3.3.2). Declines in crop yields are widely reported for Africa (60% of observations), with serious consequences for subsistence and rain-fed agriculture and food security (Savo et al., 2016). In Bangladesh, by 2050, damages and losses are expected for poor households dependent on freshwater fish stocks due to lack of mobility, limited access to land and strong reliance on local ecosystems (Dasgupta et al., 2017). Small Island Developing States (SIDS) are expected to experience challenging conditions at 1.5°C warming due to increased risk of internal migration and displacement and limits to adaptation (see Chapter 3, Box 3.5, Cross-Chapter Box 12 in this chapter). An anticipated decline of marine fisheries of 3 million metric tonnes per degree warming would have serious regional impacts for the Indo-Pacific region and the Arctic (Cheung et al., 2016).

5.2.2 Avoided Impacts of 1.5°C versus 2°C Warming for Poverty and Inequality

Avoided impacts between 1.5°C and 2°C warming are expected to have significant positive implications for sustainable development, and reducing poverty and inequality. Using the SSPs (see Chapter 1, Cross-Chapter Box 1 in Chapter 1, Section 5.5.2), Byers et al. (2018) model the number of people exposed to multi-sector climate risks and vulnerable to poverty (income < $10/day), comparing 2°C and 1.5°C; the respective declines are from 86 million to 24 million for SSP1 (sustainability), from 498 million to 286 million for SSP2 (middle of the road), and from 1220 million to 763 million for SSP3 (regional rivalry), which suggests overall 62–457 million fewer people exposed and vulnerable at 1.5°C warming. Across the SSPs, the largest populations exposed and vulnerable are in South Asia (Byers et al., 2018). The avoided impacts on poverty at 1.5°C relative to 2°C are projected to depend at least as much or more on development scenarios than on warming (Wiebe et al., 2015; Hallegatte and Rozenberg, 2017).

Limiting warming to 1.5°C is expected to reduce the number of people exposed to hunger, water stress and disease in Africa (Clements, 2009). It is also expected to limit the number of poor people exposed to floods and droughts at higher degrees of warming, especially in African and Asian countries (Winsemius et al., 2018). Challenges for poor populations – relating to food and water security, clean energy

access and environmental well-being – are projected to be less at 1.5°C, particularly for vulnerable people in Africa and Asia (Byers et al., 2018). The overall projected socio-economic losses compared to the present day are less at 1.5°C (8% loss of gross domestic product per capita) compared to 2°C (13%), with lower-income countries projected to experience greater losses, which may increase economic inequality between countries (Pretis et al., 2018).

5.2.3 Risks from 1.5°C versus 2°C Global Warming and the Sustainable Development Goals

The risks that can be avoided by limiting global warming to 1.5ºC rather than 2°C have many complex implications for sustainable development (ICSU, 2017; Gomez-Echeverri, 2018). There is *high confidence* that constraining warming to 1.5°C rather than 2°C would reduce risks for unique and threatened ecosystems, safeguarding the services they provide for livelihoods and sustainable development and making adaptation much easier (O'Neill et al., 2017b), particularly in Central America, the Amazon, South Africa and Australia (Schleussner et al., 2016; O'Neill et al., 2017b; Reyer et al., 2017b; Bathiany et al., 2018).

In places that already bear disproportionate economic and social challenges to their sustainable development, people will face lower risks at 1.5°C compared to 2°C. These include North Africa and the Levant (less water scarcity), West Africa (less crop loss), South America and Southeast Asia (less intense heat), and many other coastal nations and island states (lower sea level rise, less coral reef loss) (Schleussner et al., 2016; Betts et al., 2018). The risks for food, water and ecosystems, particularly in subtropical regions such as Central America and countries such as South Africa and Australia, are expected to be lower at 1.5°C than at 2°C warming (Schleussner et al., 2016). Fewer people would be exposed to droughts and heat waves and the associated health impacts in countries such as Australia and India (King et al., 2017; Mishra et al., 2017).

Limiting warming to 1.5°C would make it markedly easier to achieve the SDGs for poverty eradication, water access, safe cities, food security, healthy lives and inclusive economic growth, and would help to protect terrestrial ecosystems and biodiversity (*medium evidence, high agreement*) (Table 5.2 available at the end of the chapter). For example, limiting species loss and expanding climate refugia will make it easier to achieve SDG 15 (see Chapter 3, Section 3.4.3). One indication of how lower temperatures benefit the SDGs is to compare the impacts of Representative Concentration Pathway (RCP) 4.5 (lower emissions) and RCP8.5 (higher emissions) on the SDGs (Ansuategi et al., 2015). A low emissions pathway allows for greater success in achieving SDGs for reducing poverty and hunger, providing access to clean energy, reducing inequality, ensuring education for all and making cities more sustainable. Even at lower emissions, a medium risk of failure exists to meet goals for water and sanitation, and marine and terrestrial ecosystems.

Action on climate change (SDG 13), including slowing the rate of warming, would help reach the goals for water, energy, food and land (SDGs 6, 7, 2 and 15) (Obersteiner et al., 2016; ICSU, 2017) and contribute to poverty eradication (SDG 1) (Byers et al., 2018). Although the literature that connects 1.5°C to the SDGs is limited, a pathway that stabilizes warming at 1.5°C by the end of the century is expected to increase the chances of achieving the SDGs by 2030, with greater potential to eradicate poverty, reduce inequality and foster equity (*limited evidence, medium agreement*). There are no studies on overshoot and dimensions of sustainable development, although literature on 4°C of warming suggests the impacts would be severe (Reyer et al., 2017b).

Table 5.1 | Sustainable development implications of avoided impacts between 1.5°C and 2°C global warming.

Impacts	Chapter 3 Section	1.5°C	2°C	Sustainable Development Goals (SDGs) More Easily Achieved when Limiting Warming to 1.5°C
Water scarcity	3.4.2.1	4% more people exposed to water stress	8% more people exposed to water stress, with 184–270 million people more exposed	SDG 6 water availability for all
	Table 3.4	496 (range 103–1159) million people exposed and vulnerable to water stress	586 (range 115–1347) million people exposed and vulnerable to water stress	
Ecosystems	3.4.3, Table 3.4	Around 7% of land area experiences biome shifts	Around 13% (range 8–20%) of land area experiences biome shifts	SDG 15 to protect terrestrial ecosystems and halt biodiversity loss
	Box 3.5	70–90% of coral reefs at risk from bleaching	99% of coral reefs at risk from bleaching	
Coastal cities	3.4.5.1	31–69 million people exposed to coastal flooding	32–79 million exposed to coastal flooding	SDG 11 to make cities and human settlements safe and resilient
	3.4.5.2	Fewer cities and coasts exposed to sea level rise and extreme events	More people and cities exposed to flooding	
Food systems	3.4.6, Box 3.1	Significant declines in crop yields avoided, some yields may increase	Average crop yields decline	SDG 2 to end hunger and achieve food security
	Table 3.4	32–36 million people exposed to lower yields	330–396 million people exposed to lower yields	
Health	3.4.5.1	Lower risk of temperature-related morbidity and smaller mosquito range	Higher risks of temperature-related morbidity and mortality and larger geographic range of mosquitoes	SDG 3 to ensure healthy lives for all
	3.4.5.2	3546–4508 million people exposed to heat waves	5417–6710 million people exposed to heat waves	

Cross-Chapter Box 12 | Residual Risks, Limits to Adaptation and Loss and Damage

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Introduction

Residual climate-related risks, limits to adaptation, and loss and damage (see Glossary) are increasingly assessed in the scientific literature (van der Geest and Warner, 2015; Boyd et al., 2017; Mechler et al., 2019). The AR5 (IPCC, 2013; Oppenheimer et al., 2014) documented impacts that have been detected and attributed to climate change, projected increasing climate-related risks with continued global warming, and recognized barriers and limits to adaptation. It recognized that adaptation is constrained by biophysical, institutional, financial, social and cultural factors, and that the interaction of these factors with climate change can lead to soft adaptation limits (adaptive actions currently not available) and hard adaptation limits (adaptive actions appear infeasible leading to unavoidable impacts) (Klein et al., 2014).

Loss and damage: concepts and perspectives

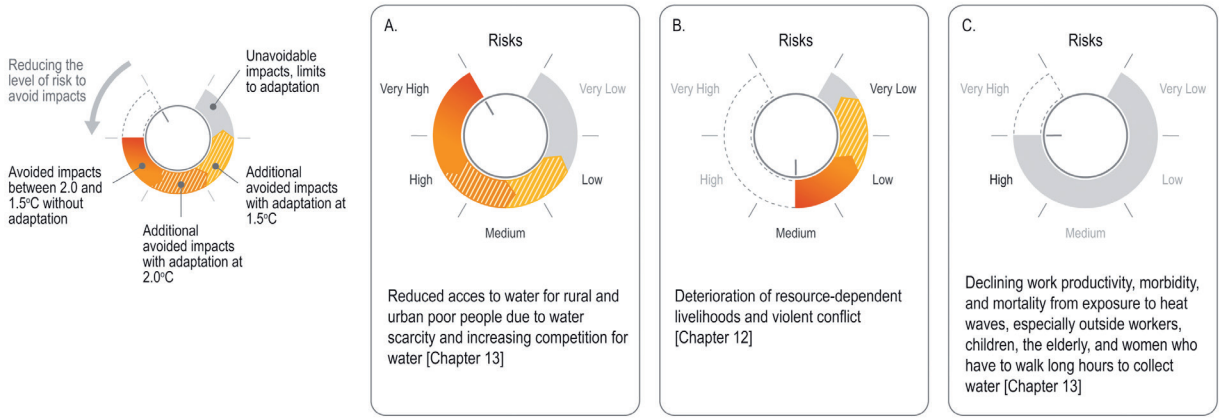
'Loss and Damage' (L&D) has been discussed in international climate negotiations for three decades (INC, 1991; Calliari, 2016; Vanhala and Hestbaek, 2016). A work programme on L&D was established as part of the Cancun Adaptation Framework in 2010 supporting developing countries particularly vulnerable to climate change impacts (UNFCCC, 2011a). In 2013, the Conference of the Parties (COP) 19 established the Warsaw International Mechanism for Loss and Damage (WIM) as a formal part of the United Nations Framework Convention on Climate Change (UNFCCC) architecture (UNFCCC, 2014). It acknowledges that L&D 'includes, and in some cases involves more than, that which can be reduced by adaptation' (UNFCCC, 2014). The Paris Agreement recognized 'the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change' through Article 8 (UNFCCC, 2015).

There is no one definition of L&D in climate policy, and analysis of policy documents and stakeholder views has demonstrated ambiguity (Vanhala and Hestbaek, 2016; Boyd et al., 2017). UNFCCC documents suggest that L&D is associated with adverse impacts of climate change on human and natural systems, including impacts from extreme events and slow-onset processes (UNFCCC, 2011b, 2014, 2015). Some documents focus on impacts in developing or particularly vulnerable countries (UNFCCC, 2011b, 2014). They refer to economic (loss of assets and crops) and non-economic (biodiversity, culture, health) impacts, the latter also being an action area under the WIM workplan, and irreversible and permanent loss and damage. Lack of clarity of what the term addresses (avoidance through adaptation and mitigation, unavoidable losses, climate risk management, existential risk) was expressed among stakeholders, with further disagreement ensuing about what constitutes anthropogenic climate change versus natural climate variability (Boyd et al., 2017).

Limits to adaptation and residual risks

The AR5 described adaptation limits as points beyond which actors' objectives are compromised by intolerable risks threatening key objectives such as good health or broad levels of well-being, thus requiring transformative adaptation for overcoming soft limits (see Chapter 4, Sections 4.2.2.3, 4.5.3 and Cross-Chapter Box 9, Section 5.3.1) (Dow et al., 2013; Klein et al., 2014). The AR5 WGII risk tables, based on expert judgment, depicted the potential for, and the limits of, additional adaptation to reduce risk. Near-term (2030–2040) risks can be used as a proxy for 1.5°C warming by the end of the century and compared to longer-term (2080–2100) risks associated with an approximate 2°C warming. Building on the AR5 risk approach, Cross-Chapter Box 12, Figure 1 provides a stylised application example to poverty and inequality.

Cross-Chapter Box 12 (continued)



Cross-Chapter Box 12, Figure 1 | Stylized reduced risk levels due to avoided impacts between 2°C and 1.5°C warming (in solid red-orange), additional avoided impacts with adaptation under 2°C (striped orange) and under 1.5°C (striped yellow), and unavoidable impacts (losses) with no or very limited potential for adaptation (grey), extracted from the AR5 WGII risk tables (Field et al., 2014), and underlying chapters by Adger et al. (2014) and Olsson et al. (2014). For some systems and sectors (A), achieving 1.5°C could reduce risks to low (with adaptation) from very high (without adaptation) and high (with adaptation) under 2°C. For other areas (C), no or very limited adaptation potential is anticipated, suggesting limits, with the same risks for 1.5°C and 2°C. Other risks are projected to be medium under 2°C with further potential for reduction, especially with adaptation, to very low levels (B).

Limits to adaptation, residual risks, and losses in a 1.5°C warmer world

The literature on risks at 1.5°C (versus 2°C and more) and potentials for adaptation remains limited, particularly for specific regions, sectors, and vulnerable and disadvantaged populations. Adaptation potential at 1.5°C and 2°C is rarely assessed explicitly, making an assessment of residual risk challenging. Substantial progress has been made since the AR5 to assess which climate change impacts on natural and human systems can be attributed to anthropogenic emissions (Hansen and Stone, 2016) and to examine the influence of anthropogenic emissions on extreme weather events (NASEM, 2016), and on consequent impacts on human life (Mitchell et al., 2016), but less so on monetary losses and risks (Schaller et al., 2016). There has also been some limited research to examine local-level limits to adaptation (Warner and Geest, 2013; Filho and Nalau, 2018). What constitutes losses and damages is context-dependent and often requires place-based research into what people value and consider worth protecting (Barnett et al., 2016; Tschakert et al., 2017). Yet assessments of non-material and intangible losses are particularly challenging, such as loss of sense of place, belonging, identity, and damage to emotional and mental well-being (Serdeczny et al., 2017; Wewerinke-Singh, 2018a). Warming of 1.5°C is not considered 'safe' for most nations, communities, ecosystems and sectors, and poses significant risks to natural and human systems as compared to the current warming of 1°C (high confidence) (see Chapter 3, Section 3.4, Box 3.4, Box 3.5, Table 3.5, Cross-Chapter Box 6 in Chapter 3). Table 5.2, drawing on findings from Chapters 3, 4 and 5, presents examples of soft and hard limits in natural and human systems in the context of 1.5°C and 2°C of warming.

Cross-Chapter Box 12, Table 1 | Soft and hard adaptation limits in the context of 1.5°C and 2°C of global warming.

System/Region	Example	Soft Limit	Hard Limit
Coral reefs	Loss of 70–90% of tropical coral reefs by mid-century under 1.5°C scenario (total loss under 2°C scenario) (see Chapter 3, Sections 3.4.4 and 3.5.2.1, Box 3.4)		✓
Biodiversity	6% of insects, 8% of plants and 4% of vertebrates lose over 50% of the climatically determined geographic range at 1.5°C (18% of insects, 16% of plants and 8% of vertebrates at 2°C) (see Chapter 3, Section 3.4.3.3)		✓
Poverty	24–357 million people exposed to multi-sector climate risks and vulnerable to poverty at 1.5°C (86–1220 million at 2°C) (see Section 5.2.2)	✓	
Human health	Twice as many megacities exposed to heat stress at 1.5°C compared to present, potentially exposing 350 million additional people to deadly heat wave conditions by 2050 (see Chapter 3, Section 3.4.8)	✓	✓
Coastal livelihoods	Large-scale changes in oceanic systems (temperature and acidification) inflict damage and losses to livelihoods, income, cultural identity and health for coastal-dependent communities at 1.5°C (potential higher losses at 2°C) (see Chapter 3, Sections 3.4.4, 3.4.5, 3.4.6.3, Box 3.4, Box 3.5, Cross-Chapter Box 6, Chapter 4, Section 4.3.5; Section 5.2.3)	✓	✓
Small Island Developing States	Sea level rise and increased wave run up combined with increased aridity and decreased freshwater availability at 1.5°C warming potentially leaving several atoll islands uninhabitable (see Chapter 3, Sections 3.4.3, 3.4.5, Box 3.5, Chapter 4, Cross-Chapter Box 9)		✓

Cross-Chapter Box 12 (continued)

Approaches and policy options to address residual risk and loss and damage

Conceptual and applied work since the AR5 has highlighted the synergies and differences with adaptation and disaster risk reduction policies (van der Geest and Warner, 2015; Thomas and Benjamin, 2017), suggesting more integration of existing mechanisms, yet careful consideration is advised for slow-onset and potentially irreversible impacts and risk (Mechler and Schinko, 2016). Scholarship on justice and equity has provided insight on compensatory, distributive and procedural equity considerations for policy and practice to address loss and damage (Roser et al., 2015; Wallimann-Helmer, 2015; Huggel et al., 2016). A growing body of legal literature considers the role of litigation in preventing and addressing loss and damage and finds that litigation risks for governments and business are bound to increase with improved understanding of impacts and risks as climate science evolves (high confidence) (Mayer, 2016; Banda and Fulton, 2017; Marjanac and Patton, 2018; Wewerinke-Singh, 2018b). Policy proposals include international support for experienced losses and damages (Crosland et al., 2016; Page and Heyward, 2017), addressing climate displacement, donor-supported implementation of regional public insurance systems (Surminski et al., 2016) and new global governance systems under the UNFCCC (Biermann and Boas, 2017).

5.3 Climate Adaptation and Sustainable Development

Adaptation will be extremely important in a 1.5°C warmer world since substantial impacts will be felt in every region (*high confidence*) (Chapter 3, Section 3.3), even if adaptation needs will be lower than in a 2°C warmer world (see Chapter 4, Sections 4.3.1 to 4.3.5, 4.5.3, Cross-Chapter Box 10 in Chapter 4). Climate adaptation options comprise structural, physical, institutional and social responses, with their effectiveness depending largely on governance (see Glossary), political will, adaptive capacities and availability of finance (see Chapter 4, Sections 4.4.1 to 4.4.5) (Betzold and Weiler, 2017; Sonwa et al., 2017; Sovacool et al., 2017). Even though the literature is scarce on the expected impacts of future adaptation measures on sustainable development specific to warming experiences of 1.5°C, this section assesses available literature on how (i) prioritising sustainable development enhances or impedes climate adaptation efforts (Section 5.3.1); (ii) climate adaptation measures impact sustainable development and the SDGs in positive (synergies) or negative (trade-offs) ways (Section 5.3.2); and (iii) adaptation pathways towards a 1.5°C warmer world affect sustainable development, poverty and inequalities (Section 5.3.3). The section builds on Chapter 4 (see Section 4.3.5) regarding available adaptation options to reduce climate vulnerability and build resilience (see Glossary) in the context of 1.5°C-compatible trajectories, with emphasis on sustainable development implications.

5.3.1 Sustainable Development in Support of Climate Adaptation

Making sustainable development a priority, and meeting the SDGs, is consistent with efforts to adapt to climate change (*very high confidence*). Sustainable development is effective in building adaptive capacity if it addresses poverty and inequalities, social and economic exclusion, and inadequate institutional capacities (Noble et al., 2014; Abel et al., 2016; Colloff et al., 2017). Four ways in which sustainable development leads to effective adaptation are described below.

First, sustainable development enables transformational adaptation (see Chapter 4, Section 4.2.2.2) when an integrated approach is adopted, with inclusive, transparent decision-making, rather than addressing current vulnerabilities as stand-alone climate problems (Mathur et al., 2014; Arthurson and Baum, 2015; Shackleton et al., 2015; Lemos et al., 2016; Antwi-Agyei et al., 2017b). Ending poverty in its multiple dimensions (SDG 1) is often a highly effective form of climate adaptation (Fankhauser and McDermott, 2014; Leichenko and Silva, 2014; Hallegatte and Rozenberg, 2017). However, ending poverty is not sufficient, and the positive outcome as an adaptation strategy depends on whether increased household wealth is actually directed towards risk reduction and management strategies (Nelson et al., 2016), as shown in urban municipalities (Colenbrander et al., 2017; Rasch, 2017) and agrarian communities (Hashemi et al., 2017), and whether finance for adaptation is made available (Section 5.6.1).

Second, local participation is effective when wider socio-economic barriers are addressed via multiscale planning (McCubbin et al., 2015; Nyantakyi-Frimpong and Bezner-Kerr, 2015; Toole et al., 2016). This is the case, for instance, when national education efforts (SDG 4) (Muttarak and Lutz, 2014; Striessnig and Loichinger, 2015) and indigenous knowledge (Nkomwa et al., 2014; Pandey and Kumar, 2018) enhance information sharing, which also builds resilience (Santos et al., 2016; Martinez-Baron et al., 2018) and reduces risks for maladaptation (Antwi-Agyei et al., 2018; Gajjar et al., 2018).

Third, development promotes transformational adaptation when addressing social inequalities (Section 5.5.3, 5.6.4), as in SDGs 4, 5, 16 and 17 (O'Brien, 2016; O'Brien, 2017). For example, SDG 5 supports measures that reduce women's vulnerabilities and allow women to benefit from adaptation (Antwi-Agyei et al., 2015; Van Aelst and Holvoet, 2016; Cohen, 2017). Mobilization of climate finance, carbon taxation and environmentally motivated subsidies can reduce inequalities (SDG 10), advance climate mitigation and adaptation (Chancel and Picketty, 2015), and be conducive to strengthening and enabling environments for resilience building (Nhamo, 2016; Halonen et al., 2017).

Fourth, when sustainable development promotes livelihood security, it enhances the adaptive capacities of vulnerable communities and households. Examples include SDG 11 supporting adaptation in cities

to reduce harm from disasters (Kelman, 2017; Parnell, 2017); access to water and sanitation (SDG 6) with strong institutions (SDG 16) (Rasul and Sharma, 2016); SDG 2 and its targets that promote adaptation in agricultural and food systems (Lipper et al., 2014); and targets for SDG 3 such as reducing infectious diseases and providing health cover are consistent with health-related adaptation (ICSU, 2017; Gomez-Echeverri, 2018).

Sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity and promote livelihood security for poor and disadvantaged populations (*high confidence*). Transformational adaptation (see Chapter 4, Sections 4.2.2.2 and 4.5.3) would require development that takes into consideration multidimensional poverty and entrenched inequalities, local cultural specificities and local knowledge in decision-making, thereby making it easier to achieve the SDGs in a 1.5°C warmer world (*medium evidence, high agreement*).

5.3.2 Synergies and Trade-Offs between Adaptation Options and Sustainable Development

There are short-, medium-, and long-term positive impacts (synergies) and negative impacts (trade-offs) between the dual goals of keeping temperatures below 1.5°C global warming and achieving sustainable development. The extent of synergies between development and adaptation goals will vary by the development process adopted for a particular SDG and underlying vulnerability contexts (*medium evidence, high agreement*). Overall, the impacts of adaptation on sustainable development, poverty eradication and reducing inequalities in general, and the SDGs specifically, are expected to be largely positive, given that the inherent purpose of adaptation is to lower risks. Building on Chapter 4 (see Section 4.3.5), this section examines synergies and trade-offs between adaptation and sustainable development for some key sectors and approaches.

Agricultural adaptation: The most direct synergy is between SDG 2 (zero hunger) and adaptation in cropping, livestock and food systems, designed to maintain or increase production (Lipper et al., 2014; Rockström et al., 2017). Farmers with effective adaptation strategies tend to enjoy higher food security and experience lower levels of poverty (FAO, 2015; Douxchamps et al., 2016; Ali and Erenstein, 2017). Vermeulen et al. (2016) report strong positive returns on investment across the world from agricultural adaptation with side benefits for environment and economic well-being. Well-adapted agricultural systems contribute to safe drinking water, health, biodiversity and equity goals (DeClerck et al., 2016; Myers et al., 2017). Climate-smart agriculture has synergies with food security, though it can be biased towards technological solutions, may not be gender sensitive, and can create specific challenges for institutional and distributional aspects (Lipper et al., 2014; Arakelyan et al., 2017; Taylor, 2017).

At the same time, adaptation options increase risks for human health, oceans and access to water if fertiliser and pesticides are used without regulation or when irrigation reduces water availability for other purposes (Shackleton et al., 2015; Campbell et al., 2016). When agricultural insurance and climate services overlook the poor, inequality may rise (Dinku et al., 2014; Carr and Owusu-Daaku, 2015; Georgeson et al., 2017a; Carr and Onzere, 2018). Agricultural adaptation measures may increase workloads, especially for women, while changes in crop mix can result in loss of income or culturally inappropriate food (Carr and Thompson, 2014; Thompson-Hall et al., 2016; Bryan et al., 2017), and they may benefit farmers with more land to the detriment of land-poor farmers, as seen in the Mekong River Basin (see Chapter 3, Cross-Chapter Box 6 in Chapter 3).

Adaptation to protect human health: Adaptation options in the health sector are expected to reduce morbidity and mortality (Arbuthnott et al., 2016; Ebi and Otmani del Barrio, 2017). Heat-early-warning systems help lower injuries, illnesses and deaths (Hess and Ebi, 2016), with positive impacts for SDG 3. Institutions better equipped to share information, indicators for detecting climate-sensitive diseases, improved provision of basic health care services and coordination with other sectors also improve risk management, thus reducing adverse health outcomes (Dasgupta et al., 2016; Dovie et al., 2017). Effective adaptation creates synergies via basic public health measures (K.R. Smith et al., 2014; Dasgupta, 2016) and health infrastructure protected from extreme weather events (Watts et al., 2015). Yet trade-offs can occur when adaptation in one sector leads to negative impacts in another sector. Examples include the creation of urban wetlands through flood control measures which can breed mosquitoes, and migration eroding physical and mental well-being, hence adversely affecting SDG 3 (K.R. Smith et al., 2014; Watts et al., 2015). Similarly, increased use of air conditioning enhances resilience to heat stress (Petkova et al., 2017), yet it can result in higher energy consumption, undermining SDG 13.

Coastal adaptation: Adaptation to sea level rise remains essential in coastal areas even under a climate stabilization scenario of 1.5°C (Nicholls et al., 2018). Coastal adaptation to restore ecosystems (for instance by planting mangrove forests) supports SDGs for enhancing life and livelihoods on land and oceans (see Chapter 4, Sections 4.3.2.3). Synergistic outcomes between development and relocation of coastal communities are enhanced by participatory decision-making and settlement designs that promote equity and sustainability (van der Voorn et al., 2017). Limits to coastal adaptation may rise, for instance in low-lying islands in the Pacific, Caribbean and Indian Ocean, with attendant implications for loss and damage (see Chapter 3 Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, Box 5.3).

Migration as adaptation: Migration has been used in various contexts to protect livelihoods from challenges related to climate change (Marsh, 2015; Jha et al., 2017), including through remittances (Betzold and Weiler, 2017). Synergies between migration and the achievement of sustainable development depend on adaptive measures and conditions in both sending and receiving regions (Fatima et al., 2014; McNamara, 2015; Entzinger and Scholten, 2016; Ober and Sakdapolrak, 2017; Schwan and Yu, 2017). Adverse developmental impacts arise when vulnerable women or the elderly are left behind or if migration is culturally disruptive (Wilkinson et al., 2016; Albert et al., 2017; Islam and Shamsuddoha, 2017).

Ecosystem-based adaptation: Ecosystem-based adaptation (EBA) can offer synergies with sustainable development (Morita and Matsumoto,

2015; Ojea, 2015; Szabo et al., 2015; Brink et al., 2016; Butt et al., 2016; Conservation International, 2016; Huq et al., 2017), although assessments remain difficult (see Chapter 4, Section 4.3.2.2) (Doswald et al., 2014). Examples include mangrove restoration reducing coastal vulnerability, protecting marine and terrestrial ecosystems, and increasing local food security, as well as watershed management reducing flood risks and improving water quality (Chong, 2014). In drylands, EBA practices, combined with community-based adaptation, have shown how to link adaptation with mitigation to improve livelihood conditions of poor farmers (Box 5.1). Synergistic developmental outcomes arise where EBA is cost effective, inclusive of indigenous and local knowledge and easily accessible by the poor (Ojea, 2015; Daigneault et al., 2016; Estrella et al., 2016). Payment for ecosystem services can provide incentives to land owners and natural resource managers to preserve environmental services with synergies with SDGs 1 and 13 (Arriagada et al., 2015), when implementation challenges are overcome (Calvet-Mir et al., 2015; Wegner, 2016; Chan et al., 2017). Trade-offs include loss of other economic land use types, tension between biodiversity and adaptation priorities, and conflicts over governance (Wamsler et al., 2014; Ojea, 2015).

Community-based adaptation: Community-based adaptation (CBA) (see Chapter 4, Sections 4.3.3.2) enhances resilience and sustainability of adaptation plans (Ford et al., 2016; Fernandes-Jesus et al., 2017; Grantham and Rudd, 2017; Gustafson et al., 2017). Yet negative impacts occur if it fails to fairly represent vulnerable populations and to foster long-term social resilience (Ensor, 2016; Taylor Aiken et al., 2017). Mainstreaming CBA into planning and decision-making enables the attainment of SDGs 5, 10 and 16 (Archer et al., 2014; Reid and Huq, 2014; Vardakoulias and Nicholles, 2014; Cutter, 2016; Kim et al., 2017). Incorporating multiple forms of indigenous and local knowledge is an important element of CBA, as shown for instance in the Arctic region (see Chapter 4, Section 4.3.5.5, Box 4.3, Cross-Chapter Box 9) (Apgar et al., 2015; Armitage, 2015; Pearce et al., 2015; Chief et al., 2016; Cobbinah and Anane, 2016; Ford et al., 2016). Indigenous and local knowledge can be synergistic with achieving SDGs 2, 6 and 10 (Ayers et al., 2014; Lasage et al., 2015; Regmi and Star, 2015; Berner et al., 2016; Chief et al., 2016; Murtinho, 2016; Reid, 2016).

There are clear synergies between adaptation options and several SDGs, such as poverty eradication, elimination of hunger, clean water and health (*robust evidence, high agreement*), as well-integrated adaptation supports sustainable development (Eakin et al., 2014; Weisser et al., 2014; Adam, 2015; Smucker et al., 2015). Substantial synergies are observed in the agricultural and health sectors, and in ecosystem-based adaptations. However, particular adaptation strategies can lead to adverse consequences for developmental outcomes (*medium evidence, high agreement*). Adaptation strategies that advance one SDG can result in trade-offs with other SDGs; for instance, agricultural adaptation to enhance food security (SDG 2) causing negative impacts for health, equality and healthy ecosystems (SDGs 3, 5, 6, 10, 14 and 15), and resilience to heat stress increasing energy consumption (SDGs 3 and 7) and high-cost adaptation in resource-constrained contexts (*medium evidence, medium agreement*).

5.3.3 Adaptation Pathways towards a 1.5°C Warmer World and Implications for Inequalities

In a 1.5°C warmer world, adaptation measures and options would need to be intensified, accelerated and scaled up. This entails not only the right 'mix' of options (asking 'right for whom and for what?') but also a forward-looking understanding of dynamic trajectories, that is adaptation pathways (see Chapter 1, Cross-Chapter Box 1 in Chapter 1), best understood as decision-making processes over sets of potential action sequenced over time (Câmpeanu and Fazey, 2014; Wise et al., 2014). Given the scarcity of literature on adaptation pathways that navigate place-specific warming experiences at 1.5°C, this section presents insights into current local decision-making for adaptation futures. This grounded evidence shows that choices between possible pathways, at different scales and for different groups of people, are shaped by uneven power structures and historical legacies that create their own, often unforeseen change (Fazey et al., 2016; Bosomworth et al., 2017; Lin et al., 2017; Murphy et al., 2017; Pelling et al., 2018).

Pursuing a place-specific adaptation pathway approach towards a 1.5°C warmer world harbours the potential for significant positive outcomes, with synergies for well-being possibilities to 'leap-frog the SDGs' (J.R.A. Butler et al., 2016), in countries at all levels of development (*medium evidence, high agreement*). It allows for identifying local, socially salient tipping points before they are crossed, based on what people value and trade-offs that are acceptable to them (Barnett et al., 2014, 2016; Gorddard et al., 2016; Tschakert et al., 2017). Yet evidence also reveals adverse impacts that reinforce rather than reduce existing social inequalities and hence may lead to poverty traps (*medium evidence, high agreement*) (Nagoda, 2015; Warner et al., 2015; Barnett et al., 2016; J.R.A. Butler et al., 2016; Godfrey-Wood and Naess, 2016; Pelling et al., 2016; Albert et al., 2017; Murphy et al., 2017).

Past development trajectories as well as transformational adaptation plans can constrain adaptation futures by reinforcing dominant political-economic structures and processes, and narrowing option spaces; this leads to maladaptive pathways that preclude alternative, locally relevant and sustainable development initiatives and increase vulnerabilities (Warner and Kuzdas, 2017; Gajjar et al., 2018). Such dominant pathways tend to validate the practices, visions and values of existing governance regimes and powerful members of a community while devaluing those of less privileged stakeholders. Examples from Romania, the Solomon Islands and Australia illustrate such pathway dynamics in which individual economic gains and prosperity matter more than community cohesion and solidarity; this discourages innovation, exacerbates inequalities and further erodes adaptive capacities of the most vulnerable (Davies et al., 2014; Fazey et al., 2016; Bosomworth et al., 2017). In the city of London, United Kingdom, the dominant adaptation and disaster risk management pathway promotes resilience that emphasizes self-reliance; yet it intensifies the burden on low-income citizens, the elderly, migrants and others unable to afford flood insurance or protect themselves against heat waves (Pelling et al., 2016). Adaptation pathways in the Bolivian Altiplano have transformed subsistence farmers into world-leading quinoa producers, but loss of social cohesion and traditional values, dispossession and loss of ecosystem services now constitute undesirable trade-offs (Chelleri et al., 2016).

A narrow view of adaptation decision-making, for example focused on technical solutions, tends to crowd out more participatory processes (Lawrence and Haasnoot, 2017; Lin et al., 2017), obscures contested values and reinforces power asymmetries (Bosomworth et al., 2017; Singh, 2018). A situated and context-specific understanding of adaptation pathways that galvanizes diverse knowledge, values and joint initiatives helps to overcome dominant path dependencies, avoid trade-offs that intensify inequities and challenge policies detached from place (Fincher et al., 2014; Wyborn et al., 2015; Murphy et al., 2017; Gajjar et al., 2018). These insights suggest that adaptation pathway approaches to prepare for 1.5°C warmer futures would be difficult to achieve without considerations for inclusiveness, place-specific trade-off deliberations, redistributive measures and procedural justice mechanisms to facilitate equitable transformation (*medium evidence, high agreement*).

Box 5.1 | Ecosystem- and Community-Based Practices in Drylands

Drylands face severe challenges in building climate resilience (Fuller and Lain, 2017), yet small-scale farmers can play a crucial role as agents of change through ecosystem- and community-based practices that combine adaptation, mitigation and sustainable development.

Farmer managed natural regeneration (FMNR) of trees in cropland is practised in 18 countries across sub-Saharan Africa, Southeast Asia, Timor-Leste, India and Haiti and has, for example, permitted the restoration of over five million hectares of land in the Sahel (Niang et al., 2014; Bado et al., 2016). In Ethiopia, the Managing Environmental Resources to Enable Transitions programme, which entails community-based watershed rehabilitation in rural landscapes, supported around 648,000 people, resulting in the rehabilitation of 25,400,000 hectares of land in 72 severely food-insecure districts across Ethiopia between 2012 and 2015 (Gebrehaweria et al., 2016). In India, local farmers have benefitted from watershed programmes across different agro-ecological regions (Singh et al., 2014; Datta, 2015).

These low-cost, flexible community-based practices represent low-regrets adaptation and mitigation strategies. These strategies often contribute to strengthened ecosystem resilience and biodiversity, increased agricultural productivity and food security, reduced household poverty and drudgery for women, and enhanced agency and social capital (Niang et al., 2014; Francis et al., 2015; Kassie et al., 2015; Mbow et al., 2015; Reij and Winterbottom, 2015; Weston et al., 2015; Bado et al., 2016; Dumont et al., 2017). Small check dams in dryland areas and conservation agriculture can significantly increase agricultural output (Kumar et al., 2014; Agoramoorthy and Hsu, 2016; Pradhan et al., 2018). Mitigation benefits have also been quantified (Weston et al., 2015); for example, FMNR of more than five million hectares in Niger has sequestered 25–30 Mtonnes of carbon over 30 years (Stevens et al., 2014).

However, several constraints hinder scaling-up efforts: inadequate attention to the socio-technical processes of innovation (Grist et al., 2017; Scoones et al., 2017), difficulties in measuring the benefits of an innovation (Coe et al., 2017), farmers' inability to deal with long-term climate risk (Singh et al., 2017), and difficulties for matching practices with agro-ecological conditions and complementary modern inputs (Kassie et al., 2015). Key conditions to overcome these challenges include: developing agroforestry value chains and markets (Reij and Winterbottom, 2015) and adaptive planning and management (Gray et al., 2016). Others include inclusive processes giving greater voice to women and marginalized groups (MRFCJ, 2015a; UN Women and MRFCJ, 2016; Dumont et al., 2017), strengthening community land and forest rights (Stevens et al., 2014; Vermeulen et al., 2016), and co-learning among communities of practice at different scales (Coe et al., 2014; Reij and Winterbottom, 2015; Sinclair, 2016; Binam et al., 2017; Dumont et al., 2017; Epule et al., 2017).

5.4 Mitigation and Sustainable Development

The AR5 WGIII examined the potential of various mitigation options for specific sectors (energy supply, industry, buildings, transport, and agriculture, forestry, and other land use; AFOLU); it provided a narrative of dimensions of sustainable development and equity as a framing for evaluating climate responses and policies, respectively, in Chapters 4, 7, 8, 9, 10 and 11 (IPCC, 2014a). This section builds on the analyses of Chapters 2 and 4 of this report to re-assess mitigation and sustainable development in the context of 1.5°C global warming as well as the SDGs.

5.4.1 Synergies and Trade-Offs between Mitigation Options and Sustainable Development

Adopting stringent climate mitigation options can generate multiple positive non-climate benefits that have the potential to reduce the costs of achieving sustainable development (IPCC, 2014b; Ürge-Vorsatz et al., 2014, 2016; Schaeffer et al., 2015; von Stechow et al., 2015). Understanding the positive impacts (synergies) but also the negative impacts (trade-offs) is key for selecting mitigation options and policy choices that maximize the synergies between mitigation and developmental actions (Hildingsson and Johansson, 2015; Nilsson

et al., 2016; Delponte et al., 2017; van Vuuren et al., 2017b; McCollum et al., 2018b). Aligning mitigation response options to sustainable development objectives can ensure public acceptance (IPCC, 2014a), encourage faster action (Lechtenboehmer and Knoop, 2017) and support the design of equitable mitigation (Holz et al., 2018; Winkler et al., 2018) that protect human rights (MRFCJ, 2015b) (Section 5.5.3).

This sub-section assesses available literature on the interactions of individual mitigation options (see Chapter 2, Section 2.3.1.2, Chapter 4, Sections 4.2 and 4.3) with sustainable development and the SDGs and underlying targets. Table 5.2 presents an assessment of these synergies and trade-offs and the strength of the interaction using an SDG-interaction score (see Glossary) (McCollum et al., 2018b), with evidence and agreements levels. Figure 5.2 presents the information of Table 5.2, showing gross (not net) interactions with the SDGs. This detailed assessment of synergies and trade-offs of individual mitigation options with the SDGs (Table 5.2 a–d and Figure 5.2) reveals that the number of synergies exceeds that of trade-offs. Mitigation response options in the energy demand sector, AFOLU and oceans have more positive interactions with a larger number of SDGs compared to those on the energy supply side (*robust evidence, high agreement*).

5.4.1.1 Energy Demand: Mitigation Options to Accelerate Reduction in Energy Use and Fuel Switch

For mitigation options in the energy demand sectors, the number of synergies with all sixteen SDGs exceeds the number of trade-offs (Figure 5.2 and Table 5.2) (*robust evidence, high agreement*). Most of the interactions are of a reinforcing nature, hence facilitating the achievement of the goals.

Accelerating energy efficiency in all sectors, which is a necessary condition for a 1.5°C warmer world (see Chapters 2 and 4), has synergies with a large number of SDGs (*robust evidence, high agreement*) (Figure 5.2 and Table 5.2). The diffusion of efficient equipment and appliances across end use sectors has synergies with international partnership (SDG 17) and participatory and transparent institutions (SDG 16) because innovations and deployment of new technologies require transnational capacity building and knowledge sharing. Resource and energy savings support sustainable production and consumption (SDG 12), energy access (SDG 7), innovation and infrastructure development (SDG 9) and sustainable city development (SDG 11). Energy efficiency supports the creation of decent jobs by new service companies providing services for energy efficiency, but the net employment effect of efficiency improvement remains uncertain due to macro-economic feedback (SDG 8) (McCollum et al., 2018b).

In the buildings sector, accelerating energy efficiency by way of, for example, enhancing the use of efficient appliances, refrigerant transition, insulation, retrofitting and low- or zero-energy buildings generates benefits across multiple SDG targets. For example, improved cook stoves make fuel endowments last longer and hence reduce deforestation (SDG 15), support equal opportunity by reducing school absences due to asthma among children (SDGs 3 and 4) and empower rural and indigenous women by reducing drudgery (SDG 5) (*robust evidence, high agreement*) (Derbez et al., 2014; Lucon et al., 2014; Maidment et al., 2014; Scott et al., 2014; Cameron et al., 2015; Fay et al., 2015; Liddell and Guiney, 2015; Shah et al., 2015; Sharpe et al., 2015; Wells et al., 2015; Willand et al., 2015; Hallegatte et al., 2016; Kusumaningtyas and Aldrian, 2016; Berrueta et al., 2017; McCollum et al., 2018a).

In energy-intensive processing industries, 1.5ºC-compatible trajectories require radical technology innovation through maximum electrification, shift to other low emissions energy carriers such as hydrogen or biomass, integration of carbon capture and storage (CCS) and innovations for carbon capture and utilization (CCU) (see Chapter 4, Section 4.3.4.5). These transformations have strong synergies with innovation and sustainable industrialization (SDG 9), supranational partnerships (SDGs 16 and 17) and sustainable production (SDG 12). However, possible trade-offs due to risks of CCS-based carbon leakage, increased electricity demands, and associated price impacts affecting energy access and poverty (SDGs 7 and 1) would need careful regulatory attention (Wesseling et al., 2017). In the mining industry, energy efficiency can be synergetic or face trade-offs with sustainable management (SDG 6), depending on the option retained for water management (Nguyen et al., 2014). Substitution and recycling are also an important driver of 1.5ºC-compatible trajectories in industrial systems (see Chapter 4, Section 4.3.4.2). Structural changes and reorganization of economic activities in industrial park/clusters following the principles of industrial symbiosis (circular economy) improves the overall sustainability by reducing energy and waste (Fan et al., 2017; Preston and Lehne, 2017) and reinforces responsible production and consumption (SDG 12) through recycling, water use efficiency (SDG 6), energy access (SDG 7) and ecosystem protection and restoration (SDG 15) (Karner et al., 2015; Zeng et al., 2017).

In the transport sector, deep electrification may trigger increases of electricity prices and adversely affect poor populations (SDG 1), unless pro-poor redistributive policies are in place (Klausbruckner et al., 2016). In cities, governments can lay the foundations for compact, connected low-carbon cities, which are an important component of 1.5ºC-compatible transformations (see Chapter 4, Section 4.3.3) and show synergies with sustainable cities (SDG 11) (Colenbrander et al., 2016).

Behavioural responses are important determinants of the ultimate outcome of energy efficiency on emission reductions and energy access (SDG 7) and their management requires a detailed understanding of the drivers of consumption and the potential for and barriers to absolute reductions (Fuchs et al., 2016). Notably, the rebound effect tends to offset the benefits of efficiency for emissions reductions through growing demand for energy services (Sorrell, 2015; Suffolk and Poortinga, 2016). However, high rebound can help in providing faster access to affordable energy (SDG 7.1) where the goal is to reduce energy poverty and unmet energy demand (see Chapter 2, Section 2.4.3) (Chakravarty et al., 2013). Comprehensive policy design – including rebound supressing policies, such as carbon pricing and policies that encourage awareness building and promotional material design – is needed to tap the full potential of energy savings, as applicable to a 1.5°C warming context (Chakravarty and Tavoni, 2013; IPCC, 2014b; Karner et al., 2015; Zhang et al., 2015; Altieri et al., 2016; Santarius et al., 2016) and to address policy-related trade-offs and welfare-enhancing benefits (*robust evidence, high agreement*) (Chakravarty et al., 2013; Chakravarty and Roy, 2016; Gillingham et al., 2016).

Other behavioural responses will affect the interplay between energy efficiency and sustainable development. Building occupants reluctant to change their habits may miss out on welfare-enhancing energy efficiency opportunities (Zhao et al., 2017). Preferences for new products and premature obsolescence for appliances is expected to adversely affect sustainable consumption and production (SDG 12) with ramifications for resource use efficiency (Echegaray, 2016). Changes in user behaviour towards increased physical activity, less reliance on motorized travel over short distances and the use of public transport would help to decarbonize the transport sector in a synergetic manner with SDGs 3, 11 and 12 (Shaw et al., 2014; Ajanovic, 2015; Chakrabarti and Shin, 2017), while reducing inequality in access to basic facilities (SDG 10) (Lucas and Pangbourne, 2014; Kagawa et al., 2015). However, infrastructure design and regulations would need to ensure road safety and address risks of road accidents for pedestrians (Hwang et al., 2017; Khreis et al., 2017) to ensure sustainable infrastructure growth in human settlements (SDGs 9 and 11) (Lin et al., 2015; SLoCaT, 2017).

5.4.1.2 Energy Supply: Accelerated Decarbonization

Decreasing the share of coal in energy supply in line with 1.5ºC-compatible scenarios (see Chapter 2, Section 2.4.2) reduces adverse impacts of upstream supply-chain activities, in particular air and water pollution and coal mining accidents, and enhances health by reducing air pollution, notably in cities, showing synergies with SDGs 3, 11 and 12 (Yang et al., 2016; UNEP, 2017).

Fast deployment of renewables such as solar, wind, hydro and modern biomass, together with the decrease of fossil fuels in energy supply (see Chapter 2, Section 2.4.2.1), is aligned with the doubling of renewables in the global energy mix (SDG 7.2). Renewables could also support progress on SDGs 1, 10, 11 and 12 and supplement new technology (*robust evidence, high agreement*) (Chaturvedi and Shukla, 2014; Rose et al., 2014; Smith and Sagar, 2014; Riahi et al., 2015; IEA, 2016; van Vuuren et al., 2017a; McCollum et al., 2018a). However, some trade-offs with the SDGs can emerge from offshore installations, particularly SDG 14 in local contexts (McCollum et al., 2018a). Moreover, trade-offs between renewable energy production and affordability (SDG 7) (Labordena et al., 2017) and other environmental objectives would need to be scrutinised for potential negative social outcomes. Policy interventions through regional cooperation-building (SDG 17) and institutional capacity (SDG 16) can enhance affordability (SDG 7) (Labordena et al., 2017). The deployment of small-scale renewables, or off-grid solutions for people in remote areas (Sánchez and Izzo, 2017), has strong potential for synergies with access to energy (SDG 7), but the actualization of these potentials requires measures to overcome technology and reliability risks associated with large-scale deployment of renewables (Giwa et al., 2017; Heard et al., 2017). Bundling energy-efficient appliances and lighting with off-grid renewables can lead to substantial cost reduction while increasing reliability (IEA, 2017). Low-income populations in industrialized countries are often left out of renewable energy generation schemes, either because of high start-up costs or lack of home ownership (UNRISD, 2016).

Nuclear energy, the share of which increases in most of the 1.5ºC-compatible pathways (see Chapter 2, Section 2.4.2.1), can increase the risks of proliferation (SDG 16), have negative environmental effects (e.g., for water use; SDG 6) and have mixed effects for human health when replacing fossil fuels (SDGs 7 and 3) (see Table 5.2). The use of fossil CCS, which plays an important role in deep mitigation pathways (see Chapter 2, Section 2.4.2.3), implies continued adverse impacts of upstream supply-chain activities in the coal sector, and because of lower efficiency of CCS coal power plants (SDG 12), upstream impacts and local air pollution are likely to be exacerbated (SDG 3). Furthermore, there is a non-negligible risk of carbon dioxide leakage from geological storage and the carbon dioxide transport infrastructure (SDG 3) (Table 5.2).

Economies dependent upon fossil fuel-based energy generation and/or export revenue are expected to be disproportionally affected by future restrictions on the use of fossil fuels under stringent climate goals and higher carbon prices; this includes impacts on employment, stranded assets, resources left underground, lower capacity use and early phasing out of large infrastructure already under construction (*robust evidence, high agreement*) (Box 5.2) (Johnson et al., 2015; McGlade and Ekins, 2015; UNEP, 2017; Spencer et al., 2018). Investment in coal continues to be attractive in many countries as it is a mature technology and provides cheap energy supplies, large-scale employment and energy security (Jakob and Steckel, 2016; Vogt-Schilb and Hallegatte, 2017; Spencer et al., 2018). Hence, accompanying policies and measures would be required to ease job losses and correct for relatively higher prices of alternative energy (Oosterhuis and Ten Brink, 2014; Oei and Mendelevitch, 2016; Garg et al., 2017; HLCCP, 2017; Jordaan et al., 2017; OECD, 2017; UNEP, 2017; Blondeel and van de Graaf, 2018; Green, 2018). Research on historical transitions shows that managing the impacts on workers through retraining programmes is essential in order to align the phase-down of mining industries with meeting ambitious climate targets, and the objectives of a 'just transition' (Galgóczi, 2014; Caldecott et al., 2017; Healy and Barry, 2017). This aspect is even more important in developing countries where the mining workforce is largely semi- or unskilled (Altieri et al., 2016; Tung, 2016). Ambitious emissions reduction targets can unlock very strong decoupling potentials in industrialized fossil exporting economies (Hatfield-Dodds et al., 2015).

Box 5.2 | Challenges and Opportunities of Low-Carbon Pathways in Gulf Cooperative Council Countries

The Gulf Cooperative Council (GCC) region (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and United Arab Emirates) is characterized by high dependency on hydrocarbon resources (natural oil and gas), with high risks of socio-economic impacts of policies and response measures to address climate change. The region is also vulnerable to the decrease of the global demand and price of hydrocarbons as a result of climate change response measures. The projected declining use of oil and gas under low emissions pathways creates risks of significant economic losses for the GCC region (e.g., Waisman et al., 2013; Van de Graaf and Verbruggen, 2015; Al-Maamary et al., 2016; Bauer et al., 2016), given that natural gas and oil revenues contributed to about 70% of government budgets and > 35% of the gross domestic product in 2010 (Callen et al., 2014).

The current high energy intensity of the domestic economies (Al-Maamary et al., 2017), triggered mainly by low domestic energy prices (Alshehry and Belloumi, 2015), suggests specific challenges for aligning mitigation towards 1.5°C-consistent trajectories, which would require strong energy efficiency and economic development for the region.

The region's economies are highly reliant on fossil fuel for their domestic activities. Yet the renewables deployment potentials are large, deployment is already happening (Cugurullo, 2013; IRENA, 2016) and positive economic benefits can be envisaged (Sgouridis et al., 2016). Nonetheless, the use of renewables is currently limited by economics and structural challenges (Lilliestam and Patt, 2015; Griffiths, 2017a). Carbon capture and storage (CCS) is also envisaged with concrete steps towards implementation (Alsheyab, 2017; Ustadi et al., 2017); yet the real potential of this technology in terms of scale and economic dimensions is still uncertain.

Beyond the above mitigation-related challenges, the region's human societies and fragile ecosystems are highly vulnerable to the impacts of climate change, such as water stress (Evans et al., 2004; Shaffrey et al., 2009), desertification (Bayram and Öztürk, 2014), sea level rise affecting vast low coastal lands, and high temperature and humidity with future levels potentially beyond adaptive capacities (Pal and Eltahir, 2016). A low-carbon pathway that manages climate-related risks within the context of sustainable development requires an approach that jointly addresses both types of vulnerabilities (Al Ansari, 2013; Lilliestam and Patt, 2015; Babiker, 2016; Griffiths, 2017b).

The Nationally Determined Contributions (NDCs) for GCC countries identified energy efficiency, deployment of renewables and technology transfer to enhance agriculture, food security, protection of marine resources, and management of water and costal zones (Babiker, 2016). Strategic vision documents, such as Saudi Arabia's 'Vision 2030', identify emergent opportunities for energy price reforms, energy efficiency, turning emissions into valuable products, and deployment of renewables and other clean technologies, if accompanied with appropriate policies to manage the transition and in the context of economic diversification (Luomi, 2014; Atalay et al., 2016; Griffiths, 2017b; Howarth et al., 2017).

5.4.1.3 Land-based agriculture, forestry and ocean: mitigation response options and carbon dioxide removal

In the AFOLU sector, dietary change towards global healthy diets, that is, a shift from over-consumption of animal-related to plant-related diets, and food waste reduction (see Chapter 4, Section 4.3.2.1) are in synergy with SDGs 2 and 6, and SDG 3 through lower consumption of animal products and reduced losses and waste throughout the food system, contributing to achieving SDGs 12 and 15 (Bajželj et al., 2014; Bustamante et al., 2014; Tilman and Clark, 2014; Hiç et al., 2016).

Power dynamics play an important role in achieving behavioural change and sustainable consumption (Fuchs et al., 2016). In forest management (see Chapter 4, Section 4.3.2.2), encouraging responsible sourcing of forest products and securing indigenous land tenure has the potential to increase economic benefits by creating decent jobs (SDG 8), maintaining biodiversity (SDG 15), facilitating innovation and upgrading technology (SDG 9), and encouraging responsible and just decision-making (SDG 16) (*medium evidence, high agreement*) (Ding et al., 2016; WWF, 2017).

Emerging evidence indicates that future mitigation efforts that would be required to reach stringent climate targets, particularly those associated with carbon dioxide removal (CDR) (e.g., afforestation and reforestation and bioenergy with carbon capture and storage; BECCS), may also impose significant constraints upon poor and vulnerable communities (SDG 1) via increased food prices and competition for arable land, land appropriation and dispossession (Cavanagh and Benjaminsen, 2014; Hunsberger et al., 2014; Work, 2015; Muratori et al., 2016; Smith et al., 2016; Burns and Nicholson, 2017; Corbera et al., 2017) with disproportionate negative impacts upon rural poor and indigenous populations (SDG 1) (*robust evidence, high agreement*) (Section 5.4.2.2, Table 5.2, Figure 5.2) (Grubert et al., 2014; Grill et al., 2015; Zhang and Chen, 2015; Fricko et al., 2016; Johansson et al., 2016; Aha and Ayitey, 2017; De Stefano et al., 2017; Shi et al., 2017). Crops for bioenergy may increase irrigation needs and exacerbate water stress with negative associated impacts on SDGs 6 and 10 (Boysen et al., 2017).

Ocean iron fertilization and enhanced weathering have two-way interactions with life under water and on land and food security (SDGs

2, 14 and 15) (Table 5.2). Development of blue carbon resources through coastal (mangrove) and marine (seaweed) vegetative ecosystems encourages: integrated water resource management (SDG 6) (Vierros, 2017); promotes life on land (SDG 15) (Potouroglou et al., 2017); poverty reduction (SDG 1) (Schirmer and Bull, 2014; Lamb et al., 2016); and food security (SDG 2) (Ahmed et al., 2017a, b; Duarte et al., 2017; Sondak et al., 2017; Vierros, 2017; Zhang et al., 2017).

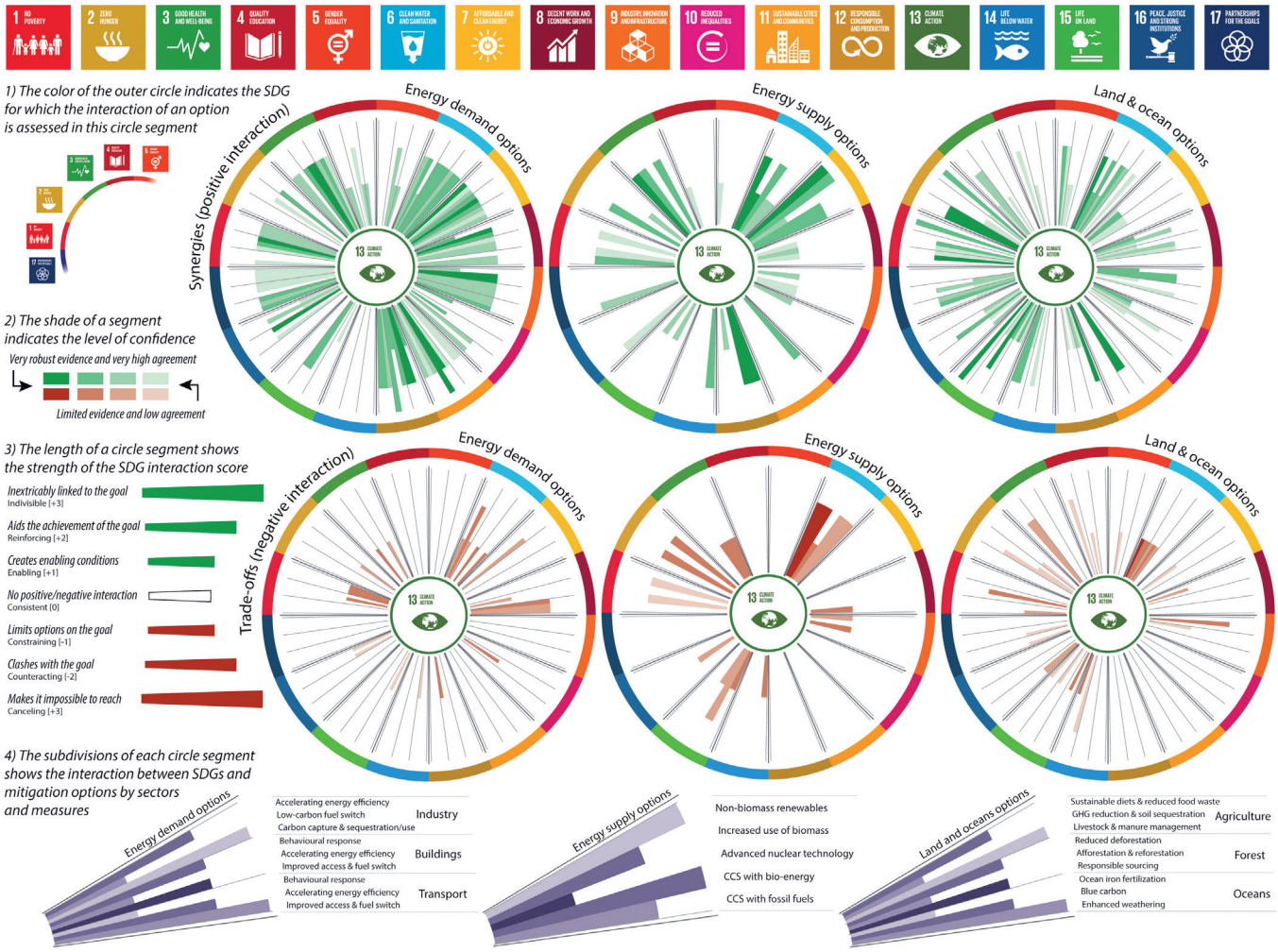


Figure 5.2 | Synergies and trade-offs and gross Sustainable Development Goal (SDG)-interaction with individual mitigation options. The top three wheels represent synergies and the bottom three wheels show trade-offs. The colours on the border of the wheels correspond to the SDGs listed above, starting at the 9 o'clock position, with reading guidance in the top-left corner with the quarter circle (Note 1). Mitigation (climate action, SDG 13) is at the centre of the circle. The coloured segments inside the circles can be counted to arrive at the number of synergies (green) and trade-offs (red). The length of the coloured segments shows the strength of the synergies or trade-offs (Note 3) and the shading indicates confidence (Note 2). Various mitigation options within the energy demand sector, energy supply sector, and land and ocean sector, and how to read them within a segment are shown in grey (Note 4). See also Table 5.2.

5.4.2 Sustainable Development Implications of 1.5°C and 2°C Mitigation Pathways

While previous sections have focused on individual mitigation options and their interaction with sustainable development and the SDGs, this section takes a systems perspective. Emphasis is on quantitative pathways depicting path-dependent evolutions of human and natural systems over time. Specifically, the focus is on fundamental transformations and thus stringent mitigation policies consistent with 1.5°C or 2°C, and the differential synergies and trade-offs with respect to the various sustainable development dimensions.

Both 1.5°C and 2°C pathways would require deep cuts in greenhouse gas (GHG) emissions and large-scale changes of energy supply and demand, as well as in agriculture and forestry systems (see Chapter 2, Section 2.4). For the assessment of the sustainable development implications of these pathways, this chapter draws upon studies that show the aggregated impact of mitigation for multiple sustainable development dimensions (Grubler et al., 2018; McCollum et al., 2018b; Rogelj et al., 2018) and across multiple integrated assessment modelling (IAM) frameworks. Often these tools are linked to disciplinary models covering specific SDGs in more detail (Cameron et al., 2016; Rao et al., 2017; Grubler et al., 2018; McCollum et al.,

2018b). Using multiple IAMs and disciplinary models is important for a robust assessment of the sustainable development implications of different pathways. Emphasis is on multi-regional studies, which can be aggregated to the global scale. The recent literature on 1.5°C mitigation pathways has begun to provide quantifications for a range of sustainable development dimensions, including air pollution and health, food security and hunger, energy access, water security, and multidimensional poverty and equity.

5.4.2.1 Air pollution and health

GHGs and air pollutants are typically emitted by the same sources. Hence, mitigation strategies that reduce GHGs or the use of fossil fuels typically also reduce emissions of pollutants, such as particulate matter (e.g., PM2.5 and PM10), black carbon (BC), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and other harmful species (Clarke et al., 2014) (Figure 5.3), causing adverse health and ecosystem effects at various scales (Kusumaningtyas and Aldrian, 2016).

Mitigation pathways typically show that there are significant synergies for air pollution, and that the synergies increase with the stringency of the mitigation policies (Amann et al., 2011; Rao et al., 2016; Klimont et al., 2017; Shindell et al., 2017; Markandya et al., 2018). Recent multimodel comparisons indicate that mitigation pathways consistent with 1.5°C would result in higher synergies with air pollution compared to pathways that are consistent with 2°C (Figures 5.4 and 5.5). Shindell et al. (2018) indicate that health benefits worldwide over the century of 1.5°C pathways could be in the range of 110 to 190 million fewer premature deaths compared to 2°C pathways. The synergies for air pollution are highest in the developing world, particularly in Asia. In addition to significant health benefits, there are also economic benefits from mitigation, reducing the investment needs in air pollution control technologies by about 35% globally (or about 100 billion USD2010 per year to 2030 in 1.5°C pathways; McCollum et al., 2018b) (Figure 5.4).

5.4.2.2 Food security and hunger

Stringent climate mitigation pathways in line with 'well below 2°C' or '1.5°C' goals often rely on the deployment of large-scale land-related measures, like afforestation and/or bioenergy supply (Popp et al., 2014; Rose et al., 2014; Creutzig et al., 2015). These land-related measures can compete with food production and hence raise food security concerns (Section 5.4.1.3) (P. Smith et al., 2014). Mitigation studies indicate that so-called 'single-minded' climate policy, aiming solely at limiting warming to 1.5°C or 2°C without concurrent measures in the food sector, can have negative impacts for global food security (Hasegawa et al., 2015; McCollum et al., 2018b). Impacts of 1.5°C mitigation pathways can be significantly higher than those of 2°C pathways (Figures 5.4 and 5.5). An important driver of the food security impacts in these scenarios is the increase of food prices and the effect of mitigation on disposable income and wealth due to GHG pricing. A recent study indicates that, on aggregate, the price and income effects on food may be bigger than the effect due to competition over land between food and bioenergy (Hasegawa et al., 2015).

In order to address the issue of trade-offs with food security, mitigation policies would need to be designed in a way that shields the population at risk of hunger, including through the adoption of different complementary measures, such as food price support. The investment needs of complementary food price policies are found to be globally relatively much smaller than the associated mitigation investments of 1.5°C pathways (Figure 5.3) (McCollum et al., 2018b). Besides food support price, other measures include improving productivity and efficiency of agricultural production systems (FAO and NZAGRC, 2017a, b; Frank et al., 2017) and programmes focusing on forest land-use change (Havlík et al., 2014). All these lead to additional benefits of mitigation, improving resilience and livelihoods.

Van Vuuren et al. (2018) and Grubler et al. (2018) show that 1.5°C pathways without reliance on BECCS can be achieved through a fundamental transformation of the service sectors which would significantly reduce energy and food demand (see Chapter 2, Sections 2.1.1, 2.3.1 and 2.4.3). Such low energy demand (LED) pathways would result in significantly reduced pressure on food security, lower food prices and fewer people at risk of hunger. Importantly, the trade-offs with food security would be reduced by the avoided impacts in the agricultural sector due to the reduced warming associated with the 1.5°C pathways (see Chapter 3, Section 3.5). However, such feedbacks are not comprehensively captured in the studies on mitigation.

5.4.2.3 Lack of energy access/energy poverty

A lack of access to clean and affordable energy (especially for cooking) is a major policy concern in many countries, especially in those in South Asia and Africa where major parts of the population still rely primarily on solid fuels for cooking (IEA and World Bank, 2017). Scenario studies which quantify the interactions between climate mitigation and energy access indicate that stringent climate policy which would affect energy prices could significantly slow down the transition to clean cooking fuels, such as liquefied petroleum gas or electricity (Cameron et al., 2016).

Estimates across six different IAMs (McCollum et al., 2018b) indicate that, in the absence of compensatory measures, the number of people without access to clean cooking fuels may increase. Redistributional measures, such as subsidies on cleaner fuels and stoves, could compensate for the negative effects of mitigation on energy access. Investment costs of the redistributional measures in 1.5°C pathways (on average around 120 billion USD2010 per year to 2030; Figure 5.4) are much smaller than the mitigation investments of 1.5°C pathways (McCollum et al., 2018b). The recycling of revenues from climate policy might act as a means to help finance the costs of providing energy access to the poor (Cameron et al., 2016).

5.4.2.4 Water security

Transformations towards low emissions energy and agricultural systems can have major implications for freshwater demand as well as water pollution. The scaling up of renewables and energy efficiency as depicted by low emissions pathways would, in most instances, lower water demands for thermal energy supply facilities ('water-for-energy') compared to fossil energy technologies, and thus reinforce targets related to water access and scarcity (see Chapter 4, Section 4.2.1). However, some low-carbon options such as bioenergy, centralized solar

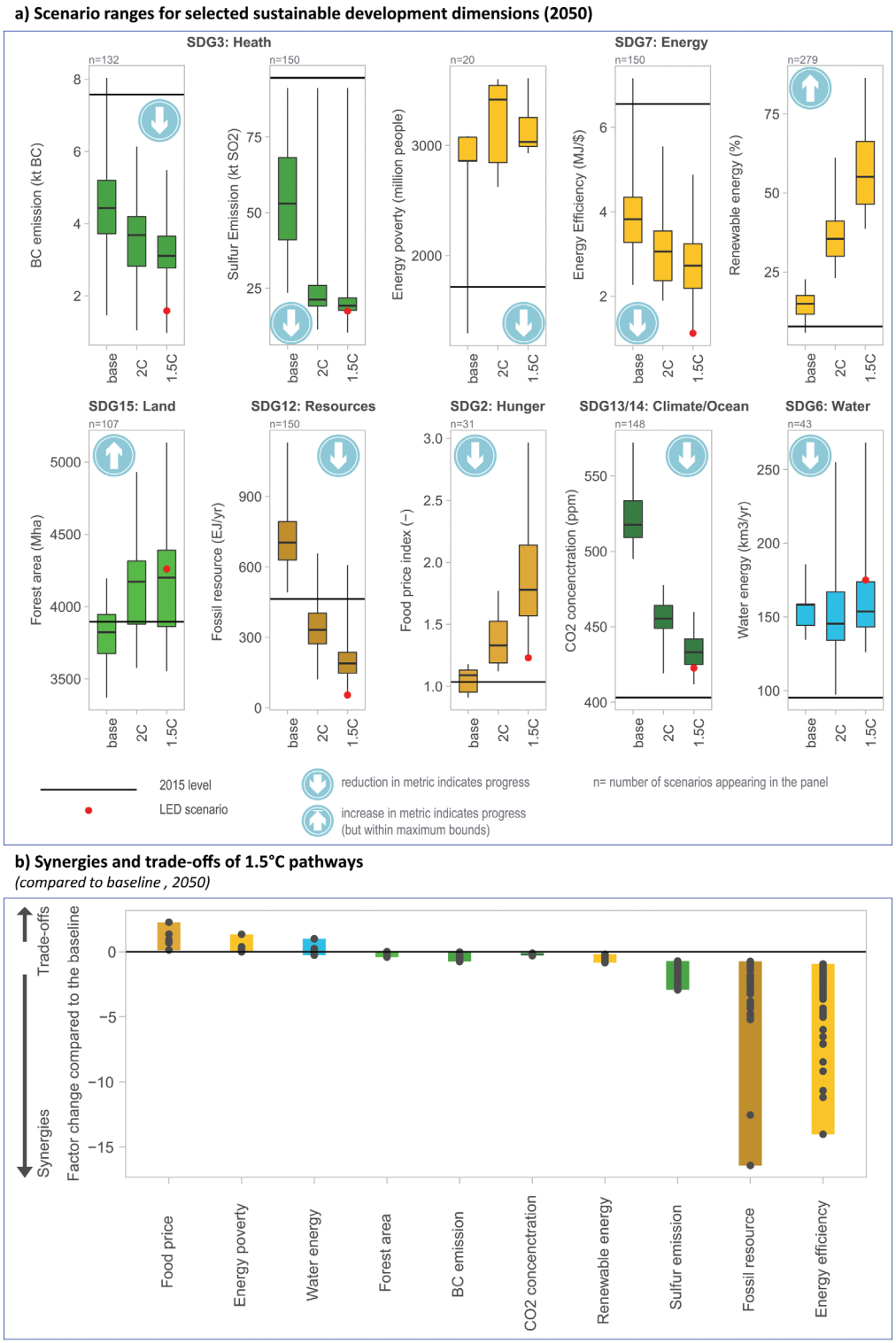


Figure 5.3 | Sustainable development implications of mitigation actions in 1.5°C pathways. Panel (a) shows ranges for 1.5°C pathways for selected sustainable development dimensions compared to the ranges of 2°C pathways and baseline pathways. The panel (a) depicts interquartile and the full range across the scenarios for Sustainable Development Goal (SDG) 2 (hunger), SDG 3 (health), SDG 6 (water), SDG 7 (energy), SDG 12 (resources), SDG 13/14 (climate/ocean) and SDG 15 (land). Progress towards achieving the SDGs is denoted by arrow symbols (increase or decrease of indicator). Black horizontal lines show 2015 values for comparison. Note that sustainable development effects are estimated for the effect of mitigation and do not include benefits from avoided impacts (see Chapter 3, Section 3.5). Low energy demand (LED) denotes estimates from a pathway with extremely low energy demand reaching 1.5°C without bioenergy with carbon capture and storage (BECCS). Panel (b) presents the resulting full range for synergies and trade-offs of 1.5°C pathways compared to the corresponding baseline scenarios. The y-axis in panel (b) indicates the factor change in the 1.5°C pathway compared to the baseline. Note that the figure shows gross impacts of mitigation and does not include feedbacks due to avoided impacts. The realization of the side effects will critically depend on local circumstances and implementation practice. Trade-offs across many sustainable development dimensions can be reduced through complementary/re-distributional measures. The figure is not comprehensive and focuses on those sustainable development dimensions for which quantifications across models are available. Sources: 1.5°C pathways database from Chapter 2 (Grubler et al., 2018; McCollum et al., 2018b).

power, nuclear and hydropower technologies could, if not managed properly, have counteracting effects that compound existing water-related problems in a given locale (Byers et al., 2014; Fricko et al., 2016; IEA, 2016; Fujimori et al., 2017a; Wang, 2017; McCollum et al., 2018a).

Under stringent mitigation efforts, the demand for bioenergy can result in a substantial increase of water demand for irrigation, thereby potentially contributing to water scarcity in water-stressed regions (Berger et al., 2015; Bonsch et al., 2016; Jägermeyr et al., 2017). However, this risk can be reduced by prioritizing rain-fed production of bioenergy (Hayashi et al., 2015, 2018; Bonsch et al., 2016), but might have adverse effects for food security (Boysen et al., 2017).

Reducing food and energy demand without compromising the needs of the poor emerges as a robust strategy for both water conservation and GHG emissions reductions (von Stechow et al., 2015; IEA, 2016; Parkinson et al., 2016; Grubler et al., 2018). The results underscore the importance of an integrated approach when developing water, energy and climate policy (IEA, 2016).

Estimates across different models for the impacts of stringent mitigation pathways on energy-related water uses seem ambiguous. Some pathways show synergies (Mouratiadou et al., 2018) while others indicate trade-offs and thus increases of water use due to mitigation (Fricko et al., 2016). The synergies depend on the adopted policy implementation or mitigation strategies and technology portfolio. A number of adaptation options exist (e.g., dry cooling), which can effectively reduce electricity-related water trade-offs (Fricko et al., 2016; IEA, 2016). Similarly, irrigation water use will depend on the regions where crops are produced, the sources of bioenergy (e.g., agriculture vs. forestry) and dietary change induced by climate policy. Overall, and also considering other water-related SDGs, including access to safe drinking water and sanitation as well as waste-water treatment, investments into the water sector seem to be only modestly affected by stringent climate policy compatible with 1.5°C (Figure 5.4) (McCollum et al., 2018b).

In summary, the assessment of mitigation pathways shows that to meet the 1.5°C target, a wide range of mitigation options would need to be deployed (see Chapter 2, Sections 2.3 and 2.4). While pathways aiming at 1.5°C are associated with high synergies for some sustainable development dimensions (such as human health and air pollution, forest preservation), the rapid pace and magnitude of the required changes would also lead to increased risks for trade-offs for other sustainable development dimensions (particularly food security) (Figures 5.4 and 5.5). Synergies and trade-offs are expected to be unevenly distributed between regions and nations (Box 5.2), though little literature has formally examined such distributions under 1.5°C-consistent mitigation scenarios. Reducing these risks requires smart policy designs and mechanisms that shield the poor and redistribute the burden so that the most vulnerable are not disproportionately affected. Recent scenario analyses show that associated investments for reducing the trade-offs for, for example, food, water and energy access to be significantly lower than the required mitigation investments (McCollum et al., 2018b). Fundamental transformation of demand, including efficiency and behavioural changes, can help to significantly reduce the reliance on risky technologies, such as BECCS, and thus reduce the risk of potential

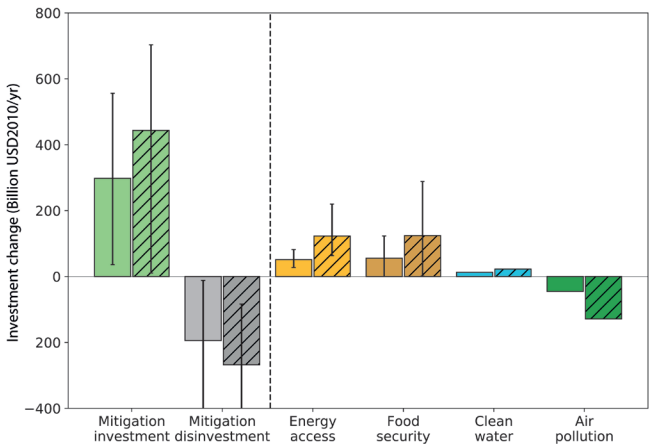


Figure 5.4 | Investment into mitigation up until 2030 and implications for investments for four sustainable development dimensions. Cross-hatched bars show the median investment in 1.5°C pathways across results from different models, and solid bars for 2°C pathways, respectively. Whiskers on bars represent minima and maxima across estimates from six models. Clean water and air pollution investments are available only from one model. Mitigation investments show the change in investments across mitigation options compared to the baseline. Negative mitigation investments (grey bars) denote disinvestment (reduced investment needs) into fossil fuel sectors compared to the baseline. Investments for different sustainable development dimensions denote the investment needs for complementary measures in order to avoid trade-offs (negative impacts) of mitigation. Negative sustainable development investments for air pollution indicate cost savings, and thus synergies of mitigation for air pollution control costs. The values compare to about 2 trillion USD2010 (range of 1.4 to 3 trillion) of total energy-related investments in the 1.5°C pathways. Source: Estimates from CD-LINKS scenarios summarised by McCollum et al., 2018b.

trade-offs between mitigation and other sustainable development dimensions (von Stechow et al., 2015; Grubler et al., 2018; van Vuuren et al., 2018). Reliance on demand-side measures only, however, would not be sufficient for meeting stringent targets, such as 1.5°C and 2°C (Clarke et al., 2014).

5.5 Sustainable Development Pathways to 1.5°C

This section assesses what is known in the literature on development pathways that are sustainable and climate-resilient and relevant to a 1.5°C warmer world. Pathways, transitions from today's world to achieving a set of future goals (see Chapter 1, Section 1.2.3, Cross-Chapter Box 1), follow broadly two main traditions: first, as integrated pathways describing the required societal and systems transformations, combining quantitative modelling and qualitative narratives at multiple spatial scales (global to sub-national); and second, as country- and community-level, solution-oriented trajectories and decision-making processes about context- and place-specific opportunities, challenges and trade-offs. These two notions of pathways offer different, though complementary, insights into the nature of 1.5°C-relevant trajectories and the short-term actions that enable long-term goals. Both highlight to varying degrees the urgency, ethics and equity dimensions of possible trajectories and society- and system-wide transformations, yet at different scales, building on Chapter 2 (see Section 2.4) and Chapter 4 (see Section 4.5).

5.5.1 Integration of Adaptation, Mitigation and Sustainable Development

Insights into climate-compatible development (see Glossary) illustrate how integration between adaptation, mitigation and sustainable development works in context-specific projects, how synergies are achieved and what challenges are encountered during implementation (Stringer et al., 2014; Suckall et al., 2014; Antwi-Agyei et al., 2017a; Bickersteth et al., 2017; Kalafatis, 2017; Nunan, 2017). The operationalization of climate-compatible development, including climate-smart agriculture and carbon-forestry projects (Lipper et al., 2014; Campbell et al., 2016; Quan et al., 2017), shows multilevel and multisector trade-offs involving 'winners' and 'losers' across governance levels (*high confidence*) (Kongsager and Corbera, 2015; Naess et al., 2015; Karlsson et al., 2017; Tanner et al., 2017; Taylor, 2017; Wood, 2017; Ficklin et al., 2018). Issues of power, participation, values, equity, inequality and justice transcend case study examples of attempted integrated approaches (Nunan, 2017; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017), also reflected in policy frameworks for integrated outcomes (Stringer et al., 2014; Di Gregorio et al., 2017; Few et al., 2017; Tanner et al., 2017).

Ultimately, reconciling trade-offs between development needs and emissions reductions towards a 1.5°C warmer world requires a dynamic view of the interlinkages between adaptation, mitigation and sustainable development (Nunan, 2017). This entails recognition of the ways in which development contexts shape the choice and effectiveness of interventions, limit the range of responses afforded to communities and governments, and potentially impose injustices upon vulnerable groups (UNRISD, 2016; Thornton and Comberti, 2017). A variety of approaches, both quantitative and qualitative, exist to examine possible sustainable development pathways under which climate and sustainable development goals can be achieved, and synergies and trade-offs for transformation identified (Sections 5.3 and 5.4).

5.5.2 Pathways for Adaptation, Mitigation and Sustainable Development

This section focuses on the growing body of pathways literature describing the dynamic and systemic integration of mitigation and adaptation with sustainable development in the context of a 1.5°C warmer world. These studies are critically important for the identification of 'enabling' conditions under which climate and the SDGs can be achieved, and thus help the design of transformation strategies that maximize synergies and avoid potential trade-offs (Sections 5.3 and 5.4). Full integration of sustainable development dimensions is, however, challenging, given their diversity and the need for high temporal, spatial and social resolution to address local effects, including heterogeneity related to poverty and equity (von Stechow et al., 2015). Research on long-term climate change mitigation and adaptation pathways has covered individual SDGs to different degrees. Interactions between climate and other SDGs have been explored for SDGs 2, 3, 4, 6, 7, 8, 12, 14 and 15 (Clarke et al., 2014; Abel et al., 2016; von Stechow et al., 2016; Rao et al., 2017), while interactions with SDGs 1, 5, 11 and 16 remain largely underexplored in integrated long-term scenarios (Zimm et al., 2018).

Quantitative pathways studies now better represent 'nexus' approaches to assess sustainable development dimensions. In such approaches (see Chapter 4, Section 4.3.3.8), a subset of sustainable development dimensions are investigated together because of their close relationships (Welsch et al., 2014; Conway et al., 2015; Keairns et al., 2016; Parkinson et al., 2016; Rasul and Sharma, 2016; Howarth and Monasterolo, 2017). Compared to single-objective climate–SDG assessments (Section 5.4.2), nexus solutions attempt to integrate complex interdependencies across diverse sectors in a systems approach for consistent analysis. Recent pathways studies show how water, energy and climate (SDGs 6, 7 and 13) interact (Parkinson et al., 2016; McCollum et al., 2018b) and call for integrated water–energy investment decisions to manage systemic risks. For instance, the provision of bioenergy, important in many 1.5°C-consistent pathways, can help resolve 'nexus challenges' by alleviating energy security concerns, but can also have adverse 'nexus impacts' on food security, water use and biodiversity (Lotze-Campen et al., 2014; Bonsch et al., 2016). Policies that improve resource use efficiency across sectors can maximize synergies for sustainable development (Bartos and Chester, 2014; McCollum et al., 2018b; van Vuuren et al., 2018). Mitigation compatible with 1.5°C can significantly reduce impacts and adaptation needs in the nexus sectors compared to 2°C (Byers et al., 2018). In order to avoid trade-offs due to high carbon pricing of 1.5°C pathways, regulation in specific areas may complement price-based instruments. Such combined policies generally lead also to more early action maximizing synergies and avoiding some of the adverse climate effects for sustainable development (Bertram et al., 2018).

The comprehensive analysis of climate change in the context of sustainable development requires suitable reference scenarios that lend themselves to broader sustainable development analyses. The Shared Socio-Economic Pathways (SSPs) (Chapter 1, Cross-Chapter Box 1 in Chapter 1) (O'Neill et al., 2017a; Riahi et al., 2017) constitute an important first step in providing a framework for the integrated assessment of adaptation and mitigation and their climate–development linkages (Ebi et al., 2014). The five underlying SSP narratives (O'Neill et al., 2017a) map well into some of the key SDG dimensions, with one of the pathways (SSP1) explicitly depicting sustainability as the main theme (van Vuuren et al., 2017b).

To date, no pathway in the literature proves to achieve all 17 SDGs because several targets are not met or not sufficiently covered in the analysis, hence resulting in a sustainability gap (Zimm et al., 2018). The SSPs facilitate the systematic exploration of different sustainable dimensions under ambitious climate objectives. SSP1 proves to be in line with eight SDGs (3, 7, 8, 9, 10, 11, 13 and 15) and several of their targets in a 2°C warmer world (van Vuuren et al., 2017b; Zimm et al., 2018). However, important targets for SDGs 1, 2 and 4 (i.e., people living in extreme poverty, people living at the risk of hunger and gender gap in years of schooling) are not met in this scenario.

The SSPs show that sustainable socio-economic conditions will play a key role in reaching stringent climate targets (Riahi et al., 2017; Rogelj et al., 2018). Recent modelling work has examined 1.5°C-consistent, stringent mitigation scenarios for 2100 applied to the SSPs, using six different IAMs. Despite the limitations of these models, which are coarse approximations of reality, robust trends can be identified

(Rogelj et al., 2018). SSP1 – which depicts broader 'sustainability' as well as enhancing equity and poverty reductions – is the only pathway where all models could reach 1.5°C and is associated with the lowest mitigation costs across all SSPs. A decreasing number of models was successful for SSP2, SSP4 and SSP5, respectively, indicating distinctly higher risks of failure due to high growth and energy intensity as well as geographical and social inequalities and uneven regional development. And reaching 1.5°C has even been found infeasible in the less sustainable SSP3 – 'regional rivalry' (Fujimori et al., 2017b; Riahi et al., 2017). All these conclusions hold true if a 2°C objective is considered (Calvin et al., 2017; Fujimori et al., 2017b; Popp et al., 2017; Riahi et al., 2017). Rogelj et al. (2018) also show that fewer scenarios are, however, feasible across different SSPs in case of 1.5°C, and mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways.

There is a wide range of SSP-based studies focusing on the connections between adaptation/impacts and different sustainable development dimensions (Hasegawa et al., 2014; Ishida et al., 2014; Arnell et al., 2015; Bowyer et al., 2015; Burke et al., 2015; Lemoine and Kapnick, 2016; Rozenberg and Hallegatte, 2016; Blanco et al., 2017; Hallegatte and Rozenberg, 2017; O'Neill et al., 2017a; Rutledge et al., 2017; Byers et al., 2018). New methods for projecting inequality and poverty (downscaled to sub-national rural and urban levels as well as spatially explicit levels) have enabled advanced SSP-based assessments of locally sustainable development implications of avoided impacts and related adaptation needs. For instance, Byers et al. (2018) find that, in a 1.5°C warmer world, a focus on sustainable development can reduce the climate risk exposure of populations vulnerable to poverty by more than an order of magnitude (Section 5.2.2). Moreover, aggressive reductions in between-country inequality may decrease the emissions intensity of global economic growth (Rao and Min, 2018). This is due to the higher potential for decoupling of energy from income growth in lower-income countries, due to high potential for technological advancements that reduce the energy intensity of growth of poor countries – critical also for reaching 1.5°C in a socially and economically equitable way. Participatory downscaling of SSPs in several European Union countries and in Central Asia shows numerous possible pathways of solutions to the 2°C–1.5°C goal, depending on differential visions (Tàbara et al., 2018). Other participatory applications of the SSPs, for example in West Africa (Palazzo et al., 2017) and the southeastern United States (Absar and Preston, 2015), illustrate the potentially large differences in adaptive capacity within regions and between sectors.

Harnessing the full potential of the SSP framework to inform sustainable development requires: (i) further elaboration and extension of the current SSPs to cover sustainable development objectives explicitly; (ii) the development of new or variants of current narratives that would facilitate more SDG-focused analyses with climate as one objective (among other SDGs) (Riahi et al., 2017); (iii) scenarios with high regional resolution (Fujimori et al., 2017b); (iv) a more explicit representation of institutional and governance change associated with the SSPs (Zimm et al., 2018); and (v) a scale-up of localized and spatially explicit vulnerability, poverty and inequality estimates, which have emerged in recent publications based on the SSPs (Byers et al., 2018) and are essential to investigate equity dimensions (Klinsky and Winkler, 2018).

5.5.3 Climate-Resilient Development Pathways

This section assesses the literature on pathways as solution-oriented trajectories and decision-making processes for attaining transformative visions for a 1.5°C warmer world. It builds on climate-resilient development pathways (CRDPs) introduced in the AR5 (Section 5.1.2) (Olsson et al., 2014) as well as growing literature (e.g., Eriksen et al., 2017; Johnson, 2017; Orindi et al., 2017; Kirby and O'Mahony, 2018; Solecki et al., 2018) that uses CRDPs as a conceptual and aspirational idea for steering societies towards low-carbon, prosperous and ecologically safe futures. Such a notion of pathways foregrounds decision-making processes at local to national levels to situate transformation, resilience, equity and well-being in the complex reality of specific places, nations and communities (Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Gajjar et al., 2018; Klinsky and Winkler, 2018; Patterson et al., 2018; Tàbara et al., 2018).

Pathways compatible with 1.5°C warming are not merely scenarios to envision possible futures but processes of deliberation and implementation that address societal values, local priorities and inevitable trade-offs. This includes attention to politics and power that perpetuate business-as-usual trajectories (O'Brien, 2016; Harris et al., 2017), the politics that shape sustainability and capabilities of everyday life (Agyeman et al., 2016; Schlosberg et al., 2017), and ingredients for community resilience and transformative change (Fazey et al., 2018). Chartering CRDPs encourages locally situated and problem-solving processes to negotiate and operationalize resilience 'on the ground' (Beilin and Wilkinson, 2015; Harris et al., 2017; Ziervogel et al., 2017). This entails contestation, inclusive governance and iterative engagement of diverse populations with varied needs, aspirations, agency and rights claims, including those most affected, to deliberate trade-offs in a multiplicity of possible pathways (*high confidence*) (see Figure 5.5) (Stirling, 2014; Vale, 2014; Walsh-Dilley and Wolford, 2015; Biermann et al., 2016; J.R.A. Butler et al., 2016; O'Brien, 2016, 2018; Harris et al., 2017; Jones and Tanner, 2017; Mapfumo et al., 2017; Rosenbloom, 2017; Gajjar et al., 2018; Klinsky and Winkler, 2018; Lyon, 2018; Tàbara et al., 2018).

5.5.3.1 Transformations, equity and well-being

Most literature related to CRDPs invokes the concept of transformation, underscoring the need for urgent and far-reaching changes in practices, institutions and social relations in society. Transformations towards a 1.5°C warmer world would need to address considerations for equity and well-being, including in trade-off decisions (see Figure 5.1).

To attain the anticipated *transformations*, all countries as well as non-state actors would need to strengthen their contributions, through bolder and more committed cooperation and equitable effort-sharing (*medium evidence, high agreement*) (Rao, 2014; Frumhoff et al., 2015; Ekwurzel et al., 2017; Millar et al., 2017; Shue, 2017; Holz et al., 2018; Robinson and Shine, 2018). Sustaining decarbonization rates at a 1.5°C-compatible level would be unprecedented and not possible without rapid transformations to a net-zero-emissions global economy by mid-century or the later half of the century (see Chapters 2 and 4). Such efforts would entail overcoming technical, infrastructural, institutional and behavioural barriers across all sectors and levels

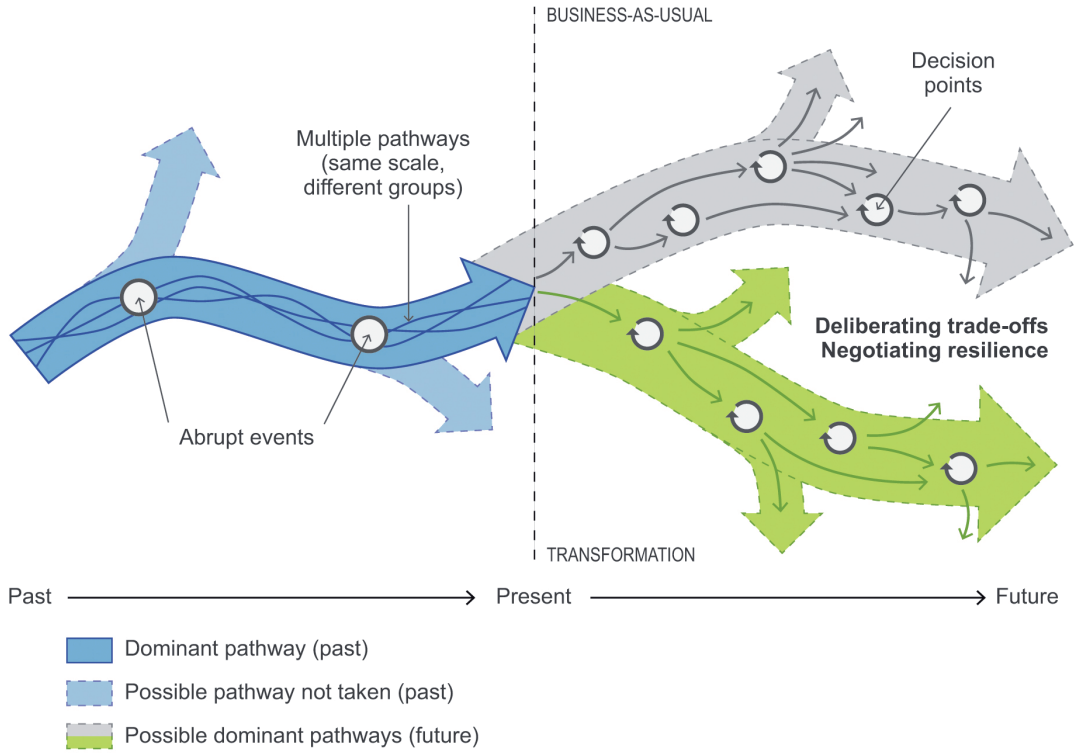


Figure 5.5 | Pathways into the future, with path dependencies and iterative problem-solving and decision-making (after Fazey et al., 2016).

of society (Pfeiffer et al., 2016; Seto et al., 2016) and defeating path dependencies, including poverty traps (Boonstra et al., 2016; Enqvist et al., 2016; Lade et al., 2017; Haider et al., 2018). Transformation also entails ensuring that 1.5°C-compatible pathways are inclusive and desirable, build solidarity and alliances, and protect vulnerable groups, including against disruptions of transformation (Patterson et al., 2018).

There is growing emphasis on the role of *equity, fairness* and *justice* (see Glossary) regarding context-specific transformations and pathways to a 1.5°C warmer world (*medium evidence, high agreement*) (Shue, 2014; Thorp, 2014; Dennig et al., 2015; Moellendorf, 2015; Klinsky et al., 2017b; Roser and Seidel, 2017; Sealey-Huggins, 2017; Klinsky and Winkler, 2018; Robinson and Shine, 2018). Consideration for what is equitable and fair suggests the need for stringent decarbonization and up-scaled adaptation that do not exacerbate social injustices, locally and at national levels (Okereke and Coventry, 2016), uphold human rights (Robinson and Shine, 2018), are socially desirable and acceptable (von Stechow et al., 2016; Rosenbloom, 2017), address values and beliefs (O'Brien, 2018), and overcome vested interests (Normann, 2015; Patterson et al., 2016). Attention is often drawn to huge disparities in the cost, benefits, opportunities and challenges involved in transformation within and between countries, and the fact that the suffering of already poor, vulnerable and disadvantaged populations may be worsened, if care to protect them is not taken (Holden et al., 2017; Klinsky and Winkler, 2018; Patterson et al., 2018).

Well-being for all (Dearing et al., 2014; Raworth, 2017) is at the core of an ecologically safe and socially just space for humanity, including health and housing, peace and justice, social equity, gender equality and political voices (Raworth, 2017). It is in alignment with transformative social development (UNRISD, 2016) and the 2030 Agenda of 'leaving no one behind'. The social conditions to enable well-being for all are to reduce entrenched inequalities within and between countries (Klinsky and Winkler, 2018); rethink prevailing values, ethics and behaviours (Holden et al., 2017); allow people to live a life in dignity while avoiding actions that undermine capabilities (Klinsky and Golub, 2016); transform economies (Popescu and Ciurlau, 2016; Tàbara et al., 2018); overcome uneven consumption and production patterns (Dearing et al., 2014; Häyhä et al., 2016; Raworth, 2017) and conceptualize development as well-being rather than mere economic growth (*medium evidence, high agreement*) (Gupta and Pouw, 2017).

5.5.3.2 Development trajectories, sharing of efforts and cooperation

The potential for pursuing sustainable and climate-resilient development pathways towards a 1.5°C warmer world differs between and within nations, due to differential development achievements and trajectories, and opportunities and challenges (*very high confidence*) (Figure 5.1). There are clear differences between high-income countries where social achievements are high, albeit often with negative effects on the environment, and most developing nations where vulnerabilities to climate change are high and social support and life satisfaction are low, especially in the Least Developed Countries (LDCs) (Sachs et al., 2017; O'Neill et al., 2018). Differential starting points for CRDPs between and within countries, including path dependencies (Figure 5.5), call for sensitivity to context (Klinsky and Winkler, 2018). For the developing world, limiting warming to 1.5°C also means potentially

severely curtailed development prospects (Okereke and Coventry, 2016) and risks to human rights from both climate action and inaction to achieve this goal (Robinson and Shine, 2018) (Section 5.2). Within-country development differences remain, despite efforts to ensure inclusive societies (Gupta and Arts, 2017; Gupta and Pouw, 2017). Cole et al. (2017), for instance, show how differences between provinces in South Africa constitute barriers to sustainable development trajectories and for operationalising nation-level SDGs, across various dimensions of social deprivation and environmental stress, reflecting historic disadvantages.

Moreover, various equity and effort- or burden-sharing approaches to climate stabilization in the literature describe how to sketch national potentials for a 1.5°C warmer world (e.g., Anand, 2004; CSO Equity Review, 2015; Meinshausen et al., 2015; Okereke and Coventry, 2016; Bexell and Jönsson, 2017; Otto et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017; Holz et al., 2018; Kartha et al., 2018; Winkler et al., 2018;). Many approaches build on the AR5 'responsibility – capacity – need' assessment (Clarke et al., 2014), complement other proposed national-level metrics for capabilities, equity and fairness (Heyward and Roser, 2016; Klinsky et al., 2017a), or fall under the wider umbrella of fair share debates on responsibility, capability and the right to development in climate policy (Fuglestvedt and Kallbekken, 2016). Importantly, different principles and methodologies generate different calculated contributions, responsibilities and capacities (Skeie et al., 2017).

The notion of nation-level fair shares is now also discussed in the context of limiting global warming to 1.5°C and the Nationally Determined Contributions (NDCs) (see Chapter 4, Cross-Chapter Box 11 in Chapter 4) (CSO Equity Review, 2015; Mace, 2016; Pan et al., 2017; Robiou du Pont et al., 2017; Holz et al., 2018; Kartha et al., 2018; Winkler et al., 2018). A study by Pan et al. (2017) concluded that all countries would need to contribute to ambitious emissions reductions and that current pledges for 2030 by seven out of eight high-emitting countries would be insufficient to meet 1.5°C. Emerging literature on justice-centred pathways to 1.5°C points towards ambitious emissions reductions domestically and committed cooperation internationally whereby wealthier countries support poorer ones, technologically, financially and otherwise to enhance capacities (Okereke and Coventry, 2016; Holz et al., 2018; Robinson and Shine, 2018; Shue, 2018). These findings suggest that equitable and 1.5°C-compatible pathways would require fast action across all countries at all levels of development rather than late accession of developing countries (as assumed under SSP3, see Chapter 2), with external support for prompt mitigation and resilience-building efforts in the latter (*medium evidence, medium agreement*).

Scientific advances since the AR5 now also make it possible to determine contributions to climate change for non-state actors (see Chapter 4, Section 4.4.1) and their potential to contribute to CRDPs (*medium evidence, medium agreement*). These non-state actors includes cities (Bulkeley et al., 2013, 2014; Byrne et al., 2016), businesses (Heede, 2014; Frumhoff et al., 2015; Shue, 2017), transnational initiatives (Castro, 2016; Andonova et al., 2017) and industries. Recent work demonstrates the contributions of 90 industrial carbon producers to global temperature and sea level rise, and their responsibilities to contribute to investments in and support for mitigation and adaptation (Heede, 2014; Ekwurzel et al., 2017; Shue, 2017) (Sections 5.6.1 and 5.6.2).

At the level of groups and individuals, equity in pursuing climate resilience for a 1.5°C warmer world means addressing disadvantage, inequities and empowerment that shape transformative processes and pathways (Fazey et al., 2018), and deliberate efforts to strengthen the capabilities, capacities and well-being of poor, marginalized and vulnerable people (Byrnes, 2014; Tokar, 2014; Harris et al., 2017; Klinsky et al., 2017a; Klinsky and Winkler, 2018). Community-driven CRDPs can flag potential negative impacts of national trajectories on disadvantaged groups, such as low-income families and communities of colour (Rao, 2014). They emphasize social equity, participatory governance, social inclusion and human rights, as well as innovation, experimentation and social learning (see Glossary) (*medium evidence, high agreement*) (Sections 5.5.3.3 and 5.6).

5.5.3.3 Country and community strategies and experiences

There are many possible pathways towards climate-resilient futures (O'Brien, 2018; Tàbara et al., 2018). Literature depicting different sustainable development trajectories in line with CRDPs is growing, with some of it being specific to 1.5°C global warming. Most experiences to date are at local and sub-national levels (Cross-Chapter Box 13 in this chapter), while state-level efforts align largely with green economy trajectories or planning for climate resilience (Box 5.3). Due to the fact that these strategies are context-specific, the literature is scarce on comparisons, efforts to scale up and systematic monitoring.

States can play an enabling or hindering role in a transition to a 1.5°C warmer world (Patterson et al., 2018). The literature on strategies to reconcile low-carbon trajectories with sustainable development and ecological sustainability through green growth, inclusive growth, de-growth, post-growth and development as well-being *shows low agreement* (see Chapter 4, Section 4.5). Efforts that align best with CRDPs are described as 'transformational' and 'strong' (Ferguson, 2015). Some view 'thick green' perspectives as enabling equity, democracy and agency building (Lorek and Spangenberg, 2014; Stirling, 2014; Ehresman and Okereke, 2015; Buch-Hansen, 2018), others show how green economy and sustainable development pathways can align (Brown et al., 2014; Georgeson et al., 2017b), and how a green economy can help link the SDGs with NDCs, for instance in Mongolia, Kenya and Sweden (Shine, 2017). Others still critique the continuous reliance on market mechanisms (Wanner, 2014; Brockington and Ponte, 2015) and disregard for equity and distributional and procedural justice (Stirling, 2014; Bell, 2015).

Country-level pathways and achievements vary significantly (*robust evidence, medium agreement*). For instance, the Scandinavian countries rank at the top of the Global Green Economy Index (Dual Citizen LLC, 2016), although they also tend to show high spill-over effects (Holz et al., 2018) and transgress their biophysical boundaries (O'Neill et al., 2018). State-driven efforts in non-member countries of the Organisation for Economic Co-operation and Development include Ethiopia's 'Climate-resilient Green Economy Strategy', Mozambique's 'Green Economy Action Plan' and Costa Rica's ecosystem- and conservation-driven

green transition paths. China and India have adopted technology and renewables pathways (Brown et al., 2014; Death, 2014, 2015, 2016; Khanna et al., 2014; Chen et al., 2015; Kim and Thurbon, 2015; Wang et al., 2015; Weng et al., 2015). Brazil promotes low per capita GHG emissions, clean energy sources, green jobs, renewables and sustainable transportation, while slowing rates of deforestation (see Chapter 4, Box 4.7) (Brown et al., 2014; La Rovere, 2017). Yet concerns remain regarding persistent inequalities, ecosystem monetization, lack of participation in green-style projects (Brown et al., 2014) and labour conditions and risk of displacement in the sugarcane ethanol sector (McKay et al., 2016). Experiences with low-carbon development pathways in LDCs highlight the crucial role of identifying synergies across scale, removing institutional barriers and ensuring equity and fairness in distributing benefits as part of the right to development (Rai and Fisher, 2017).

In small islands states, for many of which climate change hazards and impacts at 1.5°C pose significant risks to sustainable development (see Chapter 3 Box 3.5, Chapter 4 Box 4.3, Box 5.3), examples of CRDPs have emerged since the AR5. This includes the SAMOA Pathway: SIDS Accelerated Modalities of Action (see Chapter 4, Box 4.3) (UNGA, 2014; Government of Kiribati, 2016; Steering Committee on Partnerships for SIDS and UN DESA, 2016; Lefale et al., 2017) and the Framework for Resilient Development in the Pacific, a leading example of integrated regional climate change adaptation planning for mitigation and sustainable development, disaster risk management and low-carbon economies (SPC, 2016). Small islands of the Pacific vary significantly in their capacity and resources to support effective integrated planning (McCubbin et al., 2015; Barnett and Walters, 2016; Cvitanovic et al., 2016; Hemstock et al., 2017; Robinson and Dornan, 2017). Vanuatu (Box 5.3) has developed a significant coordinated national adaptation plan to advance the 2030 Agenda for Sustainable Development, respond to the Paris Agreement and reduce the risk of disasters in line with the Sendai targets (UNDP, 2016; Republic of Vanuatu, 2017).

Box 5.3 | Republic of Vanuatu – National Planning for Development and Climate Resilience

The Republic of Vanuatu is leading Pacific Small Island Developing States (SIDS) to develop a nationally coordinated plan for climate-resilient development in the context of high exposure to hazard risk (MoCC, 2016; UNU-EHS, 2016). The majority of the population depends on subsistence, rain-fed agriculture and coastal fisheries for food security (Sovacool et al., 2017). Sea level rise, increased prolonged drought, water shortages, intense storms, cyclone events and degraded coral reef environments threaten human security in a 1.5°C warmer world (see Chapter 3, Box 3.5) (SPC, 2015; Aipira et al., 2017). Given Vanuatu's long history of climate hazards and disasters, local adaptive capacity is relatively high, despite barriers to the use of local knowledge and technology, and low rates of literacy and women's participation (McNamara and Prasad, 2014; Aipira et al., 2017; Granderson, 2017). However, the adaptive capacity of Vanuatu and other SIDS is increasingly constrained due to more frequent severe weather events (see Chapter 3, Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4) (Gero et al., 2013; Kuruppu and Willie, 2015; SPC, 2015; Sovacool et al., 2017).

Vanuatu has developed a national sustainable development plan for 2016–2030: the People's Plan (Republic of Vanuatu, 2016). This coordinated, inclusive plan of action on economy, environment and society aims to strengthen adaptive capacity and resilience to climate change and disasters. It emphasizes rights of all Ni-Vanuatu, including women, youth, the elderly and vulnerable groups (Nalau et al., 2016). Vanuatu has also developed a Coastal Adaptation Plan (Republic of Vanuatu, 2016), an integrated Climate Change and Disaster Risk Reduction Policy (2016–2030) (SPC, 2015) and the first South Pacific National Advisory Board on Climate Change & Disaster Risk Reduction (SPC, 2015; UNDP, 2016).

Vanuatu aims to integrate planning at multiple scales, and increase climate resilience by supporting local coping capacities and iterative processes of planning for sustainable development and integrated risk assessment (Aipira et al., 2017; Eriksson et al., 2017; Granderson, 2017). Climate-resilient development is also supported by non-state partnerships, for example, the 'Yumi stap redi long climate change'–the Vanuatu non-governmental organization Climate Change Adaptation Program (Maclellan, 2015). This programme focuses on equitable governance, with particular attention to supporting women's voices in decision-making through allied programmes addressing domestic violence, and rights-based education to reduce social marginalization; alongside institutional reforms for greater transparency, accountability and community participation in decision-making (Davies, 2015; Maclellan, 2015; Sterrett, 2015; Ensor, 2016; UN Women, 2016).

Power imbalances embedded in the political economy of development (Nunn et al., 2014), gender discrimination (Aipira et al., 2017) and the priorities of climate finance (Cabezon et al., 2016) may marginalize the priorities of local communities and influence how local risks are understood, prioritised and managed (Kuruppu and Willie, 2015; Baldacchino, 2017; Sovacool et al., 2017). However, the experience of the low death toll after Cyclone Pam suggests effective use of local knowledge in planning and early warning may support resilience at least in the absence of storm surge flooding (Handmer and Iveson, 2017; Nalau et al., 2017). Nevertheless, the very severe infrastructure damage of Cyclone Pam 2015 highlights the limits of individual Pacific SIDS efforts and the need for global and regional responses to a 1.5°C warmer world (see Chapter 3, Box 3.5, Chapter 4, Box 4.3) (Dilling et al., 2015; Ensor, 2016; Shultz et al., 2016; Rey et al., 2017).

Communities, towns and cities also contribute to low-carbon pathways, sustainable development and fair and equitable climate resilience, often focused on processes of power, learning and contestation as entry points to more localised CRDPs (*medium evidence, high agreement*) (Cross-Chapter Box 13 in this chapter, Box 5.2). In the Scottish Borders Climate Resilient Communities Project (United Kingdom), local flood management is linked with national policies to foster cross-scalar and inclusive governance, with attention to systemic disadvantages, shocks and stressors, capacity building, learning for change and climate narratives to inspire hope and action, all of which are essential for community resilience in a 1.5°C warmer world (Fazey et al., 2018). Narratives and storytelling are vital for realizing place-based 1.5°C futures as they create space for agency, deliberation, co-constructing meaning, imagination and desirable and dignified pathways (Veland et al., 2018). Engagement with possible futures, identity and self-reliance is also documented for Alaska, where warming has already exceeded 1.5°C and indigenous communities invest in renewable energy, greenhouses for food security and new fishing practices to overcome loss of sea ice, flooding and erosion (Chapin et al., 2016; Fazey et al., 2018). The Asian Cities Climate Change Resilience Network facilitates shared learning dialogues, risk-to-resilience workshops, and iterative, consultative planning in flood-prone cities in India; vulnerable communities, municipal governmental agents, entrepreneurs and technical experts negotiate different visions, trade-offs and local politics to identify desirable pathways (Harris et al., 2017).

Transforming our societies and systems to limit global warming to 1.5°C and ensuring equity and well-being for human populations and ecosystems in a 1.5°C warmer world would require ambitious and well-integrated adaptation–mitigation–development pathways that deviate fundamentally from high-carbon, business-as-usual futures (Okereke and Coventry, 2016; Arts, 2017; Gupta and Arts, 2017; Sealey-Huggins, 2017). Identifying and negotiating socially acceptable, inclusive and equitable pathways towards climate-resilient futures is a challenging, yet important, endeavour, fraught with complex moral, practical and political difficulties and inevitable trade-offs (*very high confidence*). The ultimate questions are: what futures do we want (Bai et al., 2016; Tàbara et al., 2017; Klinsky and Winkler, 2018; O'Brien, 2018; Veland et al., 2018), whose resilience matters, for what, where, when and why (Meerow and Newell, 2016), and 'whose vision … is being pursued and along which pathways' (Gillard et al., 2016).

Cross-Chapter Box 13 | Cities and Urban Transformation

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Global Urbanization in a 1.5°C Warmer World

The concentration of economic activity, dense social networks, human resource capacity, investment in infrastructure and buildings, relatively nimble local governments, close connection to surrounding rural and natural environments, and a tradition of innovation provide urban areas with transformational potential (see Chapter 4, Section 4.3.3) (Castán Broto, 2017). In this sense, the urbanization megatrend that will take place over the next three decades, and add approximately 2 billion people to the global urban population (UN, 2014), offers opportunities for efforts to limit warming to 1.5°C.

Cities can also, however, concentrate the risks of flooding, landslides, fire and infectious and parasitic disease that are expected to heighten in a 1.5°C warmer world (Chapter 3). In African and Asian countries where urbanization rates are highest, these risks could expose and amplify pre-existing stresses related to poverty, exclusion, and governance (Gore, 2015; Dodman et al., 2017; Jiang and O'Neill, 2017; Pelling et al., 2018; Solecki et al., 2018). Through its impact on economic development and investment, urbanization often leads to increased consumption and environmental degradation and enhanced vulnerability and risk (Rosenzweig et al., 2018). In the absence of innovation, the combination of urbanization and urban economic development could contribute 226 GtCO2 in emissions by 2050 (Bai et al., 2018). At the same time, some new urban developments are demonstrating combined carbon and Sustainable Development Goals (SDG) benefits (Wiktorowicz et al., 2018), and it is in towns and cities that building renovation rates can be most easily accelerated to support the transition to 1.5°C pathways (Kuramochi et al., 2018), including through voluntary programmes (Van der Heijden, 2018).

Urban transformations and emerging climate-resilient development pathways

The 1.5°C pathways require action in all cities and urban contexts. Recent literature emphasizes the need to deliberate and negotiate how resilience and climate-resilient pathways can be fostered in the context of people's daily lives, including the failings of everyday development such as unemployment, inadequate housing and a growing informal sector and settlements (informality), in order

Cross-Chapter Box 13 (continued)

to acknowledge local priorities and foster transformative learning (Vale, 2014; Shi et al., 2016; Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Macintyre et al., 2018). Enhancing deliberate transformative capacities in urban contexts also entails new and relational forms of envisioning agency, equity, resilience, social cohesion and well-being (Section 5.5.3) (Gillard et al., 2016; Ziervogel et al., 2016). Two examples of urban transformation are explored here.

The built environment, spatial planning, infrastructure, energy services, mobility and urban–rural linkages necessary in rapidly growing cities in South Asia and Africa in the next three decades present mitigation, adaptation and development opportunities that are crucial for a 1.5°C world (Newman et al., 2017; Lwasa et al., 2018; Teferi and Newman, 2018). Realizing these opportunities would require the structural challenges of poverty, weak and contested local governance, and low levels of local government investment to be addressed on an unprecedented scale (Wachsmuth et al., 2016; Chu et al., 2017; van Noorloos and Kloosterboer, 2017; Pelling et al., 2018).

Urban governance is critical to ensuring that the necessary urban transitions deliver economic growth and equity (Hughes et al., 2018). The proximity of local governments to citizens and their needs can make them powerful agents of climate action (Melica et al., 2018), but urban governance is enhanced when it involves multiple actors (Ziervogel et al., 2016; Pelling et al., 2018), supportive national governments (Tait and Euston-Brown, 2017), and sub-national climate networks (see Chapter 4, Section 4.4.1). Governance is complicated for the urban population currently living in informality. This population is expected to triple, to three billion, by 2050 (Satterthwaite et al., 2018), placing a significant portion of the world's population beyond the direct reach of formal climate mitigation and adaptation policies (Revi et al., 2014). How to address the co-evolved and structural conditions that lead to urban informality and associated vulnerability to 1.5°C of warming is a central question for this report. Brown and McGranahan (2016) cite evidence that the informal urban 'green economy' that has emerged out of necessity in the absence of formal service provisions is frequently low-carbon and resource-efficient.

Realising the potential for low carbon transitions in informal urban settlements would require an express recognition of the unpaid-for contributions of women in the informal economy, and new partnerships between the state and communities (Ziervogel et al., 2017; Pelling et al., 2018; Satterthwaite et al., 2018). There is no guarantee that these partnerships will evolve or cohere into the type of service delivery and climate governance system that could steer the change on a scale required to limit to warming to 1.5°C (Jaglin, 2014). However, work by transnational networks, such as Shack/Slum Dwellers International, C40, the Global Covenant of Mayors, and the International Council for Local Environmental Initiatives, as well as efforts to combine in-country planning for Nationally Determined Contributions (NDCs) (Andonova et al., 2017; Fuhr et al., 2018) with those taking place to support the New Urban Agenda and National Urban Policies, represent one step towards realizing the potential (Tait and Euston-Brown, 2017). So too do 'old urban agendas', such as slum upgrading and universal water and sanitation provision (McGranahan et al., 2016; Satterthwaite, 2016; Satterthwaite et al., 2018).

Transition Towns (TTs) are a type of urban transformation that have emerged mainly in high-income countries. The grassroots TT movement (origin in the United Kingdom) combines adaptation, mitigation and just transitions, mainly at the level of communities and small towns. It now has more than 1,300 registered local initiatives in more than 40 countries (Grossmann and Creamer, 2017), many of them in the United Kingdom, the United States, and other high-income countries. TTs are described as 'progressive localism' (Cretney et al., 2016), aiming to foster a 'communitarian ecological citizenship' that goes beyond changes in consumption and lifestyle (Kenis, 2016). They aspire to promote equitable communities resilient to the impacts of climate change, peak oil and unstable global markets; re-localization of production and consumption; and transition pathways to a post-carbon future (Feola and Nunes, 2014; Evans and Phelan, 2016; Grossmann and Creamer, 2017).

TT initiatives typically pursue lifestyle-related low-carbon living and economies, food self-sufficiency, energy efficiency through renewables, construction with locally sourced material and cottage industries (Barnes, 2015; Staggenborg and Ogrodnik, 2015; Taylor Aiken, 2016). Social and iterative learning through the collective involves dialogue, deliberation, capacity building, citizen science engagements, technical re-skilling to increase self-reliance, for example canning and preserving food and permaculture, future visioning and emotional training to share difficulties and loss (Feola and Nunes, 2014; Barnes, 2015; Boke, 2015; Taylor Aiken, 2015; Kenis, 2016; Mehmood, 2016; Grossmann and Creamer, 2017).

Important conditions for successful transition groups include flexibility, participatory democracy, care ethics, inclusiveness and consensus-building, assuming bridging or brokering roles, and community alliances and partnerships (Feola and Nunes, 2014; Mehmood, 2016; Taylor Aiken, 2016; Grossmann and Creamer, 2017). Smaller scale rural initiatives allow for more experimentation

Cross-Chapter Box 13 (continued)

(Cretney et al., 2016), while those in urban centres benefit from stronger networks and proximity to power structures (North and Longhurst, 2013; Nicolosi and Feola, 2016). Increasingly, TTs recognize the need to participate in policymaking (Kenis and Mathijs, 2014; Barnes, 2015).

Despite high self-ratings of success, some TT initiatives are too inwardly focused and geographically isolated (Feola and Nunes, 2014), while others have difficulties in engaging marginalized, non-white, non-middle-class community members (Evans and Phelan, 2016; Nicolosi and Feola, 2016; Grossmann and Creamer, 2017). In the United Kingdom, expectations of innovations growing in scale (Taylor Aiken, 2015) and carbon accounting methods required by funding bodies (Taylor Aiken, 2016) undermine local resilience building. Tension between explicit engagements with climate change action and efforts to appeal to more people have resulted in difficult trade-offs and strained member relations (Grossmann and Creamer, 2017) though the contribution to changing an urban culture that prioritizes climate change is sometimes underestimated (Wiktorowicz et al., 2018).

Urban actions that can highlight the 1.5°C agenda include individual actions within homes (Werfel, 2017; Buntaine and Prather, 2018); demonstration zero carbon developments (Wiktorowicz et al., 2018); new partnerships between communities, government and business to build mass transit and electrify transport (Glazebrook and Newman, 2018); city plans to include climate outcomes (Millard-Ball, 2013); and support for transformative change across political, professional and sectoral divides (Bai et al., 2018).

5.6 Conditions for Achieving Sustainable Development, Eradicating Poverty and Reducing Inequalities in 1.5°C Warmer Worlds

This chapter has described the fundamental, urgent and systemic transformations that would be needed to achieve sustainable development, eradicate poverty and reduce inequalities in a 1.5°C warmer world, in various contexts and across scales. In particular, it has highlighted the societal dimensions, putting at the centre people's needs and aspirations in their specific contexts. Here we synthesize some of the most pertinent enabling conditions (see Glossary) to support these profound transformations. These conditions are closely interlinked and connected by the overarching concept of governance, which broadly includes institutional, socio-economic, cultural and technological elements (see Chapter 1, Cross-Chapter Box 4 in Chapter 1).

5.6.1 Finance and Technology Aligned with Local Needs

Significant gaps in green investment constrain transitions to a low-carbon economy aligned with development objectives (Volz et al., 2015; Campiglio, 2016). Hence, unlocking new forms of public, private and public–private financing is essential to support environmental sustainability of the economic system (Croce et al., 2011; Blyth et al., 2015; Falcone et al., 2018) (see Chapter 4, Section 4.4.5). To avoid risks of undesirable trade-offs with the SDGs caused by national budget constraints, improved access to international climate finance is essential for supporting adaptation, mitigation and sustainable development, especially for LDCs and SIDS (*medium evidence, high agreement*) (Shine and Campillo, 2016; Wood, 2017). Care needs to be taken when international donors or partnership arrangements influence project financing structures (Kongsager and Corbera, 2015; Purdon, 2015; Phillips et al., 2017; Ficklin et al., 2018). Conventional climate funding schemes, especially the Clean Development Mechanism (CDM), have shown positive effects on sustainable development but also adverse consequences, for example, on adaptive capacities of rural households and uneven distribution of costs and benefits, often exacerbating inequalities (*robust evidence, high agreement*) (Aggarwal, 2014; Brohé, 2014; He et al., 2014; Schade and Obergassel, 2014; Smits and Middleton, 2014; Wood et al., 2016a; Horstmann and Hein, 2017; Kreibich et al., 2017). Close consideration of recipients' context-specific needs when designing financial support helps to overcome these limitations as it better aligns community needs, national policy objectives and donors' priorities; puts the emphasis on the increase of transparency and predictability of support; and fosters local capacity building (*medium evidence, high agreement*) (Barrett, 2013; Boyle et al., 2013; Shine and Campillo, 2016; Ley, 2017; Sánchez and Izzo, 2017).

The development and transfer of technologies is another enabler for developing countries to contribute to the requirements of the 1.5°C objective while achieving climate resilience and their socio-economic development goals (see Chapter 4, Section 4.4.4). International-level governance would be needed to boost domestic innovation and the deployment of new technologies, such as negative emission technologies, towards the 1.5°C objective (see Chapter 4, Section 4.3.7), but the alignment with local needs depends on close consideration of the specificities of the domestic context in countries at all levels of development (de Coninck and Sagar, 2015; IEA, 2015; Parikh et al., 2018). Technology transfer supporting development in developing countries would require an understanding of local and national actors and institutions (de Coninck and Puig, 2015; de Coninck and Sagar, 2017; Michaelowa et al., 2018), careful attention to the capacities in the entire innovation chain (Khosla et al., 2017; Olawuyi, 2017) and transfer of not only equipment but also knowledge (*medium evidence, high agreement*) (Murphy et al., 2015).

5.6.2 Integration of Institutions

Multilevel governance in climate change has emerged as a key enabler for systemic transformation and effective governance (see Chapter 4,

Section 4.4.1). On the one hand, low-carbon and climate-resilient development actions are often well aligned at the lowest scale possible (Suckall et al., 2015; Sánchez and Izzo, 2017), and informal, local institutions are critical in enhancing the adaptive capacity of countries and marginalized communities (Yaro et al., 2015). On the other hand, international and national institutions can provide incentives for projects to harness synergies and avoid trade-offs (Kongsager et al., 2016).

Governance approaches that coordinate and monitor multiscale policy actions and trade-offs across sectoral, local, national, regional and international levels are therefore best suited to implement goals towards 1.5°C warmer conditions and sustainable development (Ayers et al., 2014; Stringer et al., 2014; von Stechow et al., 2016; Gwimbi, 2017; Hayward, 2017; Maor et al., 2017; Roger et al., 2017; Michaelowa et al., 2018). Vertical and horizontal policy integration and coordination is essential to take into account the interplay and trade-offs between sectors and spatial scales (Duguma et al., 2014; Naess et al., 2015; von Stechow et al., 2015; Antwi-Agyei et al., 2017a; Di Gregorio et al., 2017; Runhaar et al., 2018), enable the dialogue between local communities and institutional bodies (Colenbrander et al., 2016), and involve non-state actors such as business, local governments and civil society operating across different scales (*robust evidence, high agreement*) (Hajer et al., 2015; Labriet et al., 2015; Hale, 2016; Pelling et al., 2016; Kalafatis, 2017; Lyon, 2018).

5.6.3 Inclusive Processes

Inclusive governance processes are critical for preparing for a 1.5°C warmer world (Fazey et al., 2018; O'Brien, 2018; Patterson et al., 2018). These processes have been shown to serve the interests of diverse groups of people and enhance empowerment of often excluded stakeholders, notably women and youth (MRFCJ, 2015a; Dumont et al., 2017). They also enhance social- and co-learning which, in turn, facilitates accelerated and adaptive management and the scaling up of capacities for resilience building (Ensor and Harvey, 2015; Reij and Winterbottom, 2015; Tschakert et al., 2016; Binam et al., 2017; Dumont et al., 2017; Fazey et al., 2018; Lyon, 2018; O'Brien, 2018), and provides opportunities to blend indigenous, local and scientific knowledge (*robust evidence, high agreement*) (see Chapter 4, Section 4.3.5.5, Box 4.3, Section 5.3) (Antwi-Agyei et al., 2017a; Coe et al., 2017; Thornton and Comberti, 2017) . Such co-learning has been effective in improving deliberative decision-making processes that incorporate different values and world views (Cundill et al., 2014; C. Butler et al., 2016; Ensor, 2016; Fazey et al., 2016; Gorddard et al., 2016; Aipira et al., 2017; Chung Tiam Fook, 2017; Maor et al., 2017), and create space for negotiating diverse interests and preferences (*robust evidence, high agreement*) (O'Brien et al., 2015; Gillard et al., 2016; DeCaro et al., 2017; Harris et al., 2017; Lahn, 2018).

5.6.4 Attention to Issues of Power and Inequality

Societal transformations to limit global warming to 1.5°C and strive for equity and well-being for all are not power neutral (Section 5.5.3). Development preferences are often shaped by powerful interests that determine the direction and pace of change, anticipated benefits and beneficiaries, and acceptable and unacceptable trade-offs (Newell et al., 2014; Fazey et al., 2016; Tschakert et al., 2016; Winkler and Dubash, 2016; Wood et al., 2016b; Karlsson et al., 2017; Quan et al., 2017; Tanner et al., 2017). Each development pathway, including legacies and path dependencies, creates its own set of opportunities and challenges and winners and losers, both within and across countries (Figure 5.5) (*robust evidence, high agreement*) (Mathur et al., 2014; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017; Ficklin et al., 2018; Gajjar et al., 2018).

Addressing the uneven distribution of power is critical to ensure that societal transformation towards a 1.5°C warmer world does not exacerbate poverty and vulnerability or create new injustices but rather encourages equitable transformational change (Patterson et al., 2018). Equitable outcomes are enhanced when they pay attention to just outcomes for those negatively affected by change (Newell et al., 2014; Dilling et al., 2015; Naess et al., 2015; Sovacool et al., 2015; Cervigni and Morris, 2016; Keohane and Victor, 2016) and promote human rights, increase equality and reduce power asymmetries within societies (*robust evidence, high agreement*) (UNRISD, 2016; Robinson and Shine, 2018).

5.6.5 Reconsidering Values

The profound transformations that would be needed to integrate sustainable development and 1.5°C-compatible pathways call for examining the values, ethics, attitudes and behaviours that underpin societies (Hartzell-Nichols, 2017; O'Brien, 2018; Patterson et al., 2018). Infusing values that promote sustainable development (Holden et al., 2017), overcome individual economic interests and go beyond economic growth (Hackmann, 2016), encourage desirable and transformative visions (Tàbara et al., 2018), and care for the less fortunate (Howell and Allen, 2017) is part and parcel of climate-resilient and sustainable development pathways. This entails helping societies and individuals to strive for sufficiency in resource consumption within planetary boundaries alongside sustainable and equitable well-being (O'Neill et al., 2018). Navigating 1.5°C societal transformations, characterized by action from local to global, stresses the core commitment to social justice, solidarity and cooperation, particularly regarding the distribution of responsibilities, rights and mutual obligations between nations (*medium evidence, high agreement*) (Patterson et al., 2018; Robinson and Shine, 2018).

5.7 Synthesis and Research Gaps

The assessment in Chapter 5 illustrates that limiting global warming to 1.5°C above pre-industrial levels is fundamentally connected with achieving sustainable development, poverty eradication and reducing inequalities. It shows that avoided impacts between 1.5°C and 2°C temperature stabilization would make it easier to achieve many aspects of sustainable development, although important risks would remain at 1.5°C (Section 5.2). Synergies between adaptation and mitigation response measures with sustainable development and the SDGs can often be enhanced when attention is paid to well-being and equity while, when unaddressed, poverty and inequalities may be exacerbated (Section 5.3 and 5.4). Climate-resilient development pathways (CRDPs)

open up routes towards socially desirable futures that are sustainable and liveable, but concrete evidence reveals complex trade-offs along a continuum of different pathways, highlighting the role of societal values, internal contestations and political dynamics (Section 5.5). The transformations towards sustainable development in a 1.5°C warmer world, in all contexts, involve fundamental societal and systemic changes over time and across scale, and a set of enabling conditions without which the dual goal is difficult if not impossible to achieve (Sections 5.5 and 5.6).

This assessment is supported by growing knowledge on the linkages between a 1.5°C warmer world and different dimensions of sustainable development. However, several gaps in the literature remain:

Limited evidence exists that explicitly examines the real-world implications of a 1.5°C warmer world (and overshoots) as well as avoided impacts between 1.5°C versus 2°C for the SDGs and sustainable development more broadly. Few projections are available for households, livelihoods and communities. And literature on differential localized impacts and their cross-sector interacting and cascading effects with multidimensional patterns of societal vulnerability, poverty and inequalities remains scarce. Hence, caution is needed when global-level conclusions about adaptation and mitigation measures in a 1.5°C warmer world are applied to sustainable development in local, national and regional settings.

Limited literature has systematically evaluated context-specific synergies and trade-offs between and across adaptation and mitigation response measures in 1.5°C-compatible pathways and the SDGs. This hampers the ability to inform decision-making and fair and robust policy packages adapted to different local, regional or national circumstances. More research is required to understand how trade-offs and synergies will intensify or decrease, differentially across geographic regions and time, in a 1.5°C warmer world and as compared to higher temperatures.

Limited availability of interdisciplinary studies also poses a challenge for connecting the socio-economic transformations and the governance aspects of low emissions, climate-resilient transformations. For example, it remains unclear how governance structures enable or hinder different groups of people and countries to negotiate pathway options, values and priorities.

The literature does not demonstrate the existence of 1.5°C-compatible pathways achieving the 'universal and indivisible' agenda of the 17 SDGs, and hence does not show whether and how the nature and pace of changes that would be required to meet 1.5°C climate stabilization could be fully synergetic with all the SDGs.

The literature on low emissions and CRDPs in local, regional and national contexts is growing. Yet the lack of standard indicators to monitor such pathways makes it difficult to compare evidence grounded in specific contexts with differential circumstances, and therefore to derive generic lessons on the outcome of decisions on specific indicators. This knowledge gap poses a challenge for connecting local-level visions with global-level trajectories to better understand key conditions for societal and systems transformations that reconcile urgent climate action with well-being for all.

Frequently Asked Questions

FAQ 5.1 | What are the Connections between Sustainable Development and Limiting Global Warming to 1.5°C above Pre-Industrial Levels?

Summary: *Sustainable development seeks to meet the needs of people living today without compromising the needs of future generations, while balancing social, economic and environmental considerations. The 17 UN Sustainable Development Goals (SDGs) include targets for eradicating poverty; ensuring health, energy and food security; reducing inequality; protecting ecosystems; pursuing sustainable cities and economies; and a goal for climate action (SDG 13). Climate change affects the ability to achieve sustainable development goals, and limiting warming to 1.5°C will help meet some sustainable development targets. Pursuing sustainable development will influence emissions, impacts and vulnerabilities. Responses to climate change in the form of adaptation and mitigation will also interact with sustainable development with positive effects, known as synergies, or negative effects, known as trade-offs. Responses to climate change can be planned to maximize synergies and limit trade-offs with sustainable development.*

For more than 25 years, the United Nations (UN) and other international organizations have embraced the concept of sustainable development to promote well-being and meet the needs of today's population without compromising the needs of future generations. This concept spans economic, social and environmental objectives including poverty and hunger alleviation, equitable economic growth, access to resources, and the protection of water, air and ecosystems. Between 1990 and 2015, the UN monitored a set of eight Millennium Development Goals (MDGs). They reported progress in reducing poverty, easing hunger and child mortality, and improving access to clean water and sanitation. But with millions remaining in poor health, living in poverty and facing serious problems associated with climate change, pollution and land-use change, the UN decided that more needed to be done. In 2015, the UN Sustainable Development Goals (SDGs) were endorsed as part of the 2030 Agenda for Sustainable Development. The 17 SDGs (Figure FAQ 5.1) apply to all countries and have a timeline for success by 2030. The SDGs seek to eliminate extreme poverty and hunger; ensure health, education, peace, safe water and clean energy for all; promote inclusive and sustainable consumption, cities, infrastructure and economic growth; reduce inequality including gender inequality; combat climate change and protect oceans and terrestrial ecosystems.

Climate change and sustainable development are fundamentally connected. Previous IPCC reports found that climate change can undermine sustainable development, and that well-designed mitigation and adaptation responses can support poverty alleviation, food security, healthy ecosystems, equality and other dimensions of sustainable development. Limiting global warming to 1.5°C would require mitigation actions and adaptation measures to be taken at all levels. These adaptation and mitigation actions would include reducing emissions and increasing resilience through technology and infrastructure choices, as well as changing behaviour and policy.

These actions can interact with sustainable development objectives in positive ways that strengthen sustainable development, known as synergies. Or they can interact in negative ways, where sustainable development is hindered or reversed, known as trade-offs.

An example of a synergy is sustainable forest management, which can prevent emissions from deforestation and take up carbon to reduce warming at reasonable cost. It can work synergistically with other dimensions of sustainable development by providing food (SDG 2) and clean water (SDG 6) and protecting ecosystems (SDG 15). Other examples of synergies are when climate adaptation measures, such as coastal or agricultural projects, empower women and benefit local incomes, health and ecosystems.

An example of a trade-off can occur if ambitious climate change mitigation compatible with 1.5°C changes land use in ways that have negative impacts on sustainable development. An example could be turning natural forests, agricultural areas, or land under indigenous or local ownership to plantations for bioenergy production. If not managed carefully, such changes could undermine dimensions of sustainable development by threatening food and water security, creating conflict over land rights and causing biodiversity loss. Another trade-off could occur for some countries, assets, workers and infrastructure already in place if a switch is made from fossil fuels to other energy sources without adequate planning for such a transition. Trade-offs can be minimized if effectively managed, as when care is taken to improve bioenergy crop yields to reduce harmful land-use change or where workers are retrained for employment in lower carbon sectors.

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FAQ 5.1 (continued)

Limiting temperature increase to 1.5°C can make it much easier to achieve the SDGs, but it is also possible that pursuing the SDGs could result in trade-offs with efforts to limit climate change. There are trade-offs when people escaping from poverty and hunger consume more energy or land and thus increase emissions, or if goals for economic growth and industrialization increase fossil fuel consumption and greenhouse gas emissions. Conversely, efforts to reduce poverty and gender inequalities and to enhance food, health and water security can reduce vulnerability to climate change. Other synergies can occur when coastal and ocean ecosystem protection reduces the impacts of climate change on these systems. The sustainable development goal of affordable and clean energy (SDG 7) specifically targets access to renewable energy and energy efficiency, which are important to ambitious mitigation and limiting warming to 1.5°C.

The link between sustainable development and limiting global warming to 1.5°C is recognized by the SDG for climate action (SDG 13), which seeks to combat climate change and its impacts while acknowledging that the United Nations Framework Convention on Climate Change (UNFCCC) is the primary international, intergovernmental forum for negotiating the global response to climate change.

The challenge is to put in place sustainable development policies and actions that reduce deprivation, alleviate poverty and ease ecosystem degradation while also lowering emissions, reducing climate change impacts and facilitating adaptation. It is important to strengthen synergies and minimize trade-offs when planning climate change adaptation and mitigation actions. Unfortunately, not all trade-offs can be avoided or minimized, but careful planning and implementation can build the enabling conditions for long-term sustainable development.

FAQ5.1: **The United Nations Sustainable Development Goals (SDGs)**

The link between sustainable development and limiting global warming to 1.5°C is recognised by the Sustainable Development Goal for climate action (SDG 13)

FAQ 5.1, Figure 1 | Climate change action is one of the United Nations Sustainable Development Goals (SDGs) and is connected to sustainable development more broadly. Actions to reduce climate risk can interact with other sustainable development objectives in positive ways (synergies) and negative ways (trade-offs).

Frequently Asked Questions

FAQ 5.2 | What are the Pathways to Achieving Poverty Reduction and Reducing Inequalities while Reaching a 1.5°C World?

Summary: *There are ways to limit global warming to 1.5°C above pre-industrial levels. Of the pathways that exist, some simultaneously achieve sustainable development. They entail a mix of measures that lower emissions and reduce the impacts of climate change, while contributing to poverty eradication and reducing inequalities. Which pathways are possible and desirable will differ between and within regions and nations. This is due to the fact that development progress to date has been uneven and climate-related risks are unevenly distributed. Flexible governance would be needed to ensure that such pathways are inclusive, fair and equitable to avoid poor and disadvantaged populations becoming worse off. Climate-resilient development pathways (CRDPs) offer possibilities to achieve both equitable and low-carbon futures.*

Issues of equity and fairness have long been central to climate change and sustainable development. Equity, like equality, aims to promote justness and fairness for all. This is not necessarily the same as treating everyone equally, since not everyone comes from the same starting point. Often used interchangeably with fairness and justice, equity implies implementing different actions in different places, all with a view to creating an equal world that is fair for all and where no one is left behind.

The Paris Agreement states that it 'will be implemented to reflect equity… in the light of different national circumstances' and calls for 'rapid reductions' of greenhouse gases to be achieved 'on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty'. Similarly, the UN SDGs include targets to reduce poverty and inequalities, and to ensure equitable and affordable access to health, water and energy for all.

Equity and fairness are important for considering pathways that limit warming to 1.5°C in a way that is liveable for every person and species. They recognize the uneven development status between richer and poorer nations, the uneven distribution of climate impacts (including on future generations) and the uneven capacity of different nations and people to respond to climate risks. This is particularly true for those who are highly vulnerable to climate change, such as indigenous communities in the Arctic, people whose livelihoods depend on agriculture or coastal and marine ecosystems, and inhabitants of small island developing states. The poorest people will continue to experience climate change through the loss of income and livelihood opportunities, hunger, adverse health effects and displacement.

Well-planned adaptation and mitigation measures are essential to avoid exacerbating inequalities or creating new injustices. Pathways that are compatible with limiting warming to 1.5°C and aligned with the SDGs consider mitigation and adaptation options that reduce inequalities in terms of who benefits, who pays the costs and who is affected by possible negative consequences. Attention to equity ensures that disadvantaged people can secure their livelihoods and live in dignity, and that those who experience mitigation or adaptation costs have financial and technical support to enable fair transitions.

CRDPs describe trajectories that pursue the dual goal of limiting warming to 1.5°C while strengthening sustainable development. This includes eradicating poverty as well as reducing vulnerabilities and inequalities for regions, countries, communities, businesses and cities. These trajectories entail a mix of adaptation and mitigation measures consistent with profound societal and systems transformations. The goals are to meet the short-term SDGs, achieve longer-term sustainable development, reduce emissions towards net zero around the middle of the century, build resilience and enhance human capacities to adapt, all while paying close attention to equity and well-being for all.

The characteristics of CRDPs will differ across communities and nations, and will be based on deliberations with a diverse range of people, including those most affected by climate change and by possible routes towards transformation. For this reason, there are no standard methods for designing CRDPs or for monitoring their progress towards climate-resilient futures. However, examples from around the world demonstrate that flexible and inclusive governance structures and broad participation often help support iterative decision-making, continuous learning and experimentation. Such inclusive processes can also help to overcome weak institutional arrangements and power structures that may further exacerbate inequalities.

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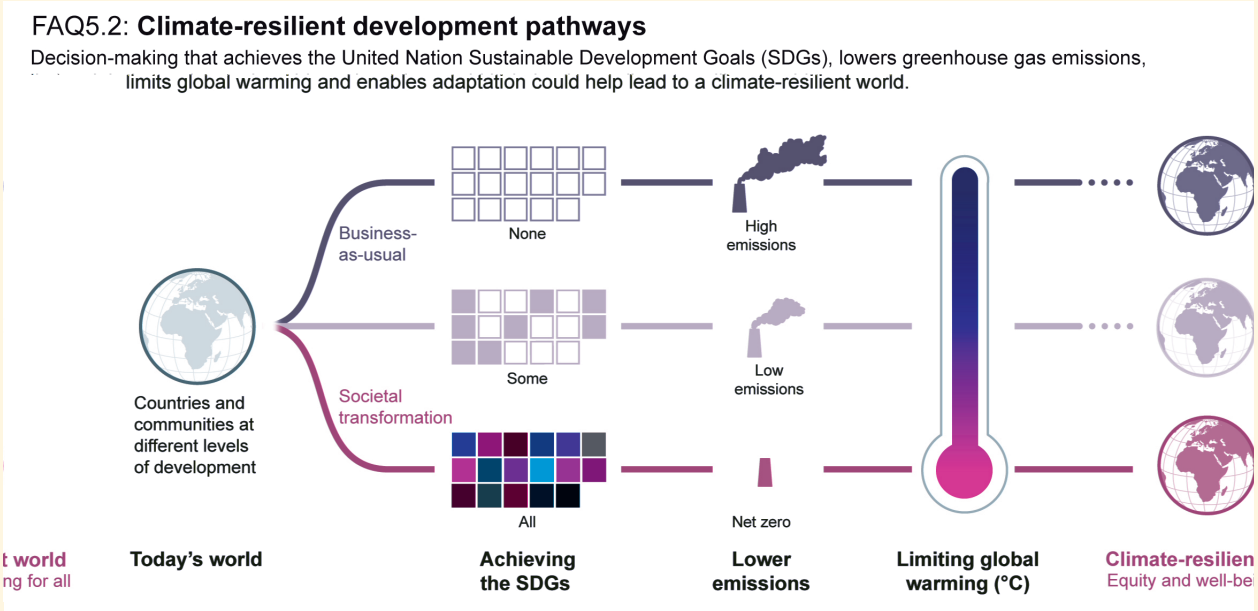
FAQ 5.2 (continued)



FAQ 5.2, Figure 1 | Climate-resilient development pathways (CRDPs) describe trajectories that pursue the dual goals of limiting warming to 1.5°C while strengthening sustainable development. Decision-making that achieves the SDGs, lowers greenhouse gas emissions and limits global warming could help lead to a climate-resilient world, within the context of enhancing adaptation.

Ambitious actions already underway around the world can offer insight into CRDPs for limiting warming to 1.5°C. For example, some countries have adopted clean energy and sustainable transport while creating environmentally friendly jobs and supporting social welfare programmes to reduce domestic poverty. Other examples teach us about different ways to promote development through practices inspired by community values. For instance, *Buen Vivir*, a Latin American concept based on indigenous ideas of communities living in harmony with nature, is aligned with peace; diversity; solidarity; rights to education, health, and safe food, water, and energy; and well-being and justice for all. The Transition Movement, with origins in Europe, promotes equitable and resilient communities through low-carbon living, food self-sufficiency and citizen science. Such examples indicate that pathways that reduce poverty and inequalities while limiting warming to 1.5°C are possible and that they can provide guidance on pathways towards socially desirable, equitable and low-carbon futures.

Table 5.2 | Mitigation – SDG table
Social-Demand

		1 NO POVERTY					2 ZERO HUNGER					3 GOOD HEALTH AND WELL-BEING					4 QUALITY EDUCATION				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement	**Reduces Poverty** ↑	[+2]	🕮	☺	★	[0]					**Air, Water Pollution Reduction and Better Health (3.9)** ↑	[+2]	🕮🕮	☺☺	★★	**Technical Education, Vocational Training, Education for Sustainability (4.3/4.4/4.5/4.7)** ↑	[+1]	🕮🕮	☺☺	★★
		% of people living below poverty line declines from 49% to 18% in South African context.					No direct interaction					People living in deprived communities feel positive and predict considerable financial savings. Efficiency changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. In extractive industries there are trade-off unless strategically managed. Behavioural changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment.					Awareness, knowledge, technical and managerial capability are closely linked, energy audit, information for trade unions, product/appliance labeling help in sustainability education.				
		Altieri et al., 2016										Vassolo and Döll, 2005; Xi et al., 2013; Nguyen et al., 2014; Holland et al., 2015; Zhang et al., 2015; Fricko et al., 2016					Apeaning and Thollander, 2013; Fernando and Evans, 2015; Roy et al., 2018				
	Low-carbon Fuel Switch	[0]					[0]					**Water and Air Pollution Reduction and Better Health (3.9)** ↑	[+2]	🕮🕮	☺☺	★★	**Technical Education, Vocational Training, Education for Sustainability (4.b/4.7)** ↑	[+1]	🕮🕮	☺☺	★★
		No direct interaction					No direct interaction					Industries are becoming suppliers of energy, waste heat, water and roof tops for solar energy generation, and hence helping to improve air and water quality.					New technology deployment creates demand for awareness and knowledge with technical and managerial capability; otherwise acts as barrier for rapid expansion.				
												Vassolo and Döll, 2005; Nguyen et al., 2014; Holland et al., 2015; Karner et al., 2015; Fricko et al., 2016					Apeaning and Thollander, 2013; Fernando and Evans, 2015; Roy et al., 2018				
	Decarbonization/CCS/CCU	[0]					[0]					**Disease and Mortality (3.1/3.2/3.3/3.4)** ↓	[-1]	🕮🕮	☺☺☺	★★★	[0]				
		No direct interaction					No direct interaction					There is a risk of CO_2 leakage both from geological formations as well as from the transportation infrastructure from source to sequestration locations.					No direct interaction				
												Wang and Jaffe, 2004; Hertwich et al., 2008; Apps et al., 2010; Veltman et al., 2010; Koornneef et al., 2011; Singh et al., 2011; Siirila et al., 2012; Atchley et al., 2013; Corsten et al., 2013; IPCC, 2014									

Social-Demand (continued)

		1 NO POVERTY					2 ZERO HUNGER					3 GOOD HEALTH AND WELL-BEING					4 QUALITY EDUCATION				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Buildings	Behavioural Response	**Poverty Reduction via Financial Savings (1.1)**										**Improved Warmth and Comforts**									
		↑	[+2]	🕮	☺	★		[0]				↑	[+2]	🕮🕮🕮	☺☺☺	★★★		[0]			
		People living in deprived communities feel positive and predict considerable financial savings.					No direct interaction					Home occupants reported warmth as the most important aspect of comfort which was largely temperature-related and low in energy costs. Residents living in deprived areas expect improved warmth in their properties after energy efficiency measures are employed.					No direct interaction				
		Scott et al., 2014										Huebner et al., 2013; Yue et al., 2013; Scott et al., 2014; Zhao et al., 2017									
	Accelerating Energy Efficiency Improvement	**Poverty and Development (1.1/1.2/1.3/1.4)**					**Food Security (2.1)**					**Healthy Lives and Well-being for All at All Ages (3.2/3.9)**					**Equal Access to Educational Institutions (4.1/4.2/4.3/4.5)**				
		↑ / ↓	[+2,-1]	🕮🕮🕮	☺☺☺	★★★	↑	[+2]	🕮	☺	★	↑	[+2]	🕮🕮🕮🕮	☺☺☺☺	★★★★	↑	[+2]	🕮	☺	★
		Energy efficiency interventions lead to cost savings which are realized due to reduced energy bills that further lead to poverty reduction. Participants with low incomes experience greater benefits. 'Energy efficiency and biomass strategies benefitted the poor more than wind and solar, whose benefits are captured by industry. Carbon mitigation can increase or decrease inequalities. The distributional costs of new energy policies (e.g., supporting renewables and energy efficiency) are dependent on instrument design. If costs fall disproportionately on the poor, then this could impair progress towards universal energy access and, by extension, counteract the fight to eliminate poverty. (Quote from McCollum et al., 2018).					Using the improved stoves supports local food security and has significantly impacted on food security. By making fuel last longer, the improved stoves help improve food security and also provide a better buffer against fuel shortages induced by climate change-related events such as droughts, floods or hurricanes (Berrueta et al. 2017).					Efficient stoves improve health, especially for indigenous and poor rural communities. Household energy efficiency has positive health impacts on children's respiratory health, weight and susceptibility to illness, and the mental health of adults. Household energy efficiency improves winter warmth, lowers relative humidity with benefits for cardiovascular and respiratory health. Further improved indoor air quality by thermal regulation and occupant comfort are realised. However, in one instance, negative health impacts (asthma) of increased household energy efficiency were also noted when housing upgrades took place without changes in occupant behaviours. Home occupants reported warmth as the most important aspect of comfort which was largely temperature-related and low in energy costs. Residents living in the deprived areas expect improved warmth in their properties after energy efficiency measures are employed.					Household energy efficiency measures reduce school absences for children with asthma due to indoor pollution.				
		Casillas and Kammen, 2012; Hirth and Ueckerdt, 2013; Jakob and Steckel, 2014; Maidment et al., 2014; Scott et al., 2014; Fay et al., 2015; Cameron et al., 2016; Hallegatte et al., 2016b; Berrueta et al., 2017; McCollum et al., 2018					Berrueta et al., 2017					Djamila et al., 2013; Huebner et al., 2013; Yue et al., 2013; Bhojvaid et al., 2014; Derbez et al., 2014; Maidment et al., 2014; Scott et al., 2014; Cameron et al., 2015; Liddell and Guiney, 2015; Sharpe et al., 2015; Wells et al., 2015; Willand et al., 2015; Berrueta et al., 2017; Zhao et al., 2017					Maidment et al., 2014				
	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Poverty and Development (1.1/1.2/1.3/1.4)**					**Food Security and Agricultural Productivity (2.1/2.4)**					**Disease and Mortality (3.1/3.2/3.3/3.4)**					**Equal Access to Educational Institutions (4.1/4.2/4.3/4.5)**				
		↑	[+2]	🕮🕮🕮	☺☺☺	★★★★	~ / ↓	[0,-1]	🕮🕮	☺☺☺	★★	↑	[+2]	🕮🕮🕮	☺☺☺	★★★★	↑	[+1]	🕮	☺☺☺	★★
		Access to modern energy forms (electricity, clean stoves, high-quality lighting) is fundamental to human development since the energy services made possible by them help alleviate chronic and persistent poverty. Strength of the impact varies in the literature. (Quote from McCollum et al., 2018)					Modern energy access is critical to enhance agricultural yields/productivity, decrease post-harvest losses and mechanize agri-processing – all of which can aid food security. However, large-scale bioenergy and food production may compete for scarce land and other inputs (e.g., water, fertilizers), depending on how and where biomass supplies are grown and the indirect land use change impacts that result. If not implemented thoughtfully, this could lead to higher food prices globally, and thus reduce access to affordable food for the poor. Enhanced agricultural productivities can ameliorate the situation by allowing as much bioenergy to be produced on as little land as possible.					Access to modern energy services can contribute to fewer injuries and diseases related to traditional solid fuel collection and burning, as well as utilization of kerosene lanterns. Access to modern energy services can facilitate improved health care provision, medicine and vaccine storage, utilization of powered medical equipment, and dissemination of health-related information and education. Such services can also enable thermal comfort in homes and contribute to food preservation and safety. (Quote from McCollum et al., 2018)					Access to modern energy is necessary for schools to have quality lighting and thermal comfort, as well as modern information and communication technologies. Access to modern lighting and energy allows for studying after sundown and frees constraints on time management that allow for higher school enrolment rates and better literacy outcomes. (Quote from McCollum et al., 2018)				
		Kirubi et al., 2009; Casillas and Kammen, 2010; Cook, 2011; Pachauri et al., 2012; Pode, 2013; Pueyo et al., 2013; Zulu and Richardson, 2013; Bonan et al., 2014; Rao et al., 2014; Burlig and Preonas, 2016; McCollum et al., 2018					Cabraal et al., 2005; Tilman et al., 2009; van Vuuren et al., 2009; Asaduzzaman et al., 2010; Finco and Doppler, 2010; Msangi et al., 2010; Smith et al., 2013, 2014; Lotze-Campen et al., 2014; Hasegawa et al., 2015; Sola et al., 2016; McCollum et al., 2018					Lam et al., 2012; Lim et al., 2012; Smith et al., 2013; Aranda et al., 2014; McCollum et al., 2018					Lipscomb et al., 2013; van de Walle et al., 2013; McCollum et al., 2018				

Social-Demand (continued)

		1 NO POVERTY					2 ZERO HUNGER					3 GOOD HEALTH AND WELL-BEING					4 QUALITY EDUCATION				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Transport	Behavioural Response	**Equal Right to Economic Resources Access Basic Services (1.1/1.4/1.a/1.b)**					**Ensure Access to Safe Nutritious Food (2.1/2.2)**					**Road Traffic Accidents (3.4/3.6)**					**Equal Safe Access to Educational Institutions (4.1/4.2/4.3/4.5)**				
		↑ / ↓	[+2,-1]	📖📖📖	☺☺☺	★★★	↑	[+2]	📖	☺	★★★	↑ / ↓	[+2,-1]	📖📖📖	☺☺☺	★★	↑	[+1]	📖	☺☺☺	★★
		The costs of daily mobility can have important economic stress impacts, not only impacting carless families with low-mobility, but in countries with high levels of car dependence, the costs of motoring can be burdensome, raising questions of affordability for households with limited economic resources. During economic crisis, public transport authorities may react by reducing levels of service and increasing fares, likely exacerbating the situation for low-income households.					Low-income community residents (non-white) who lack local access to affordable, quality sources of nutrition have to travel outside their immediate neighbourhood to find better sources of food to feed themselves and their families. Lack of locally available healthy food often exacerbates the rates of obesity in many of these communities since it is often difficult or expensive to travel long distances on a regular basis to shop for food.					Active travel modes, such as walking and cycling, represent strategies not only for boosting energy efficiency but also, potentially, for improving health and well-being (e.g., lowering rates of diabetes, obesity, heart disease, dementia and some cancers). However, a risk associated with these measures is that they could increase rates of road traffic accidents, if the existing infrastructure is unsatisfactory. Overall health effects will depend on the severity of the injuries sustained from these potential accidents relative to the health benefits accruing from increased exercise (McCollum et al., 2018).					Poor road quality affects school travel safety, so collaborative efforts need to address safety issues from a dual perspective, first by working to change the existing infrastructure and use of roads to better address the traffic problems that children currently face walking to school, and then to better situate schools and control the roadways and land uses around them in the future.				
		Dodson et al., 2004; Cascajo et al., 2017					Clifton, 2004; Hillier, 2011; Krukowski et al., 2013; LeDoux and Vojnovic, 2013; Ghosh-Dastidar et al., 2014; Zenk et al., 2015; Lowery et al., 2016					Woodcock et al., 2009; Creutzig et al., 2012; Haines and Dora, 2012; Saunders et al., 2013; Shaw et al., 2014, 2017; Chakrabarti and Shin, 2017; Hwang et al., 2017; McCollum et al., 2018					Yu, 2015				
	Accelerating Energy Efficiency Improvement	**End Poverty in all its Forms Everywhere (1.1/1.4/1.a/1.b)**					[0]					**Reduce Illnesses from Hazardous Air, Water and Soil Pollution (3.9)**					[0]				
		↑ / ↓	[+2,-1]	📖📖📖	☺☺☺	★★★	No direct interaction					↑	[+2]	📖📖📖	☺☺☺	★★★	No direct interaction				
		Decarbonization of public buses in Sweden is receiving attention more than efficiency improvement. With more electrification, electricity prices go up and affordability can worsen for the poor unless redistributive policies are in place.										Locally relevant policies targeting traffic reductions and ambitious diffusion of electric vehicles results in measured changes in non-climatic exposure for population, including ambient air pollution, physical activity and noise. The transition to low-carbon equitable and sustainable transport can be fostered by numerous short- and medium-term strategies that would benefit energy security, health, productivity and sustainability. An evidence-based approach that takes into account GHG emissions, ambient air pollutants, economic factors (affordability, cost optimization), social factors (poverty alleviations, public health benefits) and political acceptability is needed to tackle these challenges.									
		Xylia and Silveira, 2017										Figueroa et al., 2014; Schucht et al., 2015; Klausbruckner et al., 2016; Peng et al., 2017									
	Improved Access and Fuel Switch to Modern Low-carbon Energy	**End Poverty in all its Forms Everywhere (1.1/1.4/1.a/1.b)**					**Ensure Access to Food Security (2.1/2.3/2.a/2.b/2.c)**					**Reduce Illnesses from Hazardous Air Pollution (3.9)**					[0]				
		↑ / ↓	[+2,-1]	📖📖📖	☺☺☺	★★★	~	[0]	📖	☺	★	↑	[+2]	📖	☺	★	No direct interaction				
		Increasingly volatile global oil prices have raised concerns for the vulnerability of households to fuel price increases. Pricing measures as a key component of sustainable transport policy need to consider equity. Pro-poor mitigation policies are needed to reduce climate impact and reduce threat; for example, investing more and better in infrastructure by leveraging private resources and using designs that account for future climate change and the related uncertainty. Communities in poor areas cope with and adapt to multiple-stressors including climate change. Coping strategies provide short-term relief but in the long-term may negatively affect development goals. And responses generate a trade-off between adaptation, mitigation and development. For African cities with slums, due to high commuting costs, many walk to work places which limit access. In Latin America triple informality leading to low productivity and living standards.					21 projects aiming at resilient transport infrastructure development to improve access (e.g., C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) do not substantially contribute to realizing the (indirect) transport targets with mostly a rural focus: agricultural productivity (SDG 2) and access to safe drinking water (SDG 6).					Projects aiming at resilient transport infrastructure development (e.g., C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are targeted at reducing air pollution; electric vehicles using electricity from renewables or low carbon sources combined with e-mobility options such as trolley buses, metros, trams and electro buses, as well as promoting walking and biking, especially for short distances, need consideration.									
		Dodson and Sipe, 2008; Suckall et al., 2014; Hallegatte et al., 2016a; Klausbruckner et al., 2016; CAF, 2017; Lall et al., 2017					SLoCaT, 2017					Ajanovic, 2015; SLoCaT, 2017									

Social-Supply

		1 NO POVERTY					2 ZERO HUNGER					3 GOOD HEALTH AND WELL-BEING					4 QUALITY EDUCATION				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	**Poverty and Development (1.1/1.2/1.3/1.4)**										**Air Pollution (3.9)**					**Vocational Trainig, Education for Sustainability (4.b/4.7)**				
		↑	[+2]	📖📖📖	☺☺☺	★★★	[0]					↑	[+2]	📖📖📖	☺☺☺	★★★★	↑	[+1]	📖	☺	★
		Deployment of renewable energy and improvements in energy efficiency globally will aid climate change mitigation efforts, and this, in turn, can help to reduce the exposure of the world's poor to climate-related extreme events, negative health impacts and other environmental shocks (McCollum et al., 2018).					No direct interaction					Promoting most types of renewables and boosting efficiency greatly aids the achievement of targets to reduce local air pollution and improve air quality; however, the order of magnitude of the effects, both in terms of avoided emissions and monetary valuation, varies significantly between different parts of the world. Benefits would especially accrue to those living in the dense urban centres of rapidly developing countries. Utilization of biomass and biofuels might not lead to any air pollution benefits, however, depending on the control measures applied. In addition, household air quality can be significantly improved through lowered particulate emissions from access to modern energy services (McCollum et al., 2018).					Decentralized renewable energy systems (e.g., home- or village-scale solar power) can support education and vocational training.				
		Riahi et al., 2012; IPCC, 2014; Hallegatte et al., 2016b; McCollum et al., 2018										Haines et al., 2007; Nemet et al., 2010; Kaygusuz, 2011; Riahi et al., 2012; van Vliet et al., 2012; Anenberg et al., 2013; Rafaj et al., 2013; Rao et al., 2013, 2016; West et al., 2013; Chaturvedi and Shukla, 2014; Rose et al., 2014; Smith and Sagar, 2014; IEA, 2016; McCollum et al., 2018					Anderson et al., 2017				
	Increased Use of Biomass	**Poverty and Development (1.1/1.2/1.3/1.4)**					**Farm Employment and Incomes (2.3)**					**Disease and Mortality (3.1/3.2/3.3/3.4), Air Pollution (3.9)**					[0]				
		↑ / ↓	[+2,-2]	📖📖	☺☺	★	↑ / ↓	[+2,-2]	📖📖📖	☺☺☺	★★★	↑	[+2]	📖📖📖	☺☺☺	★★★	No direct interaction				
		Large-scale bioenergy production could lead to the creation of agricultural jobs, as well as higher farm wages and more diversified income streams for farmers. Modern energy access can make marginal lands more cultivable, thus potentially generating on-farm jobs and incomes; on the other hand, greater farm mechanization can also displace labour. However, large-scale bioenergy production could alter the structure of global agricultural markets in a way that is, potentially, unfavourable to small-scale food producers. See SDG2 (McCollum et al., 2018).					Large-scale bioenergy production could lead to the creation of agricultural jobs, as well as higher farm wages and more diversified income streams for farmers. Modern energy access can make marginal lands more cultivable, thus potentially generating on-farm jobs and incomes; on the other hand, greater farm mechanization can also displace labour. However, large-scale bioenergy production could alter the structure of global agricultural markets in a way that is, potentially, unfavourable to small-scale food producers. The distributional effects of bioenergy production are underexplored in the literature (McCollum et al., 2018).					Replacing coal by biomass can reduce adverse impacts of upstream supply-chain activities, in particular local air and water pollution, and prevent coal mining accidents. Improvements to local air pollution in power generation compared to coal-fired power plants depend on the technology and fuel of biomass power plants, but could be significant when switching from outdated coal combustion technologies to state-of-the-art biogas power generation.									
		Balishter and Singh, 1991; Gohin, 2008; de Moraes et al., 2010; van der Horst and Vermeylen, 2011; Corbera and Pascual, 2012; Rud, 2012; Creutzig et al., 2013; Davis et al., 2013; Satolo and Bacchi, 2013; Muys et al., 2014; Ertem et al., 2017; McCollum et al., 2018					Balishter and Singh, 1991; Gohin, 2008; de Moraes et al., 2010; van der Horst and Vermeylen, 2011; Corbera and Pascual, 2012; Rud, 2012; Creutzig et al., 2013; Davis et al., 2013; Satolo and Bacchi, 2013; Muys et al., 2014; Ertem et al., 2017; McCollum et al., 2018					IPCC, 2005, 2014; Miller et al., 2007; Hertwich et al., 2008; de Best-Waldhober et al., 2009; Shackley et al., 2009; Wallquist et al., 2009, 2010; Wong-Parodi and Ray, 2009; Chan and Griffiths, 2010; Veltman et al., 2010; Epstein et al., 2011; Koornneef et al., 2011; Reiner and Nuttall, 2011; Singh et al., 2011; Ashworth et al., 2012; Burgherr et al., 2012; Chen et al., 2012; Asfaw et al., 2013; Corsten et al., 2013; Einsiedel et al., 2013									

Social-Supply (continued)

		1 NO POVERTY					2 ZERO HUNGER					3 GOOD HEALTH AND WELL-BEING					4 QUALITY EDUCATION				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Nuclear/Advanced Nuclear	No direct interaction	[0]				No direct interaction	[0]				**Disease and Mortality (3.1/3.2/3.3/3.4)** ↓ [-1] 📖📖📖 ☺☺☺ ★★★ In spite of the industry's overall safety track record, a non-negligible risk for accidents in nuclear power plants and waste treatment facilities remains. The long-term storage of nuclear waste is a politically fraught subject, with no large-scale long-term storage operational worldwide. Negative impacts from upstream uranium mining and milling are comparable to those of coal, hence replacing fossil fuel combustion by nuclear power would be neutral in that aspect. Increased occurrence of childhood leukaemia in populations living within 5 km of nuclear power plants was identified by some studies, even though a direct causal relation to ionizing radiation could not be established and other studies could not confirm any correlation (*low evidence/agreement* on this issue). Abdelouas, 2006; Cardis et al., 2006; Kaatsch et al., 2008; Al-Zoughool and Krewski, 2009; Heinävaara et al., 2010; Schnelzer et al., 2010; Brugge and Buchner, 2011; Møller and Mousseau, 2011; Møller et al., 2011, 2012; Moomaw et al., 2011; UNSCEAR, 2011; Sermage-Faure et al., 2012; Ten Hoeve and Jacobson, 2012; Tirmarche et al., 2012; Hiyama et al., 2013; Mousseau and Møller, 2013; Smith et al., 2013; WHO, 2013; IPCC, 2014; von Stechow et al., 2016					[0]	No direct interaction			
	CCS: Bioenergy	**Poverty and Development (1.1/1.2/1.3/1.4)** ↑ / ↓ [+2,-2] 📖📖 ☺☺ ★ See effects of increased bioenergy use.					**Farm Employment and Incomes (2.3)** ↑ / ↓ [+1,-2] 📖📖📖 ☺☺☺ ★★★ See increased use of biomass effects. In addition, the concern that more bioenergy (for BECCS) necessarily leads to unacceptably high food prices is not founded on large agreement in the literature. AR5, for example, finds a significantly lower effect of large-scale bioenergy deployment on food prices by mid-century than the effect of climate change on crop yields. Also, Muratori et al. (2016) show that BECCS reduces the upward pressure on food crop prices by lowering carbon prices and lowering the total biomass demand in climate change mitigation scenarios. On the other hand, competition for land use may increase food prices and thereby increase risk of hunger. Use of agricultural residue for bioenergy can reduce soil carbon, thereby threatening agricultural productivity. See literature on increased biomass use: IPCC, 2014; Muratori et al., 2016; Dooley and Kartha, 2018					**Disease and Mortality (3.1/3.2/3.3/3.4)** ↑ / ↓ [+2,-1] 📖📖 ☺☺☺ ★★★ See positive impacts of increased biomass use. At the same time, there is a non-negligible risk of CO_2 leakage both from geological formations as well as from the transportation infrastructure from source to sequestration locations. Wang and Jaffe, 2004; Hertwich et al., 2008; Apps et al., 2010; Veltman et al., 2010; Koornneef et al., 2011; Singh et al., 2011; Siirila et al., 2012; Atchley et al., 2013; Corsten et al., 2013; IPCC, 2014					[0]	No direct interaction			
Advanced Coal	CCS: Fossil	[0]	No direct interaction				[0]	No direct interaction				**Disease and Mortality (3.1/3.2/3.3/3.4)** ↓ [-1] 📖📖 ☺☺☺ ★★★ The use of fossil CCS implies continued adverse impacts of upstream supply-chain activities in the coal sector, and because of lower efficiency of CCS coal power plants, upstream impacts and local air pollution are likely to be exacerbated. Furthermore, there is a non-negligible risk of CO_2 leakage from geological storage or the CO_2 transport infrastructure from source to sequestration location. Wang and Jaffe, 2004; Hertwich et al., 2008; Apps et al., 2010; Veltman et al., 2010; Koornneef et al., 2011; Singh et al., 2011; Siirila et al., 2012; Atchley et al., 2013; Corsten et al., 2013; IPCC, 2014					[0]	No direct interaction			

Social-Other

		1 NO POVERTY					2 ZERO HUNGER					3 GOOD HEALTH AND WELL-BEING					4 QUALITY EDUCATION				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	**Poverty and Development (1.1/1.2/1.3/1.4)**					**Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)**					**Tobacco Control (3.a/3.a.1)**					[0]				
		~ / ↓	[0,-1]	📖📖	☺☺☺	★★	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	↑	[+1]	📖	☺	★	No direct interaction				
		Cutting livestock consumption can increase food security for some if land grows food not feed, but can also undermine livelihoods and culture where livestock has long been the best use of land, such as in parts of Sub-Saharan Africa.					Curbing consumer waste of major food crops (i.e., wheat, rice and vegetables) and meats (i.e., beef, pork and poultry) in China, USA and India alone could feed ~413 million people per year (West et al., 2014). One billion extra people could be fed if food crop losses could be halved (Kummu et al., 2012). Reducing waste, especially from meat and dairy, could play a role in delivering food security and reduce the need for sustainable intensification (Smith, 2013). Dietary change toward global healthy diets could improve nutritional health, food security and reduce emissions.					Consume fewer foods with low nutritional value, e.g., alcohol (Garnett, 2011). Demand-side measures aimed at reducing the proportion of livestock products in human diets, where the consumption of animal products is higher than recommended, are associated with multiple health benefits, especially in industrialized countries (Bustamante et al., 2014).									
		IPCC, 2014					Garnett, 2011; Beddington et al., 2012; Kummu et al., 2012; Smith, 2013; Bajželj et al., 2014; Tilman and Clark, 2014; West et al., 2014; Lamb et al., 2016					Garnett, 2011; Bustamante et al., 2014									
	Land-based GHG Reduction and Soil Carbon Sequestration	**Poverty and Development (1.1/1.2/1.3/1.4)**					**Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)**					**Ensure Healthy Lives (3.c)**					**Ensure Inclusive and Quality Education (4.4/4.7)**				
		↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	↑ / ↓	[+2,-2]	📖📖	☺☺	★★	↑ / ↓	[+2,-2]	📖📖	☺	★
		Many CSA interventions aim to improve rural livelihoods, thereby contributing to poverty alleviation. Agroforestry or integrated crop–livestock–biogas systems can substitute costly, external inputs, saving on household expenditures – or even lead to the selling of some of the products, providing the farmer with extra income, leading to increased adaptive capacity (Bogdanski, 2012).					Safe application of biotechnology, both conventional and modern methods, can help to improve agricultural productivity, improving crop adaptability and thereby catering to food security. Reducing tillage, eliminating fallow and keeping the soil covered with residue, cover crops or perennial vegetation helps prevent soil erosion and has the potential to increase soil organic matter. Efficient land-management techniques can help in increasing crop yields, and so food security issues can be addressed. Yield projections are actually higher for developing countries than for developed countries, reflecting the fact that they have more 'catch-up' potential (Evenson, 1999). Action is needed throughout the food system on moderating demand, reducing waste, improving governance and producing more food (Godfray and Garnett, 2014). Improving cropland management is the key to increase crop productivity without further degrading soil and water resources (Branca et al., 2011). CSA practices increase productivity and prioritize food security.					Growing crops such as cassava, sorghum and millet, even in harsh conditions, is important to the diets of very poor people. Policy scenarios show that reduced research support, delayed industrialization, delayed biotechnology and climate change will delay progress in reducing childhood malnutrition. The global effects are small, but local effects for some countries, e.g., Bangladesh and Nigeria, are significant (Evenson, 1999).					Science-based action within CSA is required to integrate data sets and sound metrics for testing hypotheses about feedback regarding climate, weather data products and agricultural productivity, such as the nonlinearity of temperature effects on crop yield and the assessment of trade-offs and synergies that arise from different agricultural intensification strategies (Steenwerth et al., 2014). Low commodity prices have led to declining investment in research and development, farmer education, etc. (Lamb et al., 2016).				
		Branca et al., 2011; Bogdanski, 2012; Scherr et al., 2012; Vermeulen et al., 2012; Campbell et al., 2014; Lipper et al., 2014; Mbow et al., 2014; Steenwerth et al., 2014; Hammond et al., 2017					Evenson, 1999; West and Post, 2002; Johnson et al., 2007; Branca et al., 2011; McCarthy et al., 2011; Behnassi et al., 2014; Campbell et al., 2014; Godfray and Garnett, 2014; Harvey et al., 2014; Lipper et al., 2014					Evenson, 1999; Godfray and Garnett, 2014					Steenwerth et al., 2014; Lamb et al., 2016				
	Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems	**Poverty Reduction and Minimize Exposure to Risk (1.5)**					**Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)**					**Ensure Healthy Lives (3.c)**					[0]				
		↑	[+2]	&	J	«	↑	[+2]	&&&&	JJJJ	««««	↑ / ↓	[+2,-2]	&&	JJ	««	No direct interaction				
		With mixed-farming systems farmers can not only mitigate risks by producing a multitude of commodities, but they can also increase the productivity of both crops and animals in a more profitable and sustainable way.					Fostering transitions towards more productive livestock production systems targeting land-use change appears to be the most efficient lever to deliver food availability outcomes. Genomic selection should be able to at least double the rate of genetic gain in the dairy industry. Given the prevalence of mixed crop–livestock systems in many parts of the world, closer integration of crops and livestock in such systems can give rise to increased productivity and increased soil fertility (Thornton, 2010). Managing the indirect effects of livestock systems intensification is critical for the sustainability of the global food system: such as improving productivity and the close link to land sparing (Herrero and Thornton, 2013). In East Africa pastoralists have shifted from cows to camels, which are better adapted to survive periods of water scarcity and able to consistently provide more milk (Steenwerth et al., 2014). Scenarios where zero human-edible concentrate feed is used for livestock, soil erosion potential reduces by 12%.					Biodigestion, which has positive public health aspects, particularly where toilets are coupled with the biodigester; anaerobic conditions kill pathogenic organisms as well as digestive toxins. Separation processes can improve or worsen health risks related to food crops or to livestock.									
		Sansoucy, 1995					Thornton, 2010, 2013; Herrero and Thornton, 2013; Havlik et al., 2014; Steenwerth et al., 2014; Schader et al., 2015					Sansoucy, 1995; Burton, 2007									

Social-Other (continued)

		1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	4 QUALITY EDUCATION
		Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence
Forest	Reduced Deforestation, REDD+	**Poverty Reduction (1.5)** ↑ [+2] 📖 ☺ ★ Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth. Katila et al., 2017	**Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)** ↑ / ↓ [+1,-2] 📖📖 ☺ ★ Food security may lead to the conversion of productive land under forest, including community forests, into agricultural production. In a similar fashion, the production of biomass for energy purposes (SDG 7) may reduce land available for food production and/or for community forest activities . Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017; Dooley and Kartha, 2018	[0] No direct interaction	**Ensure Inclusive and Quality Education (4.4/4.7)** ↑ [+1] 📖 ☺ ★ Local forest users learn to understand laws, regulations and policies which facilitate their participation in society. Education and capacity building provide technical skill and knowledge (Katila et al., 2017). Katila et al., 2017
	Afforestation and Reforestation	**Poverty and Development (1.1/1.2/1.3/1.4)** ↑ / ↓ [+2,-2] 📖📖 ☺☺ ★★★ Clean Development Mechanism (CDM) can have different implications on local community livelihoods. For example, willingness to adopt afforestation is influenced in particular by Australian landholder's perceptions of its potential to provide a diversified income stream, and its impacts on flexibility of land management ; land sparing would have far reaching implications for the UK countryside and would affect landowners and rural communities ; and livelihoods could be threatened if subsistence agriculture is targeted . Zomer et al., 2008; Schirmer and Bull, 2014; Lamb et al., 2016; Dooley and Kartha, 2018	**Food Security (2.1)** ↑ / ↓ [+1,-1] 📖 ☺ ★ CDM can have different implications on local to regional food security and local community livelihoods. Zomer et al., 2008; Dooley and Kartha, 2018	**Ensure Healthy Lives (3.c)** ↑ [+1] 📖 ☺ ★ Urban trees are increasingly seen as a way to reduce harmful air pollutants and therefore improve cardio-respiratory health. Jones and McDermott, 2018	**Promote Knowledge and Skill to Promote SD (4.7)** ↓ [-1] 📖 ☺ ★ Most landholders reported having low levels of knowledge about tree planting for carbon sequestration – particularly available programmes, prices and markets, and government rules and regulations . Schirmer and Bull, 2014
	Behavioural Response (Responsible	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction
Oceans	Ocean Iron Fertilization	[0] No direct interaction	**Food Security (2.2/2.3)** ↑ / ↓ [+1,-1] 📖📖 ☺ ★ OIF can have different implications on fish stocks and aquaculture, and it might actually increase food availability for fish stocks (increasing yields); but potentially at the cost of reducing the yields of fisheries outside the enhancement region by depleting other nutrients. Lampitt et al., 2008; Smetacek and Naqvi, 2008; Williamson et al., 2012	[0] No direct interaction	[0] No direct interaction
	Blue Carbon	**Poverty and Development (1.1/1.2/1.5)** ↑ [+3] 📖📖📖 ☺☺☺ ★★★ Avoiding loss of mangroves and maintaining the 2000 stock could save a value of ecosystem services from mangroves in South East Asia of approximately 2.16 billion USD until 2050 (2007 prices), with a 95% prediction interval of 1.58–2.76 billion USD (case study area South East Asia); seaweed aquaculture will enhance carbon uptake and provide employment; traditional management systems provide benefits for blue carbon and support livelihoods for local communities; greening of aquaculture can significantly enhance carbon storage; PES schemes could help capture the benefits derived from multiple ecosystem services beyond carbon sequestration. Zomer et al., 2008; Schirmer and Bull, 2014; Lamb et al., 2016	**Food Production (2.3/2.4)** ↑ [+3] 📖📖📖 ☺☺☺ ★★★ Avoiding loss of mangroves and maintaining the 2000 stock could save a value of ecosystem services from mangroves in South East Asia including fisheries; seaweed aquaculture will provide employment; traditional management systems provide livelihoods for local communities; greening of aquaculture can increase income and well-being; and mariculture is a promising approach for China. Brander et al., 2012; Ahmed et al., 2017a, 2017b; Duarte et al., 2017; Sondak et al., 2017; Vierros, 2017; Zhang et al., 2017	[0] No direct interaction	[0] No direct interaction
	Enhanced Weathering	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction

Social 2-Demand

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES					16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement	No direct interaction	[0]				**Knowledge and Skills Needed to Promote SD (4.7)** ↑	[+1]	📖	☺☺☺	★★★ There is need for skill in managing in-house energy efficiency. Sometimes ESCOs also help. Energy audits, but many times absence of skill acts as barrier for energy efficiency improvement. In many countries, especially developing countries, these act as barriers. Apeaning and Thollander, 2013; Johansson and Thollander, 2018	No direct interaction	[0]				**Global Partnership (17.6/17.7)** ↑	[+2]	📖📖	☺☺☺	★★★ A driving force for energy efficiency is collaboration among companies, networks, experience sharing and management tools. Sharing among countries can help accelerate managerial action. Absence of information, budgetary funding, lack of access to capital, etc. are Apeaning and Thollander, 2013; Griffin et al., 2018; Johansson and Thollander, 2018; Lawrence et al., 2018
	Low-carbon Fuel Switch	No direct interaction	[0]				No direct interaction	[0]				No direct interaction	[0]				**Global Partnership (17.6/17.7)** ↑	[+2]	📖	☺☺	★★ Ultra-low carbon steel making and breakthrough technologies are under trial across many countries and helping in enhancing the learning. Abdul Quader et al., 2016
	Decarbonization/CCS/CCU	No direct interaction	[0]				No direct interaction	[0]				No direct interaction	[0]				**Global Partnership (17.6/17.7)** ↑	[+2]	📖	☺☺☺	★★★ EPI plants are capital intensive and are mostly operated by multinationals with long investment cycles. In developed countries new innovation investments are happening in brown fields. Such large innovation investments need strong collaboration among partners/competitors which can be facilitated by public funds. They happen at national and supranational scales and across sectors, needs fresh revisit at Intellectual Property Rights issues. Global production of bio-based polymers increasingly need public support and incentives to push forward. Wesseling et al., 2017; Griffin et al., 2018

Social 2-Demand (continued)

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES					16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Buildings	Behavioural Response	[0] No direct interaction					[0] No direct interaction					**Environmental Justice (16.7)** ↑ [+2] 🕮 ☺ ★ Consumption perspectives strengthen environmental justice discourse (as it claims to be a more just way of calculating global and local environmental effects) while possibly also increasing the participatory environmental discourse. Hult and Larsson, 2016					[0] No direct interaction				
	Accelerating Energy Efficiency Improvement	**Gender Equality and Women's Empowerment (5.1/5.4)** ↑ [+1] 🕮 ☺☺ ★★ Efficient stoves lead to empowerment of rural and indigenous women. Bhojvaid et al., 2014; Berrueta et al., 2017					**Empowerment and Inclusion (10.1/10.2/10.3/10.4)** ↑/↓ [1,-1] 🕮🕮🕮 ☺☺☺ ★★★ Energy efficiency measures and the provision of energy access can free up resources that can then be put towards other productive uses (e.g., educational and employment opportunities), especially for women and children in poor, rural areas. The distributional costs of new energy policies are dependent on instrument design. If costs fall disproportionately on the poor, then this could work against the promotion of social, economic and political equality for all. The impacts of energy efficiency measures and policies on inequality can be both positive, if they reduce energy costs, or negative, if mandatory standards increase the need for purchasing more expensive equipment and appliances. Dinkelman, 2011; Casillas and Kammen, 2012; Pachauri et al., 2012; Cayla and Osso, 2013; Hirth and Ueckerdt, 2013; Pueyo et al., 2013; Jakob and Steckel, 2014; Fay et al., 2015; Cameron et al., 2016; Hallegatte et al., 2016b; McCollum et al., 2018					**Capacity and Accountability (16.1/16.3/16.5/16.6/16.7/16.8)** ↑ [+2] 🕮🕮🕮 ☺☺☺ ★★★★ Institutions that are effective, accountable and transparent are needed at all levels of government (local to national to international) for providing energy access, promoting modern renewables and boosting efficiency. Strengthening the participation of developing countries in international institutions (e.g., international energy agencies, UN organizations, WTO, regional development banks and beyond) will be important for issues related to energy trade, foreign direct investment, labour migration and knowledge and technology transfer. Reducing corruption, where it exists, will help these bodies and related domestic institutions maximize their societal impacts. Limiting armed conflict and violence will aid most efforts related to sustainable development, including progress in the energy dimension. Acemoglu, 2009; Tabellini, 2010; Acemoglu et al., 2014; ICSU and ISSC, 2015; McCollum et al., 2018					**Enhance Policy Coherence for Sustainable Development (17.4)** ↑ [+2] 🕮 ☺ ★ Implementing refrigerant transition and energy efficiency improvement policies in parallel for room ACs, roughly doubles the benefit of either policy implemented in isolation. Shah et al., 2015				
	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Women's Safety and Worth (5.1/5.2/5.4)/Opportunities for Women (5.1/5.5)** ↑ [+1] 🕮🕮 ☺☺ ★★ Improved access to electric lighting can improve women's safety and girls' school enrolment. Cleaner cooking fuel and lighting access can reduce health risks and drudgery, which women disproportionately face. Access to modern energy services has the potential to empower women by improving their income-earning and entrepreneurial opportunities and reducing drudgery. Participating in energy supply chains can increase women's opportunities and agency and improve business outcomes. Chowdhury, 2010; Dinkelman, 2011; Kaygusuz, 2011; Köhlin et al., 2011; Clancy et al., 2012; Haves, 2012; Matinga, 2012; Anenberg et al., 2013; Pachauri and Rao, 2013; Burney et al., 2017; McCollum et al.,					[0] No direct interaction					**Capacity and Accountability (16.1/16.3/16.5/16.6/16.7/16.8)** ↑ [+2] 🕮🕮🕮 ☺☺☺ ★★★★ Institutions that are effective, accountable and transparent are needed at all levels of government (local to national to international) for providing energy access, promoting modern renewables and boosting efficiency. Strengthening the participation of developing countries in international institutions (e.g., international energy agencies, UN organizations, WTO, regional development banks and beyond) will be important for issues related to energy trade, foreign direct investment, labour migration, and knowledge and technology transfer. Reducing corruption, where it exists, will help these bodies and related domestic institutions maximize their societal impacts. Limiting armed conflict and violence will aid most efforts related to sustainable development, including progress in the energy dimension. Acemoglu, 2009; Tabellini, 2010; Acemoglu et al., 2014; ICSU and ISSC, 2015; McCollum et al., 2018					**Promote Transfer and Diffusion of Technology (17.6/17.7)** ↑ [+2] 🕮 ☺ ★ Green building technology in Kazakhstan was based on transfer of knowledge among various parties. Kim and Sun, 2017				

Social 2-Demand (continued)

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES					16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Transport	Behavioural response	**Recognize Women's Unpaid Work (5.1/5.4)/Opportunities for Women (5.1/5.5)**					**Reduce Inequality (10.2)**					**Accountable and Transparent Institutions at All Levels (16.6/16.8)**					**Help Promote Global Partnership (17.1/17.3/17.5/17.6/17.7)**				
		↑	[+1]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺	★★	↑ / ↓	[+1, -1]	📖	☺	★	↑	[+2]	📖	☺	★
		The woman's average trip to work differs markedly from the man's average trip. Working-poor women rely on extensive social networks creating communities of spatial necessity, bartering for basic needs to overcome transportation constraints. Women earn lower wages and so are less likely to justify longer commutes. Many women need to manage dual roles as workers and mothers. Women tend to perform multi-purpose commuting, combining both work and household needs .					The equity impacts of climate change mitigation measures for transport, and indeed of transport policy intervention overall, are poorly understood by policymakers. This is in large part because standard assessment of these impacts is not a statutory requirement of current policymaking. Managing transport energy demand growth will have to be advanced alongside efforts in passenger travel towards reducing the deep inequalities in access to transport services that currently affect the poor worldwide. Free provision of roads and parking spaces converts vast amounts of public land and capital into under-priced space for cars, in extreme cases like Los Angeles, USA, roads and streets free for parking and driving are 20% of land area; as governments give drivers free land, people drive more than they would otherwise. High levels of car dependence and the costs of motoring can be burdensome, and lead to increasing debt, raising questions of affordability for households with limited resources, particularly low-income houses located in suburban areas					With behavioural change towards walking for short distances, pedestrian safety on the road might reduce, unless public policy is appropriately formulated. Prevalence of high levels of triple forms of informality, in jobs, housing and transportation, are responsible for low productivity and low standards of living, and are a major challenge for policies targeting urban growth in Latin America.					Projects aiming at resilient transport infrastructure development (e.g., C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multi-stakeholder coalitions.				
		Crane, 2007; Rogalsky, 2010					Figueroa et al., 2014; Lucas and Pangbourne, 2014; Walks, 2015; Manville, 2017; Belton Chevallier et al., 2018					CAF, 2017; SLoCaT, 2017					SLoCaT, 2017				
	Accelerating Energy Efficiency Improvement	[0]					[0]					**Responsive, Inclusive, Participatory Decision-making (16.7)**					**Help Promote Global Partnership (17.1/17.3/17.5/17.6/17.7)**				
												↑	[+2]	📖📖	☺☺	★★	↑	[+2]	📖	☺	★
		No direct interaction					No direct interaction					In transport mitigation it is necessary to conduct needs assessments and stakeholder consultation to determine plausible challenges, prior to introducing desired planning reforms. Further, the involved personnel should actively engage transport-based stakeholders during policy identification and its implementation to achieve the desired results. User behaviour and stakeholder integration are key for successful transport policy implementation.					Projects aiming at resilient transport infrastructure development and technology adoption (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multi-stakeholder coalitions.				
												Aggarwal, 2017; AlSabbagh et al., 2017					SLoCaT, 2017				
	Improved Access and Fuel Switch to Modern Low-carbon Energy	[0]					**Reduce Inequality (10.2)**					**Responsive, Inclusive, Participatory Decision-making (16.7)**					**Help Promote Global Partnership (17.1/17.3/17.5/17.6/17.7)**				
							↑	[+2]	📖📖	☺☺	★★	↑ / ↓	[+1, -1]	📖	☺	★	↑	[+2]	📖	☺	★
		No direct interaction					The equity impacts of climate change mitigation measures for transport, and indeed of transport policy intervention overall, are poorly understood by policymakers. This is in large part because standard assessment of these impacts is not a statutory requirement of current policymaking. Managing transport energy demand growth will have to be advanced alongside efforts in passenger travel towards reducing the deep inequalities in access to transport services that currently affect the poor worldwide.					Formal transport infrastructure improvement in many cities in developing countries leads to eviction from informal settlements; need for appropriate redistributive policies and cooperation and partnerships with all stakeholders.					Projects aiming at resilient transport infrastructure development (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multi-stakeholder coalitions.				
							Figueroa et al., 2014; Lucas and Pangbourne, 2014					Colenbrander et al., 2016					SLoCaT, 2017				

Social 2-Supply

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES					16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	**Gender Equality and Women's Empowerment (5.1/5.4)**					**Empowerment and Inclusion (10.1/10.2/10.3/10.4)**					**Energy Justice**					**International Cooperation (All Goals)**				
		↑	[+1]	📖	☺	★	↑	[+1]	📖📖	☺☺	★★	↑	[+2]	📖	☺	★	↑ / ~	[+2,0]	📖📖	☺☺	★★
		Decentralized renewable energy systems (e.g., home- or village-scale solar power) can reduce the burden on girls and women of procuring traditional biomass.					Decentralized renewable energy systems (e.g., home- or village-scale solar power) can enable a more participatory, democratic process for managing energy-related decisions within communities.					The energy justice framework serves as an important decision-making tool in order to understand how different principles of justice can inform energy systems and policies. Islar et al. (2017) state that off-grid and micro-scale energy development offers an alternative path to fossil-fuel use and top-down resource management as they democratize the grid and increase marginalized communities' access to renewable energy, education and health care.					International cooperation (in policy) and collaboration (in science) is required for the protection of shared resources. Fragmented approaches have been shown to be more costly. Specific to SDG7, to achieve the targets for energy access, renewables and efficiency, it will be critical that all countries: (i) are able to mobilize the necessary financial resources (e.g., via taxes on fossil energy, sustainable financing, foreign direct investment, financial transfers from industrialized to developing countries); (ii) are willing to disseminate knowledge and share innovative technologies between each other; (iii) follow recognized international trade rules while at the same time ensuring that the least developed countries are able to take part in that trade; (iv) respect each other's policy space and decisions; (v) forge new partnerships between their public and private entities and within civil society; and (vi) support the collection of high-quality, timely and reliable data relevant to furthering their missions. There is some disagreement in the literature on the effect of some of the above strategies, such as free trade. Regarding international agreements, 'no-regrets options', where all sides gain through cooperation, are seen as particularly beneficial (e.g., nuclear test ban treaties) (McCollum et al., 2018).				
		Schwerhoff and Sy, 2017					Walker and Devine-Wright, 2008; Cass et al., 2010; Cumbers, 2012; Kunze and Becker, 2015; McCollum et al., 2018					Islar et al., 2017					UN, 1989; Ramaker et al., 2003; Clarke et al., 2009; NCE, 2015; Riahi et al., 2015, 2017; Eis et al., 2016; O'Neill et al., 2017; McCollum et al., 2018				
	Increased use of Biomass	[0] No direct interaction					[0] No direct interaction					[0] No direct interaction					[0] No direct interaction				
	Nuclear/Advanced Nuclear	[0] No direct interaction					[0] No direct interaction					**Reduce Illicit Arms Trade (16.4)**					[0] No direct interaction				
												↓	[-1]	📖📖	☺☺	★★					
												Continued use of nuclear power poses a constant risk of proliferation.									
												Adamantiades and Kessides, 2009; Rogner, 2010; Sagan, 2011; von Hippel et al., 2011, 2012; Yim and Li, 2013; IPCC, 2014									
	CCS: Bioenergy	[0] No direct interaction					[0] No direct interaction					[0] No direct interaction					[0] No direct interaction				
Advanced Coal	CCS: Fossil	[0] No direct interaction					[0] No direct interaction					[0] No direct interaction					[0] No direct interaction				

Social 2-Other

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES					16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	[0] No direct interaction					[0] No direct interaction					**making (16.6/16.7/16.a)** ↑ / ↓ [+1,-1] 📖📖📖 ☺☺ ★★ Appropriate incentives to reduce food waste may require some policy innovation and experimentation, but a strong commitment for devising and monitoring them seems essential. A financial incentive to minimize waste could be created through effective taxation (e.g., by taxing foods with the highest wastage rates, or by increasing taxes on waste disposal). Decision makers should try to integrate agricultural, environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets coupled with reduction in food waste. It is surprising that politicians and policymakers demonstrate little regarding the need to have strategies to reduce meat consumption and to encourage more sustainable eating practices. Garnett, 2011; Dagevos and Voordouw, 2013; Bajželj et al., 2014; Lamb et al., 2016					**Resource Mobilization and Strengthen Partnership** ↑ / ↓ [+1,-1] 📖 ☺ ★ Decision makers should try to integrate agricultural, environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets coupled with reduction in food waste. It is surprising that politicians and policymakers demonstrate little regarding the need to have strategies to reduce meat consumption and to encourage more sustainable eating practices . Garnett, 2011; Dagevos and Voordouw, 2013				
	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	**Equal Access, Empowerment of Women (5.5)** ↑ / ~ [+2,0] 📖📖 ☺☺ ★★★ Many programmes for CSA have been used to empower women and to improve gender equality. Women often have an especially important role to play in adaptation, because of their gendered indigenous knowledge on matters such as agriculture (Terry, 2009). Without access to land, credit and agricultural technologies, women farmers face major constraints in their capacity to diversify into alternative livelihoods (Demetriades and Esplen, 2008). Denton, 2002; Nelson et al., 2002; Morton, 2007; Demetriades and Esplen, 2009; Terry, 2009; Bernier et al., 2013; Jost et al., 2016					**Empower Economic and Political Inclusion of All, Irrespective of Sex (10.2)** ↑ / ~ [+1,0] 📖📖 ☺☺ ★★ In many rural societies women are side-lined from decisions regarding agriculture even when male household heads are absent, and they often lack access to important inputs such as irrigation water, credit, tools and fertilizer. To be effective, agricultural mitigation strategies need to take these and other aspects of local gender relations into account (Terry, 2009). Women's key role in maintaining biodiversity, through conserving and domesticating wild edible plant seed, and in food crop breeding, is not sufficiently recognized in agricultural and economic policymaking; nor is the importance of biodiversity to sustainable rural livelihoods in the face of predicted climate changes (Nelson et al., 2002). Nelson et al., 2002; Demetriades and Esplen, 2009; Terry, 2009					**Build Effective, Accountable and Inclusive Institutions (16.6/16.7/16.8)** ~ / ↓ [0,-1] 📖📖📖 ☺☺ ★★ Action is needed throughout the food system for improving governance and producing more food (Godfray and Garnett, 2014). CSA requires policy intervention for careful adjustment of agricultural practices to natural conditions, a knowledge-intensive approach, huge financial investment, etc., so having strong institutional frameworks is very important. The main source of climate finance for CSA in developing countries is the public sector. Lack of institutional capacity (as a means for securing creation of equal institutions among social groups and individuals) can reduce feasibility of AFOLU mitigation measures in the near future, especially in areas where small-scale farmers or forest users are the main stakeholders (Bustamante et al., 2014). Behnassi et al., 2014; Bustamante et al., 2014; Godfray and Garnett, 2014; Lipper et al., 2014; Steenwerth et al., 2014					**Resource Mobilization and Strengthen Multi-stakeholder Partnership (17.1/ 17.3/17.5/17.17)** ↑ [+2] 📖📖📖 ☺☺☺ ★★★ CSA requires more careful adjustment of agricultural practices to natural conditions, a knowledge-intensive approach, huge financial investment and policy and institutional innovation, etc. Besides private investment, quality of public investment is also important (Behnass et al., 2014). Sources of climate finance for CSA in developing countries include bilateral donors and multilateral financial institutions, besides public sector finance. CSA is committed to new ways of engaging in participatory research and partnerships with producers (Steenwerth et al., 2014). Behnassi et al., 2014; Lipper et al., 2014; Steenwerth et al., 2014				
	Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems	**Equal Access to Economic Resources, Promote Empowerment of Women (5.5/5.a/5.b)** ↑ / ~ [+2,0] 📖 ☺ ★ Most of the animal farming activities such as fodder collection and feeding are performed by women. Alongside the considerable involvement and contribution of women, gender inequalities are pervasive in Indian villages in terms of accessing natural resources, extension services, marketing opportunities and financial services as well as in exercising their decision-making powers. Therefore, there is a need to correct gender bias in the farming sector. Efforts are needed to increase the capacity of women to negotiate with confidence and meet their strategic needs. Access to and control and management of small ruminants, grazing areas and feed resources empower women and lead to an overall positive impact on the welfare of the household. Patel et al., 2016					**Empower Economic and Political Inclusion of All, Irrespective of Sex (10.2)** ↑ / ~ [+1,0] 📖 ☺ ★ Livestock ownership is increasing women's decision-making and economic power within both the household and the community. Access to and control and management of small ruminants, grazing areas and feed resources empower women and lead to an overall positive impact on the welfare of the household. Patel et al., 2016					**Responsible Decision-making (16.7)** ↑ [+1] 📖 ☺ ★ To minimize the economic and social cost, policies should target emissions at their source—on the supply side—rather than on the demand side as supply-side policies have lower calorie cost than demand-side policies. The role of livestock system transitions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies. Havlík et al., 2014					**Improve Domestic Capacity for Tax Collection (17.1)** ↑ [+2] 📖📖 ☺☺ ★★ The role of livestock system transitions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies (Havlík et al., 2014). Mechanisms for affecting behavioural change in livestock systems need to be better understood by implementing combinations of incentives and taxes simultaneously in different parts of the world (Herrero and Thornton, 2013). Herrero and Thornton, 2013; Havlík et al., 2014				

Social 2-Other (continued)

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES					16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Forest	Reduced Deforestation, REDD+	**Opportunities for Women (5.1/5.5)**					**Reduced Inequality, Empowerment and Inclusion (10.1/10.2/10.3/10.4)**					**Build Effective, Accountable and Inclusive Institutions, Responsible Decision-making (16.6/16.7/16.8)**					**Resource Mobilization and Strengthen Multi-stakeholder Partnership (17.1/ 17.3/17.5/17.17)**				
		↑ / ↓	[+1,-1]	📖	☺	★	↑	[+2]	📖	☺	★	↑	[+2]	📖📖	☺☺☺	★★★	↑ / ↓	[+1,-1]	📖	☺	★
		Women have been less involved in REDD+ initiative (pilot project) design decisions and processes than men. Girls and women have an important role in forestry activities, related to fuel-wood, forest-food and pharmaceutical. Their empowerment contributes to sustainable forestry as well as reducing inequality .					Urges developed countries to support, through multilateral and bilateral channels, the development of REDD+ national strategies or action plans and implementation . Girls and women have an important role in forestry activities, related to fuel-wood, forest-food and medicine. Their empowerment contributes to sustainable forestry as well as reducing inequality .					Institutional building (National Forest Monitoring Systems, Safeguard Information Systems, etc.), with full and effective participation of all relevant countries . REDD+ actions also deliver non-carbon benefits (e.g. local socioeconomic benefits, governance improvements). Forest governance is another central aspect in recent studies, including the debate on decentralization of forest management, logging concessions in public-owned commercially valuable forests and timber certification, primarily in temperate forests .					To provide finance and technology to developing countries to support emissions reductions. Be supported by adequate and predictable financial and technology support, including support for capacity building . Partnerships in the form of significant aid money from, e.g., Norway, other bilateral donors and the World Bank's Forest Carbon Partnership Facility (FCPF) are forthcoming . Estimates of opportunity cost for REDD+ are very low. Lower costs and/or higher carbon prices could combine to protect more forests, including those with lower carbon content. Conversely, where the cost of action is high, a large amount of additional funding would be required for the forest to be protected (Miles and Kapos, 2008). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public-owned commercially valuable forests and timber certification, primarily in temperate forests . Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods and boost regional and national economic growth .				
		Brown, 2011; Larson et al., 2014; Katila et al., 2017					Bastos Lima et al., 2017; Katila et al., 2017					Bustamante et al., 2014; Bastos Lima et al., 2015, 2017					Miles and Kapos, 2008; Bustamante et al., 2014; Andrew, 2017; Bastos Lima et al., 2017; Katila et al., 2017				
	Afforestation and Reforestation	**Opportunities for Women (5.1/5.5)**					**Empower Economic and Political Inclusion of All, Irrespective of Sex (10.2)**					**Responsible Decision-making (16.7)**					**Resource Mobilization and Strengthen Partnership (17.1/17.14)**				
		↑	[+1]	📖	☺	★	↑	[+1]	📖	☺	★	↑	[+1]	📖	☺	★	↑	[+2]	📖📖	☺☺	★★
		Many women in developing countries are already prominently engaged in economic sectors related to climate adaptation and mitigation efforts such as agriculture, renewable energy and forest management and are important drivers and leaders in climate responses that are innovative and effective, benefitting not only their families but also their wider communities. Women's participation in the decision-making process of forest management, for example, has been shown to increase rates of reforestation while decreasing the illegal extraction of forest products.					Women's participation in the decision-making process of forest management, for example, has been shown to increase rates of reforestation while decreasing the illegal extraction of forest products.					Land-related mitigation, such as biofuel production, as well as conservation and reforestation action can increase competition for land and natural resources, so these measures should be accompanied by complementary policies. (Quoted from Epstein and Theur, 2017)					Financing at the national and international level is required to grow more seedlings/sapling, restore land, create awareness and education factsheets, provide training to local communities regarding the benefits of afforestation and reforestation. Article 12 of the Kyoto Protocol further sets a Clean Development Mechanism through which countries in Annex I earn 'certified emissions reductions' through projects implemented in developing countries (Montanarella and Alva, 2015). Afforestation and reforestation in India are being carried out under various programmes, namely social forestry initiated in the early 1980s, the Joint Forest Management Programme initiated in 1990, afforestation under National Afforestation and Eco-development Board programmes since 1992, and private farmer and industry initiated plantation forestry. If the current rate of afforestation and reforestation is assumed to continue, the carbon stock could increase by 11% by 2030 (Ravindranath et al., 2008)				
		UN-Women et al., 2015					UN-Women et al., 2015					Epstein and Theuer, 2017					Ravindranath et al., 2008; Kibria, 2015; Montanarella and Alva, 2015				
	Behavioural Response (Responsible Sourcing)	[0]					[0]					**Responsible Decision-making (16.7)**					**Finance and Trade (17.1/17.10)**				
												↑	[+1]	📖📖	☺☺	★★	↑	[+1]	📖📖	☺☺	★★
		No direct interaction					No direct interaction					Indonesian factories may seek advantages through non-price competition—perhaps by highlighting decent working conditions or the existence of a union—or to see trade associations or government agencies promoting the country as a responsible sourcing location (Bartley, 2010). In the absence of domestic legal instruments providing incentives to improve sustainability of sourcing, it appears that initiatives to engage the major importing enterprises in developing responsible sourcing practices and policies is a practical approach. Unless initiatives involve all the major importers, they are unlikely to be successful since the high costs associated with accreditation would increase production costs for these firms relative to their competitors (Huang et al., 2013).					Private certification initiatives for wood product and biomass sourcing may extend their schemes with criteria for 'leakage' (external GHG effects). Also recycling of waste wood in pellets is not yet practiced, due to unclear rules in the EU Waste Directive about overseas shipping (Sikkema et al., 2014). Engagement of Chinese government and private sector stakeholders in supply-country sustainability initiatives may be the best way to support this gradual process of improvement. Although carrying out due diligence in timber sourcing can require considerable internal resources, it may be substantially less of a financial burden than the potential fines and reputational damage resulting from sourcing unknown or controversial timber (Huang et al., 2013).				
												Bartley, 2010; Huang et al., 2013					Huang et al., 2013; Sikkema et al., 2014				

Social 2-Other (continued)

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES					16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Oceans	Ocean Iron Fertilization	[0] No direct interaction					[0] No direct interaction					[0] No direct interaction					[0] No direct interaction				
	Blue Carbon	[0] No direct interaction					[0] No direct interaction					[0] No direct interaction					[0] No direct interaction				
	Enhanced Weathering	[0] No direct interaction					[0] No direct interaction					[0] No direct interaction					[0] No direct interaction				

Environment-Demand

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable and Efficient Resource (12.2/12.5/12.6/12.7/12.a)**														
		↑ / ↓	[+2,-1]	📖📖	☺☺	★★	↑	[+1]	📖📖📖	☺☺☺	★★★		[0]					[0]			
		Efficiency and behavioural changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment. Likewise, reducing material inputs for industrial processes through efficiency and behavioural changes will reduce water inputs in the material supply chains. In extractive industries there can be a trade-off with production unless strategically managed.					Once started leads to chain of actions within the sector and policy space to sustain the effort. Helps in expansion of sustainable industrial production (Ghana).					No direct interaction					No direct interaction				
		Vassolo and Döll, 2005; Nguyen et al., 2014; Holland et al., 2015; Fricko et al., 2016					Apeaning and Thollander, 2013; Fernando et al., 2017														
	Low-carbon Fuel Switch	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable Production (12.2/12.3/12.a)**										**Sustainable Production (15.1/15.5/15.9/15.10)**				
		↑ / ↓	[+2,-2]	📖📖	☺☺	★★★	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★		[0]				↑	[+1,-1]	📖	☺	★
		A switch to low-carbon fuels can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock.					A circular economy instead of linear global economy can achieve climate goals and can help in economic growth through industrialization which saves on resources, the environment and supports small, medium and even large industries, and can lead to employment generation. So new regulations, incentives and a tax regime can help in achieving the goal, especially in newly emerging developing countries - although also applicable for large industrialized countries.					No direct interaction					A circular economy help in managing local biodiversity better by having less resource use footprint				
		Hejazi et al., 2015; Fricko et al., 2016; Song et al., 2016					Liu and Bai, 2014; Lieder and Rashid, 2016; Stahel, 2016; Supino et al., 2016; Fan et al., 2017; Shi et al., 2017; Zeng et al., 2017										Shi et al., 2017				
	Decarbonisation/CCS/CCU	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable Production and Consumption (12.1/12.6/12.a)**					**Conserve and Sustainably Use Ocean (14.1/14.5)**									
		↑ / ↓	[+1,-1]	📖📖📖	☺	★★	↑	[+2]	📖	☺☺☺☺	★★★★	↓	[-1]	📖	☺	★		[0]			
		CCU/S requires access to water for cooling and processing which could contribute to localized water stress. CCS/U processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration.					EPI plants are capital intensive and are mostly operated by multinationals with long investment cycles. In developed countries new investments are happening in brown fields, while in developing countries these are in green fields. Collaboration among partners and user demand change, policy change is essential for encouraging these large risky investments.					CCU/S in the chemical industry faces challenges for transport costs and storage. In the UK cluster region have been identified for storage under sea.					No direct interaction				
		Meldrum et al., 2013; Byers et al., 2016; Fricko et al., 2016; Brandl et al., 2017					Wesseling et al., 2017					Griffin et al., 2018									

Environment-Demand (continued)

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Buildings	Behavioural Response	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Responsible and Sustainable Consumption**														
		↑	[+2]	📖📖	☺☺☺	★★★	↑	[+2]	📖📖📖	☺☺☺	★★★		[0]					[0]			
		Behavioural changes in the residential sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in residential demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment.					Technological improvements alone are not sufficient to increase energy savings. Zhao et al. (2017) found that building technology and occupant behaviours interact with each other and finally affect energy consumption from home. They found that occupant habits could not take advantage of more than 50% of energy efficiency potential allowed by an efficient building. In the electronic segment, product obsolescence represents a key challenge for sustainability. Echegaray (2016) discusses the dissonance between consumers' product durability experience, orientations to replace devices before terminal technical failure, and perceptions of industry responsibility and performance. The results from their urban sample survey indicate that technical failure is far surpassed by subjective obsolescence as a cause for fast product replacement. At the same time Liu et al. (2017) suggest that we need to go beyond individualist and structuralist perspectives to analyse sustainable consumption (i.e., combines both human agency paradigm and social structural perspective).						No direct interaction					No direct interaction			
		Bartos and Chester (2014); Fricko et al. (2016); Holland et al. (2016)					Sweeney et al., 2013; Webb et al., 2013; Allen et al., 2015; Echegaray (2015); He et al., 2016; Hult and Larsson, 2016; Isenhour and Feng, 2016; van Sluisveld et al., 2016; Zhao et al., 2017; Liu et al., 2017; Sommerfeld et al., 2017														
	Accelerating Energy Efficiency Improvement	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable Practices and Lifestyles (12.6/12.7/12.8)**										**Reduced Deforestation (15.2)**				
		↑	[+2]	📖📖📖	☺☺☺	★★★	↑	[+1]	📖📖📖	☺☺☺	★★★		[0]				↑	[+2]	📖📖	☺☺☺	★★★
		Efficiency changes in the residential sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in residential demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment. A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. As water is used to convert energy into useful forms, energy efficiency is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment. Subsidies for renewables are anticipated to lead to the benefits and trade-offs outlined when deploying renewables. Subsidies for renewables could lead to improved water access and treatment if subsidies support projects that provide both water and energy services (e.g., solar desalination).					Sustainable practices adopted by public and private bodies in their operations (e.g., for goods procurement, supply chain management and accounting) create an enabling environment in which renewable energy and energy efficiency measures may gain greater traction (McCollum et al., 2018).						No direct interaction					Improved stoves has helped halt deforestation in rural India.			
		Bilton et al., 2011; Scott, 2011; Kumar et al., 2012; Meldrum et al., 2013; Bartos and Chester, 2014; Hendrickson and Horvath, 2014; Kern et al., 2014; Holland et al., 2015; Fricko et al., 2016; Kim et al., 2017					Stefan and Paul, 2008; ECF, 2014; CDP, 2015; Khan et al., 2015; NCE, 2015; McCollum et al., 2018										Bhojvaid et al., 2014				

Environment-Demand (continued)

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Access to Improved Water and Sanitation (6.1/6.2), Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable Use and Management of Natural Resource (12.2)**					[0]					**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**				
		↑ / ↓	[+2,-1]	📖📖	☺☺	★★★	↑ / ↓	[+2,-1]	📖📖	☺☺	★★★						↑	[+2]	📖📖	☺☺☺	★★★
		A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Improved access to energy can support clean water and sanitation technologies. If energy access is supported with water-intensive energy sources, there could be trade-offs with water efficiency targets.					A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Improved access to energy can support clean water and sanitation technologies. If energy access is supported with water-intensive energy sources, there could be trade-offs with water efficiency targets.					No direct interaction					Ensuring that the world's poor have access to modern energy services would reinforce the objective of halting deforestation, since firewood taken from forests is a commonly used energy resource among the poor (McCollum et al., 2018).				
		Hejazi et al., 2015; Cibin et al., 2016; Fricko et al., 2016; Song et al., 2016; Rao and Pachauri, 2017					Hejazi et al., 2015; Cibin et al., 2016; Fricko et al., 2016; Song et al., 2016; Rao and Pachauri, 2017										Bazilian et al., 2011; Karekezi et al., 2012; Bailis et al., 2015; Winter et al., 2015; McCollum et al., 2018				
Transport	Behavioural Response	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Ensure Sustainable Consumption amd Production Patterns (12.3)**					[0]					[0]				
		↑	[+2]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺	★★										
		Behavioural changes in the transport sector that lead to reduced transport demand can lead to reduced transport energy supply. As water is used to produce a number of important transport fuels, the reduction in transport demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment.					Urban carbon mitigation must consider the supply chain management of imported goods, the production efficiency within the city, the consumption patterns of urban consumers, and the responsibility of the ultimate consumers outside the city. Important for climate policy of monitoring the CO_2 clusters that dominate CO_2 emissions in global supply chains, because they offer insights on where climate policy can be effectively directed.					No direct interaction					No direct interaction				
		Vidic et al., 2013; Holland et al., 2015; Fricko et al., 2016; Tiedeman et al., 2016					Kagawa et al., 2015; Lin et al., 2015; Creutzig et al., 2016														
	Accelerating Energy Efficiency Improvement	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable Consumption (12.2/12.8)**					[0]					[0]				
		↑	[+2]	📖📖📖	☺☺☺	★★★	↑	[+2]	📖📖📖	☺☺☺	★★★										
		Similar to behavioural changes, efficiency measures in the transport sector that lead to reduced transport demand can lead to reduced transport energy supply. As water is used to produce a number of important transport fuels, the reduction in transport demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment.					Relational complex transport behaviour resulting in significant growth in energy-inefficient car choices, as well as differences in mobility patterns (distances driven, driving styles) and actual fuel consumption between different car segments all affect non-progress on transport decarbonization. Consumption choices and individual lifestyles are situated and tied to the form of the surrounding urbanization. Major behavioural changes and emissions reductions require understanding of this relational complexity, consideration of potential interactions with other policies, and the local context and implementation of both command-and-control as well as market-based measures.					No direct interaction					No direct interaction				
		Vidic et al., 2013; Holland et al., 2015; Fricko et al., 2016; Tiedeman et al., 2016					Stanley et al., 2011; Gallego et al., 2013; Heinonen et al., 2013; Aamaas and Peters, 2017; Azevedo and Leal, 2017; Gössling and Metzler, 2017														

Environment-Demand (continued)

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Ensure Sustainable Consumption and Production Patterns (12.3)**					[0]					[0]				
		↑ / ↓	[+2,-1]	📖📖	☺☺	★★★	↑	[+2]	📖📖📖	☺☺☺	★★★										
		A switch to low-carbon fuels in the transport sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Transport electrification could lead to trade-offs with water use if the electricity is provided with water intensive power generation.					Due to persistent reliance on fossil fuels, it is posited that transport is more difficult to decarbonize than other sectors. This study partially confirms that transport is less reactive to a given carbon tax than the non-transport sectors: in the first half of the century, transport mitigation is delayed by 10–30 years compared to non-transport mitigation. The extent to which earlier mitigation is possible strongly depends on implemented technologies and model structures.					No direct interaction					No direct interaction				
		Hejazi et al., 2015; Fricko et al., 2016; Song et al., 2016					Figueroa et al., 2014; IPCC, 2014; Pietzcker et al., 2014; Creutzig et al., 2015														

Environement-Supply

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind hydro	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)/ Access to Improved Water and Sanitation (6.1/6.2)**					**Natural Resource Protection (12.2/12.3/12.4/12.5)**					**Marine Economies (14.7)/ Marine Protection (14.1/14.2/14.4/14.5)**					**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**				
		↑ / ↓	[+2,-2]			★★★★	↑	[+2]			★★★★	↑ / ↓	[2,-1]			★★★	↓	[-1]			★★★
		Wind/solar renewable energy technologies are associated with very low water requirements compared to existing thermal power plant technologies. Widespread deployment is therefore anticipated to lead to improved water efficiency and avoided thermal pollution. However, managing wind and solar variability can increase water use at thermal power plants and can cause poor water quality downstream from hydropower plants. Access to distributed renewables can provide power to improve water access, but could also lead to increased groundwater pumping and stress if mismanaged. Developing dams to support reliable hydropower production can fragment rivers and alter natural flows reducing water and ecosystem quality. Developing dams to support reliable hydropower production can result in disputes for water in basins with up- and down-stream users. Storing water in reservoirs increases evaporation, which could offset water conservation targets and reduce availability of water downstream. However, hydropower plays an important role in energy access for water supply in developing regions, can support water security, and has the potential to reduce water demands if used without reservoir storage to displace other water intensive energy processes.					Renewable energy and energy efficiency slow the depletion of several types of natural resources, namely coal, oil, natural gas and uranium. In addition, the phasing-out of fossil fuel subsidies encourages less wasteful energy consumption; but if that is done, then the policies implemented must take care to minimize any counteracting adverse side-effects on the poor (e.g., fuel price rises). (Quote from McCollum et al., 2018)					Ocean-based energy from renewable sources (e.g., offshore wind farms, wave and tidal power) are potentially significant energy resource bases for island countries and countries situated along coastlines. Multi-use platforms combining renewable energy generation, aqua-culture, transport services and leisure activities can lay the groundwork for more diversified marine economies. Depending on the local context and prevailing regulations, ocean-based energy installations could either induce spatial competition with other marine activities, such as tourism, shipping, resources exploitation, and marine and coastal habitats and protected areas, or provide further grounds for protecting those exact habitats, therefore enabling marine protection. (Quote from McCollum et al., 2018) Hydropower disrupts the integrity and connectivity of aquatic habitats and impacts the productivity of inland waters and their fisheries.					Landscape and wildlife impact for wind; habitat impact for hydropower.				
		Bilton et al., 2011; Scott et al., 2011; Kumar et al., 2012; Ziv et al., 2012; Meldrum et al., 2013; Kern et al., 2014; Grill et al., 2015; Fricko et al., 2016; Grubert, 2016; De Stefano et al., 2017					Banerjee et al., 2012; Riahi et al., 2012; Schwanitz et al., 2014; Bhattacharyya et al., 2016; Cameron et al., 2016; McCollum et al., 2018					Inger et al., 2009; Michler-Cieluch et al., 2009; Buck and Krause, 2012; WBGU, 2013; Cooke et al., 2016; Matthews and McCartney, 2018; McCollum et al., 2018					Alho, 2011; Garvin et al., 2011; Grodsky et al., 2011; Jain et al., 2011; Kumar et al., 2011; Kunz et al., 2011; Wiser et al., 2011; Dahl et al., 2012; de Lucas et al., 2012; Ziv et al., 2012; Lovich and Ennen, 2013; Smith et al., 2013; Matthews and McCartney, 2018				
	Increased Use of Biomass	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Natural Resource Protection (12.2/12.3/12.4/12.5)**					[0]					**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**				
		↑ / ↓	[+1,-2]			★★★★	↑	[+2]			★★★★	No direct interaction					↑ / ↓	[+1,-2]			★★
		Biomass expansion could lead to increased water stress when irrigated feedstocks and water-intensive processing steps are used. Bioenergy crops can alter flow over land and through soils as well as require fertilizer, and this can reduce water availability and quality. Planting bioenergy crops on marginal lands or in some situations to replace existing crops can lead to reductions in soil erosion and fertilizer inputs, improving water quality.					Switching to renewable energy reduces the depletion of finite natural resources.										Protecting terrestrial ecosystems, sustainably managing forests, halting deforestation, preventing biodiversity loss and controlling invasive alien species could potentially clash with renewable energy expansion, if that would mean constraining large-scale utilization of bioenergy or hydropower. Good governance, cross-jurisdictional coordination and sound implementation practices are critical for minimizing trade-offs (McCollum et al., 2018).				
		Hejazi et al., 2015; Bonsch et al., 2016; Cibin et al., 2016; Song et al., 2016; Gao and Bryan, 2017; Griffiths et al., 2017; Ha and Wu, 2017; Taniwaki et al., 2017; Woodbury et al., 2018					Banerjee et al., 2012; Riahi et al., 2012; Schwanitz et al., 2014; Bhattacharyya et al., 2016; Cameron et al., 2016; McCollum et al., 2018										Smith et al., 2010, 2014; Acheampong et al., 2017; McCollum et al., 2018				

Environement-Supply (continued)

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Nuclear/Advanced Nuclear	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**															**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**				
		↑ / ↓	[+2,-1]	&&&	JJJ	«««		[0]					[0]				↓	[-1]	&&	JJ	««
		Nuclear power generation requires water for cooling which can lead to localized water stress and the resulting cooling effluents can cause thermal pollution in rivers and oceans.					No direct interaction					No direct interaction					Safety and waste concerns from uranium mining and milling.				
		Webster et al., 2013; Holland et al., 2015; Fricko et al., 2016; Raptis et al., 2016															Bickerstaff et al., 2008; Sjoberg and Sjoberg, 2009; Ahearne, 2011; Corner et al., 2011; Visschers and Siegrist, 2012; IPCC, 2014				
	CCS: Bioenergy	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Natural Resource Protection (12.2/12.3/12.4/12.5)**										**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**				
		↑ / ↓	[+1,-2]	📖📖	☻	★★	↑	[+1]	📖📖	☻☻	★★		[0]				↑ / ↓	[+1,-2]	📖	☻☻☻	★★
		CCU/S requires access to water for cooling and processing which could contribute to localized water stress. However, CCS/U processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration. The bioenergy component adds the additional trade-offs associated with bioenergy use. Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress.					Switching to renewable energy reduces the depletion of finite natural resources. On the other hand, the availability of underground storage is limited and therefore reduces the benefits of switching from finite resources to bioenergy.					No direct interaction					Protecting terrestrial ecosystems, sustainably managing forests, halting deforestation, preventing biodiversity loss and controlling invasive alien species could potentially clash with renewable energy expansion, if that would mean constraining large-scale utilization of bioenergy or hydropower. Good governance, cross-jurisdictional coordination and sound implementation practices are critical for minimizing trade-offs (McCollum et al., 2018). Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress.				
		Meldrum et al., 2013; Byers et al., 2016; Fricko et al., 2016; Brandl et al., 2017; Dooley and Kartha, 2018					Banerjee et al., 2012; Riahi et al., 2012; Schwanitz et al., 2014; Bhattacharyya et al., 2016; Cameron et al., 2016; McCollum et al., 2018										Smith et al., 2010, 2014; Acheampong et al., 2017; Dooley and Kartha, 2018, McCollum et al., 2018)				
Advanced Coal	CCS: Fossil	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**																			
		↑ / ↓	[+1,-2]	📖📖📖	☻	★★		[0]					[0]					[0]			
		CCU/S requires access to water for cooling and processing which could contribute to localized water stress. However, CCS/U processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration. Coal mining to support clean coal CCS will negatively impact water resources due to the associated water demands, waste water and land-use requirements.					No direct interaction					No direct interaction					No direct interaction				
		Meldrum et al., 2013; Byers et al., 2016; Fricko et al., 2016; Brandl et al., 2017																			

Environement-Other

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Ensure Sustainable Consumption and Production Patterns, Sustainable Practices and Lifestyle (12.3/12.4/12.6/12.7/12.8)**										**Conservation of Biodiversity and Restoration of Land (15.1/15.5/15.9)**				
		↑ / ↓	[+2,-1]	📖📖📖📖	☺☺☺☺	★★★★	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★		[0]				↑	[+1]	📖	☺	★
		Reduced food waste avoids direct water demand and waste water for crops and food processing, and avoids water used for energy supply by reducing agricultural, food processing and waste management energy inputs. Healthy diets will support water efficiency targets if the shift towards healthy foods results in food supply chains that are less water intensive than the supply chains supporting the historical dietary pattern.					Reduce loss and waste in food systems, processing, distribution and by changing household habits. To reduce environmental impact of livestock both production and consumption trends in this sector should be traced. Livestock production needs to be intensified in a responsible way (i.e., be made more efficient in the way that it uses natural resources). Wasted food represents a waste of all the emissions generated during the course of producing and distributing that food. Mitigation measures include: eat no more than needed to maintain a healthy body weight; eat seasonal, robust, field-grown vegetables rather than protected, fragile foods prone to spoilage and requiring heating and lighting in their cultivation, refrigeration stage; consume fewer foods with low nutritional value e.g., alcohol, tea, coffee, chocolate and bottled water (these foods are not needed in our diet and need not be produced); shop on foot or over the Internet (reduced energy use). Reduction in food waste will not only pave the path for sustainable production but will also help in achieving sustainable consumption (Garnett, 2011). Reduce meat consumption to encourage more sustainable eating practices.					No direct interaction					Reducing food waste has secondary benefits like protecting soil from degradation, and decreasing pressure for land conversion into agriculture and thereby protecting biodiversity. The agricultural area that becomes redundant through the dietary transitions can be used for other agricultural purposes such as energy crop production, or will revert to natural vegetation. A global food transition to less meat, or even a complete switch to plant-based protein food, could have a dramatic effect on land use. Up to 2,700 Mha of pasture and 100 Mha of crop land could be abandoned (Quoted from Stehfest et al., 2009)				
		Khan et al., 2009; Ingram, 2011; Kummu et al., 2012; Haileselassie et al., 2013; Bajželj et al., 2014; Tilman and Clark, 2014; Walker et al., 2014; Ran et al., 2016					Stehfest et al., 2009; Steinfeld and Gerber, 2010; Garnett, 2011; Ingram, 2011; Beddington et al., 2012; Kummu et al., 2012; Bellarby et al., 2013; Dagevos and Voordouw, 2013; Smith, 2013; Bajželj et al., 2014; Hedenus et al., 2014; Tilman and Clark, 2014; West et al., 2014; Hiç et al., 2016; Lamb et al., 2016										Stehfest et al., 2009; Kummu et al., 2012				
	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Ensure Sustainable Production Patterns (12.3)**										**Conservation of Biodiversity and Restoration of Land (15.1/15.5/15.9)**				
		↑ / ↓	[+1,-1]	📖📖📖	☺☺	★★★	↑	[+1]	📖	☺	★		[0]				↑ / ↓	[+1,-1]	📖📖📖	☺☺☺	★★★
		Soil carbon sequestration can alter the capacity of soils to store water, which impacts the hydrological cycle and could be positive or negative from a water perspective, dependent on existing conditions. CSA enrich linkages across sectors including management of water resources. Minimum tillage systems have been reported to reduce water erosion and thus sedimentation of water courses (Bustamante et al., 2014).					Millet or sorghum yield can double as compared with unimproved land by more than 1 tonne per hectare due to sustainable intensification. An integrated approach to safe applications of both conventional and modern agricultural biotechnologies will contribute to increased yield (Lakshmi et al., 2015).					No direct interaction					Agricultural intensification can promote conservation of biological diversity by reducing deforestation, and by rehabilitation and restoration of biodiverse communities on previously developed farm or pasture land. However, planting monocultures on biodiversity hot spots can have adverse side-effects, reducing biodiversity. Genetically modified crops reduce demand for cultivated land. Adaptation of integrated landscape approaches can provide various ecosystem services. CSA enrich linkages across sectors including management of land and bio-resources. Land sparing has the potential to be beneficial for biodiversity, including for many species of conservation concern, but benefits will depend strongly on the use of spared land. In addition, high yield farming involves trade-offs and is likely to be detrimental for wild species associated with farm land (Lamb et al., 2016).				
		Behnassi et al., 2014; Bustamante et al., 2014; P. Smith et al., 2016b					Campbell et al., 2014; Lakshmi et al., 2015										Lybbert and Sumner, 2010; Behnassi et al., 2014; Harvey et al., 2014; IPCC, 2014; Lamb et al., 2016)				

Environement-Other (continued)

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Agriculture and Livestock	Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Ensure Sustainable Production Patterns and Restructing Taxation (12.3/12c)**					[0]					**Restoration of Land (15.1)**				
		↑ / ↓	[+2,-1]	📖📖📖	☺☺☺	★★★	↑	[+1]	📖📖	☺☺	★★	No direct interaction					↑	[+1]	📖	☺	★
		Livestock efficiency measures are expected to reduce water required for livestock systems as well as associated livestock waste water flows. However, efficiency measures that include agricultural intensification could increase water demands locally, leading to increased water stress if the intensification is mismanaged. In scenarios where zero human-edible concentrate feed is used for livestock, freshwater use reduces by 21%.					In the future, many developed countries will see a continuing trend in which livestock breeding focuses on other attributes in addition to production and productivity, such as product quality, increasing animal welfare, disease resistance (Thornton, 2010). Diet composition and quality are key determinants of the productivity and feed-use efficiency of farm animals (Herrero, et al., 2013). Mechanisms for effecting behavioural change in livestock systems need to be better understood by implementing combinations of incentives and taxes simultaneously in different parts of the world (Herrero and Thornton, 2013). Reducing the amount of human-edible crops that are fed to livestock represents a reversal of the current trend of steep increases in livestock production, and especially of monogastrics, so would require drastic changes in production and consumption (Schader et al., 2015).										Grasslands are valuable, but improved management is required as grass accounts for close to 50% of feed use in livestock systems . The scenario with 100% reduction of food-competing-feedstuffs resulted in a 335 Mha decrease in arable land area, which corresponds to a decrease of 22% in arable and 7% in the total agricultural area .				
		Haileselassie et al., 2013; Schader et al., 2015; Kong et al., 2016; Ran et al., 2016					Thornton, 2010; Herrero and Thornton, 2013; Herrero et al., 2013; Schader et al., 2015										Herrero et al., 2013; Schader et al., 2015				
Forest	Reduced Deforestation, REDD+	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Ensure Sustainable Consumption (12.3)**					[0]					**Conservation of Biodiversity, Sustainability of Terrestrial Ecosystems (15.2/15.3/15.4/15.5/15.9)**				
		↑ / ↓	[+1,-1]	📖📖	☺☺	★★	↑	[+1]	📖	☺	★	No direct interaction					↑	[+1]	📖📖📖	☺☺☺	★★★
		Forest management alters the hydrological cycle which could be positive or negative from a water perspective and is dependent on existing conditions. Conservation of ecosystem services indirectly could help countries maintain watershed integrity. Forests provide sustainable and regulated provision and help in water purification.					Reduce the human pressure on forests, including actions to address drivers of deforestation.										Policies and programmes for reducing deforestation and forest degradation for rehabilitation and restoration of degraded lands can promote conservation of biological diversity. Reduce the human pressure on forests, including actions to address drivers of deforestation. Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP.				
		Zomer et al., 2008; Kibria, 2015; Bonsch et al., 2016; Gao and Bryan, 2017; Griffiths et al., 2017; Katila et al., 2017					Bastos Lima et al., 2017										Miles and Kapos, 2008; IPCC, 2014; Bastos Lima et al., 2015; Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017				
	Afforestation and Reforestation	**Enhance Water Quality (6.3)**					[0]					**Marine Economies (14.7)/Marine Protection and Income Generation (14.1/14.2/14.4/14.5)**					**Conservation of Biodiversity and Restoration of Land (15.1/15.5/15.9)**				
		↑ / ↓	[+2,-1]	📖📖📖	☺☺☺	★★★	No direct interaction					↑	[+2]	📖	☺	★	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★
		Similar to REDD+, forest management alters the hydrological cycle which could be positive or negative from a water perspective and is dependent on existing conditions. Forest landscape restoration can have a large impact on water cycles. Strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by modifying landscape water balances. Watershed scale reforestation can result in the restoration of water quality. Fast-growing species can increase nutrient input and water inputs that can cause ecological damage and alter local hydrological patterns. Reforestation of mixed native species and in carefully chosen sites could increase biodiversity and restore waterways, reducing run-off and erosion (Dooley and Kartha, 2018).										Mangroves would help to enhance fisheries and tourism businesses.					Identified large amounts of land (749 Mha) globally as biophysically suitable and meeting the CDM eligibility criteria . Forest landscape restoration can conserve biodiversity and reduce land degradation. Mangroves reduce impacts of disasters (cyclones/storms/floods) acting as live seawalls and enhance forest resources/biodiversity. Forest goal can conserve/restore 3.9–8.8 m ha/year average, 77.2–176.9 m ha in total and 7.7–17.7 m ha /year in 2030 of forest area by 2030 (Wolosin, 2014). Forest and biodiversity conservation, protected area formation and forestry-based afforestation are practices that enhance resilience of forest ecosystems to climate change (IPCC, 2014). Strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by modifying landscape water balances and protect livestock. It can restore biologically diverse communities on previously developed farmland . Large-scale restoration is likely to benefit ecosystem service provision, including recreation, biodiversity, conservation and flood mitigation. Reforestation of mixed native species and in carefully chosen sites could increase biodiversity, reducing run-off and erosion .				
		Zomer et al., 2008; Bustamante et al., 2014; Kibria, 2015; Lamb et al., 2016; Dooley and Kartha, 2018										Kibria, 2015					Zomer et al., 2008; Bustamante et al., 2014; IPCC, 2014; Kibria, 2015; Lamb et al., 2016; Epstein and Theuer, 2017; Dooley and Kartha, 2018				

Environement-Other (continued)

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Forest	Behavioural Response (Responsible Sourcing)	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)** ↑ / ↓ [+2,-1] 📖 ☺☺ ★★ Responsible sourcing will have co-benefits for water efficiency and pollution prevention if the sourcing strategies incorporate water metrics. There is a risk that shifting supply sources could lead to increased water use in another part of the economy. At local levels, forest certification programmes and practicing sustainable forest management provide freshwater supplies. van Oel and Hoekstra, 2012; Launiainen et al., 2014; Hontelez, 2016					**Ensure Sustainable Production Patterns (12.3)** ↑ [+1] 📖 ☺ ★ At local levels, forest certification programmes and practicing sustainable forest management provide the provision of raw materials for a 'low ecological footprint' economy. Hontelez, 2016					[0] No direct interaction					**Sustainability and Conservation (15.1/15.2/15.3)** ↑ / ↓ [+1,-1] 📖 ☺ ★ At the macro level, forest certification has done little to stem the tide of forest degradation, conversion of forest land to agriculture, and illegal logging—all of which remain serious threats to Indonesian forests (Bartley, 2010). At local levels, forest certification programmes and practicing sustainable forest management help in biodiversity protection. Bartley, 2010; Hontelez, 2016				
Oceans	Ocean Iron Fertilization	[0] No direct interaction					[0] No direct interaction					**Nutrient Pollution, Ocean Acidification, Fish Stocks, MPAs, SISD (14.1/14.3/14.4/14.5/14.7)** ↑ / ↓ [+1,-2] 📖📖📖 ☺☺ ★ OIF could exacerbate or reduce nutrient pollution, increase the likelihood of mid-water deoxygenation, increase ocean acidification, might contribute to the rebuilding of fish stocks in producing plankton, therefore generating benefits for SISD, but might also be in conflict with designing MPAs. Gnanadesikan et al., 2003; Jin and Gruber, 2003; Denman, 2008; Lampitt et al., 2008; Smetacek and Naqvi, 2008; Güssow et al., 2010; Oschlies et al., 2010; Trick et al., 2010; Williamson et al., 2012					[0] No direct interaction				
Oceans	Blue Carbon	**Integrated Water Resources Management (6.3/6.5)** ↑ [+2] 📖 ☺ ★ Development of blue carbon resources (coastal and marine vegetated ecosystems) can lead to coordinated management of water in coastal areas. Vierros et al., 2015					[0] No direct interaction					**Ocean Acidification, Nutrient Pollution (14.3/14.1)** ↑ / ~ [+2,0] 📖 ☺☺☺ ★★★ Mangroves could buffer acidification in their immediate vicinity; seaweeds have not been able to mitigate the effect on ocean foraminifera. Pettit et al., 2015; Sippo et al., 2016					**Conservation of Biodiversity and Restoration of Land (15.1/15.2/15.3/15.4/15.9)** ↑ [+3] 📖 ☺☺☺☺ ★★★★ Average difference of 31 mm per year in elevation rates between areas with seagrass and unvegetated areas (case study areas: Scotland, Kenya, Tanzania and Saudi Arabia); mangroves fostering sediment accretion of about 5mm a year. Alongi, 2012; Potouroglou et al., 2017				
Oceans	Enhanced Weathering	[0] No direct interaction					[0] No direct interaction					**Ocean Acidification, Nutrient Pollution (14.3/14.1)** ↑ / ↓ [+2,-1] 📖📖📖 ☺☺☺ ★★★ Enhanced weathering (either by spreading lime or quicklime, in combination with CCS, over the ocean or olivine at beaches or the catchment area of rivers) opposes ocean acidification. "End-of-century ocean acidification is reversed under RCP4.5 and reduced by about two-thirds under RCP8.5; additionally, surface ocean aragonite saturation state, a key control on coral calcification rates, is maintained above 3.5 throughout the low latitudes, thereby helping maintain the viability of tropical coral reef ecosystems ." However, marine biology would also be affected, in particular if spreading olivine is used, which works like ocean (iron) fertilization. Köhler et al., 2010, 2013; Hartmann et al., 2013; Paquay and Zeebe, 2013; P. Smith et al., 2016a; Taylor et al., 2016					**Protect Inland Freshwater Systems (14.1)** ↓ [-2] 📖 ☺ ★ Olivine can contain toxic metals such as nickel which could accumulate in the environment or disrupt the local ecosystem by changing the pH of the water (in case of spreading in the catchment area of rivers). Hartmann et al., 2013				

Economic-Demand

		7 AFFORDABLE AND CLEAN ENERGY					8 DECENT WORK AND ECONOMIC GROWTH					9 INDUSTRY, INNOVATION AND INFRASTRUCTURE					11 SUSTAINABLE CITIES AND COMMUNITIES				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement	**Energy Savings (7.1/7.3/7.a/7.b)**					**Reduces Unemployment (8.2/8.3/8.4/8.5/8.6)**					**Infrastructure Renewal (9.1/9.3/9.5/9.a)**					**Sustainable Cities (15.6/15.8/15.9)**				
		↑	[+2]	📖📖📖📖	☺☺☺	★★★★	↑	[+1]	📖📖	☺☺☺	★★★	↑	[+1]	📖📖	☺☺	★★	↑	[+2]	📖	☺	★
		Energy efficiency leads to reduced energy demand and hence energy supply and energy security, reduces import. Positive rebound effect can raise demand but to a very less extent due to low rebound effect in industry sector in many countries and by appropriate mix of industries (China) can maintain energy savings gain. Supplying surplus energy to cities is also happening, proving maintenance culture, switching off idle equipment helps in saving energy (e.g Ghana).					Unemployment rate reduction from 25% to 12% in South Africa. Enhances firm productivity and technical and managerial capacity of the employees. New jobs for managing energy efficiency opens up opportunities in energy service delivery sector.					Transitioning to a more renewables-based energy system that is highly energy efficient is well-aligned with the goal of upgrading energy infrastructure and making the energy industry more sustainable. At the same time, infrastructure upgrades in other parts of the economy, such as modernized telecommunications networks, can create the conditions for a successful expansion of renewable energy and energy efficiency measures (e.g., smart metering and demand-side management; McCollum et al., 2018).					Industries are becoming suppliers of energy, waste heat and water to neighbourial human settlements, and therefore there is a reduced primary energy demand, which also makes towns and cities grow sustainably.				
		Apeaning and Thollander, 2013; Chakravarty et al., 2013; IPCC, 2014; Karner et al., 2015; Zhang et al., 2015; Li et al., 2016; Fernando et al., 2017; Wesseling et al., 2017					Altieri et al., 2016; Fernando et al., 2017; Johansson and Thollander, 2018					Riahi et al., 2012; Apeaning and Thollander, 2013; Goldthau, 2014; Bhattacharyya et al., 2016; Meltzer, 2016; McCollum et al., 2018					Karner et al., 2015				
	Low-Carbon Fuel Switch	**Sustainable and Modern (7.2/7.a)**					**Economic Growth with Decent Employment (8.1/8.2/8.3/8.4)**					**Innovation and New Infrastructure (9.2/9.3/9.4/9.5/9.a)**					**Sustainable Cities (15.6/15.8/15.9)**				
		↑	[+2]	📖	☺	★	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	↑	[+2]	📖	☺	★
		Industries are becoming suppliers of energy, waste heat, water and roof tops used for solar energy generation, and therefore helping to reduce primary energy demand. CHP in chemical industries can help in providing surplus power in the grid.					The circular economy instead of linear global economy can achieve climate goals and can help in economic growth through industrialization, which saves on resources and the environment and supports small, medium and even large industries, which can lead to employment generation. So new regulations, incentives and a revised tax regime can help in achieving the goal.					A circular economy instead of linear global economy is helping new innovation, and infrastructure can achieve climate goals and can help in economic growth through industrialization which saves on resources and the environment and supports small, medium and even large industries, which can lead to employment generation. So new regulations, incentives and revised tax regime can help in achieving the goal.					Industries are becoming suppliers of energy, waste heat, water and roof tops used for solar energy generation, and supply to neighbourial human settlements, therefore reducing primary energy demand, which also makes towns and cities grow sustainably.				
		Karner et al., 2015; Griffin et al., 2018					Stahel, 2013, 2017; Liu et al., 2014; Leider et al., 2015; Supino et al., 2015; Zheng et al., 2016; Fan et al., 2017; Shi et al., 2017					Stahel, 2013, 2017; Liu et al., 2014; Leider et al., 2015; Supino et al., 2015; Zheng et al., 2016; Fan et al., 2017; Shi et al., 2017					Karner et al., 2015				
	Decarbonization/CCS/CCU	**Affordable and Sustainable Energy Sources**					**Decouple Growth from Environmental Degradation (8.1/8.2/8.4)**					**Innovation and New Infrastructure (9.2/9.4/9.5)**									
		↑ / ↓	[+2,-2]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺☺	★★★	↑	[+2]	📖	☺☺☺☺	★★★★		[0]			
		CCS for EPIs can be incremental, but need additional space and can need additional energy, sometimes compensating for higher efficiency. For example, recirculating blast R furnace and CCS for iron steel means high energy demand; electric melting in glass can mean higher electricity prices; in the paper industry, new separation and drying technologies are key to reducing the energy intensity, allowing for carbon neutral operation in the future; bio-refineries can reduce petro-refineries; DRI in iron and steel with H2 encourages innovation in hydrogen infrastructure; and the chemicals industry also encourage renewable electricity and hydrogen as bio-based polymers can increase biomass price.					EPI s are important players for economic growth. Deep decarbonization of EPIs through radical innovation is consistent with well-below 2°C scenarios.					Deep decarbonization through radical technological change in EPI will lead to radical innovations, for example, in completely changing industries' innovation strategies, plants and equipment, skills, production techniques, design, etc. Radical CCS will need new infrastructure to transport CO_2.					No direct interaction				
		Griffin et al., 2017; Wesseling et al., 2017					Denis-Ryan et al., 2016; Åhman et al., 2017; Wesseling et al., 2017					Denis-Ryan et al., 2016; Åhman et al., 2017; Wesseling et al., 2017; Griffin et al., 2018									

Economic-Demand (continued)

		7 AFFORDABLE AND CLEAN ENERGY					8 DECENT WORK AND ECONOMIC GROWTH					9 INDUSTRY, INNOVATION AND INFRASTRUCTURE					11 SUSTAINABLE CITIES AND COMMUNITIES				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Buildings	Behavioural Response	**Saving Energy, Improvement in Energy Efficiency (7.3/7.a/7.b)**					**Progressively Improve Resource Efficiency (8.4), Employment Opportunities (8.2/8.3/8.5/8.6)**					**Innovation and New Infrastructure (9.2/9.4/9.5)**					**Sustainable Cities (15.6/15.8/15.9)**				
		↑	[+2]	📖📖📖📖	☺☺☺☺	★★★	↑	[+2]	📖	☺	★	↑	[+2]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺	★★
		Lifestyle change measures and adoption behaviour affect residential energy use and implementation of efficient technologies as residential HVAC systems. Also, social influence can drive energy savings in users exposed to energy consumption feedback. Effect of autonomous motivation on energy savings behaviour is greater than that of other more established predictors, such as intentions, subjective norms, perceived behavioural control and past behaviour. Use of a hybrid engineering approach using social psychology and economic behaviour models are suggested for residential peak electricity demand response. However, some take-back in energy savings can happen due to rebound effects unless managed appropriately or accounted for welfare improvement. Adjusting thermostats helps in saving energy. Uptake of energy efficient appliances by households with an introduction to appliance standards, training, promotional material dissemination and the desire to save on energy bills are helping to change acquisition behaviour.					Behavioural change programmes help in sustaining energy savings through new infrastructure developments.					Adoption of smart meters and smart grids following community-based social marketing help with infrastructure expansion. People are adopting solar rooftops, white roof/vertical garden/green roofs at much faster rates due to new innovations and regulations.					Behavioural change programmes help in making cities more sustainable.				
		Chakravarty et al., 2013; Gyamfi et al., 2013; Hori et al., 2013; Huebner et al., 2013; Jain et al., 2013; Sweeney et al., 2013; Webb et al., 2013; Yue et al., 2013; Anda and Temmen, 2014; Allen et al., 2015; Noonan et al., 2015; de Koning et al., 2016; Isenhour and Feng, 2016; Santarius et al., 2016; Song et al., 2016; van Sluisveld et al., 2016; Sommerfeld et al., 2017; Zhao et al., 2017; Roy et al., 2018					Anda and Temmen, 2014					Anda and Temmen, 2014; Roy et al., 2018					Anda and Temmen, 2014; Roy et al., 2018				
	Accelerating Energy Efficiency Improvement	**Increase in Energy Savings (7.3)**					**Employment Opportunities (8.2/8.3/8.5/8.6)/Strong Financial Institutions (8.10)**					**Innovation and New Infrastructure (9.2/9.4/9.5)**					**Urban Environmental Sustainability (11.3/11.6/11.b/11.c)**				
		↑	[+2]	📖📖📖	☺☺☺	★★★★	↑ / ↓	[+2,-1]	📖📖	☺	★★	↑	[+2]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺☺	★★★★
		There is high agreement among researchers based on a great deal of evidence across various countries that energy efficiency improvement reduces energy consumption and therefore leads to energy savings (e.g., efficient stoves save bioenergy). Countries with higher hours of use due to higher ambient temperatures or more carbon intensive electricity grids benefit more from available improvements in energy efficiency and use of refrigerant transition.					Deploying renewables and energy efficient technologies, when combined with other targeted monetary and fiscal policies, can help spur innovation and reinforce local, regional and national industrial and employment objectives. Gross employment effects seem likely to be positive; however, uncertainty remains regarding the net employment effects due to several uncertainties surrounding macro-economic feedback loops playing out at the global level. Moreover, the distributional effects experienced by individual actors may vary significantly. Strategic measures may need to be taken to ensure that a large-scale switch to renewable energy minimizes any negative impacts on those currently engaged in the business of fossil fuels (e.g., government support could help businesses re-tool and workers re-train). To support clean energy and energy efficiency efforts, strengthened financial institutions in developing country communities are necessary for providing capital, credit and insurance to local entrepreneurs attempting to enact change (McCollum et al., 2018).					Adoption of smart meters and smart grids following community-based social marketing help in infrastructure expansion. Statutory norms to enhance energy and resource efficiency in buildings is encouraging green building projects.					Renewable energy technologies and energy efficient urban infrastructure solutions (e.g., public transit) can also promote urban environmental sustainability by improving air quality and reducing noise. Efficient transportation technologies powered by renewably based energy carriers will be a key building block of any sustainable transport system (McCollum et al., 2018). Green buildings help in sustainable construction.				
		McLeod et al., 2013; Noris et al., 2013; Bhojvaid et al., 2014; Holopainen et al., 2014; Kwong et al., 2014; Yang et al., 2014; Cameron et al., 2015; Liddell and Guiney, 2015; Shah et al., 2015; Berrueta et al., 2017; Kim et al., 2017; Salvalai et al., 2017					Babiker and Eckaus, 2007; Fankhauser and Tepic, 2007; Gohin, 2008; Frondel et al., 2010; Dinkelman, 2011; Guivarch et al., 2011; Jackson and Senker, 2011; Borenstein, 2012; Creutzig et al., 2013; Blyth et al., 2014; Clarke et al., 2014; Dechezleprêtre and Sato, 2014; Bertram et al., 2015; Johnson et al., 2015; IRENA, 2016; A. Smith et al., 2016; Berrueta et al., 2017; McCollum et al., 2018					Anda and Temmen, 2014; Roy et al., 2018					Creutzig et al., 2012; Kahn Ribeiro et al., 2012; Riahi et al., 2012; Bongardt et al., 2013; Grubler and Fisk, 2013; Raji et al., 2015; Kim et al., 2017; McCollum et al., 2018				

Economic-Demand (continued)

		7 AFFORDABLE AND CLEAN ENERGY					8 DECENT WORK AND ECONOMIC GROWTH					9 INDUSTRY, INNOVATION AND INFRASTRUCTURE					11 SUSTAINABLE CITIES AND COMMUNITIES				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Meeting Energy Demand**					**Sustainable Economic Growth and Employment**					**Innovation and New Infrastructure (9.2/9.4/9.5)**					**Housing (11.1)**				
		↑	[+2]	📖📖📖	☺☺☺	★★★	↑	[+2]	📖📖	☺☺☺	★★	↑	[+2]	📖📖	☺☺	★★	↑	[+3]	📖📖📖	☺☺☺	★★★★
		Renewable energies could potentially serve as the main source to meet energy demand in rapidly growing developing country cities. Ali et al. (2015) estimated the potential of solar, wind and biomass renewable energy options to meet part of the electricity demand in Karachi, Pakistan.					Creutzig et al. (2014) assessed the potential for renewable energies in the European region. They found that a European energy transition with a high-level of renewable energy installations in the periphery could act as an economic stimulus, decrease trade deficits and possibly have positive employment effects. Provision of energy access can play a critical enabling role for new productive activities, livelihoods and employment. Reliable access to modern energy services can have an important influence on productivity and earnings (McCollum et al., 2018).					Adoption of smart meters and smart grids following community-based social marketing help in infrastructure expansion. Statutory norms to enhance energy and resource efficiency in buildings is encouraging green building projects. Introduction of incentives and norms for solar rooftops/white/green roofs in cities are helping to accelerate innovation and the expansion of infrastructure.					Ensuring access to basic housing services implies that households have access to modern energy forms. (Quote from McCollum et al., 2018) Solar roof tops in Macau make cities sustainable. Introduction of incentives and norms for solar/white/green rooftops in cities are helping to accelerate the expansion of the infrastructure.				
		Li et al., 2013; Peng and Lu, 2013; Pietzcker, 2013; Pode, 2013; Yanine and Sauma, 2013; Zulu and Richardson, 2013; Connolly et al., 2014; Creutzig et al., 2014; Pietzcker et al., 2014; Ali et al., 2015; O'Mahony and Dufour, 2015; Abanda et al., 2016; Mittlefehldt, 2016; Biligii et al., 2017; Byravan et al., 2017; Islar et al., 2017; Ozturk et al., 2017					Grogan and Sadanand, 2013; Pueyo et al., 2013; Rao et al., 2013; Chakravorty et al., 2014; Creutzig et al., 2014; Ali et al., 2015; Bernard and Torero, 2015; Byravan et al., 2017; McCollum et al., 2018					Roy et al., 2018; Anda and Temmen, 2014					Bhattacharyya et al., 2016; Song et al., 2016; UN, 2016; McCollum et al., 2018; Roy et al., 2018				
Transport	Behavioural Response	**Energy Savings (7.3/7.a/7.b)**					**Promote Sustained, Inclusive Economic Growth (8.3)**					**Build Resilient Infrastructure (9.1)**					**Make Cities and Human Settlements Inclusive, Safe, Resilient**				
		↑	[+2]	📖📖	☺☺	★★	↓	[-2]	📖📖📖	☺☺☺	★★★	↑	[+2]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺	★★
		Behavioural responses will reduce the volume of transport needs and, by extension, energy demand.					Policy contradictions (e.g., standards, efficient technologies leading to increased electricity prices leading the poor to switch away from clean(er) fuels) and unintended outcomes (e.g., redistribution of income generated by carbon taxes) results in contradictions of the primary aims of (productive) job creation and poverty alleviation, and in trade-offs between mitigation, adaptation and development policies. Detailed assessments of mitigation policies consequences requires developing methods and reliable evidence to enable policymakers to more systematically identify how different social groups may be affected by the different available policy options.					As people prefer more mass transportation – train lines, tram lines, BRTs, gondola lift systems, bicycle-sharing systems and hybrid buses – and telecommuting, the need for new infrastructure increases.					Climate change threatens to worsen poverty, therefore pro-poor mitigation policies are needed to reduce this threat; for example, investing more and better in infrastructure by leveraging private resources and using designs that account for future climate change and the related uncertainty.				
		Figueroa and Ribeiro, 2013; Ahmad and Puppim de Oliveira, 2016					Lucas and Pangbourne, 2014; Suckall et al., 2014; Klausbruckner et al., 2016					Dulac, 2013; Aamaas and Peters, 2017; Martínez-Jaramillo et al., 2017; Xylia and Silveira, 2017					Ahmad and Puppim de Oliveira, 2016; Hallegatte et al., 2016a				
	Accelerating Energy Efficiency Improvement	**Energy Savings (7.3/7.a/7.b)**					**Promote Sustained, Inclusive Economic Growth (8.3)**					**Build Resilient Infrastructure (9.1)**					**Make Cities Sustainable (11.2/11.3)**				
		↑	[+2]	📖	☺	★	↑ / ↓	[+2,-2]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺	★★	↑	[+2]	📖	☺	★
		Accelerating efficiency in tourism transport reduces energy demand (China).					Significant opportunities to slow travel growth and improve efficiency exist and, similarly, alternatives to petroleum exist but have different characteristics in terms of availability, cost, distribution, infrastructure, storage and public acceptability. Production of new technologies, fuels and infrastructure can favour economic growth; however, efficient financing of increased capital spending and infrastructure is critical.					Combining promotion of mass transportation – train lines, tram lines, BRTs, gondola lift systems, bicycle-sharing systems and hybrid buses – and telecommuting reduces traffic and significantly contributes to meeting climate targets. A comprehensive package of complementary mitigation options is necessary for deep and sustained emissions reductions. In Sweden, a public bus fleet is aiming more towards decarbonization than efficiency.					The two most important elements of making cities sustainable are efficient buildings and transport (e.g., Macau).				
		Shukxin et al., 2016					Gouldson et al., 2015; Karkatsoulis et al., 2016					Dulac, 2013; Aamaas and Peters, 2017; Martínez-Jaramillo et al., 2017; Xylia and Silveira, 2017					Song et al., 2016				
	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Increase Share of Renewable (7.2)**					**Promote Sustained, Inclusive Economic Growth (8.3)**					**Help Building Inclusive Infrastructure (9.1/9.a)**					**Make Cities and Human Settlements Inclusive, Safe, Resilient**				
		↑	[+2]	📖📖	☺☺	★★	↑ / ↓	[+2,-2]	📖📖	☺☺	★★	↑	[+2]	📖📖📖	☺☺☺	★★★	↑	[+2]	📖📖	☺☺	★★
		Biofuel increases share of the renewables but can perform poorly if too many countries increase their use of biofuel, whereas electrification performs best when many other countries implement this technology. The strategies are not mutually exclusive and simultaneous implementation of some provides synergies for national energy security. Therefore, it is important to consider the results of material and contextual factors that co-evolve. Electric vehicles using electricity from renewables or low carbon sources combined with e-mobility options such as trolley buses, metros, trams and electro buses, as well as promote walking and biking, especially for short distances, need consideration.					The decarbonization of the freight sector tends to occur in the second part of the century, and the sector decarbonizes by a lower extent than the rest of the economy. Decarbonizing road freight on a global scale remains a challenge even when notable progress in biofuels and electric vehicles has been accounted for.					Lack of appropriate infrastructure leads to limited access to jobs for the urban poor (Africa, Latin America, India).					In rapidly growing cities, the carbon savings from investments at scale, in cost-effective low-carbon measures, could be quickly overwhelmed – in as little as 7 years – by the impacts of sustained population and economic growth, highlighting the need to build capacities that enable the exploitation not only of the economically attractive options in the short term but also of those deeper and more structural changes that are likely to be needed in the longer term. With hybrid electric vehicles and plug-in electric vehicles, there is the emergence of new concepts in transportation, such as electric highways.				
		Ajanovic, 2015; Månsson, 2016; Alahakoon, 2017; Wolfram et al., 2017					IPCC, 2014; Creutzig et al., 2015; Carrara and Longden, 2017					Figueroa et al., 2013; Gouldson et al., 2015; Vasconcellos and Mendonça, 2016; Lall et al., 2017					Figueroa et al., 2013; Gouldson et al., 2015; Vasconcellos and Mendonça, 2016; Alahakoon, 2017				

Economic-Supply

		7 AFFORDABLE AND CLEAN ENERGY					8 DECENT WORK AND ECONOMIC GROWTH					9 INDUSTRY, INNOVATION AND INFRASTRUCTURE					11 SUSTAINABLE CITIES AND COMMUNITIES				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	**Sustainable and Modern Energy (7.2/7.a)**					**Innovation and Growth (8.1/8.2/8.4)**					**Inclusive and Sustainable Industrialization (9.2/9.4)**					**Disaster Preparedness and Prevention (11.5)**				
		↑	[+3]	📖📖📖	☺☺☺	★★★★	~	[0]	📖📖	☺☺	★★	~ / ↓	[0,-1]	📖📖	☺☺☺	★★	↑	[+2]	📖📖📖	☺☺	★★★
		Decarbonization of the energy system through an upscaling of renewables will greatly facilitate access to clean, affordable and reliable energy. Hydropower plays an increasingly important role for the global electricity supply. This mitigation option is in line with the targets of SDG7 under the caveat of a transition to modern biomass.					Decarbonization of the energy system through an upscaling of renewables and energy efficiency is consistent with sustained economic growth and resource decoupling. Long-term scenarios point towards slight consumption losses caused by a rapid and pervasive expansion of such energy solutions. Whether sustainable growth, as an overarching concept, is attainable or not is more disputed in the literature. Existing literature is also undecided as to whether or not access to modern energy services causes economic growth (McCollum et al., 2018).					A rapid upscaling of renewable energies could necessitate the early retirement of fossil energy infrastructure (e.g., power plants, refineries, pipelines) on a large scale. The implications of this could in some cases be negative, unless targeted policies can help alleviate the burden on industry (McCollum et al., 2018).					Deployment of renewable energy and improvements in energy efficiency globally will aid climate change mitigation efforts, and this, in turn, can help to reduce the exposure of people to certain types of disasters and extreme events (McCollum et al., 2018).				
		Rogelj et al., 2013; Cherian, 2015; Jingura and Kamusoko, 2016					Jackson and Senker, 2011; Bonan et al., 2014; Clarke et al., 2014; NCE, 2014; OECD, 2017; York and McGee, 2017; McCollum et al., 2018					Fankhaeser et al., 2008; McCollum et al., 2008; Guivarch et al., 2011; Bertram et al., 2015; Johnson et al., 2015					Tully, 2006; Riahi et al., 2012; Daut et al., 2013; IPCC, 2014; Hallegatte et al., 2016b; McCollum et al., 2018				
	Increased Use of Biomass	**Sustainable and Modern Energy (7.2/7.a)**					**Innovation and Growth (8.1/8.2/8.4)**					**Innovation and New Infrastructure (9.2/9.4/9.5)**					[0]				
		↑	[+3]	📖📖📖	☺☺☺	★★★	↑	[+1]	📖	☺	★	↑	[+1]	📖📖	☺☺☺	★★	No direct interaction				
		Increased use of modern biomass will facilitate access to clean, affordable and reliable energy. This mitigation option is in line with the targets of SDG7.					Decarbonization of the energy system through an upscaling of renewables will greatly facilitate access to clean, affordable and reliable energy.					Access to modern and sustainable energy will be critical to sustain economic growth.									
		Rogelj et al., 2013; Cherian, 2015; Jingura and Kamusoko, 2016					Jingura and Kamusoko, 2016					Jingura and Kamusoko, 2016; Shahbaz et al., 2016									
	Nuclear/Advanced Nuclear	**Sustainable and Modern Energy (7.2/7.a)**					**Innovation and Growth (8.1/8.2/8.4)**					**Innovation and New Infrastructure (9.2/9.4/9.5)**					[0]				
		↑	[1]	📖📖	☺	★★	↑	[1]	📖📖	☺	★★	↓	[-1]	📖📖	☺☺☺	★★★	No direct interaction				
		Increased use of nuclear power can provide stable baseload power supply and reduce price volatility.					Local employment impact and reduced price volatility.					Legacy cost of waste and abandoned reactors.									
		IPCC, 2014					IPCC, 2014					Marra and Palmer, 2011; Greenberg et al., 2013; Schwenk-Ferrero, 2013; Skipperud et al., 2013; Tyler et al., 2013; IPCC, 2014									
	CCS: Bioenergy	**Sustainable and Modern Energy (7.2/7.a)**					**Innovation and Growth (8.1/8.2/8.4)**					**Innovation and New Infrastructure (9.2/9.4/9.5)**					[0]				
		↑	[+2]	📖📖📖	☺☺☺	★★★	↑	[+1]	📖	☺	★	↑	[+1]	📖	☺	★	No direct interaction				
		Increased use of modern biomass will facilitate access to clean, affordable and reliable energy.					See positive impacts of bioenergy use.					See positive impacts of bioenergy use and CCS/CCU in industrial demand.									
		IPCC, 2014																			
Advanced Coal	CCS: Fossil	**Ensure energy access and promote investment in new technologies (7.1/7.b)**					**Innovation and Growth (8.1/8.2/8.4)**					**Innovation and New Infrastructure (9.2/9.4/9.5)**					[0]				
		↑	[+2]	📖📖📖	☺☺☺	★★★	↓	[-1]	📖📖📖	☺☺☺	★★★	↑	[+1]	📖	☺	★	No direct interaction				
		Advanced and cleaner fossil fuel technology is in line with the targets of SDG7.					Lock-in of human and physical capital in the fossil resources industry.					See positive impacts of CCS/CCU in industrial demand.									
		IPCC, 2014					IPCC, 2005, 2014; Benson and Cole, 2008; Fankhaeser et al., 2008; Vergragt et al., 2011; Markusson et al., 2012; Shackley and Thompson, 2012; Bertram et al., 2015; Johnson et al., 2015														

5

Economic-Other

		7 AFFORDABLE AND CLEAN ENERGY					8 DECENT WORK AND ECONOMIC GROWTH					9 INDUSTRY, INNOVATION AND INFRASTRUCTURE					11 SUSTAINABLE CITIES AND COMMUNITIES				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	**Energy Efficiency, Universal Access (7.1/7.3)**					**Sustained and Inclusive Economic Growth (8.2)**					**Infrastructure Building and Promotion of Inclusive Industrialization (9.1/9.2)**									
		↑	[+1]	📖	☺	★	↑	[+1]	📖📖📖	☺☺☺	★★★	↑	[+1]	📖📖📖	☺☺☺	★★★		[0]			
		Reducing global food supply chain losses have several important secondary benefits like conserving energy.					23–24% of total cropland and fertilizers are used to produce losses. So reduction in food losses will help to diversify these valuable resources into other productive activities.					By targeting infrastructure, processing and distribution losses, wastage in food systems can be minimized. 23–24% of total cropland and fertilizers are used to produce losses. So reduction in food losses will help to diversify these valuable resources into other productive activities.					No interaction				
		Kummu et al., 2012					Kummu et al., 2012; Hiç et al., 2016					Ingram, 2011; Beddington et al., 2012; Kummu et al., 2012; Hiç et al., 2016; Lamb et al., 2016									
	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	**Sustainable and Modern Energy (7.b)**					**Sustainable Growth (8.2)**					**Infrastructure Building, Promotion of Inclusive Industrialization and Innovation (9.1/9.2/9.5/9.b)**									
		↑	[+1]	📖📖📖	☺☺☺	★★★	↑ / ↓	[+2,-1]	📖📖	☺☺	★★	↑ / ↓	[+2,-2]	📖📖📖	☺☺☺	★★★		[0]			
		Conventional agricultural biotechnology methods such as energy efficient farming can help in sequestration of soil carbon. Modern biotechnologies such as green energy and N-efficient GM crops can also help in C-sequestration. Biotech crops allow farmers to use less – and environmentally friendly – energy and practice soil carbon sequestration. Biofuels, both from traditional and GMO crops, such as sugar cane, oilseed, rapeseed and jatropha, can be produced. Green energy programmes through plantations of perennial nonedible oilseed producing plants and production of biodiesel for direct use in the energy sector or blending biofuels with fossil fuels in certain proportions can thereby minimize fossil fuel use. (Quoted from Lakshmi et al., 2015) GM crops reduce demand for fossil fuel-based inputs.					Many developing countries including Gulf States will benefit from CSA given the central role of agriculture in their economic and social development. (Quoted from Behnassi et al. 2014). Low commodity prices have reduced the incentive to invest in yield growth and have led to declining farm labour and farm capital investment. (Quoted from Lamb et al., 2016)					Reduced research support and delayed industrialization will have an adverse effect on food security and nourishment of children. Organic farming technologies utilizing bio-based fertilizers (composted human and animal manure) are some of the conventional biotechnological options for reducing artificial fertilizer use (Lakshmi et al., 2015). CSA requires huge financial investment and institutional innovation. CSA is committed to new ways of engaging in participatory research and partnerships with producers (Steenwerth et al., 2014). Technologies used on-farm and during food processing to increase productivity which also helps in adaptation and/or mitigation are new, so convincing potential customers is difficult. Also, low-awareness of CSA, inaccessible language, high costs, lack of verified impact of technologies, hard to reach and train farmers, low consumer demand and unequal distribution of costs/benefits across supply chains are barriers to CSA technology adoption (Long et al., 2016). Low commodity prices have reduced the incentive to invest in yield growth and have led to declining investment in research and development (Lamb et al.,					no direct interaction				
		Johnson et al., 2007; Sarin et al., 2007; Treasury, 2009; Jain and Sharma, 2010; Lybbert and Sumner, 2010; Mtui, 2011; Lakshmi et al., 2015					Behnassi et al., 2014; Lamb et al., 2016					Evenson, 1999; Behnassi et al., 2014; Steenwerth et al., 2014; Lakshmi et al., 2015; Lamb et al., 2016; Long et al., 2016									
	Greenhouse Gas Reduction from Improved Livestock Production and Manure	**Energy Efficiency (7.3)**					**Sustainable Economic Growth (8.4)**					**Technological Upgradation and Innovation (9.2)**									
		↑	[+1]	&	J	«	↑	[+1]	&	J	«	↑	[+2]	📖📖📖	☺☺☺	★★★		[0]			
		Scenarios where zero human-edible concentrate feed is used for livestock, non-renewable energy use is reduced by 36%.					Exploiting the increasingly decoupled interactions between crops and livestock could be beneficial for promoting structural changes in the livestock sector and is a prerequisite for the sustainable growth of the sector. (Quoted from Herrero et al., 2013)					Complete genome maps for poultry and cattle now exist, and these open up the way to possible advances in evolutionary biology, animal breeding and animal models for human diseases. Genomic selection should be able to at least double the rate of genetic gain in the dairy industry. (Quoted from Thornton, 2010) Nanotechnology, biogas technology and separation technologies are disruptive technologies that enhance biogas production from anaerobic digesters or to reduce odours					No direct interaction				
		Schader et al., 2015					Herrero and Thornton, 2013; Herrero et al., 2013					Sansoucy, 1995; Burton, 2007; Thornton, 2010									

Economic-Other (continued)

		7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	11 SUSTAINABLE CITIES AND COMMUNITIES
		Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence
Forest	Reduced Deforestation, REDD+	**Energy Efficiency (7.3)** ↑ / ↓ [+1,-1] 📖 ☺ ★ Consider the entire sinks and reservoirs of GHG while developing the nationally appropriate mitigation actions. For countries with a significant contribution of forest degradation (and GHG emissions) from wood fuels, this should be considered. (Quoted from Bastos Lima et al., 2017). Biomass for energy is recognized as often being inefficient, and is often harvested in an unsustainable manner, but is a renewable energy source. Bastos Lima et al., 2017; Katila et al., 2017	**Sustainable Economic Growth (8.4)** ↑ [+1] 📖 ☺ ★ Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed to erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth. Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017	**Infrastructure, Promotion of Inclusive Industrialization (9.1/9.2/9.5)** ↑ / ↓ [+1,-1] 📖 ☺ ★ Expanding road networks are recognized as one of the main drivers of deforesting and forest degradation, diminishing forest benefits to communities, On the other hand, roads can enhance market access, thereby boosting local benefits (SDG 1) from the commercialization of forest products. (Quoted from Katila et al., 2017). Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed to erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017	[0] No direct interaction
	Afforestation and Reforestation	**Energy Conservation (7.3/7.b)** ↑ [+1] 📖 ☺ ★ The US Forest Service estimates that an average NYC street tree (urban afforestation) produces 209 USD in annual benefits, which is primarily driven by aesthetic (90 USD per tree) and energy savings (from shade) benefits (47.63 USD per tree). Jones and McDermott, 2018	**Decent Job Creation and Sustainable Economic Growth (8.3/8.4)** ↑ [+2] 📖📖 ☺☺ ★★ Many tree plantations worldwide have higher growth rates which can provide higher rates of returns for investors. Agroforestry initiatives that offer significant opportunities for projects to provide benefits to smallholder farmers can also help address land degradation through community-based efforts in more marginal areas. Mangroves reduce impacts of disasters (cyclones/storms/floods) and enhance water quality, fisheries, tourism businesses and livelihoods. Zomer et al., 2008; Kibria, 2015	[0] No direct interaction	**Improving Air Quality, Green and Public Spaces (11.6/11.7/11.a/11.b)** ↑ [+2] 📖📖📖📖 ☺☺☺☺ ★★★★ Many urban tree plantations worldwide are created with a focus on multiple benefits, like air quality improvement, cultural preference for green nature, healthy community interaction as well as temperature control and biodiversity enhancement goals. Chen and Qi, 2018; Fu et al., 2018; Kowarik, 2018; McKinney and Ingo, 2018; McPherson et al., 2018; Pei et al., 2018
	Behavioural Response (Responsible Sourcing)	**Universal Access (7.3)** ↑ [+1] 📖 ☺ ★ The trade of wood pellets from clean wood waste should be facilitated with less administrative import barriers by the EU, in order to have this new option seriously accounted for as a future resource for energy. (Quoted from Sikkema et al., 2014) Recommends further harmonization of legal harvesting, sustainable sourcing and cascaded use requirements for woody biomass for energy with the current requirements of voluntary SFM certification schemes. Sikkema et al., 2014	**Decent Job Creation and Sustainable Economic Growth (8.3/8.4)** ↑ [+2] 📖 ☺ ★ Some standards seek primarily to coordinate global trade, many purport to promote ecological sustainability and social justice or to institutionalize CSR, for example, labour standards developed in the wake of sweatshops and child labour scandals. Environmental standards for pollution control, etc. Indonesian factories may seek advantages through non-price competition—perhaps by highlighting decent working conditions or the existence of a union—or to see trade associations or government promoting the country as a responsible sourcing location. Bartley, 2010	**Technological Upgradation and Innovation, Promotion of Inclusive Industrialization (9.1/9.2/9.5)** ↑ [+2] 📖📖 ☺☺ ★ Capacity for processing certified timber is often underutilized, due to the limited supply available. As a result, manufacturing firms that are seeking to tap into green markets often turn to other sources of timber. (Quoted from Bartley, 2010) Responsible sourcing, when integrated into business practices, can enable retailers to better manage brand value and reputation by avoiding negative public relations, as well as maintaining and enhancing brand integrity (Huang et al., 2013). Bartley, 2010; Huang et al., 2013	**Improving Air Quality, Green and Public Spaces, Peri-urban Spaces (11.6/11.7/11.a/11.b)** ↑ [+2] 📖📖📖📖 ☺☺☺☺ ★★★★ Many urban tree plantations worldwide are created with a focus on multiple benefits, like air quality improvement, cultural preference for green nature, healthy community interaction as well as temperature control and biodiversity enhancement goals. People's preference for urban forest gardens are encouraging new urban green spaces, and tree selection helps in building resilience to disaster. Chen and Qi, 2018; Fu et al., 2018; Kowarik, 2018; McKinney and Ingo, 2018; McPherson et al., 2018; Pei et al., 2018
Oceans	Ocean Iron Fertilization	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction
	Blue Carbon	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction
	Enhanced Weathering	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction

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Note that this reference list does not account for the references in Table 5.2, for which a separate reference list is provided.

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Annexes

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Annex I: Glossary

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Notes:
Note that subterms are in italics beneath main terms.

This glossary defines some specific terms as the Lead Authors intend them to be interpreted in the context of this report. Blue, italicized words indicate that the term is defined in the Glossary.

This annex should be cited as:
IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press

1.5°C pathway See *Pathways*.

1.5°C warmer worlds *Projected* worlds in which *global warming* has reached and, unless otherwise indicated, been limited to 1.5°C above *pre-industrial* levels. There is no single 1.5°C warmer world, and *projections* of 1.5°C warmer worlds look different depending on whether it is considered on a near-term transient trajectory or at climate equilibrium after several millennia, and, in both cases, if it occurs with or without *overshoot*. Within the 21st century, several aspects play a role for the assessment of risk and potential *impacts* in 1.5°C warmer worlds: the possible occurrence, magnitude and duration of an overshoot; the way in which emissions reductions are achieved; the ways in which policies might be able to influence the *resilience* of human and natural systems; and the nature of the regional and sub-regional risks. Beyond the 21st century, several elements of the *climate system* would continue to change even if the global mean temperatures remain stable, including further increases of sea level.

2030 Agenda for Sustainable Development A UN resolution in September 2015 adopting a plan of action for people, planet and prosperity in a new global development framework anchored in 17 *Sustainable Development Goals* (UN, 2015). See also *Sustainable Development Goals (SDGs)*.

Acceptability of policy or system change The extent to which a policy or system change is evaluated unfavourably or favourably, or rejected or supported, by members of the general public (public acceptability) or politicians or governments (political acceptability). Acceptability may vary from totally unacceptable/fully rejected to totally acceptable/fully supported; individuals may differ in how acceptable policies or system changes are believed to be.

Adaptability See *Adaptive capacity*.

Adaptation In *human systems*, the process of adjustment to actual or expected *climate* and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Incremental adaptation
Adaptation that maintains the essence and integrity of a system or process at a given scale. In some cases, incremental adaptation can accrue to result in *transformational adaptation* (Termeer et al., 2017; Tàbara et al., 2018).

Transformational adaptation
Adaptation that changes the fundamental attributes of a *socio-ecological system* in anticipation of *climate change* and its *impacts*.

Adaptation limits
The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.
- Hard adaptation limit: No adaptive actions are possible to avoid intolerable risks.
- Soft adaptation limit: Options are currently not available to avoid intolerable risks through adaptive action.

See also *Adaptation options*, *Adaptive capacity* and *Maladaptive actions (Maladaptation)*.

Adaptation behaviour See *Human behaviour*.

Adaptation limits See *Adaptation*.

Adaptation options The array of strategies and measures that are available and appropriate for addressing *adaptation*. They include a wide range of actions that can be categorized as structural, institutional, ecological or behavioural. See also *Adaptation*, *Adaptive capacity* and *Maladaptive actions (Maladaptation).*

Adaptation pathways See *Pathways*.

Adaptive capacity The ability of systems, *institutions*, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005). See also *Adaptation*, *Adaptation options and Maladaptive actions (Maladaptation)*.

Adaptive governance See *Governance*.

Aerosol A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 µm that reside in the *atmosphere* for at least several hours. The term aerosol, which includes both the particles and the suspending gas, is often used in this report in its plural form to mean aerosol particles. Aerosols may be of either natural or *anthropogenic* origin. Aerosols may influence *climate* in several ways: through both interactions that scatter and/or absorb radiation and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow- or ice-covered surfaces thereby altering their *albedo* and contributing to *climate feedback*. Atmospheric aerosols, whether natural or anthropogenic, originate from two different pathways: emissions of primary particulate matter (PM), and formation of secondary PM from gaseous *precursors*. The bulk of aerosols are of natural origin. Some scientists use group labels that refer to the chemical composition, namely: sea salt, organic carbon, *black carbon (BC)*, mineral species (mainly desert dust), sulphate, nitrate, and ammonium. These labels are, however, imperfect as aerosols combine particles to create complex mixtures. See also *Short-lived climate forcers (SLCF)* and *Black carbon (BC)*.

Afforestation Planting of new *forests* on lands that historically have not contained forests. For a discussion of the term forest and related terms such as afforestation, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000), information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). See also *Reforestation*, *Deforestation*, and *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*.

Agreement In this report, the degree of agreement within the scientific body of knowledge on a particular finding is assessed based on multiple lines of *evidence* (e.g., mechanistic understanding, theory, data, models, expert judgement) and expressed qualitatively (Mastrandrea et al., 2010). See also *Evidence*, *Confidence*, *Likelihood* and *Uncertainty*.

Air pollution Degradation of air quality with negative effects on human health or the natural or built environment due to the introduction, by natural processes or human activity, into the *atmosphere* of substances (gases, *aerosols*) which have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect. See also *Aerosol* and *Short-lived climate forcers (SLCF)*.

Albedo The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and the oceans have a low albedo. The Earth's planetary albedo changes mainly through varying cloudiness and changes in snow, ice, leaf area and land cover.

Ambient persuasive technology Technological systems and environments that are designed to change human cognitive processing,

attitudes and behaviours without the need for the user's conscious attention.

Anomaly The deviation of a variable from its value averaged over a *reference period*.

Anthropocene The 'Anthropocene' is a proposed new geological epoch resulting from significant human-driven changes to the structure and functioning of the Earth System, including the *climate system*. Originally proposed in the Earth System science community in 2000, the proposed new epoch is undergoing a formalization process within the geological community based on the stratigraphic *evidence* that human activities have changed the Earth System to the extent of forming geological deposits with a signature that is distinct from those of the *Holocene*, and which will remain in the geological record. Both the stratigraphic and Earth System approaches to defining the Anthropocene consider the mid-20th Century to be the most appropriate starting date, although others have been proposed and continue to be discussed. The Anthropocene concept has been taken up by a diversity of disciplines and the public to denote the substantive influence humans have had on the state, dynamics and future of the Earth System. See also *Holocene*.

Anthropogenic Resulting from or produced by human activities. See also *Anthropogenic emissions* and *Anthropogenic removals*.

Anthropogenic emissions Emissions of *greenhouse gases (GHGs)*, *precursors* of GHGs and aerosols caused by human activities. These activities include the burning of *fossil fuels*, *deforestation*, *land use* and *land-use changes (LULUC)*, livestock production, fertilisation, waste management and industrial processes. See also *Anthropogenic* and *Anthropogenic removals*.

Anthropogenic removals Anthropogenic removals refer to the withdrawal of *GHGs* from the *atmosphere* as a result of deliberate human activities. These include enhancing biological *sinks of CO_2* and using chemical engineering to achieve long-term removal and storage. *Carbon capture and storage (CCS)* from industrial and energy-related sources, which alone does not remove CO_2 in the atmosphere, can reduce atmospheric CO_2 if it is combined with *bioenergy* production *(BECCS)*. See also *Anthropogenic emissions*, *Bioenergy with carbon dioxide capture and storage (BECCS)* and *Carbon dioxide capture and storage (CCS)*.

Artificial intelligence (AI) Computer systems able to perform tasks normally requiring human intelligence, such as visual perception and speech recognition.

Atmosphere The gaseous envelope surrounding the earth, divided into five layers – the *troposphere* which contains half of the Earth's atmosphere, the *stratosphere*, the mesosphere, the thermosphere, and the exosphere, which is the outer limit of the atmosphere. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93 % volume mixing ratio), helium and radiatively active *greenhouse gases (GHGs)* such as *carbon dioxide (CO_2)* (0.04% volume mixing ratio) and *ozone (O_3)*. In addition, the atmosphere contains the GHG water vapour (H_2O), whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols. See also *Troposphere*, *Stratosphere*, *Greenhouse gas (GHG)* and *Hydrological cycle*.

Atmosphere–ocean general circulation model (AOGCM) See *Climate model*.

Attribution See *Detection and attribution*.

Baseline scenario In much of the literature the term is also synonymous with the term business-as-usual (BAU) *scenario*, although the term BAU has fallen out of favour because the idea of business as usual in century-long socio-economic *projections* is hard to fathom. In the context of *transformation pathways*, the term baseline scenarios refers to scenarios that are based on the assumption that no mitigation *policies* or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further policy effort. Typically, baseline scenarios are then compared to *mitigation scenarios* that are constructed to meet different goals for *greenhouse gas (GHG)* emissions, atmospheric concentrations or temperature change. The term baseline scenario is often used interchangeably with reference scenario and no policy scenario. See also *Emission scenario* and *Mitigation scenario*.

Battery electric vehicle (BEV) See *Electric vehicle (EV)*.

Biochar Stable, carbon-rich material produced by heating *biomass* in an oxygen-limited environment. Biochar may be added to soils to improve soil functions and to reduce *greenhouse gas* emissions from biomass and soils, and for *carbon sequestration*. This definition builds from IBI (2018).

Biodiversity Biological diversity means the variability among living organisms from all sources, including, inter alia, terrestrial, marine and other aquatic *ecosystems* and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (UN, 1992).

Bioenergy Energy derived from any form of *biomass* or its metabolic by-products. See also *Biomass* and *Biofuel*.

Bioenergy with carbon dioxide capture and storage (BECCS) *Carbon dioxide capture and storage (CCS)* technology applied to a *bioenergy* facility. Note that depending on the total emissions of the BECCS supply chain, *carbon dioxide (CO_2)* can be removed from the *atmosphere*. See also *Bioenergy* and *Carbon dioxide capture and storage (CCS)*.

Biofuel A fuel, generally in liquid form, produced from *biomass*. Biofuels currently include bioethanol from sugarcane or maize, biodiesel from canola or soybeans, and black liquor from the paper-manufacturing process. See also *Biomass* and *Bioenergy*.

Biomass Living or recently dead organic material. See also *Bioenergy* and *Biofuel*.

Biophilic urbanism Designing cities with green roofs, green walls and green balconies to bring nature into the densest parts of cities in order to provide *green infrastructure* and human health benefits. See also *Green infrastructure*.

Black carbon (BC) Operationally defined *aerosol* species based on measurement of light absorption and chemical reactivity and/or thermal stability. It is sometimes referred to as soot. BC is mostly formed by the incomplete combustion of *fossil fuels*, *biofuels* and *biomass* but it also occurs naturally. It stays in the *atmosphere* only for days or weeks. It is the most strongly light-absorbing component of particulate matter (PM) and has a warming effect by absorbing heat into the atmosphere and reducing the *albedo* when deposited on snow or ice. See also *Aerosol*.

Blue carbon Blue carbon is the carbon captured by living organisms in coastal (e.g., mangroves, salt marshes, seagrasses) and marine *ecosystems*, and stored in *biomass* and sediments.

Burden sharing (also referred to as Effort sharing) In the context of *mitigation*, burden sharing refers to sharing the effort of reducing the sources or enhancing the sinks of *greenhouse gases (GHGs)*

from historical or *projected* levels, usually allocated by some criteria, as well as sharing the cost burden across countries.

Business as usual (BAU) See *Baseline scenario*.

Carbon budget This term refers to three concepts in the literature: (1) an assessment of *carbon cycle* sources and *sinks* on a global level, through the synthesis of *evidence* for *fossil fuel* and cement emissions, *land-use change* emissions, ocean and land *CO_2* sinks, and the resulting atmospheric CO_2 growth rate. This is referred to as the global carbon budget; (2) the estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a *reference period*, taking into account global surface temperature contributions of other *GHGs* and climate forcers; (3) the distribution of the carbon budget defined under (2) to the regional, national, or sub-national level based on considerations of *equity*, costs or efficiency. See also *Remaining carbon budget*.

Carbon cycle The term used to describe the flow of carbon (in various forms, e.g., as *carbon dioxide (CO_2)*, carbon in *biomass*, and carbon dissolved in the ocean as carbonate and bicarbonate) through the *atmosphere*, hydrosphere, terrestrial and marine biosphere and lithosphere. In this report, the reference unit for the global carbon cycle is $GtCO_2$ or GtC (Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$).

Carbon dioxide (CO_2) A naturally occurring gas, CO_2 is also a by-product of burning *fossil fuels* (such as oil, gas and coal), of burning *biomass*, of *land-use changes (LUC)* and of industrial processes (e.g., cement production). It is the principal *anthropogenic* greenhouse gas *(GHG)* that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1. See also *Greenhouse gas (GHG)*.

Carbon dioxide capture and storage (CCS) A process in which a relatively pure stream of *carbon dioxide (CO_2)* from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the *atmosphere*. Sometimes referred to as Carbon capture and storage. See also *Carbon dioxide capture and utilisation (CCU)*, *Bioenergy with carbon dioxide capture and storage (BECCS)* and *Uptake*.

Carbon dioxide capture and utilisation (CCU) A process in which *CO_2* is captured and then used to produce a new product. If the CO_2 is stored in a product for a *climate*-relevant time horizon, this is referred to as carbon dioxide capture, utilisation and storage (CCUS). Only then, and only combined with CO_2 recently removed from the *atmosphere*, can CCUS lead to *carbon dioxide removal*. CCU is sometimes referred to as carbon dioxide capture and use. See also *Carbon dioxide capture and storage (CCS)*.

Carbon dioxide capture, utilisation and storage (CCUS) See *Carbon dioxide capture and utilisation (CCU)*.

Carbon dioxide removal (CDR) *Anthropogenic* activities removing *CO_2* from the *atmosphere* and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 *uptake* not directly caused by human activities. See also *Mitigation (of climate change)*, *Greenhouse gas removal (GGR)*, *Negative emissions*, *Direct air carbon dioxide capture and storage (DACCS)* and *Sink*.

Carbon intensity The amount of emissions of *carbon dioxide (CO_2)* released per unit of another variable such as *gross domestic product (GDP)*, output energy use or transport.

Carbon neutrality See *Net zero CO_2 emissions*.

Carbon price The price for avoided or released *carbon dioxide (CO_2)* or *CO_2-equivalent emissions*. This may refer to the rate of a carbon tax, or the price of emission permits. In many models that are used to assess the economic costs of *mitigation*, carbon prices are used as a proxy to represent the level of effort in mitigation *policies*.

Carbon sequestration The process of storing carbon in a carbon pool. See also *Blue carbon*, *Carbon dioxide capture and storage (CCS)*, *Uptake* and *Sink*.

Carbon sink See *Sink*.

Clean Development Mechanism (CDM) A mechanism defined under Article 12 of the *Kyoto Protocol* through which investors (governments or companies) from developed (Annex B) countries may finance *greenhouse gas (GHG)* emission reduction or removal projects in developing countries (Non-Annex B), and receive Certified Emission Reduction Units (CERs) for doing so. The CERs can be credited towards the commitments of the respective developed countries. The CDM is intended to facilitate the two objectives of promoting *sustainable development (SD)* in developing countries and of helping *industrialised countries* to reach their emissions commitments in a cost-effective way.

Climate Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*.

Climate change Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external *forcings* such as modulations of the solar cycles, volcanic eruptions and persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use.* Note that the *Framework Convention on Climate Change (UNFCCC)*, in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.' The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes. See also *Climate variability*, *Global warming*, *Ocean acidification (OA)* and *Detection and attribution*.

Climate change commitment Climate change commitment is defined as the unavoidable future *climate change* resulting from inertia in the geophysical and socio-economic systems. Different types of climate change commitment are discussed in the literature (see subterms). Climate change commitment is usually quantified in terms of the further change in temperature, but it includes other future changes, for example in the *hydrological cycle*, in *extreme weather events*, in extreme climate events, and in sea level.

Constant composition commitment
The constant composition commitment is the remaining *climate change* that would result if atmospheric composition, and hence *radiative forcing*, were held fixed at a given value. It results from the thermal inertia of the ocean and slow processes in the cryosphere and land surface.

Constant emissions commitment
The constant emissions commitment is the committed *climate change* that would result from keeping *anthropogenic emissions* constant.

Zero emissions commitment
The zero emissions commitment is the climate change commitment that would result from setting *anthropogenic emissions* to zero. It is determined by both inertia in physical *climate system* components (ocean, cryosphere, land surface) and *carbon cycle* inertia.

Feasible scenario commitment
The feasible scenario commitment is the *climate change* that corresponds to the lowest *emission scenario* judged feasible.

Infrastructure commitment
The infrastructure commitment is the *climate change* that would result if existing *greenhouse gas* and *aerosol* emitting infrastructure were used until the end of its expected lifetime.

Climate-compatible development (CCD) A form of development building on climate strategies that embrace development goals and development strategies that integrate climate *risk management*, *adaptation* and *mitigation*. This definition builds from Mitchell and Maxwell (2010).

Climate extreme (extreme weather or climate event) The occurrence of a value of a weather or *climate* variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both *extreme weather events* and extreme climate events are referred to collectively as 'climate extremes'. See also *Extreme weather event*.

Climate feedback An interaction in which a perturbation in one *climate* quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability.

Climate governance See *Governance*.

Climate justice See *Justice*.

Climate model A numerical representation of the *climate system* based on the physical, chemical and biological properties of its components, their interactions and *feedback* processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. There is an evolution towards more complex models with interactive chemistry and biology. *Climate models* are applied as a research tool to study and simulate the *climate* and for operational purposes, including monthly, seasonal and interannual climate predictions. See also *Earth system model (ESM)*.

Climate neutrality Concept of a state in which human activities result in no net effect on the *climate system*. Achieving such a state would require balancing of residual emissions with emission (*carbon dioxide*) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface *albedo* or local *climate*. See also *Net zero CO_2 emissions*.

Climate projection A climate *projection* is the simulated response of the *climate system* to a *scenario* of future emission or concentration of *greenhouse gases (GHGs)* and *aerosols*, generally derived using *climate models*. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/*radiative forcing* scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Climate-resilient development pathways (CRDPs) Trajectories that strengthen *sustainable development* and efforts to eradicate *poverty* and reduce inequalities while promoting *fair* and cross-scalar *adaptation* to and *resilience* in a changing *climate*. They raise the *ethics*, *equity* and *feasibility* aspects of the deep *societal transformation* needed to drastically reduce emissions to limit *global warming* (e.g., to 1.5°C) and achieve desirable and liveable futures and *well-being* for all.

Climate-resilient pathways Iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with *climate change*. See also *Development pathways* (under *Pathways*), *Transformation pathways* (under *Pathways*), and *Climate-resilient development pathways (CRDPs)*.

Climate sensitivity Climate sensitivity refers to the change in the annual *global mean surface temperature* in response to a change in the atmospheric *CO_2* concentration or other radiative forcing.

Equilibrium climate sensitivity
Refers to the equilibrium (steady state) change in the annual *global mean surface temperature* following a doubling of the atmospheric *carbon dioxide (CO_2)* concentration. As a true equilibrium is challenging to define in *climate models* with dynamic oceans, the equilibrium climate sensitivity is often estimated through experiments in AOGCMs where CO_2 levels are either quadrupled or doubled from *pre-industrial* levels and which are integrated for 100-200 years. The climate sensitivity parameter (units: °C (W m^{-2})$^{-1}$) refers to the equilibrium change in the annual global mean surface temperature following a unit change in *radiative forcing*.

Effective climate sensitivity
An estimate of the *global mean surface temperature* response to a doubling of the atmospheric *carbon dioxide (CO_2)* concentration that is evaluated from model output or observations for evolving non-equilibrium conditions. It is a measure of the strengths of the *climate feedbacks* at a particular time and may vary with *forcing* history and *climate* state, and therefore may differ from *equilibrium climate sensitivity*.

Transient climate response
The change in the *global mean surface temperature*, averaged over a 20-year period, centered at the time of atmospheric *CO_2* doubling, in a *climate model* simulation in which CO_2 increases at 1% yr-1 from *pre-industrial*. It is a measure of the strength of *climate feedbacks* and the timescale of ocean heat uptake.

Climate services Climate services refers to information and products that enhance users' knowledge and understanding about the *impacts* of *climate change* and/or *climate variability* so as to aid decision-making of individuals and organizations and enable preparedness and early climate change action. Products can include climate data products.

Climate-smart agriculture (CSA) Climate-smart agriculture (CSA) is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure *food security* in a changing *climate*. CSA aims to tackle three main objectives: sustainably increasing agricultural productivity and incomes, *adapting* and building *resilience* to *climate change*, and reducing and/or removing *greenhouse gas* emissions, where possible (FAO, 2018).

Climate system The climate system is the highly complex system consisting of five major components: the *atmosphere*, the hydrosphere,

the cryosphere, the lithosphere and the biosphere and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external *forcings* such as volcanic eruptions, solar variations and *anthropogenic* forcings such as the changing composition of the atmosphere and *land-use change*.

Climate target Climate target refers to a temperature limit, concentration level, or emissions reduction goal used towards the aim of avoiding dangerous *anthropogenic* interference with the *climate system*. For example, national climate targets may aim to reduce *greenhouse gas* emissions by a certain amount over a given time horizon, for example those under the *Kyoto Protocol*.

Climate variability Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the *climate* on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the *climate system* (internal variability), or to variations in natural or *anthropogenic* external *forcing* (external variability). See also *Climate change*.

CO_2 equivalent (CO_2-eq) emission The amount of *carbon dioxide (CO_2)* emission that would cause the same integrated *radiative forcing* or temperature change, over a given time horizon, as an emitted amount of a *greenhouse gas (GHG)* or a mixture of GHGs. There are a number of ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its global warming potential (GWP) for a 100-year time horizon. For a mix of GHGs it is obtained by summing the CO_2-equivalent emissions of each gas. CO_2-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the corresponding *climate change* responses. There is generally no connection between CO_2-equivalent emissions and resulting CO_2-equivalent concentrations.

Co-benefits The positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society or the environment. Co-benefits are often subject to *uncertainty* and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits.

Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC) Common but Differentiated Responsibilities and Respective Capabilities (CBDR–RC) is a key principle in the *United Nations Framework Convention on Climate Change (UNFCCC)* that recognises the different capabilities and differing responsibilities of individual countries in tacking *climate change*. The principle of CBDR–RC is embedded in the 1992 UNFCCC treaty. The convention states: "… the global nature of climate change calls for the widest possible cooperation by all countries and their participation in an effective and appropriate international response, in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions." Since then the CBDR-RC principle has guided the UN climate negotiations.

Conference of the Parties (COP) The supreme body of UN conventions, such as the *United Nations Framework Convention on Climate Change (UNFCCC)*, comprising parties with a right to vote that have ratified or acceded to the convention. See also *United Nations Framework Convention on Climate Change (UNFCCC)*.

Confidence The robustness of a finding based on the type, amount, quality and consistency of *evidence* (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of *agreement* across multiple lines of evidence. In this report, confidence is expressed qualitatively (Mastrandrea et al., 2010). See Section 1.6 for the list of confidence levels used. See also *Agreement*, *Evidence*, *Likelihood* and *Uncertainty*.

Conservation agriculture A coherent group of agronomic and soil management practices that reduce the disruption of soil structure and biota.

Constant composition commitment See *Climate change commitment*.

Constant emissions commitment See *Climate change commitment*.

Coping capacity The ability of people, *institutions*, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term. This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a). See also *Resilience*.

Cost–benefit analysis Monetary assessment of all negative and positive impacts associated with a given action. Cost–benefit analysis enables comparison of different interventions, investments or strategies and reveals how a given investment or policy effort pays off for a particular person, company or country. Cost–benefit analyses representing society's point of view are important for *climate change* decision-making, but there are difficulties in aggregating costs and benefits across different actors and across timescales. See also *Discounting*.

Cost-effectiveness A measure of the cost at which policy goal or outcome is achieved. The lower the cost the greater the cost-effectiveness.

Coupled Model Intercomparison Project (CMIP) The Coupled Model Intercomparison Project (CMIP) is a climate modelling activity from the World Climate Research Programme (WCRP) which coordinates and archives *climate model* simulations based on shared model inputs by modelling groups from around the world. The CMIP3 multimodel data set includes *projections* using SRES *scenarios*. The CMIP5 data set includes projections using the *Representative Concentration Pathways (RCPs)*. The CMIP6 phase involves a suite of common model experiments as well as an ensemble of CMIP-endorsed model intercomparison projects (MIPs).

Cumulative emissions The total amount of emissions released over a specified period of time. See also *Carbon budget*, and *Transient climate response to cumulative CO_2 emissions (TCRE)*.

Decarbonization The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport.

Decoupling Decoupling (in relation to *climate change*) is where economic growth is no longer strongly associated with consumption of *fossil fuels*. Relative decoupling is where both grow but at different rates. Absolute decoupling is where economic growth happens but fossil fuels decline.

Deforestation Conversion of *forest* to non-forest. For a discussion of the term forest and related terms such as *afforestation*, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). See also *Afforestation*, *Reforestation* and *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*.

Deliberative governance See *Governance*.

Demand- and supply-side measures

Demand-side measures
Policies and programmes for influencing the demand for goods and/or services. In the energy sector, demand-side management aims at reducing the demand for electricity and other forms of energy required to deliver energy services.

Supply-side measures
Policies and programmes for influencing how a certain demand for goods and/or services is met. In the energy sector, for example, supply-side *mitigation measures* aim at reducing the amount of *greenhouse gas* emissions emitted per unit of energy produced.

See also *Mitigation measures*.

Demand-side measures See *Demand- and supply-side measures*.

Detection See *Detection and attribution*.

Detection and attribution Detection of change is defined as the process of demonstrating that *climate* or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its *likelihood* of occurrence by chance due to internal variability alone is determined to be small, for example, <10%. Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of *confidence*.

Development pathways See *Pathways*.

Direct air carbon dioxide capture and storage (DACCS) Chemical process by which CO_2 is captured directly from the ambient air, with subsequent storage. Also known as direct air capture and storage (DACS).

Disaster Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery. See also *Hazard* and *Vulnerability*.

Disaster risk management (DRM) Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of *disaster* risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing *human security*, *well-being*, *quality of life*, and *sustainable development*.

Discount rate See *Discounting*.

Discounting A mathematical operation that aims to make monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate from year to year that makes future value worth less today (if the discount rate is positive). The choice of discount rate(s) is debated as it is a judgement based on hidden and/or explicit values.

(Internal) Displacement Internal displacement refers to the forced movement of people within the country they live in. Internally displaced persons (IDPs) are 'Persons or groups of persons who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular as a result of or in order to avoid the effects of armed conflict, situations of generalized violence, violations of human rights or natural or human-made disasters, and who have not crossed an internationally recognized State border.' (UN, 1998). See also *Migration*.

Disruptive innovation Disruptive innovation is demand-led technological change that leads to significant system change and is characterized by strong exponential growth.

Distributive equity See *Equity*.

Distributive justice See *Justice*.

Double dividend The extent to which revenues generated by *policy* instruments, such as carbon taxes or auctioned (tradeable) emission permits can (1) contribute to *mitigation* and (2) offset part of the potential welfare losses of climate policies through recycling the revenue in the economy by reducing other distortionary taxes.

Downscaling Downscaling is a method that derives local- to regional-scale (up to 100 km) information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional *climate models*, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods are based on observations and develop statistical relationships that link the large-scale atmospheric variables with local/regional *climate* variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information. The two methods can be combined, e.g., applying empirical/statistical downscaling to the output of a regional climate model, consisting of a dynamical downscaling of a global climate model.

Drought A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term, therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, shortage of precipitation during the growing season impinges on crop production or *ecosystem* function in general (due to *soil moisture* drought, also termed agricultural drought), and during the *runoff* and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought. See also *Soil moisture*.

Megadrought
A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.

Early warning systems (EWS) The set of technical, financial and *institutional capacities* needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a *hazard* to prepare to act promptly and appropriately to reduce the possibility of harm or loss. Dependent upon context, EWS may draw upon scientific and/or *Indigenous knowledge*. EWS are also considered for ecological applications e.g., conservation, where the organization itself is not threatened by hazard but the *ecosystem* under conservation is (an example is coral bleaching alerts), in agriculture (for example, warnings of ground frost, hailstorms) and in fisheries (storm and tsunami warnings). This glossary entry builds from the definitions used in UNISDR (2009) and IPCC (2012a).

Earth system feedbacks See *Climate feedback*.

Earth system model (ESM) A coupled atmosphere–ocean general circulation model in which a representation of the *carbon cycle* is included, allowing for interactive calculation of atmospheric CO_2 or compatible emissions. Additional components (e.g., atmospheric chemistry, *ice sheets*, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included. See also *Climate model*.

Ecosystem An ecosystem is a functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment. See also *Ecosystem services*.

Ecosystem services Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or *biodiversity* maintenance, (2) provisioning services such as food or fibre, (3) regulating services such as climate regulation or *carbon sequestration*, and (4) cultural services such as tourism or spiritual and aesthetic appreciation.

Effective climate sensitivity See *Climate sensitivity*.

Effective radiative forcing See *Radiative forcing*.

El Niño-Southern Oscillation (ENSO) The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to about seven years, is known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Tahiti and Darwin and/or the *sea surface temperatures* in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This phenomenon has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña.

Electric vehicle (EV) A vehicle whose propulsion is powered fully or mostly by electricity.

Battery electric vehicle (BEV)
A vehicle whose propulsion is entirely electric without any internal combustion engine.

Plug-in hybrid electric vehicle (PHEV)
A vehicle whose propulsion is mostly electric with batteries re-charged from an electric source but extra power and distance are provided by a hybrid internal combustion engine.

Emission pathways See *Pathways*.

Emission scenario A plausible representation of the future development of emissions of substances that are radiatively active (e.g., *greenhouse gases (GHGs)*, *aerosols*) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and *land use*) and their key relationships. Concentration *scenarios*, derived from emission scenarios, are often used as input to a *climate model* to compute *climate projections*. See also *Baseline scenario*, *Mitigation scenario*, *Socio-economic scenario*, *Scenario*, *Representative Concentration Pathways (RCPs)* (under *Pathways*), *Shared Socio-economic Pathways (SSPs)* (under *Pathways*) and *Transformation pathways* (under *Pathways*).

Emission trajectories A *projected* development in time of the emission of a *greenhouse gas (GHG)* or group of GHGs, *aerosols*, and GHG *precursors*. See also *Emission pathways* (under *Pathways*).

Emissions trading A market-based instrument aiming at meeting a *mitigation* objective in an efficient way. A cap on *GHG* emissions is divided in tradeable emission permits that are allocated by a combination of auctioning and handing out free allowances to entities within the jurisdiction of the trading scheme. Entities need to surrender emission permits equal to the amount of their emissions (e.g., tonnes of CO_2). An entity may sell excess permits to entities that can avoid the same amount of emissions in a cheaper way. Trading schemes may occur at the intra-company, domestic, or international level (e.g., the flexibility mechanisms under the *Kyoto Protocol* and the EU-ETS) and may apply to carbon dioxide (CO_2), other greenhouse gases (GHGs), or other substances.

Enabling conditions Conditions that affect the *feasibility* of *adaptation* and *mitigation* options, and can accelerate and scale-up systemic transitions that would limit temperature increase to 1.5°C and enhance capacities of systems and societies to adapt to the associated *climate change*, while achieving *sustainable development*, eradicating *poverty* and reducing *inequalities*. Enabling conditions include finance, technological innovation, strengthening *policy* instruments, *institutional capacity*, *multilevel governance*, and changes in *human behaviour* and lifestyles. They also include inclusive processes, attention to power asymmetries and unequal opportunities for development and reconsideration of values. See also *Feasibility*.

Energy efficiency The ratio of output or useful energy or energy services or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to the input of energy (measured as kWh kWh^{-1}, tonnes kWh^{-1} or any other physical measure of useful output like tonne-km transported). Energy efficiency is often described by energy intensity. In economics, energy intensity describes the ratio of economic output to energy input. Most commonly energy efficiency is measured as input energy over a physical or economic unit, i.e., kWh USD^{-1} (energy intensity), kWh $tonne^{-1}$. For buildings, it is often measured as kWh m^{-2}, and for vehicles as km $liter^{-1}$ or liter km^{-1}. Very often in policy 'energy efficiency' is intended as the measures to reduce energy demand through technological options such as insulating buildings, more efficient appliances, efficient lighting, efficient vehicles, etc.

Energy security The goal of a given country, or the global community as a whole, to maintain an adequate, stable and predictable energy supply. Measures encompass safeguarding the sufficiency of energy resources to meet national energy demand at competitive and stable prices and the *resilience* of the energy supply; enabling development and deployment of technologies; building sufficient infrastructure to generate, store and transmit energy supplies; and ensuring enforceable contracts of delivery.

Enhanced weathering Enhancing the removal of *carbon dioxide (CO_2)* from the *atmosphere* through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans.

(Model) Ensemble A group of parallel model simulations characterising historical *climate* conditions, *climate predictions*, or climate projections. Variation of the results across the ensemble members may give an estimate of modelling-based *uncertainty*. Ensembles made with the same model but different initial conditions only characterize the uncertainty associated with internal *climate variability*, whereas multimodel ensembles including simulations by several models also include the impact of model differences. Perturbed parameter ensembles, in which model parameters are varied in a systematic

manner, aim to assess the uncertainty resulting from internal model specifications within a single model. Remaining sources of uncertainty unaddressed with model ensembles are related to systematic model errors or biases, which may be assessed from systematic comparisons of model simulations with observations wherever available. See also *Climate projection*.

Equality A principle that ascribes equal worth to all human beings, including equal opportunities, rights, and obligations, irrespective of origins.

Inequality
Uneven opportunities and social positions, and processes of discrimination within a group or society, based on gender, class, ethnicity, age, and (dis) ability, often produced by uneven development. Income inequality refers to gaps between highest and lowest income earners within a country and between countries. See also *Equity*, *Ethics* and *Fairness*.

Equilibrium climate sensitivity See *Climate sensitivity*.

Equity Equity is the principle of *fairness* in burden sharing and is a basis for understanding how the *impacts* and responses to *climate change*, including costs and benefits, are distributed in and by society in more or less equal ways. It is often aligned with ideas of *equality*, fairness and *justice* and applied with respect to equity in the responsibility for, and distribution of, climate *impacts* and *policies* across society, generations, and gender, and in the sense of who participates and controls the processes of decision-making.

Distributive equity
Equity in the consequences, outcomes, costs and benefits of actions or policies. In the case of *climate change* or climate *policies* for different people, places and countries, including equity aspects of sharing burdens and benefits for *mitigation* and *adaptation*.

Gender equity
Ensuring equity in that women and men have the same rights, resources and opportunities. In the case of *climate change* gender equity recognizes that women are often more vulnerable to the *impacts* of climate change and may be disadvantaged in the process and outcomes of climate *policy*.

Inter-generational equity
Equity between generations that acknowledges that the effects of past and present emissions, *vulnerabilities* and policies impose costs and benefits for people in the future and of different age groups.

Procedural equity
Equity in the process of decision-making, including recognition and inclusiveness in participation, equal representation, bargaining power, voice and equitable access to knowledge and resources to participate.

See also *Equality*, *Ethics* and *Fairness*.

Ethics Ethics involves questions of *justice* and value. Justice is concerned with right and wrong, *equity* and *fairness*, and, in general, with the rights to which people and living beings are entitled. Value is a matter of worth, benefit, or good. See also *Equality*, *Equity* and *Fairness*.

Evidence Data and information used in the scientific process to establish findings. In this report, the degree of evidence reflects the amount, quality and consistency of scientific/technical information on which the Lead Authors are basing their findings. See also *Agreement*, *Confidence*, *Likelihood* and *Uncertainty*.

Exposure The presence of people; *livelihoods*; species or *ecosystems*; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected. See also *Hazard*, *Risk* and *Vulnerability*.

Extratropical cyclone Any cyclonic-scale storm that is not a *tropical cyclone*. Usually refers to a middle- or high-latitude migratory storm system formed in regions of large horizontal temperature variations. Sometimes called extratropical storm or extratropical low. See also *Tropical cyclone*.

Extreme weather event An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., *drought* or heavy rainfall over a season). See also *Heatwave* and *Climate extreme (extreme weather or climate event)*.

Extreme weather or climate event See *Climate extreme (extreme weather or climate event)*.

Fairness Impartial and just treatment without favouritism or discrimination in which each person is considered of equal worth with equal opportunity. See also *Equity*, *Equality* and *Ethics*.

Feasibility The degree to which climate goals and response options are considered possible and/or desirable. Feasibility depends on geophysical, ecological, technological, economic, social and *institutional* conditions for change. Conditions underpinning feasibility are dynamic, spatially variable, and may vary between different groups. See also *Enabling conditions*.

Feasible scenario commitment See *Climate change commitment*.

Feedback See *Climate feedback*.

Flexible governance See *Governance*.

Flood The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.

Food security A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2001).

Food wastage Food wastage encompasses food loss (the loss of food during production and transportation) and food waste (the waste of food by the consumer) (FAO, 2013).

Forcing See *Radiative forcing*.

Forest A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics. For a discussion of the term forest and related terms such as *afforestation*, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). See also *Afforestation*, *Deforestation* and *Reforestation*.

Fossil fuels Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.

Framework Convention on Climate Change See *United Nations Framework Convention on Climate Change (UNFCCC)*.

Gender equity See *Equity*.

General purpose technologies (GPT) General purpose technologies can be or are used pervasively in a wide range of sectors in ways that fundamentally change the modes of operation of those sectors (Helpman, 1998). Examples include the steam engine, power generator and motor, *ICT*, and biotechnology.

Geoengineering In this report, separate consideration is given to the two main approaches considered as 'geoengineering' in some of the literature: *solar radiation modification (SRM)* and *carbon dioxide removal (CDR)*. Because of this separation, the term 'geoengineering' is not used in this report. See also *Carbon dioxide removal (CDR)* and *Solar radiation modification (SRM)*.

Glacier A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallisation of snow and showing *evidence* of past or present flow. A glacier typically gains mass by accumulation of snow, and loses mass by melting and ice discharge into the sea or a lake if the glacier terminates in a body of water. Land ice masses of continental size (>50,000 km^2) are referred to as *ice sheets*. See also *Ice sheet*.

Global climate model (also referred to as general circulation model, both abbreviated as GCM) See *Climate model*.

Global mean surface temperature (GMST) Estimated global average of near-surface air temperatures over land and sea-ice, and *sea surface temperatures* over ice-free ocean regions, with changes normally expressed as departures from a value over a specified *reference period*. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[1] See also *Land surface air temperature*, *Sea surface temperature (SST)* and *Global mean surface air temperature (GSAT)*.

Global mean surface air temperature (GSAT) Global average of near-surface air temperatures over land and oceans. Changes in GSAT are often used as a measure of global temperature change in *climate models* but are not observed directly. See also *Global mean surface temperature (GMST)* and *Land surface air temperature*.

Global warming The estimated increase in *global mean surface temperature (GMST)* averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to *pre-industrial* levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. See also *Climate change* and *Climate variability*.

Governance A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognizes the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community.

Adaptive governance
An emerging term in the literature for the evolution of formal and informal *institutions* of governance that prioritize *social learning* in planning, implementation and evaluation of policy through iterative social learning to steer the use and protection of natural resources, *ecosystem services* and common pool natural resources, particularly in situations of complexity and *uncertainty*.

Climate governance
Purposeful mechanisms and measures aimed at steering social systems towards preventing, mitigating, or adapting to the risks posed by *climate change* (Jagers and Stripple, 2003).

Deliberative governance
Deliberative governance involves decision-making through inclusive public conversation, which allows opportunity for developing policy options through public discussion rather than collating individual preferences through voting or referenda (although the latter governance mechanisms can also be proceeded and legitimated by public deliberation processes).

Flexible governance
Strategies of governance at various levels, which prioritize the use of *social learning* and rapid feedback mechanisms in planning and policy making, often through incremental, experimental and iterative management processes.

Governance capacity
The ability of governance *institutions*, leaders, and non-state and civil society to plan, co-ordinate, fund, implement, evaluate and adjust policies and measures over the short, medium and long term, adjusting for *uncertainty*, rapid change and wide-ranging impacts and multiple actors and demands.

Multilevel governance
Multilevel governance refers to negotiated, non-hierarchical exchanges between *institutions* at the transnational, national, regional and local levels. Multilevel governance identifies relationships among governance processes at these different levels. Multilevel governance does include negotiated relationships among institutions at different institutional levels and also a vertical 'layering' of governance processes at different levels. Institutional relationships take place directly between transnational, regional and local levels, thus bypassing the state level (Peters and Pierre, 2001)

Participatory governance
A governance system that enables direct public engagement in decision-making using a variety of techniques for example, referenda, community deliberation, citizen juries or participatory budgeting. The approach can be applied in formal and informal *institutional* contexts from national to local, but is usually associated with devolved decision-making. This definition builds from Fung and Wright (2003) and Sarmiento and Tilly (2018).

Governance capacity See *Governance*.

Green infrastructure The interconnected set of natural and constructed ecological systems, green spaces and other landscape features. It includes planted and indigenous trees, wetlands, parks, green open spaces and original grassland and woodlands, as well as possible building and street-level design interventions that incorporate vegetation. Green infrastructure provides services and functions in the same way as conventional infrastructure. This definition builds from Culwick and Bobbins (2016).

Greenhouse gas (GHG) Greenhouse gases are those gaseous constituents of the *atmosphere*, both natural and *anthropogenic*, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), *carbon dioxide (CO_2)*, *nitrous oxide (N_2O)*, *methane (CH_4)* and

[1] Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

ozone (O_3) are the primary GHGs in the Earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the *halocarbons* and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the *Kyoto Protocol* deals with the GHGs sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). See also *Carbon dioxide (CO_2)*, *Methane (CH_4)*, *Nitrous oxide (N_2O)* and *Ozone (O_3)*.

Greenhouse gas removal (GGR) Withdrawal of a *GHG* and/or a *precursor* from the *atmosphere* by a *sink*. See also *Carbon dioxide removal (CDR)* and *Negative emissions*.

Gross domestic product (GDP) The sum of gross value added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally one year. GDP is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Gross fixed capital formation (GFCF) One component of the *GDP* that corresponds to the total value of acquisitions, minus disposals of fixed assets during one year by the business sector, governments and households, plus certain additions to the value of non-produced assets (such as subsoil assets or major improvements in the quantity, quality or productivity of land).

Halocarbons A collective term for the group of partially halogenated organic species, which includes the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), halons, methyl chloride and methyl bromide. Many of the halocarbons have large global warming potentials. The chlorine and bromine-containing halocarbons are also involved in the depletion of the ozone layer.

Hazard The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, *livelihoods*, service provision, *ecosystems* and environmental resources. See also *Disaster*, *Exposure*, *Risk*, and *Vulnerability*.

Heatwave A period of abnormally hot weather. Heatwaves and warm spells have various and in some cases overlapping definitions. See also *Extreme weather event*.

Heating, ventilation, and air conditioning (HVAC) Heating, ventilation and air conditioning technology is used to control temperature and humidity in an indoor environment, be it in buildings or in vehicles, providing thermal comfort and healthy air quality to the occupants. HVAC systems can be designed for an isolated space, an individual building or a distributed heating and cooling network within a building structure or a district heating system. The latter provides economies of scale and also scope for integration with solar heat, natural seasonal cooling/heating etc.

Holocene The Holocene is the current interglacial geological epoch, the second of two epochs within the Quaternary period, the preceding being the Pleistocene. The International Commission on Stratigraphy defines the start of the Holocene at 11,650 years before 1950. See also *Anthropocene*.

Human behaviour The way in which a person acts in response to a particular situation or stimulus. Human actions are relevant at different levels, from international, national, and *sub-national actors*, to NGO, firm-level actors, and communities, households, and individual actions.

Adaptation behaviour
Human actions that directly or indirectly affect the risks of climate change *impacts.*

Mitigation behaviour
Human actions that directly or indirectly influence *mitigation*.

Human behavioural change A transformation or modification of human actions. Behaviour change efforts can be planned in ways that mitigate *climate change* and/or reduce negative consequences of climate change *impacts*.

Human rights Rights that are inherent to all human beings, universal, inalienable, and indivisible, typically expressed and guaranteed by law. They include the right to life; economic, social, and cultural rights; and the right to development and self-determination. Based upon the definition by the UN Office of the High Commissioner for Human Rights (UNOHCHR, 2018).

Procedural rights
Rights to a legal procedure to enforce *substantive rights*.

Substantive rights
Basic human rights, including the right to the substance of being human such as life itself, liberty and happiness.

Human security A condition that is met when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In the context of *climate change*, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests and to live with dignity.

Human system Any system in which human organizations and *institutions* play a major role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, urban systems, political systems, technological systems and economic systems are all human systems in the sense applied in this report.

Hydrological cycle The cycle in which water evaporates from the oceans and the land surface, is carried over the earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates as rain or snow, which on land can be intercepted by trees and vegetation, potentially accumulates as snow or ice, provides *runoff* on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, flows out into the oceans, and ultimately evaporates again from the ocean or land surface. The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

Ice sheet A mass of land ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet *glaciers*, in some cases into the sea or into ice shelves floating on the sea. There are only two ice sheets in the modern world, one on Greenland and one on Antarctica. During glacial periods there were others. See also *Glacier*.

(climate change) Impact assessment The practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of *climate change* on natural and *human systems*.

Impacts (consequences, outcomes) The consequences of realized risks on natural and *human systems*, where risks result from the interactions of climate-related *hazards* (including *extreme weather and climate events*), *exposure*, and *vulnerability*. Impacts generally refer to effects on lives; *livelihoods*; health and *well-being*; *ecosystems* and species; economic, social and cultural assets; services (including

ecosystem services); and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial. See also *Adaptation*, *Exposure*, *Hazard*, *Loss and Damage, and losses and damages*, and *Vulnerability*.

Incremental adaptation See *Adaptation*.

Indigenous knowledge Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. For many Indigenous peoples, Indigenous knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer term actions. This knowledge is integral to cultural complexes, which also encompass language, systems of classification, resource use practices, social interactions, values, ritual and spirituality. These distinctive ways of knowing are important facets of the world's cultural diversity. This definition builds on UNESCO (2018).

Indirect land-use change (iLUC) See *Land-use change (LUC)*.

Industrial revolution A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries, including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of *fossil fuels*, initially coal, and hence emission of *carbon dioxide (CO_2)*. See also *Pre-industrial*.

Industrialized/developed/developing countries There are a diversity of approaches for categorizing countries on the basis of their level of development, and for defining terms such as industrialized, developed, or developing. Several categorizations are used in this report. (1) In the United Nations system, there is no established convention for designation of developed and developing countries or areas. (2) The United Nations Statistics Division specifies developed and developing regions based on common practice. In addition, specific countries are designated as Least Developed Countries (LDC), landlocked developing countries, *small island developing states*, and transition economies. Many countries appear in more than one of these categories. (3) The World Bank uses income as the main criterion for classifying countries as low, lower middle, upper middle and high income. (4) The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite Human Development Index (HDI) to classify countries as low, medium, high or very high human development.

Inequality See Equality.

Information and communication technology (ICT) An umbrella term that includes any information and communication device or application, encompassing: computer systems, network hardware and software, cell phones, etc.

Infrastructure commitment See *Climate change commitment*.

Institution Institutions are rules and norms held in common by social actors that guide, constrain and shape human interaction. Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations – such as parliaments, regulatory agencies, private firms and community bodies – develop and act in response to institutional frameworks and the incentives they frame. Institutions can guide, constrain and shape human interaction through direct control, through incentives, and through processes of socialization. See also *Institutional capacity*.

Institutional capacity *Institutional* capacity comprises building and strengthening individual organizations and providing technical and management training to support integrated planning and decision-making processes between organizations and people, as well as empowerment, social capital, and an enabling environment, including the culture, values and power relations (Willems and Baumert, 2003).

Integrated assessment A method of analysis that combines results and models from the physical, biological, economic and social sciences and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it. See also *Integrated assessment model (IAM)*.

Integrated assessment model (IAM) Integrated assessment models (IAMs) integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking *integrated assessments*.

One class of IAM used in respect of climate change *mitigation* may include representations of: multiple sectors of the economy, such as energy, *land use* and *land-use change*; interactions between sectors; the economy as a whole; associated *GHG* emissions and *sinks*; and reduced representations of the *climate system*. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system.

Another class of IAM additionally includes representations of the costs associated with climate change *impacts*, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a *cost–benefit* framework and have been used to estimate the *social cost of carbon*.

Integrated water resources management (IWRM) A process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital *ecosystems*.

Inter-generational equity See *Equity*.

Inter-generational justice See *Justice*.

Internal variability See *Climate variability*.

Internet of Things (IoT) The network of computing devices embedded in everyday objects such as cars, phones and computers, connected via the internet, enabling them to send and receive data.

Iron fertilization See *Ocean fertilization*.

Irreversibility A perturbed state of a dynamical system is defined as irreversible on a given timescale, if the recovery time scale from this state due to natural processes is substantially longer than the time it takes for the system to reach this perturbed state. See also *Tipping point*.

Justice Justice is concerned with ensuring that people get what is due to them, setting out the moral or legal principles of *fairness* and *equity* in the way people are treated, often based on the *ethics* and values of society.

Climate justice
Justice that links development and *human rights* to achieve a human-centred approach to addressing *climate change*, safeguarding the rights of the most vulnerable people and sharing the burdens and benefits of climate change and its impacts *equitably* and *fairly*. This definition builds upon the one used by the Mary Robinson Foundation – Climate Justice (MRFCJ, 2018).

Distributive justice
Justice in the allocation of economic and non-economic costs and benefits across society.

Inter-generational justice
Justice in the distribution of economic and non-economic costs and benefits across generations.

Procedural justice
Justice in the way outcomes are brought about including who participates and is heard in the processes of decision-making.

Social justice
Just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity, and support according to principles of justice and fairness.

See also *Equity*, *Ethics*, *Fairness*, and *Human rights*.

Kyoto Protocol The Kyoto Protocol to the *United Nations Framework Convention on Climate Change (UNFCCC)* is an international treaty adopted in December 1997 in Kyoto, Japan, at the Third Session of the *Conference of the Parties* (COP3) to the UNFCCC. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in Annex B of the Protocol (mostly OECD countries and countries with economies in transition) agreed to reduce their anthropogenic *greenhouse gas (GHG)* emissions *(carbon dioxide (CO_2)*, *methane (CH_4)*, *nitrous oxide (N_2O)*, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6)) by at least 5% below 1990 levels in the first commitment period (2008–2012). The Kyoto Protocol entered into force on 16 February 2005 and as of May 2018 had 192 Parties (191 States and the European Union). A second commitment period was agreed in December 2012 at COP18, known as the Doha Amendment to the Kyoto Protocol, in which a new set of Parties committed to reduce GHG emissions by at least 18% below 1990 levels in the period from 2013 to 2020. However, as of May 2018, the Doha Amendment had not received sufficient ratifications to enter into force. See also *United Nations Framework Convention on Climate Change (UNFCCC)* and *Paris Agreement*.

Land surface air temperature The near-surface air temperature over land, typically measured at 1.25–2 m above the ground using standard meteorological equipment.

Land use Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). In national *greenhouse gas* inventories, land use is classified according to the IPCC land use categories of forest land, cropland, grassland, wetland, settlements, other. See also *Land-use change (LUC)*.

Land-use change (LUC) Land-use change involves a change from one *land use* category to another.

Indirect land-use change (iLUC)
Refers to market-mediated or policy-driven shifts in *land use* that cannot be directly attributed to land-use management decisions of individuals or groups. For example, if agricultural land is diverted to fuel production, *forest* clearance may occur elsewhere to replace the former agricultural production.

Land use, land-use change and forestry (LULUCF)
In the context of national *greenhouse gas (GHG)* inventories under the *UNFCCC*, LULUCF is a GHG inventory sector that covers *anthropogenic emissions* and removals of GHG from carbon pools in managed lands, excluding non-CO_2 agricultural emissions. Following the 2006 IPCC Guidelines for National GHG Inventories, 'anthropogenic' land-related GHG fluxes are defined as all those occurring on 'managed land', i.e., 'where human interventions and practices have been applied to perform production, ecological or social functions'. Since managed land may include *CO_2* removals not considered as 'anthropogenic' in some of the scientific literature assessed in this report (e.g., removals associated with CO_2 fertilization and N deposition), the land-related net GHG emission estimates included in this report are not necessarily directly comparable with LULUCF estimates in National GHG Inventories.

See also *Afforestation*, *Deforestation*, *Reforestation*, and the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

Land use, land-use change and forestry (LULUCF) See *Land-use change (LUC)*.

Life cycle assessment (LCA) Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its life cycle. This definition builds from ISO (2018).

Likelihood The chance of a specific outcome occurring, where this might be estimated probabilistically. Likelihood is expressed in this report using a standard terminology (Mastrandrea et al., 2010). See Section 1.6 for the list of likelihood qualifiers used. See also *Agreement*, *Evidence*, *Confidence* and *Uncertainty*.

Livelihood The resources used and the activities undertaken in order to live. Livelihoods are usually determined by the entitlements and assets to which people have access. Such assets can be categorised as human, social, natural, physical or financial.

Local knowledge Local knowledge refers to the understandings and skills developed by individuals and populations, specific to the places where they live. Local knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions. This knowledge is a key element of the social and cultural systems which influence observations of, and responses to *climate change*; it also informs *governance* decisions. This definition builds on UNESCO (2018).

Lock-in A situation in which the future development of a system, including infrastructure, technologies, investments, *institutions*, and behavioural norms, is determined or constrained ('locked in') by historic developments.

Long-lived climate forcers (LLCF) Long-lived climate forcers refer to a set of well-mixed *greenhouse gases* with long atmospheric lifetimes. This set of compounds includes *carbon dioxide (CO_2)* and *nitrous oxide (N_2O)*, together with some fluorinated gases. They have a warming effect on *climate*. These compounds accumulate in the *atmosphere* at decadal to centennial time scales, and their effect on climate hence persists for decades to centuries after their emission. On time scales of decades to a century, already emitted emissions of long-lived climate forcers can only be abated by *greenhouse gas removal (GGR)*. See also *Short-lived climate forcers (SLCF)*.

Loss and Damage, and losses and damages Research has taken Loss and Damage (capitalized letters) to refer to political debate under the *UNFCCC* following the establishment of the Warsaw Mechanism on Loss and Damage in 2013, which is to 'address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change.' Lowercase letters (losses and damages) have been taken to refer broadly to harm from (observed) *impacts* and (projected) *risks* (see Mechler et al., in press).

Maladaptive actions (Maladaptation) Actions that may lead to increased *risk* of adverse climate-related outcomes, including via increased *GHG* emissions, increased *vulnerability* to *climate change*, or diminished welfare, now or in the future. Maladaptation is usually an unintended consequence.

Market exchange rate (MER) The rate at which a currency of one country can be exchanged with the currency of another country. In most economies such rates evolve daily while in others there are official conversion rates that are adjusted periodically. See also *Purchasing power parity (PPP)*.

Market failure When private decisions are based on market prices that do not reflect the real scarcity of goods and services but rather reflect market distortions, they do not generate an efficient allocation of resources but cause welfare losses. A market distortion is any event in which a market reaches a market clearing price that is substantially different from the price that a market would achieve while operating under conditions of perfect competition and state enforcement of legal contracts and the ownership of private property. Examples of factors causing market prices to deviate from real economic scarcity are environmental externalities, public goods, monopoly power, information asymmetry, transaction costs and non-rational behaviour.

Measurement, Reporting and Verification (MRV)

Measurement
'Processes of data collection over time, providing basic datasets, including associated accuracy and precision, for the range of relevant variables. Possible data sources are field measurements, field observations, detection through remote sensing and interviews.' (UN-REDD, 2009).

Reporting
'The process of formal reporting of assessment results to the UNFCCC, according to predetermined formats and according to established standards, especially the IPCC [Intergovernmental Panel on Climate Change] Guidelines and GPG [Good Practice Guidance].' (UN-REDD, 2009)

Verification
'The process of formal verification of reports, for example the established approach to verify national communications and national inventory reports to the UNFCCC.' (UN-REDD, 2009)

Megadrought See *Drought*.

Methane (CH_4) One of the six *greenhouse gases (GHGs)* to be mitigated under the *Kyoto Protocol* and is the major component of natural gas and associated with all hydrocarbon fuels. Significant emissions occur as a result of animal husbandry and agriculture, and their management represents a major *mitigation* option.

Migrant See *Migration*.

Migration The International Organization for Migration (IOM) defines migration as 'The movement of a person or a group of persons, either across an international border, or within a State. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification.' (IOM, 2018).

Migrant
The International Organization for Migration (IOM) defines a migrant as 'any person who is moving or has moved across an international border or within a State away from his/her habitual place of residence, regardless of (1) the person's legal status; (2) whether the movement is voluntary or involuntary; (3) what the causes for the movement are; or (4) what the length of the stay is.' (IOM, 2018).

See also *(Internal) Displacement*.

Millennium Development Goals (MDGs) A set of eight time-bound and measurable goals for combating *poverty*, hunger, disease, illiteracy, discrimination against women and environmental degradation. These goals were agreed at the UN Millennium Summit in 2000 together with an action plan to reach the goals by 2015.

Mitigation (of climate change) A human intervention to reduce emissions or enhance the *sinks* of *greenhouse gases*.

Mitigation behaviour See *Human behaviour*.

Mitigation measures In climate *policy*, mitigation measures are technologies, processes or practices that contribute to *mitigation*, for example, renewable energy (RE) technologies, waste minimization processes and public transport commuting practices. See also *Mitigation option*, and *Policies (for climate change mitigation and adaptation)*.

Mitigation option A technology or practice that reduces *GHG* emissions or enhances *sinks*.

Mitigation pathways See *Pathways*.

Mitigation scenario A plausible description of the future that describes how the (studied) system responds to the implementation of *mitigation* policies and measures. See also *Emission scenario*, *Pathways*, *Socio-economic scenario* and *Stabilization (of GHG or CO_2-equivalent concentration)*.

Monitoring and evaluation (M&E) Monitoring and evaluation refers to mechanisms put in place at national to local scales to respectively monitor and evaluate efforts to reduce *greenhouse gas* emissions and/or adapt to the *impacts* of *climate change* with the aim of systematically identifying, characterizing and assessing progress over time.

Motivation (of an individual) An individual's reason or reasons for acting in a particular way; individuals may consider various consequences of actions, including financial, social, affective and environmental consequences. Motivation can come from outside (extrinsic) or from inside (intrinsic) the individual.

Multilevel governance See *Governance*.

Narratives Qualitative descriptions of plausible future world evolutions, describing the characteristics, general logic and developments underlying a particular quantitative set of *scenarios*. Narratives are also referred to in the literature as 'storylines'. See also *Scenario*, *Scenario storyline* and *Pathways*.

Nationally Determined Contributions (NDCs) A term used under the *United Nations Framework Convention on Climate Change (UNFCCC)* whereby a country that has joined the *Paris Agreement* outlines its plans for reducing its emissions. Some countries' NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience. According to Article 4 paragraph 2 of the Paris Agreement, each Party shall prepare, communicate and maintain successive NDCs that it intends to achieve. In the lead up to 21st *Conference of the Parties* in Paris in 2015, countries submitted Intended Nationally Determined Contributions (INDCs). As countries join the Paris Agreement, unless they decide otherwise, this INDC becomes their first Nationally Determined Contribution (NDC). See also *United Nations Framework Convention on Climate Change (UNFCCC)* and *Paris Agreement*.

Negative emissions Removal of *greenhouse gases (GHGs)* from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural *carbon cycle* processes. See also *Net negative emissions*, *Net zero emissions*, *Carbon dioxide removal (CDR)* and *Greenhouse gas removal (GGR)*.

Net negative emissions A situation of net negative emissions is achieved when, as result of human activities, more *greenhouse gases* are removed from the *atmosphere* than are emitted into it. Where multiple greenhouse gases are involved, the quantification of *negative emissions* depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon). See also *Negative emissions*, *Net zero emissions* and *Net zero CO_2 emissions*.

Net zero CO_2 emissions Net zero *carbon dioxide (CO_2)* emissions are achieved when *anthropogenic* CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period. Net zero CO_2 emissions are also referred to as carbon neutrality. See also *Net zero emissions* and *Net negative emissions*.

Net zero emissions Net zero emissions are achieved when *anthropogenic emissions* of *greenhouse gases* to the *atmosphere* are balanced by *anthropogenic removals* over a specified period. Where multiple greenhouse gases are involved, the quantification of net zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon). See also *Net zero CO_2 emissions*, *Negative emissions* and *Net negative emissions*.

Nitrous oxide (N_2O) One of the six *greenhouse gases (GHGs)* to be mitigated under the *Kyoto Protocol*. The main *anthropogenic* source of N_2O is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, *fossil fuel* combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical *forests*.

Non-CO_2 emissions and radiative forcing Non-CO_2 emissions included in this report are all *anthropogenic emissions* other than *CO_2* that result in *radiative forcing*. These include *short-lived climate forcers*, such as *methane (CH_4)*, some fluorinated gases, *ozone (O_3)* precursors, *aerosols* or aerosol *precursors*, such as *black carbon* and sulphur dioxide, respectively, as well as long-lived *greenhouse gases*, such as *nitrous oxide (N_2O)* or other fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface *albedo* is referred to as non-CO_2 radiative forcing.

Non-overshoot pathways See *Pathways*.

Ocean acidification (OA) Ocean acidification refers to a reduction in the *pH* of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of *carbon dioxide (CO_2)* from the *atmosphere*, but can also be caused by other chemical additions or subtractions from the ocean. *Anthropogenic* ocean acidification refers to the component of pH reduction that is caused by human activity (IPCC, 2011, p. 37).

Ocean fertilization Deliberate increase of nutrient supply to the near-surface ocean in order to enhance biological production through which additional *carbon dioxide (CO_2)* from the *atmosphere* is sequestered. This can be achieved by the addition of micro-nutrients or macro-nutrients. Ocean fertilization is regulated by the London Protocol.

Overshoot See *Temperature overshoot*.

Overshoot pathways See *Pathways*.

Ozone (O_3) Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the *troposphere*, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a *greenhouse gas*. In the *stratosphere*, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

Paris Agreement The Paris Agreement under the *United Nations Framework Convention on Climate Change (UNFCCC)* was adopted on December 2015 in Paris, France, at the 21st session of the *Conference of the Parties (COP)* to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4 November 2016 and as of May 2018 had 195 Signatories and was ratified by 177 Parties. One of the goals of the Paris Agreement is 'Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels', recognising that this would significantly reduce the risks and impacts of climate change. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change. The Paris Agreement is intended to become fully effective in 2020. See also *United Nations Framework Convention on Climate Change (UNFCCC)*, *Kyoto Protocol* and *Nationally Determined Contributions (NDCs)*.

Participatory governance See *Governance*.

Pathways The temporal evolution of natural and/or *human systems* towards a future state. Pathway concepts range from sets of quantitative and qualitative *scenarios* or *narratives* of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals and actors across different scales.

1.5°C pathway
A pathway of emissions of *greenhouse gases* and other climate forcers that provides an approximately one-in-two to two-in-three chance, given current knowledge of the climate response, of *global warming* either remaining below 1.5°C or returning to 1.5°C by around 2100 following an *overshoot*. See also *Temperature overshoot*.

Adaptation pathways
A series of *adaptation* choices involving trade-offs between short-term and long-term goals and values. These are processes of deliberation to identify solutions that are meaningful to people in the context of their daily lives and to avoid potential *maladaptation*.

Development pathways
Development pathways are trajectories based on an array of social, economic, cultural, technological, *institutional* and biophysical features that characterise the interactions between human and natural systems and outline visions for the future, at a particular scale.

Emission pathways
Modelled trajectories of global *anthropogenic emissions* over the 21st century are termed emission pathways.

Mitigation pathways
A mitigation pathway is a temporal evolution of a set of *mitigation scenario* features, such as *greenhouse gas* emissions and socio-economic development.

Overshoot pathways
Pathways that exceed the stabilization level (concentration, *forcing*, or temperature) before the end of a time horizon of interest (e.g., before 2100) and then decline towards that level by that time. Once the target level is exceeded, removal by sinks of *greenhouse gases* is required. See also *Temperature overshoot*.

Non-overshoot pathways
Pathways that stay below the stabilization level (concentration, *forcing*, or temperature) during the time horizon of interest (e.g., until 2100).

Representative Concentration Pathways (RCPs)
Scenarios that include time series of emissions and concentrations of the full suite of *greenhouse gases (GHGs)* and *aerosols* and chemically active gases, as well as *land use*/land cover (Moss et al., 2008). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific *radiative forcing* characteristics. The term pathway emphasizes the fact that not only the long-term concentration levels but also the trajectory taken over time to reach that outcome are of interest (Moss et al., 2010). RCPs were used to develop *climate projections* in CMIP5.

- RCP2.6: One pathway where radiative forcing peaks at approximately 3 W m^{-2} and then declines to be limited at 2.6 W m^{-2} in 2100 (the corresponding Extended Concentration Pathway, or ECP, has constant emissions after 2100).
- RCP4.5 and RCP6.0: Two intermediate stabilization pathways in which radiative forcing is limited at approximately 4.5 W m^{-2} and 6.0 W m^{-2} in 2100 (the corresponding ECPs have constant concentrations after 2150).
- RCP8.5: One high pathway which leads to >8.5 W m^{-2} in 2100 (the corresponding ECP has constant emissions after 2100 until 2150 and constant concentrations after 2250).

See also *Coupled Model Intercomparison Project (CMIP)* and *Shared Socio-economic Pathways (SSPs)*.

Shared Socio-economic Pathways (SSPs)
Shared Socio-economic Pathways (SSPs) were developed to complement the RCPs with varying socio-economic challenges to *adaptation* and *mitigation* (O'Neill et al., 2014). Based on five *narratives*, the SSPs describe alternative socio-economic futures in the absence of climate *policy* intervention, comprising sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil–fuelled development (SSP5) and middle-of-the-road development (SSP2) (O'Neill, 2000; O'Neill et al., 2017; Riahi et al., 2017). The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)-based *climate projections* provides an integrative frame for climate *impact* and policy analysis.

Transformation pathways
Trajectories describing consistent sets of possible futures of *greenhouse gas (GHG)* emissions, atmospheric concentrations, or *global mean surface temperatures* implied from *mitigation* and *adaptation* actions associated with a set of broad and irreversible economic, technological, societal and behavioural changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed and *institutions* are set up and in the pace and direction of technological change.

See also *Scenario*, *Scenario storyline*, *Emission scenario*, *Mitigation scenario*, *Baseline scenario*, *Stabilization (of GHG or CO_2-equivalent concentration)* and *Narratives*.

Peri-urban areas Peri-urban areas are those parts of a city that appear to be quite rural but are in reality strongly linked functionally to the city in its daily activities.

Permafrost Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

pH pH is a dimensionless measure of the acidity of a solution given by its concentration of hydrogen ions ($[H^+]$). pH is measured on a logarithmic scale where $pH = -\log_{10}[H^+]$. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H^+, or acidity.

Plug-in hybrid electric vehicle (PHEV) See *Electric vehicle (EV)*.

Policies (for climate change mitigation and adaptation) Policies are taken and/or mandated by a government – often in conjunction with business and industry within a single country, or collectively with other countries – to accelerate *mitigation* and *adaptation* measures. Examples of policies are support mechanisms for renewable energy supplies, carbon or energy taxes, fuel efficiency standards for automobiles, etc.

Political economy The set of interlinked relationships between people, the state, society and markets as defined by law, politics, economics, customs and power that determine the outcome of trade and transactions and the distribution of wealth in a country or economy.

Poverty Poverty is a complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation or limited resources), economic conditions (such as standard of living, *inequality* or economic position) and/or social relationships (such as social class, dependency, exclusion, lack of basic security or lack of entitlement). See also *Poverty eradication*.

Poverty eradication A set of measures to end *poverty* in all its forms everywhere. See also *Sustainable Development Goals (SDGs)*.

Precursors Atmospheric compounds that are not *greenhouse gases (GHGs)* or *aerosols*, but that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates. See also *Aerosol* and *Greenhouse gas (GHG)*.

Pre-industrial The multi-century period prior to the onset of large-scale industrial activity around 1750. The *reference period* 1850–1900 is used to approximate pre-industrial *global mean surface temperature (GMST)*. See also *Industrial revolution*.

Procedural equity See *Equity*.

Procedural justice See *Justice*.

Procedural rights See *Human rights*.

Projection A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized. See also *Climate projection*, *Scenario* and *Pathways*.

Purchasing power parity (PPP) The purchasing power of a currency is expressed using a basket of goods and services that can be bought with a given amount in the home country. International comparison of, for example, *gross domestic products (GDPs)* of countries can be based on the purchasing power of currencies rather than on current exchange rates. PPP estimates tend to lower the gap between the per capita GDP in *industrialized* and developing countries. See also *Market exchange rate (MER)*.

Radiative forcing Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of *atmosphere* due to a change in a driver of *climate change*, such as a change in the concentration of *carbon dioxide (CO_2)* or the output of the Sun. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed

the effective radiative forcing. Radiative forcing is not to be confused with cloud radiative forcing, which describes an unrelated measure of the impact of clouds on the radiative flux at the top of the atmosphere.

Reasons for Concern (RFCs) Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of *climate change* may be dangerous (in the language of Article 2 of the *UNFCCC*) by aggregating risks from various sectors, considering *hazards*, *exposures*, *vulnerabilities*, capacities to adapt, and the resulting impacts.

Reducing Emissions from Deforestation and Forest Degradation (REDD+) An effort to create financial value for the carbon stored in *forests*, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to *sustainable development (SD)*. It is therefore a mechanism for *mitigation* that results from avoiding *deforestation*. REDD+ goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks. The concept was first introduced in 2005 in the 11th Session of the *Conference of the Parties (COP)* in Montreal and later given greater recognition in the 13th Session of the COP in 2007 at Bali and inclusion in the Bali Action Plan, which called for 'policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries (REDD) and the role of conservation, sustainable management of forests and enhancement of forest carbon stock in developing countries.' Since then, support for REDD has increased and has slowly become a framework for action supported by a number of countries.

Reference period The period relative to which *anomalies* are computed. See also *Anomaly*.

Reference scenario See *Baseline scenario*.

Reforestation Planting of *forests* on lands that have previously contained forests but that have been converted to some other use. For a discussion of the term forest and related terms such as *afforestation*, reforestation and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000), information provided by the *United Nations Framework Convention on Climate Change* (UNFCCC, 2013), the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). See also *Deforestation*, *Afforestation* and *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*.

Region A region is a relatively large-scale land or ocean area characterized by specific geographical and climatological features. The *climate* of a land-based region is affected by regional and local scale features like topography, *land use* characteristics and large water bodies, as well as remote influences from other regions, in addition to global climate conditions. The IPCC defines a set of standard regions for analyses of observed climate trends and climate model *projections* (see Figure 3.2; AR5, SREX).

Remaining carbon budget Estimated cumulative net global *anthropogenic* CO_2 emissions from the start of 2018 to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting *global warming* to a given level, accounting for the impact of other *anthropogenic emissions*.

Representative Concentration Pathways (RCPs) See *Pathways*.

Resilience The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also maintaining the capacity for *adaptation*, learning and *transformation*. This definition builds from the definition used by Arctic Council (2013). See also *Hazard*, *Risk* and *Vulnerability*.

Risk The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate *impacts*, the term risk is often used to refer to the potential for adverse consequences of a climate-related *hazard*, or of *adaptation* or *mitigation* responses to such a hazard, on lives, *livelihoods*, health and *well-being*, *ecosystems* and species, economic, social and cultural assets, services (including *ecosystem services*), and infrastructure. Risk results from the interaction of *vulnerability* (of the affected system), its *exposure* over time (to the hazard), as well as the (climate-related) hazard and the *likelihood* of its occurrence.

Risk assessment The qualitative and/or quantitative scientific estimation of *risks*. See also *Risk*, *Risk management* and *Risk perception*.

Risk management Plans, actions, strategies or policies to reduce the *likelihood* and/or consequences of risks or to respond to consequences. See also *Risk*, *Risk assessment* and *Risk perception*.

Risk perception The subjective judgment that people make about the characteristics and severity of a *risk*. See also *Risk*, *Risk assessment* and *Risk management*.

Runoff The flow of water over the surface or through the subsurface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate or refreeze, and is not transpired. See also *Hydrological cycle*.

Scenario A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions. See also *Baseline scenario*, *Emission scenario*, *Mitigation scenario* and *Pathways*.

Scenario storyline A *narrative* description of a *scenario* (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution. Also referred to as 'narratives' in the scenario literature. See also *Narratives*.

SDG-interaction score A seven-point scale (Nilsson et al., 2016) used to rate interactions between *mitigation options* and the *SDGs*. Scores range from +3 (indivisible) to –3 (cancelling), with a zero score indicating 'consistent' but with neither a positive or negative interaction. The scale, as applied in this report, also includes direction (whether the interaction is uni- or bi-directional) and *confidence* as assessed per IPCC guidelines.

Sea ice Ice found at the sea surface that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice concentration is the fraction of the ocean covered by ice. Sea ice less than one year old is called first-year ice. Perennial ice is sea ice that survives at least one summer. It may be subdivided into second-year ice and multi-year ice, where multi-year ice has survived at least two summers.

Sea level change (sea level rise/sea level fall) Sea level can change, both globally and locally (relative sea level change) due to (1) a change in ocean volume as a result of a change in the mass of water in the ocean, (2) changes in ocean volume as a result of changes in ocean water density, (3) changes in the shape of the ocean basins and changes

in the Earth's gravitational and rotational fields, and (4) local subsidence or uplift of the land. Global mean sea level change resulting from change in the mass of the ocean is called barystatic. The amount of barystatic sea level change due to the addition or removal of a mass of water is called its sea level equivalent (SLE). Sea level changes, both globally and locally, resulting from changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric. Barystatic and steric sea level changes do not include the effect of changes in the shape of ocean basins induced by the change in the ocean mass and its distribution.

Sea surface temperature (SST) The sea surface temperature is the subsurface bulk temperature in the top few meters of the ocean, measured by ships, buoys, and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimeter thick) in the infrared or the top centimeter or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

Sendai Framework for Disaster Risk Reduction The Sendai Framework for Disaster Risk Reduction 2015–2030 outlines seven clear targets and four priorities for action to prevent new, and to reduce existing, disaster risks. The voluntary, non-binding agreement recognizes that the State has the primary role to reduce disaster risk but that responsibility should be shared with other stakeholders, including local government and the private sector. Its aim is to achieve 'substantial reduction of disaster risk and losses in lives, *livelihoods* and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries.'

Sequestration See *Uptake*.

Shared Socio-economic Pathways (SSPs) See *Pathways*.

Short-lived climate forcers (SLCF) Short-lived climate forcers refers to a set of compounds that are primarily composed of those with short lifetimes in the *atmosphere* compared to well-mixed *greenhouse gases*, and are also referred to as near-term climate forcers. This set of compounds includes *methane (CH_4)*, which is also a well-mixed greenhouse gas, as well as *ozone (O_3)* and *aerosols*, or their *precursors*, and some halogenated species that are not well-mixed greenhouse gases. These compounds do not accumulate in the atmosphere at decadal to centennial time scales, and so their effect on *climate* is predominantly in the first decade after their emission, although their changes can still induce long-term climate effects such as *sea level change*. Their effect can be cooling or warming. A subset of exclusively warming short-lived climate forcers is referred to as short-lived climate pollutants. See also *Long-lived climate forcers (LLCF)*.

Short-lived climate pollutants (SLCP) See *Short-lived climate forcers (SLCF)*.

Sink A reservoir (natural or human, in soil, ocean, and plants) where a *greenhouse gas*, an *aerosol* or a *precursor* of a greenhouse gas is stored. Note that *UNFCCC* Article 1.8 refers to a sink as any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the *atmosphere*. See also *Uptake*.

Small island developing states (SIDS) Small island developing states (SIDS), as recognised by the United Nations OHRLLS (Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States), are a distinct group of developing countries facing specific social, economic and environmental vulnerabilities (UN-OHRLLS, 2011). They were recognized as a special case both for their environment and development at the Rio Earth Summit in Brazil in 1992. Fifty-eight countries and territories are presently classified as SIDS by the UN OHRLLS, with 38 being UN member states and 20 being Non-UN Members or Associate Members of the Regional Commissions (UN-OHRLLS, 2018).

Social cost of carbon (SCC) The net present value of aggregate climate damages (with overall harmful damages expressed as a number with positive sign) from one more tonne of carbon in the form of *carbon dioxide (CO_2)*, conditional on a global emissions trajectory over time.

Social costs The full costs of an action in terms of social welfare losses, including external costs associated with the impacts of this action on the environment, the economy (*GDP*, employment) and on the society as a whole.

Social-ecological systems An integrated system that includes human societies and *ecosystems*, in which humans are part of nature. The functions of such a system arise from the interactions and interdependence of the social and ecological subsystems. The system's structure is characterized by reciprocal feedbacks, emphasising that humans must be seen as a part of, not apart from, nature. This definition builds from Arctic Council (2016) and Berkes and Folke (1998).

Social inclusion A process of improving the terms of participation in society, particularly for people who are disadvantaged, through enhancing opportunities, access to resources, and respect for rights (UN DESA, 2016).

Social justice See *Justice*.

Social learning A process of social interaction through which people learn new behaviours, capacities, values and attitudes.

Social value of mitigation activities (SVMA) Social, economic and environmental value of *mitigation* activities that include, in addition to their climate benefits, their *co-benefits* to *adaptation* and *sustainable development* objectives.

Societal (social) transformation See *Transformation*.

Socio-economic scenario A *scenario* that describes a possible future in terms of population, *gross domestic product (GDP)*, and other socio-economic factors relevant to understanding the implications of *climate change*. See also *Baseline scenario*, *Emission scenario*, *Mitigation scenario* and *Pathways*.

Socio-technical transitions Socio-technical transitions are where technological change is associated with social systems and the two are inextricably linked.

Soil carbon sequestration (SCS) Land management changes which increase the soil organic carbon content, resulting in a net removal of CO_2 from the *atmosphere*.

Soil moisture Water stored in the soil in liquid or frozen form. Root-zone soil moisture is of most relevance for plant activity.

Solar radiation management See *Solar radiation modification (SRM)*.

Solar radiation modification (SRM) Solar radiation modification refers to the intentional modification of the Earth's shortwave radiative budget with the aim of reducing warming. Artificial injection of stratospheric *aerosols*, marine cloud brightening and land surface *albedo* modification are examples of proposed SRM methods. SRM does not fall within the definitions of *mitigation* and *adaptation* (IPCC, 2012b, p. 2). Note that in the literature SRM is also referred to as solar radiation management or albedo enhancement.

Stabilization (of GHG or CO_2-equivalent concentration) A state in which the atmospheric concentrations of one *greenhouse gas (GHG)* (e.g., *carbon dioxide*) or of a CO_2-equivalent basket of GHGs (or a combination of GHGs and *aerosols*) remains constant over time.

Stranded assets Assets exposed to devaluations or conversion to 'liabilities' because of unanticipated changes in their initially expected revenues due to innovations and/or evolutions of the business context, including changes in public regulations at the domestic and international levels.

Stratosphere The highly stratified region of the *atmosphere* above the *troposphere* extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude. See also *Atmosphere*, and *Troposphere*.

Sub-national actor Sub-national actors include state/provincial, regional, metropolitan and local/municipal governments as well as non-party stakeholders, such as civil society, the private sector, cities and other sub-national authorities, local communities and indigenous peoples.

Substantive rights See *Human rights*.

Supply-side measures See *Demand- and supply-side measures*.

Surface temperature See *Global mean surface temperature (GMST)*, *Land surface air temperature*, *Global mean surface air temperature (GSAT)* and *Sea surface temperature (SST)*.

Sustainability A dynamic process that guarantees the persistence of natural and *human systems* in an equitable manner.

Sustainable development (SD) Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987) and balances social, economic and environmental concerns. See also *Sustainable Development Goals (SDGs)* and *Development pathways* (under *Pathways*).

Sustainable Development Goals (SDGs) The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the *2030 Agenda for Sustainable Development*, including ending *poverty* and hunger; ensuring health and *well-being*, education, gender *equality*, clean water and energy, and decent work; building and ensuring *resilient* and sustainable infrastructure, cities and consumption; reducing *inequalities*; protecting land and water *ecosystems*; promoting peace, *justice* and partnerships; and taking urgent action on *climate change*. See also *Sustainable development (SD)*.

Technology transfer The exchange of knowledge, hardware and associated software, money and goods among stakeholders, which leads to the spread of technology for *adaptation* or *mitigation*. The term encompasses both diffusion of technologies and technological cooperation across and within countries.

Temperature overshoot The temporary exceedance of a specified level of *global warming*, such as 1.5°C. Overshoot implies a peak followed by a decline in global warming, achieved through *anthropogenic removal* of *CO_2* exceeding remaining CO_2 emissions globally. See also *Overshoot pathways* and *Non-overshoot pathways* (both under *Pathways*).

Tipping point A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the *climate system*, it refers to a critical threshold when global or regional *climate* changes from one stable state to another stable state. See also *Irreversibility*.

Transformation A change in the fundamental attributes of natural and human systems.

Societal (social) transformation
A profound and often deliberate shift initiated by communities toward sustainability, facilitated by changes in individual and collective values and behaviours, and a fairer balance of political, cultural, and *institutional* power in society.

Transformation pathways See *Pathways*.

Transformational adaptation See *Adaptation*.

Transformative change A system-wide change that requires more than technological change through consideration of social and economic factors that, with technology, can bring about rapid change at scale.

Transient climate response See *Climate sensitivity*.

Transient climate response to cumulative CO_2 emissions (TCRE) The transient global average surface temperature change per unit cumulative *CO_2* emissions, usually 1000 GtC. TCRE combines both information on the airborne fraction of cumulative CO_2 emissions (the fraction of the total CO_2 emitted that remains in the *atmosphere*, which is determined by *carbon cycle* processes) and on the *transient climate response (TCR)*. See also *Transient climate response* (under *Climate sensitivity*).

Transit-oriented development (TOD) An approach to urban development that maximizes the amount of residential, business and leisure space within walking distance of efficient public transport, so as to enhance mobility of citizens, the viability of public transport and the value of urban land in mutually supporting ways.

Transition The process of changing from one state or condition to another in a given period of time. Transition can be in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.

Tropical cyclone The general term for a strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with one-minute average surface winds between 18 and 32 m s^{-1}. Beyond 32 m s^{-1}, a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location. See also *Extratropical cyclone*.

Troposphere The lowest part of the *atmosphere*, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height. See also *Atmosphere* and *Stratosphere*.

Uncertainty A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain *projections* of *human behaviour*. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts) (see Moss and Schneider, 2000; IPCC, 2004; Mastrandrea et al., 2010). See also *Confidence* and *Likelihood*.

United Nations Framework Convention on Climate Change (UNFCCC) The UNFCCC was adopted in May 1992 and opened for signature at the 1992 Earth Summit in Rio de Janeiro. It entered into force in March 1994 and as of May 2018 had 197 Parties (196 States and the European Union). The Convention's ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate

system.' The provisions of the Convention are pursued and implemented by two treaties: the *Kyoto Protocol* and the *Paris Agreement*. See also *Kyoto Protocol* and *Paris Agreement*.

Uptake The addition of a substance of concern to a reservoir. See also *Carbon sequestration* and *Sink*.

Vulnerability The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. See also *Exposure*, *Hazard* and *Risk*.

Water cycle See *Hydrological cycle*.

Well-being A state of existence that fulfils various human needs, including material living conditions and quality of life, as well as the ability to pursue one's goals, to thrive, and feel satisfied with one's life. Ecosystem well-being refers to the ability of *ecosystems* to maintain their diversity and quality.

Zero emissions commitment See *Climate change commitment*.

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AII

Annex II: Acronyms

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µatm	Microatmospheres
1.5DS	1.5 Degree Scenario
2DS	2 Degree Scenario
ACCESS	Australian Community Climate and Earth-System Simulator
ACCMIP	Atmospheric Chemistry and Climate Model Intercomparison Project
ACCRN	The Asian Cities Climate Change Resilience Network
ACOLA	Australian Council of Learned Academies
ACs	Air Conditioners
ADB	Asian Development Bank
ADVANCE	Advanced Model Development and Validation for the Improved Analysis of Costs and Impacts of Mitigation Policies
AEZ	Agro-Ecological Zone
AfDB	African Development Bank
AFOLU	Agriculture, Forestry and Other Land-Use
AGCM	Atmospheric General Circulation Model
AI	Artificial Intelligence
AIM	Asia-Pacific Integrated Model
ALA	Alaska/Northwest Canada
AMAP	Arctic Monitoring and Assessment Programme
AMOC	Atlantic Meridional Overturning Circulation
AMP	Adjusting Mitigation Pathway
AMZ	Amazon
ANT	Antarctica
APEX	Air Pollutants Exposure Model
AR	Afforestation and Reforestation
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
ARC	Arctic
ASEAN	Association of Southeast Asian Nations
ASIA	Non-OECD Asia
AUD	Australian Dollar
B2DS	Beyond 2 Degrees Scenario
BASIC	Brazil, South Africa, India, China
BC	Black Carbon
BCC-CSM	Beijing Climate Center Climate System Model
BCM	Bergen Climate Model
BECCS	Bioenergy with Carbon dioxide Capture and Storage
BET	Basic Energy systems, Economy, Environment, and End-use Technology Model
BEV	Battery Electric Vehicle
BNEF	Bloomberg New Energy Finance
BNU	Beijing Normal University
BRT	Bus Rapid Transit
cm	Centimetres
C	Carbon
CA	Conservation Agriculture
CAF	Corporacion Andina de Fomento (Development Bank of Latin America)
CAM	Central America/Mexico or Community Atmosphere Model
CAMx	Comprehensive Air Quality Model with Extensions
CanESM	Canadian Earth System Model
CanRCM	Canadian Regional Climate Model
CAR	Small Islands Regions Caribbean
CAS	Central Asia
Cat-HM	Catchment-scale Hydrological Models
CbA	Community-based Adaptation
CBA	Cost-Benefit Analysis
CBD	Convention on Biological Diversity
CBDR-RC	Common But Differentiated Responsibilities and Respective Capabilities
CBS & GNH	Centre for Bhutan Studies and Gross National Happiness Research
CC	Carbon Capture
CCAM	Conformal Cubic Atmospheric Model
CCC	Constant Composition Commitment
CCCma	Canadian Centre for Climate Modelling and Analysis
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CCS	Carbon dioxide Capture and Storage
CCSM	Community Climate System Model
CCT	Cirrus Cloud Thinning
CCU	Carbon dioxide Capture and Utilisation
CCUS	Carbon dioxide Capture, Utilisation and Storage
CDD	Consecutive Dry Days
CD-LINKS	Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing
CDM	Clean Development Mechanism
CDP	Carbon Disclosure Project
CDR	Carbon Dioxide Removal

CEA	Cost-Effectiveness Analysis
CEC	Clean Energy Council
CEDS	Community Emissions Data System
CEMICS	Contextualizing Climate Engineering and Mitigation: Illusion, Complement or Substitute?
CES	Constant Elasticity of Substitution
CESM	Community Earth System Model
CEU	Central Europe
CFCs	Chlorofluorocarbons
CGCM	Coupled Global Climate Model
CGE	Computable General Equilibrium
CGI	Canada/Greenland/Iceland
CGIAR	Consultative Group on International Agricultural Research
CH_4	Methane
CHP	Combined Heat and Power
CI	Confidence Interval
CIRED	Centre International de Recherche sur l'Environnement et le Développement
CISL	Cambridge Institute for Sustainability Leadership
CLM	Climate Limited-area Modelling
CMAQ	Community Multiscale Air Quality Modeling System
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CNA	Central North America
CNRM	Centre National de Recherches Météorologiques
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CO_2eq	Carbon dioxide equivalent
CoM	Covenant of Mayors
COP	Conference of the Parties
COPPE-COFFEE	Programa de Planejamento Energético – COmputable Framework For Energy and the Environment
CORDEX	Coordinated Regional Climate Downscaling Experiment
COSMO	Consortium for Small-scale Modeling
CRCM	Canadian Regional Climate Model
CRDPs	Climate-Resilient Development Pathways
CRIEPI	Institut Central de Recherche des Industries Électriques
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
C-ROADS	Climate Rapid Overview And Decision-support Simulator
CRU	Climatic Research Unit
CSA	Climate-Smart Agriculture
CSC	Climate Service Center Germany
CSDI	Cold Spell Duration Index
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrated Solar Power
CSR	Corporate Social Responsibility
CTC	Covenant Territorial Coordinator
CWD	Consecutive Wet Days
DACCS	Direct Air Carbon dioxide Capture and Storage
DACS	Direct Air Capture and Storage
DALY	Disability Adjusted Life Year
DICE	Dynamic Integrated Climate-Economy model
DJF	December, January, February
DM8H	Daily Maximum 8-Hour exposure
DNE21+	Dynamic New Earth 21 model
DOE	Department of Energy (USA)
DRI	Direct Reduced Iron
DRM	Disaster Risk Management
DTU	Technical University of Denmark
E	Equilibrium, Evaporation or Evapotranspiration
EAF	East Africa
EAIS	East Antarctic Ice Sheet
EAS	East Asia
EbA	Ecosystems-based Adaptation
EC	European Commission
ECF	European Climate Foundation
ECMWF	European Centre for Medium-Range Weather Forecasts
ECS	Equilibrium Climate Sensitivity
EDGAR	Emission Database for Global Atmospheric Research
EEA	European Environment Agency
EGMAM	ECHO-G Middle Atmosphere Model
E-HYPE	European Hydrological Predictions for the Environment
EJ	Exajoules
EMEP	European Monitoring and Evaluation Programme

EMF	Energy Modeling Forum
EMIC	Earth-system Model of Intermediate Complexity
ENA	East North America
ENSO	El Niño-Southern Oscillation
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency (USA)
EPIs	Energy-Intensive Processing Industries
ERA	ECMWF ReAnalysis
ERF	Effective Radiative Forcing
ERFaci	Effective Radiative Forcing from aerosol-cloud interactions
ERFari	Effective Radiative Forcing from aerosol-radiation interactions
ESCOs	Energy Service Companies
ESL	Extreme Sea Level
ESM	Earth System Model
ESR	Empirical Scaling Relationship
ESRB ASC	European Systemic Risk Board Advisory Scientific Committee
ESRL	NOAA Earth System Research Laboratory
Eta-CPTEC	Eta Centro de Previsão do Tempo e Estudos Climáticos
ETP	Pacific Islands region [3] or Energy Technology Perspectives model
ETS	Emission Trading Scheme
EU	European Union
EU-FP6	European Union Sixth Framework Programme
EUG4	France, Germany, Italy, United Kingdom
EURO-CORDEX	European branch of the Coordinated Regional Climate Downscaling Experiment
EV	Electric Vehicle
EW	Enhanced Weathering
FAIR	Finite Amplitude Impulse Response model
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Database Collection of the Food and Agriculture Organization of the United Nations
FAQ	Frequently Asked Questions
FARM	Future Agricultural Resources Model
Fe	Iron
FE	Final Energy
FEMA	Federal Emergency Management Agency (USA)
FF	Fossil Fuel
FF&I	Fossil-Fuel combustion and Industrial processes
F-gas	Fluorinated gases
FGOALS	Flexible Global Ocean-Atmosphere-Land System model
FIO	First Institute of Oceanography
FMNR	Farmer Managed Natural Regeneration
FUND	Climate Framework for Uncertainty, Negotiation, and Distribution model
FUSSR	Former Union of Soviet Socialist Republics
g	Grams
GAMS	General Algebraic Modeling System
GBAM	Ground-Based Albedo Modification
GCAM	Global Change Assessment Model
GCC	Gulf Cooperative Council
GCEC	Global Commission on the Economy and Climate
GCM	General Circulation Model or Global Climate Model
GCP	Global Carbon Project
GDP	Gross Domestic Product
GE	General Equilibrium
GEA	Global Energy Assessment
GEM-E3	General Equilibrium Model for Economy - Energy - Environment
GENeSYS-MOD	Global Energy System Model
GeSI	Global e-Sustainability Initiative
GFCF	Gross Fixed Capital Formation
GFDL	Geophysical Fluid Dynamic Laboratory
GFR	Grid Flexibility Resources
Gha	Gigahectares
GHCNDEX	Global Historical Climatology Network – Daily climate Extremes
GHGs	Greenhouse Gases
GHM	Global Hydrological Models
GIS	Greenland Ice Sheet
GISS	Goddard Institute for Space Studies
GISTEMP	Goddard Institute for Space Studies Surface Temperature Analysis
GJ	Gigajoules
GLEAM	Global Livestock Environmental Assessment Model
Glob-HM	Global Hydrological Model
GLOBIOM	GLObal BIOsphere Management model
GLOFs	Glacial Lake Outburst Floods
GM	Genetically Modified
GMO	Genetically Modified Organism
GMSL	Global Mean Sea Level

GMST	Global Mean Surface Temperature
GMT	Global Mean Temperature
GNHI	Gross National Happiness Index
GPP	Gross Primary Productivity
GPT	General Purpose Technologies
GRAPE	Global Relationship Assessment to Protect the Environment model
GSAT	Global mean Surface Air Temperature
Gt	Gigatonne
GTP	Global Temperature-change Potential
GWA	Government of Western Australia
GWP	Global Warming Potential or Gross World Product
ha	Hectares
H_2	Hydrogen
HadCM	Hadley Centre Coupled Model
HadCRUT	Hadley Centre Climatic Research Unit Gridded Surface Temperature Data Set
HadEX	Hadley Centre Global Climate Extremes index
HadGEM	Hadley Centre Global Environmental Model
HadRM	Hadley Centre Regional Model
HAPPI	Half a degree Additional warming, Prognosis and Projected Impacts
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
HFCs	Hydrofluorocarbons
HLCCP	High-Level Commission on Carbon Prices
HLPE	High Level Panel of Experts on Food Security and Nutrition
HSRTF	Hurricane Sandy Rebuilding Task Force
HTM	Holocene Thermal Maximum
HYMOD	HYdrological MODel
IAEA	International Atomic Energy Agency
IAMC	Integrated Assessment Modelling Consortium
IAMs	Integrated Assessment Models
IBA	International Bar Association
IBI	International Biochar Initiative
ICAMS	Integrated Climate and Air Quality Modeling System
ICEM	International Centre for Environmental Management
ICLEI	International Council for Local Environmental Initiatives
ICPDR	International Commission for the Protection of the Danube River
ICSU	International Council for Science
ICT	Information and Communication Technology
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
IGCC	Integrated Gasification Combined Cycle
IIASA	International Institute for Applied Systems Analysis
IIF	Institute of International Finance
iLUC	Indirect Land-Use Change
IMACLIM-NLU	IMpact Assessment of CLIMate policies model – Nexus Land-Use model
IMAGE	Integrated Model to Assess the Global Environment
IMF	International Monetary Fund
IMO	International Maritime Organization
IMPACT2C	Quantifying Projected Impacts under 2°C Warming
INDCs	Intended Nationally Determined Contributions
INM	Russian Institute for Numerical Mathematics
IOM	International Organization for Migration
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institute Pierre Simon Laplace
IRENA	International Renewable Energy Agency
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ISO	International Standards Organisation
ISSC	International Social Science Council
ITF	International Transport Forum
IUCN	International Union for Conservation of Nature
IWG	Interagency Working Group on Social Cost of Greenhouse Gases
IWRM	Integrated Water Resources Management
JeDi	Jena Diversity-Dynamic Global Vegetation Model
JJA	June, July, August
JMA	Japan Meteorological Agency
JRA-55	Japanese 55-year Reanalysis
JRC	European Commission – Joint Research Centre
JULES	Joint United Kingdom Land Environment Simulator
kcal cap^{-1} day^{-1}	Kilocalories per capita per day
km	Kilometres
kt	Kilotonnes
kWh	Kilowatt hours

KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
L	Litres
L&D	Loss and Damage
LAM	Latin America and Caribbean
LDCs	Least Developed Countries
LDMz-INCA	Laboratoire de Météorologie Dynamique – INteractions between Chemistry and Aerosols
LDV	Light-Duty Vehicle
LE	Limited Evidence
LED	Low Energy Demand or Light Emitting Diode
LGM	Last Glacial Maximum
LIG	Last Interglacial
LLCFs	Long-Lived Climate Forcers
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LPJmL	Lund-Potsdam-Jena managed Land model
LTA	Land Transport Authority of Singapore
LTGG	Long-Term Global Goal
LUC	Land-Use Change
LULUCF	Land Use, Land-Use Change, and Forestry
m	Metres
m^3 cap^{-1} yr^{-1}	Cubic metres per capita per year
mg	Milligrams
mL	Millilitres
mm	Millimetres
M&E	Monitoring and Evaluation
Ma	Million years ago
MAC	Marginal Abatement Cost
MacPDM	Macro-scale – Probability-Distributed Moisture Model
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MAM	March, April, May
MCB	Marine Cloud Brightening
MCCA	Mercado Común Centroamericano
MDB	Group of Multilateral Development Banks
MDGs	Millennium Development Goals
MEA	Millennium Ecosystem Assessment
MED	South Europe/Mediterranean
MEPS	Minimum Energy Performance Standards
MER	Market Exchange Rates
MERET	Managing Environmental Resources to Enable Transitions
MERGE-ETL	Model for Evaluating Regional and Global Effects of greenhouse gas reduction policies – Endogenous Technology Learning
MESSAGE	Model for Energy Supply Systems And their General Environmental impact
Mha	Megahectare
MIROC	Model for Interdisciplinary Research on Climate
MISI	Marine Ice Sheet Instability
MIT IGSM	Massachusetts Institute of Technology Integrated Global System Model
MJ	Megajoules
MoCC	Ministry of Climate Change and Adaptation (Government of Vanuatu)
MOHC	Met Office Hadley Centre
MOPEX	Model Parameter Estimation Experiment
MPAs	Marine Protected Areas
MPI	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)
MPWP	Mid Pliocene Warm Period
MRFCJ	Mary Robinson Foundation – Climate Justice
MRI	Meteorological Research Institute of Japan Meteorological Agency
MRV	Measurement, Reporting and Verification
MSR	Multi-Sector Risk score
Mt	Megatonnes
N	Nitrogen
N_2O	Nitrous oxide
NAP	National Adaptation Plan
NAS	North Asia
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NAU	North Australia
NCAR	National Center for Atmospheric Research
NCCARF	National Climate Change Adaptation Research Facility
NCE	New Climate Economy
NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency
NEB	North-East Brazil
NEC	National Environment Commission (Royal Government of Bhutan)

NETL	National Energy Technology Laboratory (US Department of Energy)
NEU	North Europe
NF_3	Nitrogen trifluoride
NGO	Non-Governmental Organization
NH3	Ammonia
NHD	Number of Hot Days
NITI Aayog	National Institution for Transforming India
NMVOC	Non-Methane Volatile Organic Compounds
NOAA	National Oceanic and Atmospheric Administration
NorESM	Norwegian Earth System Model
NO_x	Nitrogen oxides
NPCC	New York City Panel on Climate Change
NPP	Net Primary Productivity
NPV	Net Present Value
NRC	National Research Council
NSR	Northern Sea Route
NTP	Pacific Islands region [2]
NYC	New York City
NZAGRC	New Zealand Agricultural Greenhouse Gas Research Center
O_2	Oxygen
O_3	Ozone
OA	Ocean Acidification or Ocean Alkalinization
OC	Organic Carbon
OECD	Organisation for Economic Co-operation and Development
OGCC	Optimal Gasification Combined Cycle
OHCHR	Office of the United Nations High Commissioner for Human Rights
OIF	Ocean Iron Fertilisation
ORCHIDEE	ORganising Carbon and Hydrology In Dynamic EcosystEms model
ORR	NYC Mayor's Office of Recovery & Resiliency
OS	Overshoot
pp	People
ppb	Parts per billion
ppm	Parts per million
ppt	Parts per thousand
P	Precipitation or Phosphorous
PAGE	Policy Analysis of the Greenhouse Effect model
PAHO	Pan American Health Organization
PCM	Parallel Climate Model
PDSI	Palmer Drought Severity Index
PE	Primary Energy or Partial Equilibrium
PET	Physiologically Equivalent Temperature or Potential Evapo-Transpiration
PFCs	Perfluorocarbons
Pg	Petagrams
PHEV	Plug-in Hybrid Electric Vehicle
PIK	Potsdam-Institut für Klimafolgenforschung (Potsdam Institute for Climate Impact Research)
PM_{10}	Particulate Matter with Aerodynamic Diameter <10 µm
$PM_{2.5}$	Particulate Matter with Aerodynamic Diameter <2.5 µm
POLES	Prospective Outlook on Long-term Energy Systems model
PPP	Purchasing Power Parity
PR	Probability Ratio
PV	Photovoltaics
R&D	Research and Development
RCA	Rossby Centre Regional Atmospheric Model
RCI	Rotterdam Climate Initiative
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
REDD+	Reducing Emissions from Deforestation and forest Degradation; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries
ReEDS-IPM	Regional Electricity Deployment System model – Integrated Planning Model
RegCM	Regional Climate Model system
REMIND	REgional Model of INvestments and Development
REN21	Renewable Energy Policy Network for the 21st Century
RF	Radiative Forcing
RFC	Reason for Concern
RGoB	Royal Government of Bhutan
RMI	Rocky Mountain Institute
RNCFC	Reference Non-CO_2 Forcing Contribution
RNCTC	Reference Non-CO_2 Temperature Contribution
Rx1day	Annual maximum 1-day precipitation
Rx5day	Annual maximum 5-day precipitation
SAF	Southern Africa
SAH	Sahara
SAI	Stratospheric Aerosol Injection

SAMS	South American Monsoon System
SAR	IPCC Second Assessment Report
SAS	South Asia
SAT	Surface Air Temperature
SAU	South Australia/New Zealand
SBSTA	Subsidiary Body for Scientific and Technological Advice (UNFCCC)
SCC	Social Cost of Carbon
SCS	Soil Carbon Sequestration
SD	Sustainable Development
SDGs	Sustainable Development Goals
SDGVM	Sheffield Dynamic Global Vegetation Model
SDII	Simple Daily Intensity Index
SDSN	Sustainable Development Solutions Network
SEA	Southeast Asia
SEAPs	Sustainable Energy Action Plans
SED	Structured Expert Dialogue
SEM	Semi-Empirical Model
SF_6	Sulphur hexafluoride
SFM	Sustainable Forest Management
SIDS	Small Island Developing States
SIFMA	Securities Industry and Financial Markets Association
SLCFs	Short-Lived Climate Forcers
SLCPs	Short-Lived Climate Pollutants
SLR	Sea Level Rise
SM	Supplementary Material
SMA	Soil Moisture Anomalies
SMHI	Swedish Meteorological and Hydrological Institute
SO_2	Sulphur dioxide
SOLARIS HEPPA	SOLARIS High Energy Particle Precipitation in the Atmosphere
SON	September, October, November
SO_x	Sulphur oxides
SPAs	Shared climate Policy Assumptions
SPC	Secretariat of the Pacific Community
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SPM	Summary for Policymakers
SR1.5	IPCC Special Report on Global Warming of 1.5°C
SRCCL	IPCC Special Report on Climate Change and Land
SRES	IPCC Special Report on Emissions Scenarios
SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRM	Solar Radiation Modification
SROCC	IPCC Special Report on the Ocean and Cryosphere in a Changing Climate
SSA	Southeastern South America
SSPs	Shared Socioeconomic Pathways
SST	Sea Surface Temperature
STP	Southern Tropical Pacific
SWAT	Soil & Water Assessment Tool
SWF	Social Welfare Function
SYR	IPCC Synthesis Report
t	Tonnes
tDM	Tonnes Dry Matter
tril$	Trillion dollars
T	Temperature or Transient
T&D	Transmission and Distribution
TCR	Transient Climate Response
TCRE	Transient Climate Response to cumulative CO_2 Emissions
TEAP	Technology and Economic Assessment Panel
TFE	Thematic Focus Element
TFP	Total Factor Productivity
Tg	Teragrams
TIB	Tibetan Plateau
TNn	Coldest night-time temperature of the year
TOD	Transit Oriented Development
TS	Technical Summary
Tt	Teratonnes
TTs	Transition Towns
TXx	Hottest daytime temperature of the year
UCCRN	Urban Climate Change Research Network
UHI	Urban Heat Islands
UITP	Union Internationale des Transports Publics (International Association of Public Transport)
UKCP	United Kingdom Climate Projections
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNCBD	United Nations Convention on Biological Diversity
UNDP	United Nations Development Programme
UNEP	UN Environment

UNEP-WCMC	UNEP World Conservation Monitoring Centre
UNESCO	United Nations Educational, Scientific and Cultura Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
UNICEF	United Nations International Children's Emergency Fund
UNISDR	United Nations Office for Disaster Risk Reduction
UN-OHRLLS	Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States
UNRISD	United Nations Research Institute for Social Development
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UNU	United Nations University
UNU-EHS	United Nations University – Institute for Environment and Human Security
USD	United States Dollars
UV	Ultraviolet
VISIT	Vegetation Integrative Simulator for Trace Gases
VKT	Vehicle Kilometres of Travel
VOCs	Volatile Organic Compounds
w/	With
w/o	Without
w.r.t.	With respect to
W	Watts
WAF	West Africa
WAIS	West Antarctic Ice Sheet
WAS	West Asia
WBCSD	World Business Council for Sustainable Development
WBGU	Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (German Advisory Council on Global Change)
WBM	Water Balance Model
WCED	World Commission on Environment and Development
WCRP	World Climate Research Programme
WEC	World Energy Council
WEF	Water-Energy-Food or World Economic Forum
WEM	World Energy Model
WEO	World Energy Outlook
WFP	World Food Programme
WGI	IPCC Working Group I
WGII	IPCC Working Group II
WGIII	IPCC Working Group III
WHO	World Health Organization
WIM	Warsaw International Mechanism for Loss and Damage
WIO	West Indian Ocean
WITCH	World Induced Technical Change Hybrid Model
WMGHGs	Well-Mixed Greenhouse Gases
WMO	World Meteorological Organization
WNA	West North America
WRF	Weather Research and Forecasting
WSA	West Coast South America
WSDI	Warm Spell Duration Index
WTO	World Trade Organization
yr	Year
ZEC	Zero Emissions Commitment

AIII

Annex III: Contributors to the IPCC Special Report on Global Warming of 1.5°C

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AIV

Annex IV: Expert Reviewers of the IPCC Special Report on Global Warming of 1.5°C

This annex should be cited as:

IPCC, 2018: Annex IV: Expert Reviewers of the IPCC Special Report on Global Warming of 1.5°C. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

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