Chapter 3: Impacts of 1.5ºC global warming on natural and human systems

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Executive Summary

This chapter builds on findings of the 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 for global warming of 1.5°C above the pre-industrial period. Chapter 3 explores observed impacts and projected risks for a range of natural and human systems with a focus on how risk levels change at 1.5ºC and 2ºC. The chapter also revisits major categories of risk (Reasons for Concern) based on the assessment of the new knowledge available since the AR5.

1.5°C and 2°C warmer worlds

The global climate has changed relative to the preindustrial period with multiple lines of evidence that these changes have had impacts on organisms and ecosystems, as well as 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 increasing GMST to 1.5°C or higher could impact natural and human systems (1.5°C versus 2°C) {3.3.1, 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*). In particular this includes 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 it has caused an increase in the frequency and duration of marine heatwaves. Further, there is evidence that global warming has led to an increase in the frequency, intensity and/or amount of heavy precipitation events at global scale (*medium confidence*), as well as having increased the risk of drought in the Mediterranean region (*medium confidence*) {3.3.1, 3.3.2, 3.3.3, 3.3.4}.

Changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991-2010 period compared with 1960-1979, when a global warming of approximately 0.5°C occurred (*high confidence*). The observed tendencies over that time frame are consistent with attributed changes since the mid-20th century (*high confidence*) {3.3.1, 3.3.2, 3.3.3}.

There is no single '1.5°C warmer world' (*high confidence*). Important aspects to consider (beside that of global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of global surface temperature at 1.5°C is achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional risks (*high confidence*). 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 many ecosystems (*high confidence*). The rate of change for several types of risks may also have relevance with potentially large risks in 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 (*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*) {Cross-Chapter Box 8 in this Chapter; Sections 3.2 and 3.6.2}.

Substantial global differences in temperature and extreme events are expected if GMST reaches 1.5°C versus 2°C above the preindustrial period (*high confidence*). Regional surface temperature means and extremes are higher at 2°C as compared to 1.5°C for oceans in near all locations *(high confidence)*. Temperature means and extremes are higher at 2°C as compared to 1.5°C global warming in near all inhabited land regions, and display in some regions 2-3 times greater warming when compared to the GMST (*high confidence*). There are also substantial increases in temperature means and extremes at 1.5°C versus present (*high confidence*) {3.3.1, 3.3.2}. There are decreases in the occurrence of cold extremes, but substantial increases in their temperature {3.3.1}.

Substantial changes in regional climate occur between 1.5°C and 2°C global warming (*high confidence*), depending on the variable and region in question *(high confidence)*. Particularly large differences are found for temperature extremes *(high confidence)*. Hot extremes display the strongest warming in mid-latitudes in the warm season (with increases of up to 3°C at 1.5°C of warming, i.e. a factor of two) and cold extremes at high-latitudes in the cold season (with increases of up to 4.5°C at 1.5°C of warming, i.e. a factor of three) (*high confidence*). The strongest warming of hot extremes is found 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 highly unusual hot days increase the most in the tropics, where inter-annual temperature variability is lowest; the emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C 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*) {3.3.1, 3.3.2, Cross-Chapter Box 8 in this Chapter}.

Limiting global warming to 1.5°C limits risks of increases in heavy precipitation events in several regions (*high 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 such as Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, northern Asia; mountainous regions (e.g. Tibetan Plateau); as well as Eastern Asia (including China and Japan) and in Eastern North America (*medium confidence*). {3.3.3}. Tropical cyclones are projected to increase in intensity (with associated increases in heavy precipitation) although not in frequency (*low confidence*, *limited evidence*) {3.3.3, 3.3.6}.

Limiting global warming to 1.5°C is expected to substantially reduce the probability of drought 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 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*) {3.3.4, Box 3.1, Box 3.2}.

Risks to natural and human systems are lower at 1.5ºC than 2ºC *(high confidence)*. This is owing to the smaller rates and magnitudes of climate change, including reduced frequencies and intensities of temperature-related extremes. Reduced rates of change enhance the ability of natural and human systems to adapt, with substantial benefits for a range of terrestrial, wetland, coastal and ocean ecosystems (including coral reefs and wetlands), freshwater systems, as well as food production systems, human health, tourism, energy systems, and transportation {3.3.1, 3.4}.

Some regions are projected to experience multiple compound climate-related risks at 1.5°C that will increase with warming of 2°C and higher (*high confidence*). Some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards. Multi-sector risks are projected to overlap spatially and temporally, creating new (and exacerbating current) hazards, exposures, and vulnerabilities that will affect increasing numbers of people and regions with additional warming. Small island states and economically disadvantaged populations are particularly at risk. {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}.

There is *medium confidence* that a 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, as compared to conditions at 1.5°C 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*) as well as an increase in flood hazard in some regions (*medium confidence*) when compared to present-day conditions {3.3.5}.

There is *high confidence* that the probability of a sea-ice-free Arctic Ocean during summer is substantially higher at 2°C when compared to 1.5°C. It is *very likely* that there will be at least one sea-ice-free Arctic summer out of 10 years for warming at 2°C, with the frequency decreasing to one sea-ice-free Arctic summer every 100 years at 1.5°C. There is also *high confidence* that an intermediate temperature overshoot will have no long-term consequences for Arctic sea-ice coverage and that hysteresis behaviour is not expected {3.3.8, 3.4.4.7}.

Global mean sea level rise will be around 0.1 m less by the end of the century in a 1.5°C world as compared to a 2°C warmer world (*medium confidence*). Reduced sea level rise could mean that up to 10.4 million fewer people (based on the 2010 global population and assuming no adaptation) are exposed to the impacts of sea level globally in 2100 at 1.5°C as compared to 2°C {3.4.5.1}. A slower rate of sea level rise enables greater opportunities for adaptation (*medium confidence*) {3.4.5.7}. There is *high confidence* that sea level rise will continue beyond 2100. Instabilities exist for both the Greenland and Antarctic ice sheets that could result in multi-meter rises in sea level on centennial to millennial timescales. There is medium confidence that these instabilities could be triggered under 1.5° to 2°C of global warming {3.3.9, 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 in 65 million years at least (*high confidence*). Risks have been identified for the survival, calcification, growth, development, and abundance of a broad range of taxonomic groups (i.e. from algae to fish) with substantial evidence of predictable trait-based sensitivities. Multiple lines of evidence reveal that ocean warming and acidification (corresponding to global warming of 1.5°C of global warming) is expected to impact a wide range of marine organisms, ecosystems, as well as sectors such as aquaculture and fisheries (*high confidence*) {3.3.10, 3.4.4}.

There are larger risks at 1.5°C than today for many regions and systems, with adaptation being required now and up to 1.5°C. There are, however, greater risks and effort needed for adaptation to 2°C *(high confidence)* {3.4, Box 3.4, Box 3.5, Cross-Chapter Box 6 in this Chapter}.

Future risks at 1.5°C 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 where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, *medium confidence*). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 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 (*medium confidence*). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (*high confidence*). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (*high confidence*), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.

Constraining global warming to 1.5°C rather than 2°C and higher has strong 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 terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (*high confidence*). Above 1.5°C, an expansion of desert and arid vegetation would occur in the Mediterranean biome (*medium confidence*), causing changes unparalleled in the last 10,000 years (*medium confidence*) {3.3.2.2, 3.4.3.5, 3.4.6.1., 3.5.5.10, Box 4.2}.

Many impacts are projected to be larger at higher latitudes due 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*). Further warming is projected to cause greater effects in a 2°C world than a 1.5°C world, for example, constraining warming to 1.5°C would prevent the melting of an estimated permafrost area of 2 million km^2 over centuries compared to 2°C (*high confidence*) {3.3.2, 3.4.3, 3.4.4}.

Ocean ecosystems

Ocean ecosystems are experiencing large-scale changes, with critical thresholds expected to be reached at 1.5ºC and above (*high confidence*). In the transition to 1.5°C, changes to water temperatures will drive some species (e.g. plankton, fish) to relocate to higher latitudes and for novel ecosystems to appear *(high confidence)*. Other ecosystems (e.g. kelp forests, coral reefs) are relatively less able to move, however, and will experience high rates of mortality and loss (*very high confidence*). For example, multiple lines of evidence indicate that the majority of warmer water coral reefs that exist today (70-90%) will largely disappear when global warming exceeds 1.5°C (*very high confidence*) {3.4.4, Box 3.4}.

Current ecosystem services from the ocean will be reduced at 1.5ºC, with losses being greater at 2ºC (*high confidence*). The risks of declining ocean productivity, shifts of species to higher latitudes, damage to ecosystems (e.g. coral reefs, as well as from mangroves, seagrass and other wetland ecosystems), loss of fisheries productivity (at low latitudes), and changing ocean chemistry (e.g., acidification, hypoxia, dead zones), however, 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 a 1.5°C versus 2°C of warming (*medium confidence*). Human exposure to increased flooding is projected to be substantially lower at 1.5°C as 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 to water scarcity are greater at 2°C than at 1.5°C of global warming in some regions (*medium confidence*). Limiting global warming to 1.5°C would approximately halve the fraction of world population expected to suffer water scarcity as compared to 2°C, although there is considerable variability between regions (*medium confidence*). Socioeconomic drivers, however, are expected to have a greater influence on these risks than the changes in climate (*medium confiden*ce) {3.3.5, 3.4.2, Box 3.5}.

Land Use, Food Security and Food Production Systems

Global warming of 1.5°C (as opposed to 2ºC) is projected to reduce climate induced impacts on crop yield and nutritional content in some regions (*high confidence*). Affected areas include Sub-Saharan Africa (West Africa, Southern Africa), South-East Asia, and Central and South America. 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 {3.6, 3.4.6, Box 3.1, Cross-Chapter Box 6 in this Chapter}.

Risks of food shortages are lower in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon at 1.5ºC of global warming when compared to 2°C (*medium confidence*). This suggests a transition from medium to high risk of regionally differentiated impacts between 1.5 and 2°C for food security (*medium confidence*). International food trade is *likely* to be a potential adaptation response for alleviating hunger 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*), which will increase at 1.5°C global warming. Risks are increasing for marine aquaculture and many fisheries at warming and acidification at 1.5°C (e.g., many bivalves such as oysters, and fin fish; *medium confidence*), 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 at a high risk at 1.5°C due to loss of habitat (*medium confidence*). Risks of impacts and decreasing food security become greater as warming and acidification increase, with substantial losses likely for coastal livelihoods and industries (e.g. fisheries, aquaculture) as temperatures increase beyond 1.5°C (*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 a critical feature of virtually all mitigation pathways that seek to limit global warming to 1.5ºC (*robust evidence, high agreement*). 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 (*robust evidence, high agreement*) {Cross-Chapter Box 7 in this Chapter}.

Large-scale, deployment of BECCS and/or AR would have a far-reaching land and water footprint (*medium evidence, high agreement*). Whether this footprint results 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 so as to protect natural ecosystems, and the potential to increase agricultural productivity (*high agreement, medium evidence*). In addition, BECCS and/or AR would also have substantial direct effects on regional climate through biophysical feedbacks, which are generally not included in Integrated Assessments Models (*high confidence*). {Cross-Chapter Boxes 7 and 8 in this Chapter, Section 3.6.2}

The impacts of large-scale CDR deployment can be greatly reduced if a wider portfolio of CDR options is deployed, a holistic policy for sustainable land management is adopted and if increased mitigation effort strongly limits demand for land, energy and material resources, including through lifestyle and dietary change (*medium agreement, medium evidence*). In particular, reforestation may be associated with significant co-benefits if implemented so as to restore natural ecosystems *(high confidence)* {Cross-Chapter Box 7 in this Chapter}

Human Systems: Human Health, Well-Being, Cities, and Poverty

Any increase in global warming (e.g., +0.5ºC) will affect human health (*high confidence*). Risks will be lower at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*), particularly in urban areas because of urban heat islands (*high confidence*). Risks also will be greater for ozone-related mortality if the emissions needed for the formation of ozone remain the same (*high confidence*), and for undernutrition (*medium confidence*). Risks are projected to change for some vector-borne diseases such as malaria and dengue fever (*high confidence*), with positive or negative trends depending on the disease, region, and extent of change (*high confidence*). Incorporating estimates of adaptation into projections reduces the magnitude of risks (*high confidence*) {3.4.7, 3.4.7.1}.

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 (energy, water, and transport) (*high confidence*) {3.4.5, 3.4.8}.

Poverty and disadvantage have increased with recent warming (about 1ºC) and are expected to increase in many populations as average global temperatures increase from 1ºC to 1.5°C and beyond (*medium confidence*). Outmigration in agricultural-dependent communities is positively and statistically significantly associated with global temperature (*medium confidence*). Our understanding of the linkages of 1.5ºC and 2ºC on 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

Globally, the projected impacts on economic growth in a 1.5°C warmer world are larger than those of the present-day (about 1°C), with the largest impacts expected in the tropics and the Southern Hemisphere subtropics (*limited evidence, low confidence*). At 2°C substantially lower economic growth is projected for many developed and developing countries *(limited evidence, medium confidence)*, with the potential to also limit economic damages at 1.5°C of global warming. {3.5.2, 3.5.3}.

The largest reductions in 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) (*limited evidence, medium confidence*) {3.5}.

Global warming has affected tourism and increased risks are projected for specific geographic regions and the seasonality of sun, beach, and snow sports tourism under warming of 1.5ºC (*very high confidence*). Risks will be lower for tourism markets that are less climate sensitive, such as non-environmental (e.g., gaming) or large hotel-based activities (*high confidence*) {3.4.9.1}. Risks for coastal tourism, particularly in sub-tropical and tropical regions, will increase with temperature-related degradation (e.g. heat extremes, storms) or loss of beach and coral reef assets (*high confidence*) {3.4.9.1, 3.4.4.12; 3.3.6, 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 that will increase with warming of 2ºC and higher (*high confidence*). Climate hazards at 1.5°C are lower compared to 2°C (*high confidence*). Long term risks of coastal flooding and impacts on population, infrastructure and assets (*high confidence*), freshwater stress (*medium confidence*), and risks across marine ecosystems (*high confidence*), and critical sectors (*medium confidence)* increase at 1.5°C as compared to present and further increase at 2°C, limiting adaptation opportunities and increasing loss and damage (*medium confidence*). Migration in small islands (internally and internationally) occurs due to multiple causes and for multiple purposes, mostly for better livelihood opportunities (*high confidence*) and increasingly due 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 critically important in sensitive environments such as small islands, low lying coasts and deltas at global warming of 1.5ºC and 2ºC (*high confidence*). Localised subsidence and changes to river discharge can potentially exacerbate these effects {3.4.5.4}. Adaptation is happening today (*high confidence*) and remains important over multi-centennial timescales {3.4.5.3, 3.4.5.7, Box 3.5, 5.4.5.4}.

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. 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 there has been a substantial increase since AR5 in the levels of risk associated with four of the five Reasons for Concern (RFCs) for global warming levels of up to 2°C (*high confidence*). Constraining warming to 1.5ºC rather than 2ºC avoids risk reaching a 'very high' level in RFC1 (Unique and Threatened Systems) (*high confidence*), and avoids risk reaching a 'high' level in RFC3 (Distribution of Impacts) (*high confidence*) and RFC4 (Global Aggregate Impacts) (*medium confidence*). It also reduces risks associated with RFC2 (Extreme Weather Events) and RFC5 (Large scale singular events) (*high confidence*) {3.5.2}.

In "Unique and Threatened Systems" (RFC1) the transition from high to very high risk is located between 1.5ºC and 2ºC global warming as opposed to at 2.6ºC 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}.

1. **In "Extreme Weather Events" (RFC2) the transition from moderate to high risk is located between 1.0ºC and 1.5ºC global warming,** which is very similar to the AR5 assessment but there is greater confidence in the assessment (*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' (red) to 'very high' risk within the context of assessing impacts at 1.5°C versus 2°C 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. **In "Distribution of impacts" (RFC3) a transition from moderate to high risk is now located between 1.5ºC and 2ºC global warming as compared with between 1.6**ºC **and 2.6**ºC **global warming in AR5**, due to new evidence about regionally differentiated risks to food security, water resources, drought, heat exposure, and coastal submergence *(high confidence)* {3.5}.

3. **In "Global aggregate impacts" (RFC4) a transition from moderate to high levels of risk now occurs between 1.5ºC and 2.5ºC global warming** as opposed to at 3ºC warming in AR5, owing to new evidence about global aggregate economic impacts and risks to the earth's biodiversity *(medium confidence)* {3.5}.
4. **In "Large scale singular events" (RFC5), moderate risk is located at 1ºC global warming and high risks are located at 2.5ºC global warming**, as opposed to 1.9ºC (moderate) and 4ºC global warming (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. Information for the assessment and implementation of adaptation options in Chapter 4, and the context for considering the interactions of climate change with sustainable development in Chapter 5 for the assessment of impacts on sustainability, poverty and inequalities at the level of sub-regions to households, are provided by Chapter 3.

This chapter is necessarily transdisciplinary in its coverage of the climate system, natural and managed ecosystems, and human systems and responses, due 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.

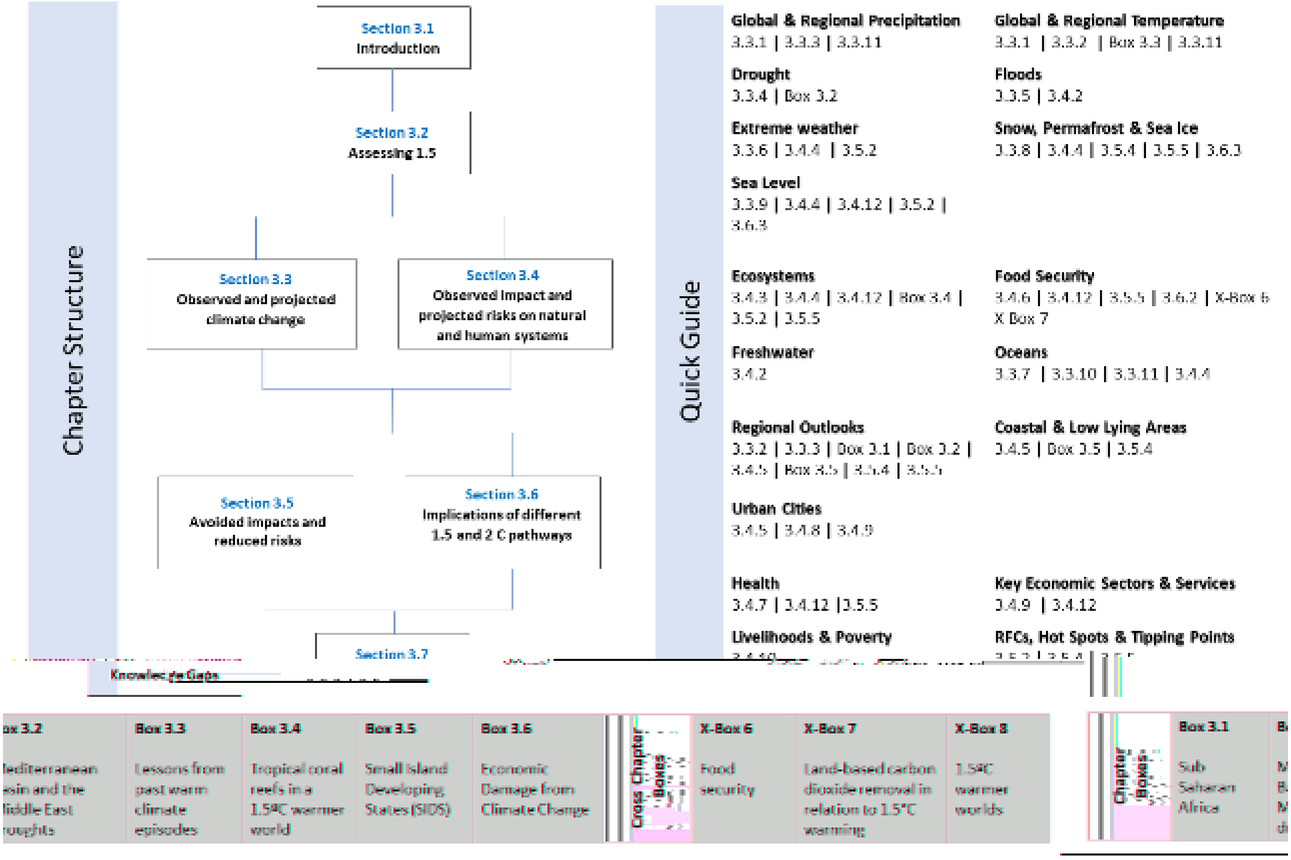

Figure 3.1: Chapter 3 structure and quick guide

The underlying literature assessed in Chapter 3 is broad, including a large number of recent publications specific to assessments for 1.5°C warming. The chapter also utilizes information covered in prior IPCC special reports, for example Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, IPCC, 2012), and many chapters which assess impacts on natural and managed ecosystems and humans and adaptation options from the IPCC WGII Fifth Assessment Report (AR5) (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 is on analyses of *transient responses* at 1.5°C and 2°C, 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 due to lack of data availability. A detailed analysis of detection and attribution is not provided. 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 forms a crucial element in understanding how the world is likely to change under global warming of 1.5°C above the preindustrial period (with reference to 2ºC). Section 3.4 explores the new literature and updates the assessment of impacts and projected risks into the future for a large number of natural and human systems. By also exploring adaptation opportunities (where the literature allows), the section prepares the ground for later discussions in subsequent chapters about opportunities to tackle both mitigation and adaptation. The section is mostly globally focussed because of limited research on regional risks and adaptation options at 1.5ºC and 2ºC. For example, on the risks of warming of 1.5°C and 2°C in urban areas, and climate-sensitive health outcomes, such as climate related disease, medical impacts of poor air quality, or mental health, were not considered because of the lack of projections of how risks might change in 1.5ºC and 2°C worlds. In addition, the complex interactions of climate change with drivers of poverty and livelihoods meant it was not possible to detect and attribute recent changes to climate change, even with increasing documentation of climate-related impacts on places where indigenous peoples live and where subsistence-oriented communities are to be found, because of limited projections of the risks associated with warming of 1.5ºC and 2ºC.

To explore avoided impacts and reduced risks at 1.5ºC compared with 2ºC, the chapter adopts the AR5 'Reasons for Concern' aggregated projected risk framework (Section 3.5). Updates in terms of the aggregation of risk are informed by the most recent literature and the assessments offered in Sections 3.3 and 3.4 with focus on the avoided impacts at 1.5°C as compared to 2°C. Economic benefits to be obtained (Section 3.5.3), climate change 'hot spots' that can 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 can be avoided (Section 3.5.5) at 1.5ºC compared to higher degrees of global warming, are all examined. These latter assessments are, however, constrained to regional analysis, and the section does not include an assessment of loss and damages.

Section 3.6 provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C global warming including some 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 1.5°C specific literature presented across all the sections in Chapter 3 highlighted knowledge gaps resulting from the heterogeneous information across systems, regions and sectors. Some of these gaps are listed 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 and projected risks to natural and managed systems, and 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 and which 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 the ecosystems) are provided in the Annex 3-1.

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 draw 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 1ºC (±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 for a further increase of 0.5°C or 1°C in global warming (see Annex 3.1 S3-2 and Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.3.11). A recent study also investigated significant changes in extremes for a 0.5°C difference in global warming based on the historical record (Schleussner et al., 2017).

Climate model simulations are necessary for the investigation of the response of the climate system to various forcings, in particular for 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 (Annex 3.1, S3.2). Climate model simulations were generally used in the context of particular 'climate scenarios' in previous IPCC reports (e.g., IPCC, 2007, 2013). This means that emission 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, if a given emission pathway was to be followed. Results were assessed for different time slices within the model projections, for example for 2016-2035 ('near term', which is slightly below a 1.5°C global warming in most scenarios, Kirtman et al., 2013), 2046-65 (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-level) 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 for distinguishing between (a) **transient climate responses** (i.e. those that 'pass through' 1.5°C or 2°C global warming), (b) **short-term stabilization responses** (i.e. late 21st-century scenarios that result in stabilization at a mean global warming of 1.5°C or 2°C by 2100), and (c) **long-term equilibrium stabilization responses** (i.e. once climate equilibrium at 1.5°C or 2°C is reached, after several millennia). 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 considered scenario yet stabilize at very different levels for a long-term warming of 1.5°C versus 2°C (Section 3.3.9).

B. That '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 2/3) over the course, or end, of the 21st century.

These scenarios should be seen as operationalisations of 1.5°C or 2°C 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 1/3, see Chapter 2 and Cross-Chapter Box 8 in this Chapter). This is due both to discrepancies between models and 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 higher 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 -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' of 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 up to 0.5°C-1°C higher than the respective target levels at most), before warming returns to below 1.5°C or 2°C achieved by 2100. During the overshoot phase, impacts would therefore correspond to higher transient temperature levels than 1.5°C or 2°C. For this reason, impacts for transient responses at these higher levels are also partly addressed in Cross-Chapter Box 8 in this Chapter on 1.5°C warmer worlds, and some analyses for changes in extremes are also displayed for higher levels of warming in Section 3.3 (Figures 3.5, 3.6, 3.9, 3.10, 3.12, 3.13). Most importantly, different overshoot scenarios may have very distinct impacts depending on (a) the peak temperature of the overshoot, (b) the length of the overshoot period, and (c) 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 the Cross-Chapter Box 8 (in this Chapter), the definition and questions surrounding overshoot will need to be addressed more comprehensively in the IPCC AR6 report.

D. The meaning of '1.5°C or 2°C' global warming climate was not defined prior to this report, although it is defined as relative to the climate associated with the Pre-Industrial Period. This requires an agreement on the exact reference time period (for 0°C warming) and the time frame over which the global warming is assessed (e.g. typically a climatic time period, such as one that is 20 or 30 years in length). As discussed in Chapter 1, a 1.5°C climate is one in which temperature differences averaged over a multi-decade timescale are 1.5°C above the pre-industrial reference period. Greater detail is provided in the Cross-Chapter Box 8. 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. regional annual temperature extremes can display a warming of up to 4.5°C on average, see Section 3.3 and Cross-Chapter Box 8 in this Chapter).

E. Non-greenhouse gas related interference 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 for 1.5°C of global warming. These issues are addressed in more detail in Section 3.6.2.2.

The assessment done in the current chapter largely focusses on the analysis of **transient responses in climate at 1.5°C versus 2°C** and higher levels of warming (see point A. above, Section 3.3). It generally uses the Empirical Scaling Relationship approach (ESR, Seneviratne et al., 2018c), also termed ‘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 (e.g., as done within the IMPACT2C project (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 of this chapter are also 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 by combining changes that have been attributed for the observed time period (corresponding already to a warming of 1°C or smaller if assessed over a shorter time period) and known projected changes at 3°C or 4°C above the pre-industrial (Annex 3.1 S3-2). In order to compare effects induced by a 0.5°C difference in global warming, it is also possible to use, in a first approximation, the historical record as a proxy in which two periods are compared in cases where they approximate this difference in warming (e.g. such as 1991-2010 and 1960-1979, e.g. Schleussner et al., 2017). Using observations, however, does not allow an accounting for possible non-linear changes that would occur above 1°C or as 1.5°C of global warming is achieved.

In some cases, assessments for **short-term stabilization responses** could also be provided, derived from using a subset of model simulations that reach a given temperature limit by 2100, or were driven with Sea Surface Temperature (SST) consistent with such scenarios. This includes new results from the ‘Half a degree additional warming, prognosis and projected impacts’ (HAPPI) project (Chapter 1, Section 1.5.2, Mitchell et al., 2017). It should be noted that 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-emission scenarios (Seneviratne et al., 2016, 2018a; 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 projections is limited for many variables and scenarios and will need to be addressed in more depth in the IPCC AR6 report.

Annex 3.1 (S3-2) of this chapter includes greater detail 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 global warming.

3.2.2 How are potential impacts on ecosystems assessed at 1.5°C versus higher levels of warming?

Considering that the observed impacts so far are for a lower global warming 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 the AR5 (Cramer et al., 2014), however, demonstrates that methodologies now exist which are capable of detecting impacts in systems strongly influenced by confounding factors (e.g. urbanization or more generally human pressure) 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 the 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 1.5ºC versus 2°C consists of identifying impacts of a global 0.5°C warming in the observational record (e.g., Schleussner et al., 2016b), 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 past climates combined with the modeling 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, biological and ecological factors) on specific natural systems that may have unusual physical and chemical characteristics (e.g., Fabricius et al., 2011; Allen et al., 2017). The latter 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. Studies projecting impacts at 1.5°C or 2°C global warming have increased in recent times (see Section 3.4) even if the four RCP scenarios used in the AR5 are not strictly associated to these levels of global warming levels. 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 time sampling (or ESR) approach (described in Section 3.2.1) to estimate the differential effect of 1.5°C and 2°C 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 an crop model using interpolation between the no-change (approximately 2010) conditions and the RCP2.6 scenario (with a global warming of +1.8°C in 2100), and 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 a number of sectoral impacts on the terrestrial and marine ecosystems. In most cases, the 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 (i.e 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 (Annex 3.1 S3-2) is crucially important in translating perspectives on 1.5°C and 2°C to scales and impacts relevant to humans and ecosystems. A major challenge that is associated with this requirement is to reproduce correctly the variance of local to regional changes, as well as the frequency and amplitude of the extreme events (Vautard et al., 2014). In addition, maintaining physical consistency between downscaled variables is also 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 regional climate to the impacts at the ecosystem level, taking into account local disturbances and local policy effects. The risks for natural and human systems are the result of intricate global and local drivers, which makes quantitative uncertainty analysis difficult. Such analyses are partly done using multi-model approaches, such as multi-climate and multi-impact models (Warszawski et al., 2013, 2014; Frieler et al., 2017). In some cases, the greater proportion of the uncertainty (e.g., crop projections) is due to variation among crop models rather than that of the downscaled climate models being used (Asseng et al., 2013). The study of the error propagation is an important issue for coupled models. Dealing correctly with the 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 (Annex 3.1 S3-2). The computation of the impact per unit of climatic change either based on models or data is a simple way to present the probabilistic ecosystem response 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 considerations need to be taken into account. Projected climates under 1.5°C of global warming can be different depending on the temporal aspects and pathways of emissions. Considerations include whether global temperature is a) temporarily at this level (i.e. is a transient phase on its way to higher levels of warming), b) arrives at 1.5°C after stabilization of greenhouse gas concentrations with or without overshoot, or c) is at this level as part of long-term climate equilibrium (after several millennia). Assessments of impacts of 1.5°C warming are generally based on climate simulations for these different possible pathways. More data and analyses are available for transient impacts (a). There are fewer data for dedicated climate model simulations that are able to assess pathways consistent with (b). There are very limited data available for the assessment of changes at climate equilibrium (c). In some cases, inferences regarding the impacts of further warming of 0.5°C above today (i.e. 1.5ºC global warming) can also be drawn from observations of similar sized changes (0.5ºC) that have occurred in the past (e.g. 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 problems 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 the 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 global warming relative to 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 WG1 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; Seneviratne et al., 2016, 2018c; Déqué et al., 2017; Maule et al., 2017; Mitchell et al., 2017; Wartenburger et al., 2017; Zaman et al., 2017; Betts et al., 2018; Jacob et al., 2018; Kharin et al., 2018; Mitchell et al., 2018; Wehner et al., 2018). The main assessment methods are as already detailed in Section 3.2.

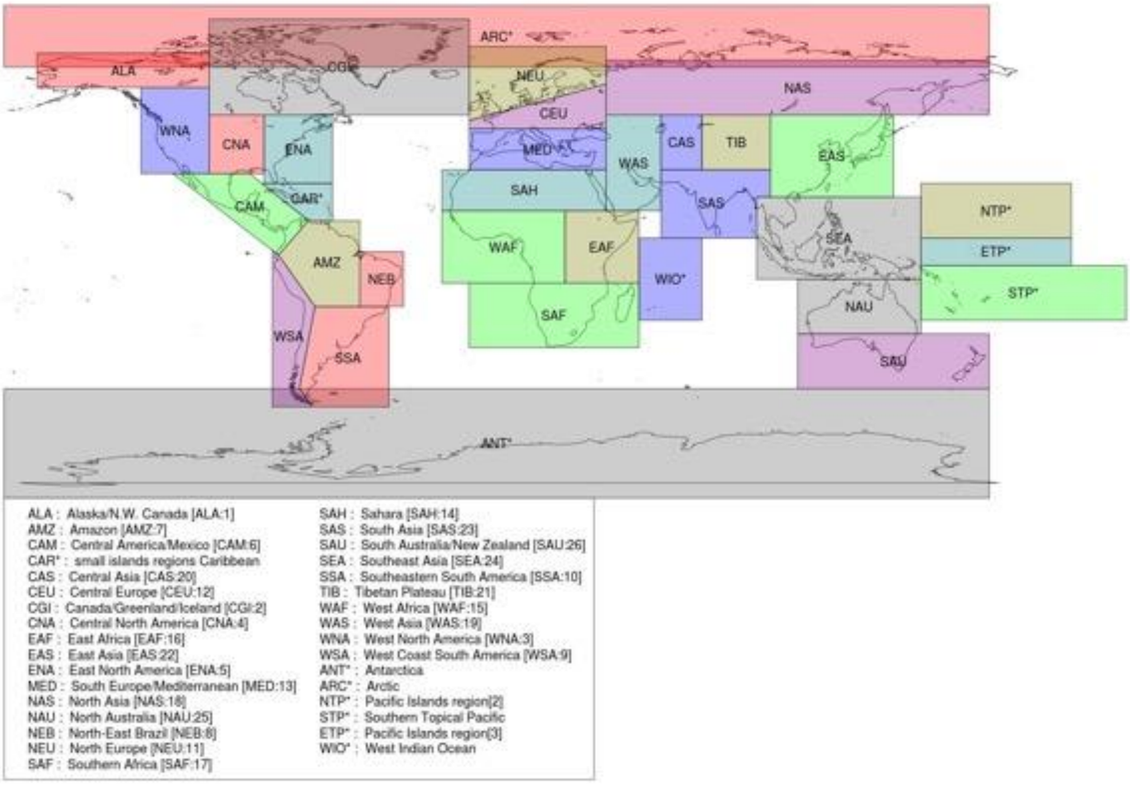

Figure 3.2: Regions used for regional analyses provided in Section 3.3. The choice of regions is based on the IPCC Fifth Assessment Report (AR5, Chapter 14, Christensen et al., 2013) and Annex 1: Atlas) and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, Chapter 3, Seneviratne et al., 2012), including seven additional regions (Arctic, Antarctic and islands) compared to the IPCC SREX report (indicated with asterisks). Analyses for regions with asterisks are provided in the Annex (Annex 3.1 S3-3).

3.3.1 Global changes in climate

There is *high confidence* that the Global Mean Surface Temperature (GMST) warming has reached 0.87°C (±0.10°C *likely* range) above pre-industrial in the 2006-2015 decade (Chapter 1). The 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] for 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 to estimate GMST (e.g., using water versus air temperature over oceans; model simulations versus observations-based estimates) can affect estimates of GMST warming (Richardson et al., 2016) (see also Annex 3.1 S3.3), the present assessment is consistent with that of the AR5 regarding a detectable and dominant effect of anthropogenic forcing on observed trends in global temperature (e.g., also confirmed in Ribes et al., 2017). As highlighted in Chapter 1, human-induced warming reached approximately 1°C (±0.2°C *likely* range) in 2017. More background on recent observed trends in global climate is provided in the Annex 3-3.

A global warming of 1.5°C implies warmer mean temperatures compared to pre-industrial times in almost all locations on both land and oceans (*high confidence*) (Figure 3.3). In addition, differences resulting from 1.5°C and 2°C global warming are detectable in mean temperatures in almost all locations on both land and ocean (*high confidence*). The land-sea contrast in temperature warming is important and implies particularly large changes in temperature over land, with larger mean warming than 1.5°C in most land regions (*high confidence*; see Section 3.3.2 for more details). The highest warming of the mean temperature is found in the northern high latitudes (*high confidence*; Figure 3.3, see Section 3.3.2 for more details). Projections for precipitation are more uncertain but highlight significant increases in mean precipitation in the Northern Hemisphere high latitudes at 2°C versus 1.5°C global warming (*medium confidence*) (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 day of the year, TXx, and the coldest day of the year TNn) and heavy precipitation (the annual maximum 5-day precipitation, Rx5day). These analyses reveal distinct patterns of changes, with highest changes in TXx in mid-latitude land, and highest changes in TNn in high latitudes (both land and oceans). Differences at 1.5°C versus 2°C are significant across the globe. Changes in heavy precipitation are less robust at the grid-cell scale, but display increases over most land areas.

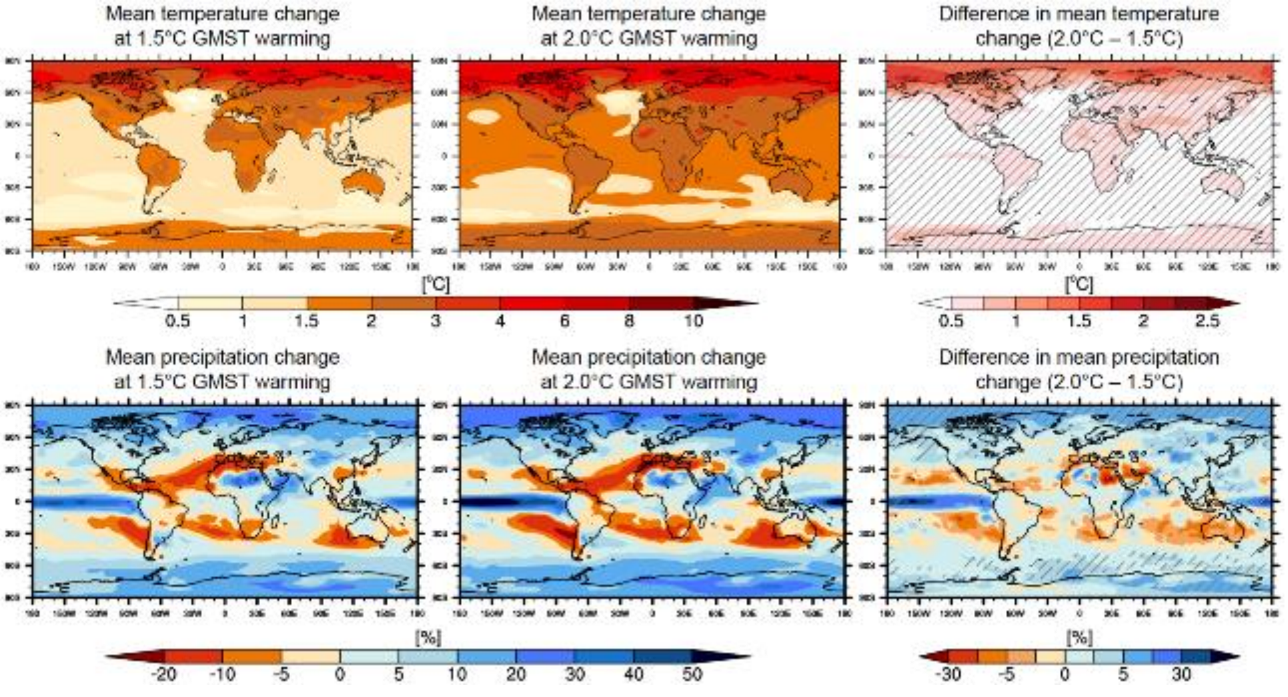

Figure 3.3: Projected mean temperature (top) and mean precipitation changes (bottom) at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Assessed from transient response over 20-year time period at given warming, 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 Annex 3.1 S3-3 for more details). Note

that the responses at 1.5°C Global Mean Surface Temperature (GMST) warming are similar for RCP2.6 simulations (see Annex 3.1 S3-3).

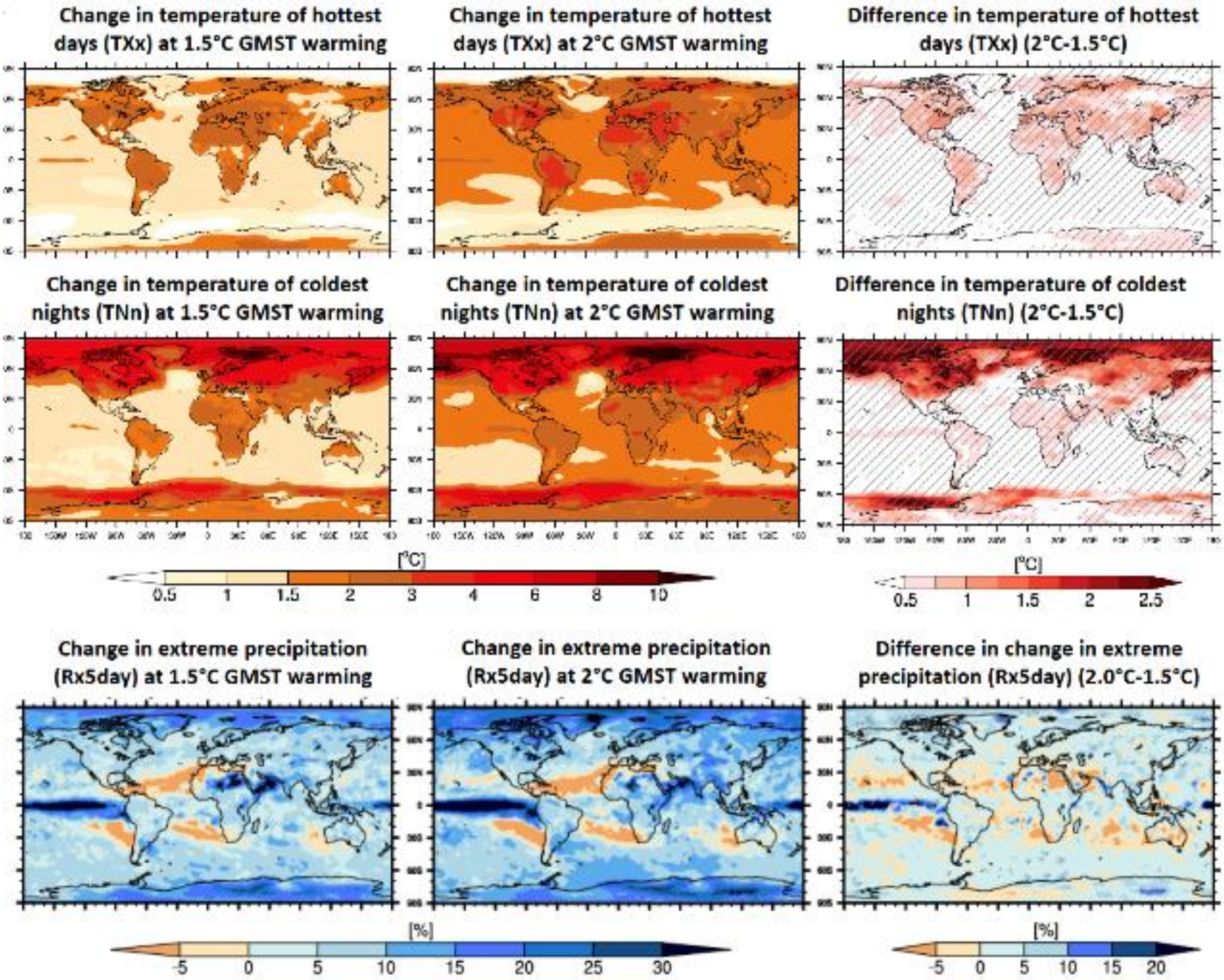

Figure 3.4: Projected change in extreme at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change): temperature of annual hottest day, TXx (top), and annual coldest day, TNn, (middle), and annual maximum 5-day precipitation, Rx5day (bottom). Same underlying methodology and data basis as Figure 3.3 (see Annex 3.1 S3-3 for more details). Note that the responses at 1.5°C Global Mean Surface Temperature (GMST) warming are similar for Representative Concentration Pathway (RCP)2.6 simulations (see Annex 3.1 S3-3).

These projected changes at 1.5°C and 2°C global warming are consistent with the attribution of global observed historical trends in temperature and precipitation means and extremes (Bindoff et al., 2013a) as well as with some observed changes for a recent global warming of 0.5°C (Schleussner et al., 2017), as also 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 of the 20th century), 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 in the North-Hemisphere high-latitudes since the mid 20th century and to global-scale increases in heavy precipitation in land regions with sufficient observations over the same time period (Bindoff et al., 2013a). Schleussner et al. (2017) have shown from 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 1960-1979, when a global warming of approximately 0.5°C occurred *(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 that some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards (for instance sea level rise and heavy precipitation in some regions, possibly leading together to more flooding, or 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. (Amir 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 at 1.5°C vs 2°C global warming 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.

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 tend 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 being concentrated at the poles and over Africa, which may lead to biases in estimated changes in GMST (see also Annex 3.1 S3-3 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 the AR5 (Bindoff et al., 2013a) and recent papers (e.g., Sun et al., 2016; Wan et al., 2018) assessed that over every continental regions and in many sub-continental regions, anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century.

It is *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. It is also *likely* that consistent changes are detectable on continental scale in North America, Europe and Australia. This is consistent with the SREX and AR5 assessments (Seneviratne et al., 2012; Hartmann et al., 2013). There is *high confidence* that these observed changes in temperature extremes can be attributed to anthropogenic forcing (AR5, 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 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 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 in the hottest day of the year, TXx) by more than 1°C and a reduction of the intensity of cold extremes by at least 2.5°C (minimum temperature in the coldest night of the years, TNn). In addition, that study shows 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 Annex 3-3 (Figure S3.6).

3.3.2.2 Projected changes at 1.5°C versus. 2°C in regional temperature means and extremes

There are several lines of evidence available for providing a regional assessment of projected change in temperature means and extremes at 1.5°C versus 2°C 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 therefrom (see Section 3.2 for details about the methodology) (e.g., Schleussner et al., 2017; Dosio and Fischer, 2018; Seneviratne et al., 2018c) dedicated simulations for 1.5°C versus 2°C 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); and analyses based on statistical pattern scaling approaches (e.g. Kharin et al., 2018). Results with these different lines of evidence display qualitatively consistent results regarding changes in temperature means and extremes at 1.5°C global warming compared to pre-industrial climate and 2°C global warming.

There are statistically significant differences in temperature means and extremes at 1.5°C versus 2°C global warming, both in the global average (Schleussner et al., 2016b; Dosio et al., 2018; Kharin et al., 2018), as well as in nearly all inhabited land regions (Wartenburger et al., 2017; Seneviratne et al., 2018c; Wehner et al., 2018) (*high confidence)*. Temperatures over oceans display significant increases between 1.5°C and 2°C 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 global warming is provided in the Annex 3.1 S3-3. As an example, Figure 3.5 shows for the IPCC SREX regions (Figure 3.2) regionally-based analyses of changes in the temperature of hot extremes as a function of warming (corresponding analyses for changes in the temperature of cold extremes are provided in the Annex 3.1 S3-3). As can be seen 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 emission 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 found to be approximately exponential, with higher increases for rare events (Fischer and Knutti, 2015; Kharin et al., 2018); see for example, Figure 3.6. This behavior 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 higher 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; Annex 3.1 S3-3). For differences in regional temperature extremes at mean global warming of 1.5°C versus 2°C, this implies differences of as much as 1°C -1.5ºC in some locations, which are thus 2-3 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). These regions are all characterized by a strong soil-moisture-temperature coupling (Vogel et al., 2017) leading to increased dryness and, consequently, a reduction in evaporative cooling and thus added warming 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, due to discrepancies in the representation of the underlying processes in present 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 GMST warming. Maps of changes in the number of Frost Days (FD) can be found in the Annex 3.1 S3-3. These analyses reveal clear patterns of changes between the two warming levels, also consistent with analysed changes in heatwave occurrence (e.g., Dosio et al., 2018). For the NHD, the largest differences are found in the tropics due to the lower interannual temperature variability (Mahlstein et al., 2011), and despite the tendency for higher absolute changes in hot temperature extremes in mid-latitudes (Figures 3.4 and 3.5). The emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). These analyses are consistent with other recent assessments. Coumou and Robinson (2013) find that under a 1.5°C warming, already 20% of the global land area, centered in low latitude regions, is projected to experience highly unusual monthly temperatures during boreal summers (a number which nearly doubles for 2°C of global warming).

Figure 3.8 includes an objective identification of "hot spots" / key risks in temperature indices subdivided by regions, based on the ESR approach applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (Wartenburger et al., 2017). It is noted that results based on the HAPPI multi-model experiment (Mitchell et al., 2017) display similar results (Seneviratne et al., 2018c). The considered regions follow the classification of Figure 3.2 and also include the global land. The figure displays red shading for all instances in which a significant difference is found between regional responses at 1.5°C versus 2°C. 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, of ii) Ice Days (ID), Frost Days (FD), and Growing Season Length (GSL) in mostly warm regions, and of iii) the minimum yearly value of the Maximum Daily Temperature (TXn) in very few regions. In terms of the sign of the changes, it can be seen that warm extremes display an increase in intensity, frequency and spell length (e.g. increase of the temperature of the hottest day of the year (TXx) in all regions, increase of proportion of days above 90th percentile of Tmax (TX90p) in all regions, increase of the length of the WSDI in all regions), while cold extremes display a decrease in intensity, frequency and spell length (e.g. increase of the temperature of the coldest night of the year (TNn) in all regions, decrease in the proportion of days below the 10th percentile of Tmin (TN10p), decrease in the length of the Cold Spell Duration Index (CSDI) in all regions). Hence, while warm extremes are intensified, it should also be noted that cold extremes become less intense and frequent (but have a higher temperatures) in affected regions.

Overall, large increases in hot extremes happen in many densely inhabited regions (Figure 3.5), both compared to present-day climate and at 2°C versus 1.5°C global warming. For instance, Dosio et al. (2018) concluded based on a modeling study that 13.8% of the world population would be exposed to severe heat waves at least once every 5 years under 1.5°C global warming, with a threefold increase (36.9%) under 2°C warming, i.e. a difference of about 1.7 billion people. They also conclude that limiting global warming to 1.5°C would result in about 420 million fewer people being frequently exposed to extreme heat waves, and about 65 million fewer people being exposed to exceptional heat waves. However, changes in vulnerability were not considered in that study.

In summary, there are statistically significant differences in temperature means and extremes at 1.5°C versus 2°C global warming, both in the global average as well as in near all land regions[1] and the ocean (*likely*). Also, 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 warming of 2°C versus 1.5°C leads to more frequent and more intense hot extremes in all land regions[1], as well as to longer warm spells, affecting many densely inhabited regions (*very likely*). Strongest increases in the frequency of hot extremes happens for the rarest events (*very likely*). On the other hand, cold extremes would become less intense and less frequent, and cold spells would be less extended (*very likely*). Temperature extremes on land generally increase more than the global average temperature (*very likely*). Extreme hot days in mid-latitudes display an up to two-fold higher warming than the GMST (*likely*). The highest levels of warming for extreme hot days are found in Central and Eastern North America, Central and Southern Europe, the Mediterranean, Western and Central Asia, and Southern Africa (*likely*). These regions have a strong soil-moisture-temperature coupling in common, leading to increased dryness and, consequently, a reduction in evaporative cooling, although there is substantial model range in the representation of these processes, in particular in Central Europe and Central North America (*likely*). The coldest nights in high-latitudes warm by as much as 1.5°C for a 0.5°C increase in GMST, i.e. a three-fold higher warming (*likely*). The NHD shows the largest differences between 1.5°C and 2.0°C in the tropics because of their low interannual temperature variability (*likely*); the emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). Limiting global warming to 1.5°C instead of 2ºC 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*).

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[1] FOOTNOTE: Using the SREX definition of regions (Figure 3.2)

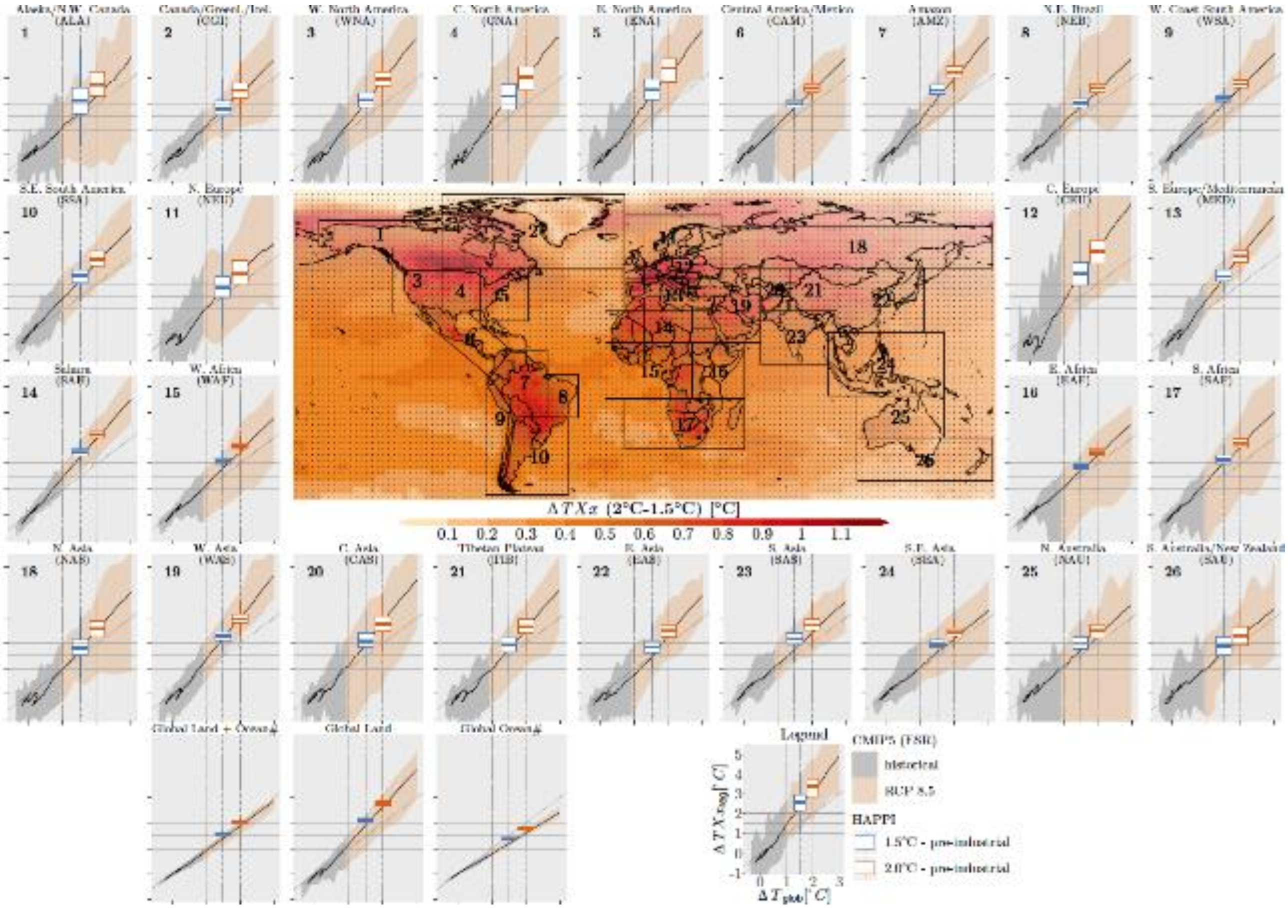


Figure 3.5: Projected changes in annual maximum daytime temperature (TXx) as function of global temperature warming for IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (Figure 3.2), based on empirical scaling relationship applied 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) multi-model 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 Annex 3.1 S3-3. (The stippling indicates significance of the differences of changes in between 1.5°C and 2°C 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 Annex 3.1 S3-3 for details.

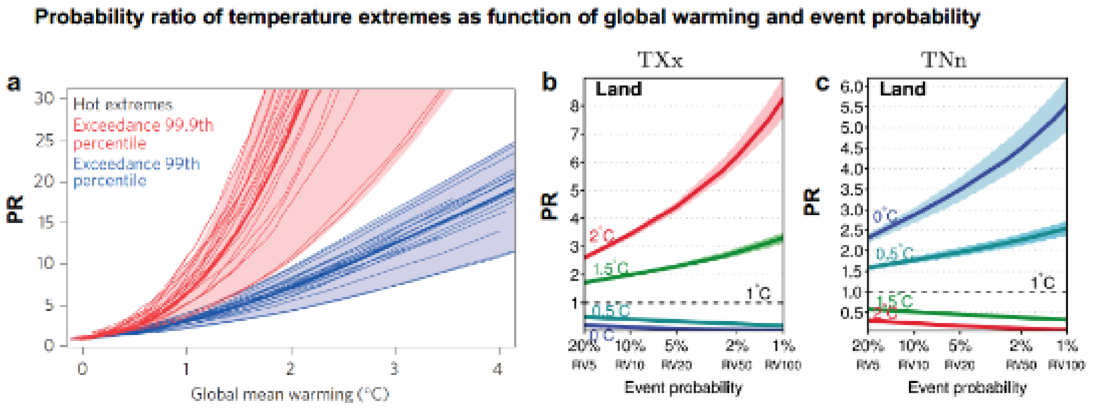


Figure 3.6: Probability ratio (PR) of exceeding extreme temperature thresholds. Left (a): PR of exceeding (blue) 99th and (red) 99.9th percentile of pre-industrial daily temperature at a given warming level relative to pre-industrial conditions averaged across land (from Fischer and Knutti, 2015). Middle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

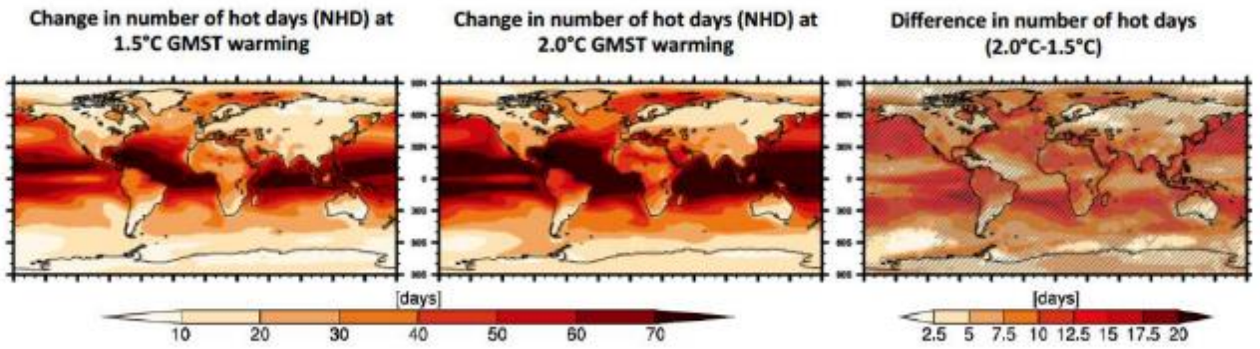
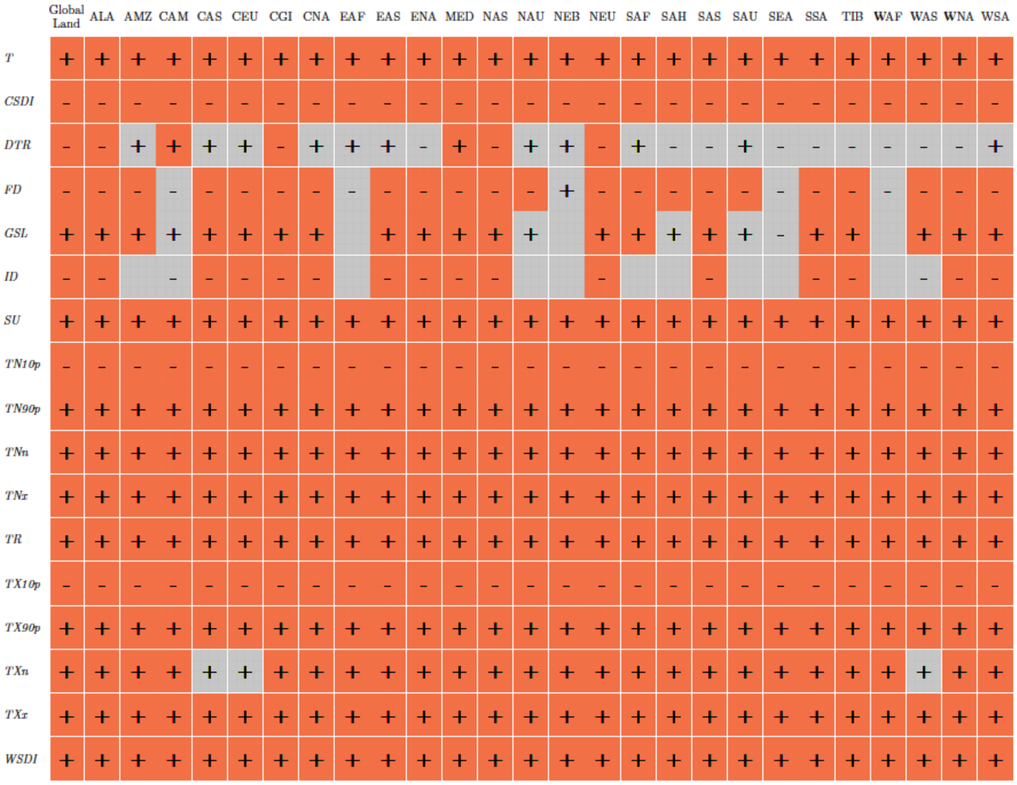


Figure 3.7: Projected change number of hot days (10% warmest days) at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Same underlying methodology and data basis as Figure 3.2 (Annex 3.1 S3-3 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
T	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
CSDI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DTR	-	-	+	+	+	+	-	+	+	+	-	+	-	+	+	-	+	-	-	+	-	-	-	-	-	-	+
FD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
GSL	+	+	+	+	+	+	+	+		+	+	+	+	+		+	+	+	+	+	-	+	+		+	+	+
ID	-	-		-	-	-	-	-		-	-	-	-			-			-			-	-		-	-	-
SU	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TN10p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TN90p	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TNn	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TNx	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TR	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TX10p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TX90p	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TXn	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TXx	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
WSDI	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Figure 3.8: Significance of differences of regional mean temperature and range of temperature indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition 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 minimum temperature (TN) below 10th percentile of TN; TN90p: Proportion of days with TN higher than 90th percentile TN; TNn: minimum yearly value of TN; TNx: maximum yearly value of TN; TR: Tropical Nights; TX10p: Proportion of days with maximum Temperature (TX) lower than 10th percentile of TX; TX90p: Proportion of days with TX higher than 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 definition). Significant differences are shown in red shading (increases indicated with + sign, decreases indicated with – sign), insignificant differences are shown in grey shading. Note that decreases in CSDI, FD, ID, TN10p and TX10p are linked to increased temperatures in cold days or nights. Significance is 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 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* due to data quality, data completeness or disagreement amongst available estimates (Hartmann et al., 2013). There is in particular *low confidence* regarding observed trends in precipitation in monsoon regions, based on the SREX report (Seneviratne et al., 2012), the AR5 (Hartmann et al., 2013), as well as on more recent publications (Singh et al., 2014; Taylor et al., 2017; Bichet and Diedhiou, 2018) Annex 3.1 S3-3).

For heavy precipitation, the 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, it assessed that in land regions where observational coverage is sufficient for assessment, 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 a global warming of 0.5°C, the observed record suggests that robust increases in observed precipitation extremes can be identified for annual maximum 1-day precipitation (RX1day) and consecutive 5-day precipitation (RX5day) for GMST changes of this magnitude (Schleussner et al., 2017) (Annex S3.3, Figure S3.7).

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

Figure 3.3 (Section 3.3.1) summarizes the projected changes in mean precipitation at 1.5°C versus 2°C. Some regions display substantial changes in mean precipitation between 1.5°C versus 2°C global warming, in particular decreases in the Mediterranean area, including Southern Europe, the Arabian Peninsula and Egypt. Some studies are also available for other regions across the world. For instance, Déqué et al. (2017) investigate the impact of a 2°C global warming on precipitation over tropical Africa and found that average precipitation does not show a significant response due to two compensating phenomena: (a) the number of rain days decreases whereas the precipitation intensity increases, and (b) the rainy season occurs later during the year with less precipitation in early summer and more precipitation in late summer. The assessment found insignificant differences between 1.5°C and 2°C scenarios for tropical Africa, which is consistent with the results of Figure 3.3. For Europe, for 2°C global warming, a robust increase of precipitation over Central and Northern Europe in winter and only over Northern Europe in summer, and decreases of precipitation in Central/Southern Europe in summer, with changes reaching 20% have been reported by Vautard et al. (2014) and is more pronounced than with +1.5°C global warming (Jacob et al., 2018).

For 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 the Annex (Annex 3.1 S3-3). These analyses show that projected changes in heavy precipitation are more uncertain than 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 for temperature this response is also found to be mostly independent of the considered emissions scenario (e.g. Representative Concentration Pathway (RCP)2.6 versus RCP8.5; also Section 3.2). This appears to be a specific feature of 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).

The differences in heavy precipitation are generally small between 1.5°C and 2°C global warming (Figure

3.9 and Annex 3.1 S3-3 Figure S3.10). Some regions display substantial increases, for instance in Southern Asia, but generally in less than 2/3 of the CMIP5 models (Annex 3.1 S3-3, Figure S3.10). Wartenburger et al. (2017) suggests that for Eastern Asia, there are substantial differences in heavy precipitation at 1.5°C versus 2°C. 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, consistent with the analysis of Jacob et al. (2014) which used more recent downscaled climate scenarios (EURO-CORDEX) and a higher resolution (12km) for +2°C global warming. There is a consistent agreement in the direction of change for +1.5°C global warming over much of Europe (Jacob et al., 2018). While there are variations between regions, the global tendency for heavy precipitation suggests an increase at 2°C versus 1.5°C (see also Fischer and Knutti, 2015), and Kharin et al., 2018), Figure 3.10, as well as Betts et al., 2018).

The 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). There are a few publications that provide more recent evaluations on projections of changes in monsoons for high-emissions scenarios (e.g., Jiang and Tian, 2013; Jones and Carvalho, 2013; Sylla et al., 2015, 2016); Annex S3-3). However, given that a) scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the AR5 and these more recent studies, and b) the fact that there appears to be no specific assessment of changes in monsoon precipitation at 1.5°C versus 2°C global warming in the present literature, and c) that there is *low confidence* in observed trends in monsoons (Section 3.3.3.1), the present assessment is that there is *low confidence* regarding projected changes in monsoons at 1.5°C and 2°C global warming, as well as regarding differences in monsoon responses at 1.5°C versus 2°C.

Similarly, as for Figure 3.8, Figure 3.11 includes an objective identification of “hot spots” / key risks in heavy precipitation indices subdivided by regions, based on (Wartenburger et al., 2017). The considered regions follow the classification of the IPCC SREX report (Figure 3.2) and also include global land areas. The figure displays red shading for all instances in which a significant difference is found between regional responses at 1.5°C versus 2°C. Hot spots displaying statistically significant changes in heavy precipitation between 1.5°C and 2°C global warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia) and high-altitude (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 heavy precipitation *(likely)*. Several regions display statistically significant differences in heavy precipitation at 1.5°C *vs.* 2°C warming (with stronger increase at 2°C), and there is a global tendency towards increases in heavy precipitation on land between these two temperature levels (*likely*). Overall, regions that display statistically significant changes in heavy precipitation between 1.5°C and 2°C global warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, 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 at 1.5°C versus 2°C in other regions.

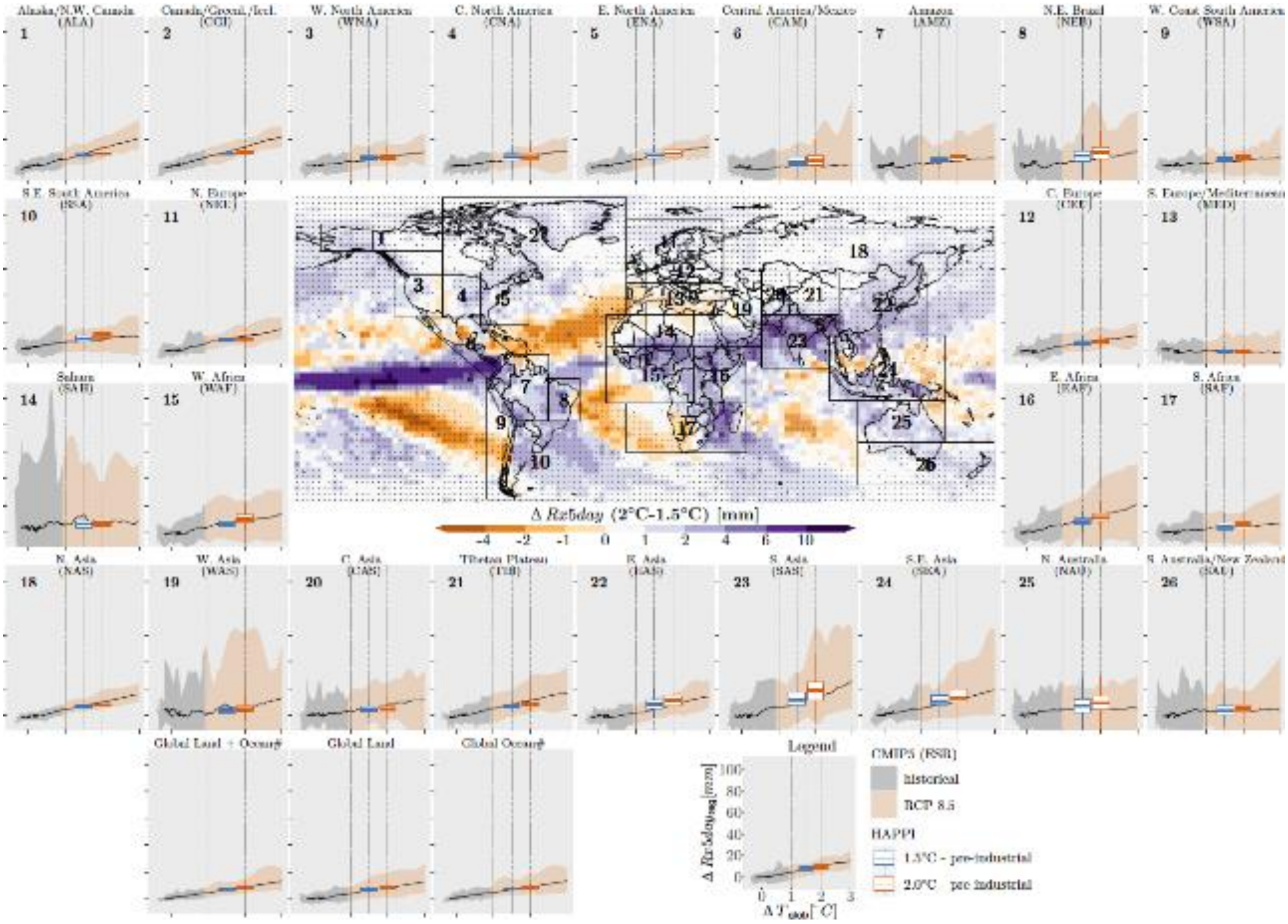


Figure 3.9: Projected changes in annual 5-day maximum precipitation (Rx5day) as function of global temperature warming for IPCC Special Report on the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (Figure 3.2), based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) together with projected changes from the HAPPI multi-model experiment (bar plots on regional analyses and central plot). Same data basis and analysis approach as in Figure 3.5 (Annex 3.1 S3-3 for more details).

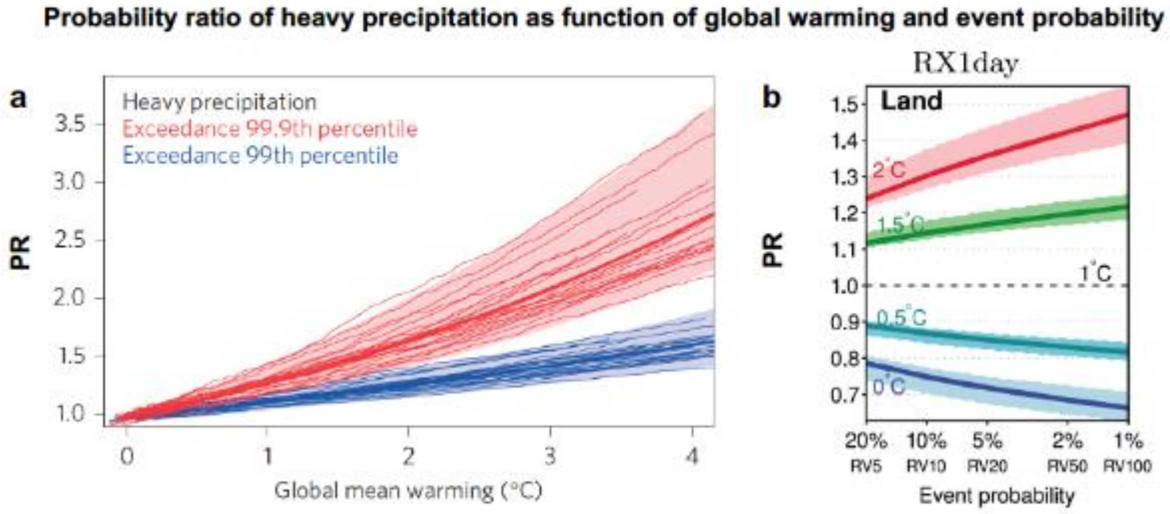
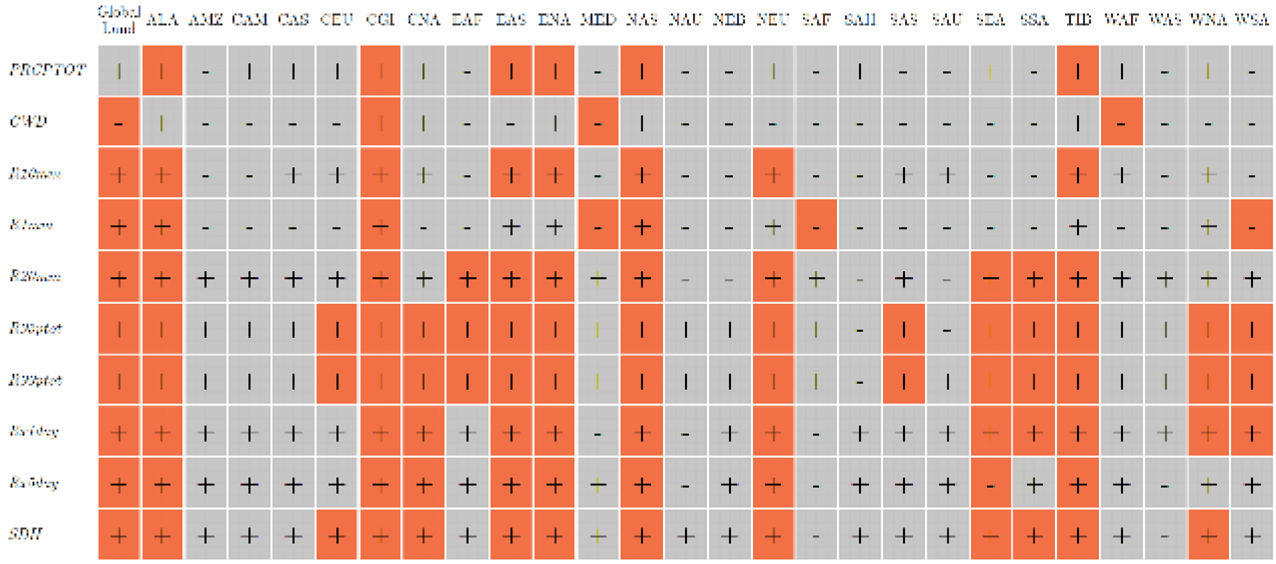


Figure 3.10: Probability ratio (PR) of exceeding extreme preciptiation (heavy precipitation) thresholds. (Left, a): PR of exceeding the (blue) 99th and (red) 99.9th percentile of pre-industrial daily precipitation at a given warming level relative to pre-industrial conditions averaged across land (fromFischer and Knutti, 2015). (Right, b): PR for precipitation extremes (Rx1d) for different event probabilities (with RV indicating return values) in the current climate (1°C warming); the shading shows the interquartile (25%-75%) range (from Kharin et al., 2018).



	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	-	|	-	-	-	-	|	|	-	-	|	-	|	-	-	-	-	-	-	-	-	-	|	-	-	-	-
R10mm	+	+	-	-	+	+	+	+	-	+	+	-	+	-	-	+	-	-	+	+	-	-	+	+	-	+	-
R1mm	+	+	-	-	-	-	+	-	-	+	+	-	+	-	-	+	-	-	-	-	-	-	+	-	-	+	-
R20mm	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	-	+	+	+	+	+	+	+
R95ptot	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	-	|	-	|	|	|	|	|	|	|
R99ptot	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	-	|	|	|	|	|	|	|	|	|
Rx1day	+	+	+	+	+	+	+	+	+	+	+	-	+	-	+	+	-	+	+	+	+	+	+	+	+	+	+
Rx5day	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	-	+	+	+	-	+	+	+	-	+	+
SDII	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+	-	+	+

Figure 3.11: Significance of differences of 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 > 10mm; R1mm: Number of days with precipitation>1mm; R20mm: Number of days with precipitation >20mm; 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 3.3 for definition). Significant differences are shown in red shading (increases indicated with + sign, decreases indicated with – sign), insignificant differences are shown in grey shading. Same data basis and analaysis approach as in Figure 3.8 (see Annex 3.1 S3-3 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 global scale, but that there was *likely* to be trends in some regions of the world, including increases in drought in the Mediterranean and West Africa and decreases in droughts in central North America and north-west Australia (Hartmann et al., 2013; Stocker et al., 2013). The AR5 assessed that there was *low confidence* in the attribution of global changes in droughts (Bindoff et al., 2013a) and did not provide assessments for the attribution of regional changes in droughts (Bindoff et al., 2013a).

The recent literature does not suggest a necessary revision of this assessment, except in the Mediterranean region. Recent publications based on observational and modeling 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). There is also new evidence documenting consistent observed drying trends in the Eastern Mediterranean (Syria; see Box 3.2). Based on this evidence, there is *medium confidence* that enhanced greenhouse forcing contributed to increased drying in the Mediterranean region (including Southern Europe, Northern Africa and the Near-East) and that this tendency will thus continue to be increased under higher levels of global warming.

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). To reduce the adverse effects of climate change, all African countries signed the Paris Agreement and through their Nationally Determined Contributions (NDCs), they committed to contribute to the global effort of mitigation of Greenhouse Gas (GHG) emissions in the aim to hold global temperature increases to ‘well below 2 degrees’ and to pursue efforts to limit warming to ‘1.5 °C above preindustrial levels’. The target of limiting to 1.5°C above pre-industrial levels is a useful message to share the urgency, but it focused the climate change debate on a temperature threshold (Section 3.3.2), while the potential impacts of these global warming levels at local to regional scales on key sectors such as agriculture, energy, health, etc. 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; 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 heat waves (e.g., Kharin et al., 2018). Increases would be even larger if the global mean temperature reaches 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 display particularly large increases in the number of hot days, both at 1.5°C and 2°C global warming (Section 3.3.2). This is due to the relatively small interannual present-day variability, which implies that climate-change signals can be detected earlier (Mahlstein et al., 2011, Section 3.3.2). Changes in total precipitation exhibit several uncertainties, mainly in the Sahel (Diedhiou et al., 2018) Section 3.3.3 and Figure 3.8). In the Guinea Coast and Central Africa, a weak change in the total precipitation is noted though it is projected in most models (70%) a decrease of the length of wet spells and a slight increase of 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 meet serious food security issues (Salem et al., 2017; Parkes et al., 2018) Cross-Chapter Box 6 and Section 3.4.6). West Africa has thus been identified as a climate-change hot spot with a likelihood of negative impact of climate change in crop yields and production (Cross-Chapter Box 6, Section 3.4.6; Sultan and Gaetani, 2016; Palazzo et al., 2017). Despite uncertainty in future projections of the precipitation in West Africa, which is essential for rain-fed agriculture, a robust evidence of yield loss might emerge. This yield loss is mainly driven by increased mean temperature while potential wetter or drier conditions as well as elevated CO_2 concentrations can 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 Cooridnated Regional Climate Downscaling Experiment (CORDEX) scenarios from 25 Regional Climate Models (RCMs) forced with different General Circulation Models (GCMs), Klutse et al. (2018) noted over West Africa a decrease of mean rainfall in models with larger warming at 1.5°C (Section 3.3.4) and Mba et al. (2018) found over Central Africa a lack of consensus in the changes in precipitation (Figure 3.8 and Section 3.3.4), though there is a tendency to a decrease of the maximum length of Consecutive Wet Days (CWD) and a significant increase of the maximum length of Consecutive Dry Days (CDD).

Over southern Africa, models agree in a positive sign of change for temperature, with temperature rising faster at 2°C (1.5ºC-2.5°C) compared to 1.5°C (0.5ºC - 1.5°C). Areas of the south-western region, especially in South Africa and parts of Namibia and Botswana are expected to experience the highest increases in temperature (Engelbrecht et al., 2015; Maúre et al., 2018; Section 3.3.2). The western part of southern Africa is projected to become drier with increasing drought frequency and number of heat waves towards the end of the 21st century (Engelbrecht et al., 2015; Dosio, 2017; Maúre et al., 2018) Section 3.3.4). 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 in 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 length of CDD with longer dry spells projected over Namibia, Botswana, northern Zimbabwe and southern Zambia. Conversely, the length of CWD is projected to decrease with robust signals over Western Cape (Maúre et al., 2018). Projected reductions in stream flow between 5% and 10% in the Zambezi River Basin have been associated with increased evaporation and transpiration rates resulting from rise in temperature (Kling et al., 2014; Section 3.3.5) with issues on hydroelectric power across the southern African region.

Over Eastern Africa, Osima et al. (2018) found that annual rainfall projections show a robust wetting signal over Somalia and a less robust decrease over central and northern Ethiopia (Section 3.3.3). The length 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).

[END BOX 3.1 HERE]

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 the AR5, which assessed these projections as being '*likely* (*medium confidence*)' (Collins et al., 2013; Stocker et al., 2013). However, given the *medium confidence*, we assess that it does not seem suitable to provide a likelihood statement, consistent 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 the AR5 (Stocker et al., 2013) assessed that soil moisture drying in the Mediterranean, Southwest USA and southern African regions was consistent with projected changes in the Hadley circulation and increased surface temperatures and concluded that there was *high confidence* in *likely* surface drying in these regions by the end of this century under the RCP8.5 scenario. However, more recent assessments have highlighted uncertainties in dryness projections due to a range of factors, including variations between considered drought and dryness indices 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 global warming) are uncertain in many regions, despite the existence of a few regions displaying consistent drying in most assessments (e.g., Seneviratne et al., 2012; Orlowsky and Seneviratne, 2013). Uncertainty is expected to be even larger for conditions of 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 global warming for a) Precipitation-Evapotranspiration (P-E, i.e. as a general measure of water availability; Wartenburger et al., 2017; Greve et al., 2018), b) soil moisture anomalies (Lehner et al., 2017; Wartenburger et al., 2017), c) consecutive dry days (Schleussner et al., 2016b; Wartenburger et al., 2017), d) the 12-month Standardized Precipitation Index (Wartenburger et al. (2017), e) the Palmer-Drought Severity Index (Lehner et al., 2017), f) annual mean runoff (Schleussner et al., 2016b, see also next section). These analyses are overall consistent, despite the known sensitivity of drought assessment to chosen drought indices (see above paragraph).

Figure 3.12 in Greve et al. (2018) derives the sensitivity of regional changes in precipitation minus evapotranspiration to global temperature changes. The analysed simulations span the full range of available emissions 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 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, i.e. whether there might be increases or decreases in water availability under higher global warming, is particularly uncertain in tropical and mid-latitude regions. An assessment of the implications of limiting global mean temperature warming to values below (i) 1.5°C or (ii) 2°C shows that opting for the 1.5°C-target might slightly influence the mean response, but could substantially reduce the risk of experiencing extreme changes in regional water availability (Greve et al., 2018).

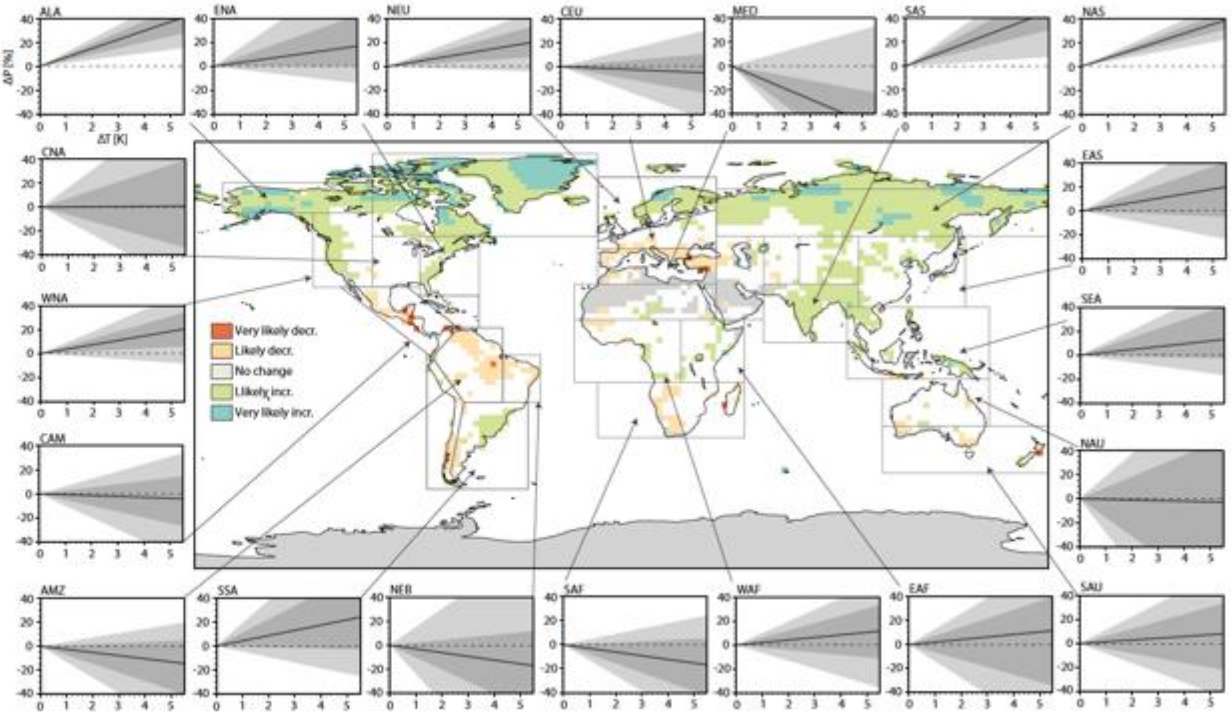


Figure 3.12: Summary of the likelihood of increases/decreases in Precipitation-Evapotranspiration (P-E) in Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations considering all scenarios and a representative subset of 14 climate models (one from each modeling center). Panel plots show the uncertainty distribution of the sensitivity of P-E to global temperature change as a function of global mean 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).

The analysis for the mean response is also qualitatively consistent with results from Wartenburger et al. (2017), which use an ESR (Section 3.2) rather than pattern scaling for a range of drought and dryness indices, as well as with a recent assessment of Lehner et al. (2017) which consider changes in droughts assessed from the soil moisture changes and from the Palmer-Drought Severity Index. We note that these two further publications do not provide a specific assessment for changes in tails of the drought and dryness distribution. The conclusions of (Lehner et al., 2017) are that a) 'risks of consecutive drought years shows little change in the US Southwest and Central Plains, but robust increases in Europe and the Mediterranean', and that b) '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 displays projected changes in CDD as a function of global temperature increase, using a similar approach as in Figures 3.5 (based on Wartenburger et al., 2017). The analyses also include results from the HAPPI experiment (Mitchell et al., 2017). Again, the CMIP5-based ESR estimates and the results of the HAPPI experiment are found to agree well. We note the large disparity of responses depending on the considered regions.

Similarly as for Figures 3.8 and 3.11, Figure 3.14 includes an objective identification of “hot spots” / key risks in dryness indices subdivided by regions, based on (Wartenburger et al., 2017). This analysis reveals the following hot spots of drying, i.e. with increases in CDD, and decreases in P-E, Soil Moisture Anomalies (SMA), and SPI12, with at least two of the indices displaying statistically significant drying: the Mediterranean region (MED; including Southern Europe, northern Africa, and the Near-East) and Southern Africa. However, drying trends are also identified for single indices in Northeastern Brazil and Western South America. In addition, subregional drying trends are projected in the Western Sahel (see also Box 3.1) and in the Amazon region and Central America and Mexico (Fig. 3.12).

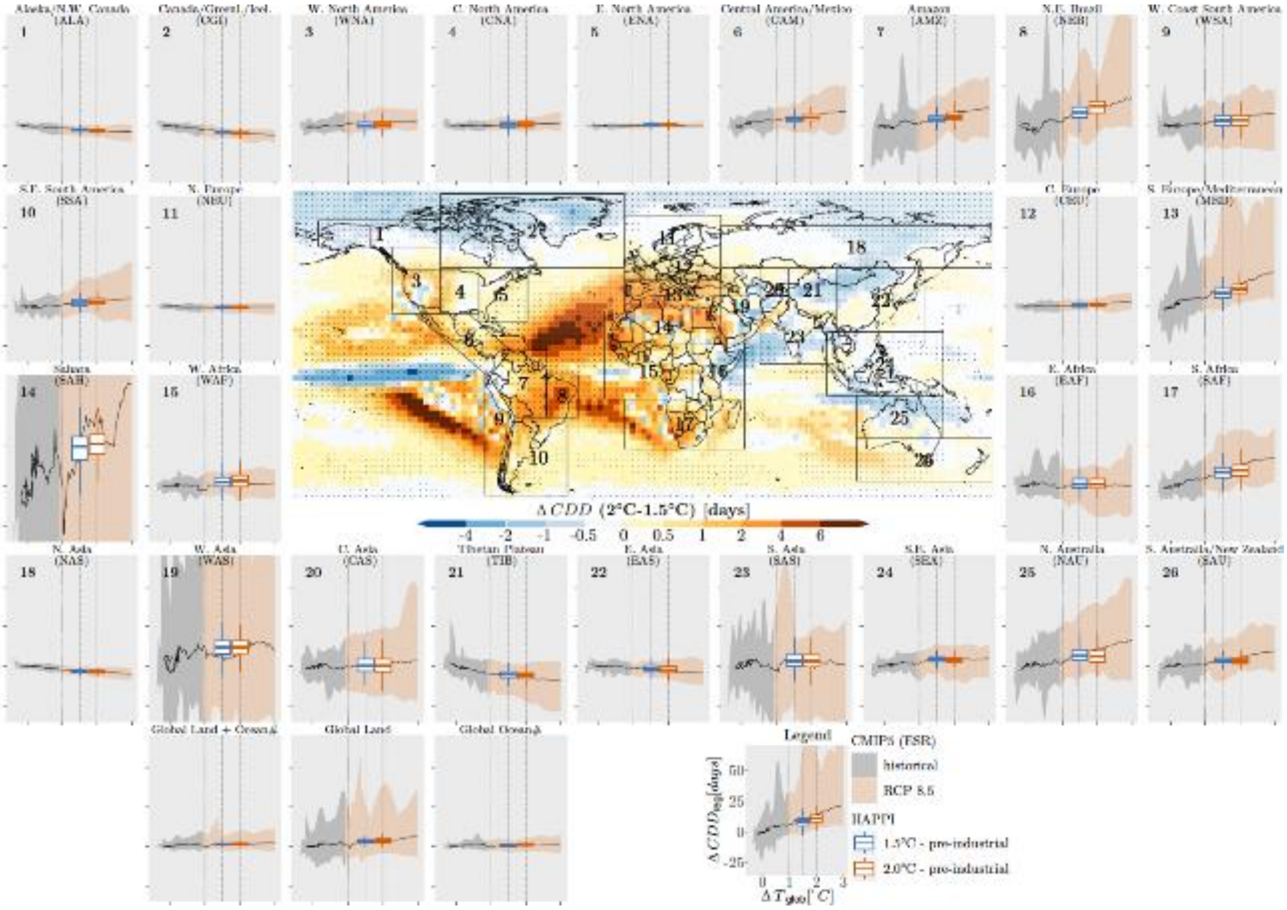
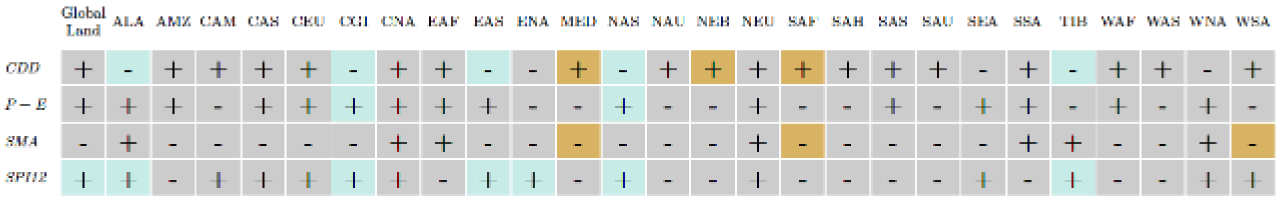


Figure 3.13: Projected changes in consecutive dry days (CDD) as function of global temperature warming for IPCC Special Report on Managng the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions, based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data together with projected changes from the HAPPI multi-model experiment (bar plots on regional analyses and central plot, respectively). Same data basis and analysis approach as in Figure 3.5 (Annex 3.1 S3-3 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: Similar as Figures 3.8 and 3.11 but for changes in dryness indices. Significance of differences of 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 Evaporation; SMA: Soil Moisture Anomalies; SPI12: 12-month SPI. Columns indicate regions and global land (see Figure 3.2 for definitions). Significant differences are shown in light blue/brownshading (increases in indices indicated with + sign, decreases indicated with – sign; the light blue shading indicates decreases in dryness (decreases in CDD, or increases in P-E, SMA or SPI12) and the light brown shading indicates increases in dryness (increases in CDD, or decreases in P-E, SMA or SPI12). Insignificant differences are shown in grey shading. Same data basis and analysis approach as in Figure 3.7 (see Annex 3.1 S3-3 for more details).

Overall, the available literature, consistent with this analysis, reports particularly strong increases in dryness and decreases in water availability in Southern Europe and the Mediterranean when shifting from a 1.5°C to a 2°C global warming (Schleussner et al., 2016b; Lehner et al., 2017; Wartenburger et al., 2017; Greve et al., 2018; Samaniego et al., 2018; Figure 3.13). The fact that this is a region that is also 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) provides additional evidence supporting this tendency, suggesting that it is a hot spot of dryness change above 1.5°C (see also Box 3.2). Some of the other identified hot spots, Southern Africa and Northeastern Brazil, are also consistently shown to display drying trends in other publications for higher levels of forcing (e.g., Orlowsky and Seneviratne, 2013), although there are so far to our knowledge no studies reporting observed drying trends in these regions. We thus form the consensus that there are substantial increases in risk of dryness (*medium confidence)* in both the Mediterranean region and South Africa at 2°C versus 1.5°C global warming, because these regions display significant changes in two dryness indicators (CDD and SMA) at these two global warming levels (Figure 3.14). There is *low confidence* elsewhere due to 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 at 2°C versus 1.5°C (Figure 3.12).

In summary, in terms of drought and dryness, limiting global warming to 1.5ºC may substantially reduce the probability of extreme changes in water availability in some regions compared to changes for 2°C global warming (*medium confidence*). When shifting from 1.5 to 2°C, available studies and analyses suggest strong increases in 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 model experiments, a drying trend is already detectable in the Mediterranean region, i.e. for a global warming of less than 1°C (*medium confidence*).

[START BOX 3.2 HERE]

Box 3.2: Mediterranean Basin and the Middle East Droughts

Human society has developed in tandem with the natural environment of the Mediterranean Basin over several millennia, laying the ground 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 the Mediterranean continue to depend on the long term interplay between an array of societal and environmental factors (Holmgren et al., 2016). This makes this region an example of strong vulnerability and various adaptation responses. Previous IPCC assessments and recent publications project regional changes in climate under increased warming, including consistent climate model projections of increased precipitation deficit amplified by strong regional warming (Seneviratne et al., 2012; Christensen et al., 2013; Collins et al., 2013; Greve and Seneviratne, 2015; Section 3.3.3).

A good example of such long history of resilience is the Eastern Mediterranean region, which has exhibited a strong negative trend in precipitation since 1960 (Mathbout et al., 2017) and experienced an intense and prolonged drought episode between 2007 and 2010 (Kelley et al., 2015). This drought was the longest and the 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 have also been noticed on the water resource (Yazdanpanah et al., 2016) and the crop performance in Iran (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/2°C warming (Section 3.3.4) can be analyzed 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 on the 1931-2008 period on Syria) and a large population increase (from 5 million in 1960 to 22 million in 2008). Koutroulis et al. (2013) projects that of the 18% decrease of water availability for Crete under a 2°C global warming at the end of the 21st century, only 6% is due to decreased precipitation (the rest is due to an increase in evapotranspiration). This study and others like it confirm an important risk of extreme drought conditions for the Middle East (even higher in continental locations than in islands) with a 1.5°C global warming (Jacob et al., 2018), consistent with current observed changes (Greve et al., 2014); Section 3.3.4). Risks of drying in the Mediterranean region can be substantially reduced if global warming is limited to 1.5°C compared to 2°C or higher levels of warming (Guiot and Cramer, 2016); see also Section 3.4.3). Higher warming levels may induce strong levels of vulnerability exacerbated by large changes in demography.

[END BOX 3.2 HERE]

3.3.5 *Runoff and fluvial flooding*

3.3.5.1 Observed and attributed changes in runof and river flooding

There has been progress since the AR5 in identifying historical changes in streamflow and continental runoff. Dai (2016) using available streamflow data shows that long-term (1948–2012) flow trends are statistically significant only for 27.5% of the 200 world's major rivers with negative trends outnumbering the positive ones. Although streamflow trends are mostly non-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 northeast United States, central and northern Europe, and most of Russia and decreased over most of Africa, East and South Asia, eastern coastal Australia, southeastern and northwestern United States, western and eastern Canada, the Mediterranean region and in some regions of Brazil (Dai, 2016).

A large part of the observed regional trends in streamflow and runoff could have resulted from internal multidecadal and multiyear climate variations, especially the Pacific Decadal Variability (PDV), the Atlantic Multidecadal Oscillation (AMO) and the El Niño-Southern Oscillation (ENSO) although the effect of anthropogenic greenhouse gasses 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 can also have a large impact on runoff at river basin scales 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 from irrigation (Gerten et al., 2008; Sterling et al., 2012). Likewise, forest and grassland fires can also modify the hydrological response at a watershed scale when the burned area is significant (Versini et al., 2013; Springer et al., 2015; Wine and Cadol, 2016).

Few studies explore observed changes in extreme streamflow and river flooding since the IPCC AR5. Mallakpour and Villarini (2015) analyzed changes of flood magnitude and frequency in Central United States considering stream gauge daily records with at least 50 years of data ending no earlier than 2011. They showed that flood frequency has increased while 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 non-statistically significant in most of the world's largest rivers *(high confidence)*, while flood frequency and extreme streamflow increased in some regions *(high confidence)*.

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

Global-scale assessments of projected changes on freshwatr 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 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 statistically significant 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 for 1.5°C, and rise to between 26% (Döll et al., 2018) and approximately 50% (Betts et al., 2018) for 2°C.

At the regional scale, projected runoff changes in general follow the spatial extent of projected changes in precipitation (see Section 3.3.3). Emerging literature shows runoff projections for different warming levels. For 2°C global warming, an increase in runoff is projected for much of the high northern latitudes, Southeast Asia, East Africa, north-eastern Europe, India, and parts of, Austria, China, Hungary, Norway, Sweden, the northwest Balkans, and Sahel (Schleussner et al., 2016b; Donnelly et al., 2017; Zhai et al., 2017; Döll et al., 2018). Addtionally, decreases are projected in the Mediterranean region, South 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 warming, runoff could decrease by 17% (likely range 8–25%) (Schleussner et al., 2016b). Consistently, Döll et al. (2018) found that for an increase in global warming from 1.5°C to 2°C, statistically insignificant changes of the mean annual streamflow around the Mediterranean region become significant with decreases of 10–30%. Donnelly et al. (2017) found an intense decrease in runoff along both the Iberian and Balkan coasts as warming level increases.

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 major river basins at 1.5°C and 2°C global warming (Figure 3.15). They found a general tendency towards increased runoff in the majority of the basins 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% for 2°C global warming. Gosling et al. (2017) analyzed the impact of global warming of 1°C, 2°C and 3°C above pre-industrial levels on river runoff at 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 increase. Donnelly et al. (2017) analyzed 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 in large parts of northern Europe, the Glomma, Wisla and Lule rivers could increase their discharges with global warming while 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. Projected mean annual runoff of the Yiluo River catchment in northern China will decrease by 22% for 1.5°C and by 21% for 2°C, while the the mean annual runoff for the Beijiang River in southern China, is projected to increase by less than 1% and 3% in comparicon to the studied baseline period for 1.5°C and 2°C respectively (L. Liu et al., 2017). Chen et al. (2017) assessed the future changes of water resources in the Upper Yangtze River basin for the same warming levels and found a slight decrease in the annual discharge for 1.5°C which reverses sign for 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 global warming and for two emission scenarios. The Uruguay basin shows increases in streamflow in all scenarios/warming targets except for the combination of RCP8.5/1.5°C warming. The increase is approximately 15% above the 1981–2000 reference period for 2°C global warming and the RCP4.5 scenario. For the other three rivers the sign of the change in mean streamflow highly depends on the RCP and GCM used.

Marx et al. (2018) analyzed how hydrological low flows in Europe are affected under different global warming levels (1.5°C, 2°C and 3°C). The Alpine region shows the strongest low flow increase from 22% for 1.5°C to 30% for 2°C because of the snow melt contribution, while in the Mediterranean low flows are expected to decrease due to the projected decreases in annual precipitation. Döll et al. (2018) found that extreme low flows in the tropical Amazon, Congo and Indonesian basins could decrease by 10% while in the southwestern part of Russia they could increase by 30% at 1.5°C. For 2°C, projected increases of 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 in Southern and Western Europe, although not in the Congo basin or Indonesia, where models show less agreement.

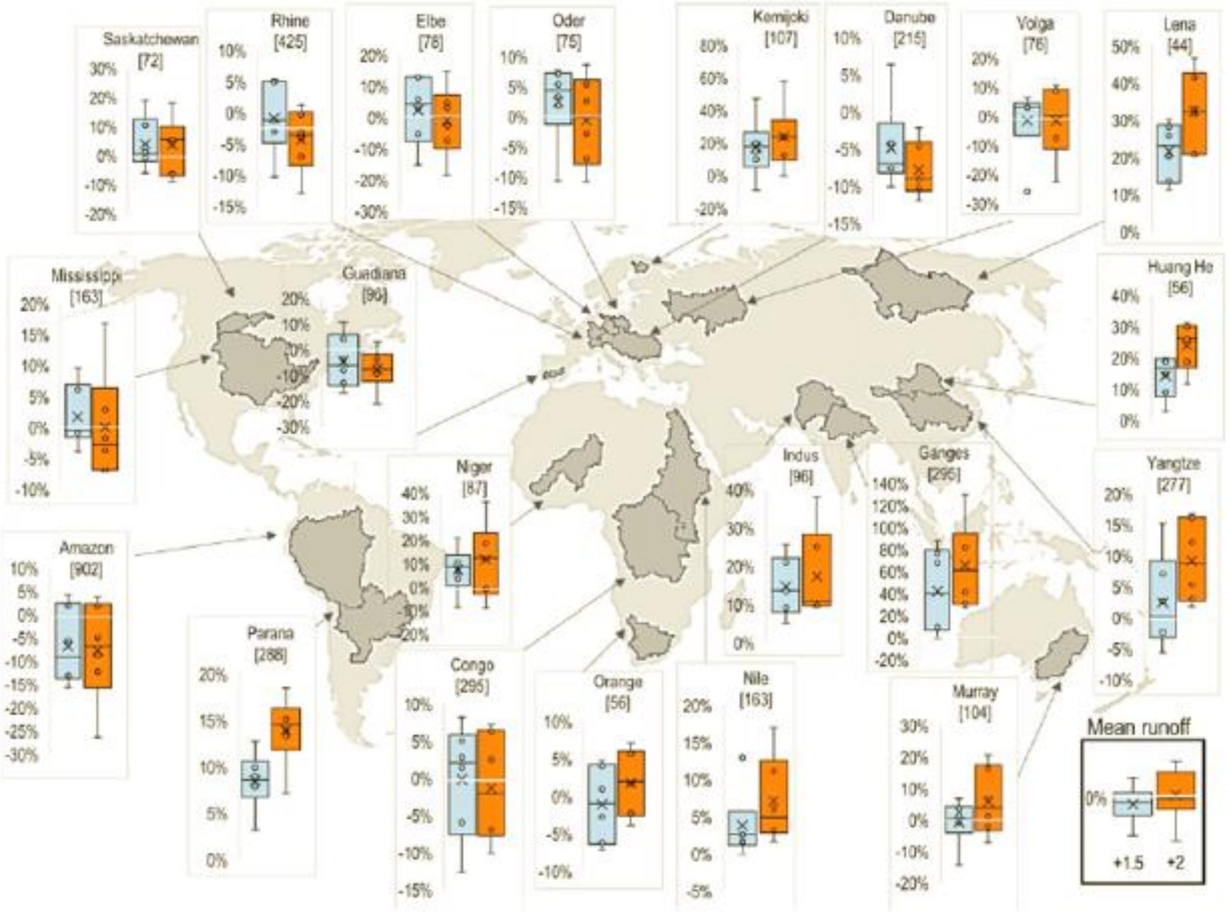


Figure 3.15: Runoff changes in twenty-one of the world major river basins at 1.5°C (blue) and 2°C (orange) global warming simulated by the Joint UK Land Environment Simulator (JULES) ecosystem–hydrology model under the ensemble of six climate projections. Boxes show the 25th and 75th percentile changes, 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) (from Betts et al., 2018).

Recent analysis 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 occurrence interval larger than the return period of present flood protections are projected to increase in all continents under all considered warming levels, leading to 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 which intensify under 2°C and include parts of South America.

At 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 global warming. Thober et al. (2018) identified the Mediterranean region as a hotspot of change with significant decreases of −11% (-13%) in high flows at 1.5°C (2°C) mainly resulting from reduced precipitation (Box 3.2). In Northern regions, high flows are projected to rise between 1%-5% for 1.5°C and 2°C respectively due to increasing precipitation, although floods could decrease by 6% in both scenarios due to 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 increasing warming level. For 2°C, flood magnitudes are expected to increase significantly in Europe south of 60°N, except for some regions (Bulgaria, Poland, southern Spain) while they are projected to decrease in most of Finland, northwestern Russia and northern Sweden, with the exception of southern Sweden and some coastal areas in Norway where floods may increase (Roudier et al., 2016). At 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 a global warming of 2°C would lead to an expansion of the area with significant increases in runoff as well as of the area affected by flood hazard compared to conditions at 1.5°C 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*) as well as 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 are focusing 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 et al., 2006; Walsh et al., 2016). Numerous studies towards and beyond 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 has recently been provided by Kang and Elsner (2015). However Klotzbach (2006), using a relatively short (twenty year) relatively homogeneous remotely sensed record 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 on 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), and 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 cyclones is increasing (Mohapatra et al., 2017). Moreover, studies that have used more homogeneous records but that were consequently limited to rather short periods of 20 to 25 years in length, have reported no statistically significant trends or decreases in the global number of these systems (Kamahori et al., 2006; Klotzbach and Landsea, 2015). CMIP5 model simulations of the historical period have also 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 larger number of studies reporting increasing trends in the global number of very intense cyclones.

GCM projections of the changing attributes of tropical cyclones under high levels of greenhouse gas forcing (3°C to 4°C) are consistently indicating 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 are contradicting these findings, however, and are indicative of 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, we assess that under 3 to 4 °C of warming *it is more likely than not* (*medium confidence*) that the global number of tropical cyclones would decrease whilst the number of very intense cyclones would increase.

Only two studies have to date 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. (2017) 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 (category 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 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 has been assessed in the IPCC SREX to *likely* increase under increasing global warming (Seneviratne et al., 2012). Two recent articles suggest that there is *high confidence* that global warming for present conditions (i.e. about 1°C of global warming, see Section 3.3.1) has 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) also explored the effects of different degrees of global warming on tropical cyclones over the southwest Indian Ocean, in transient simulations that downscaled a number of RCP8.5 GCM projections. Decreases in tropical cyclone frequencies are projected under both 1.5ºC and 2°C of global warming. The decreases in cyclone frequencies under 2°C global warming are somewhat larger than under 1.5°C of global warming, but with no further decreases projected under 3°C of global warming. This suggests that 2°C of warming, at least in these downscaling simulations, represent 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 less under 2°C of global warming compared to 1.5 °C of 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 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 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). The AR5 (Stocker et al., 2013) assessed that under high greenhouse forcing (3°C or 4°C) there is *low confidence* in projections of poleward shifts of the North-Hemisphere storm tracks, while there is *high confidence* that there would be a small poleward shift of the South-Hemisphere storm tracks.In the context of this report, we assess that there is *limited evidence* and *low confidence* in whether any projected signal for higher levels of warming is to be well-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) has been increasing at a rate just behind that of the warming trend for the planet. The surface of three ocean basins have 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, AR5 Chapter 30), with the greatest changes occurring at the highest latitudes. Isotherms (i.e. lines of equal temperature) of sea surface temperature (SST) are traveling 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). Increased heat in the upper layers of the ocean is also driving more intense storms and greater rates of inundation, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas.

Increasing land-sea temperature gradients, as induced by higher rates of continental warming compared to the surrounding oceans under climate change, 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 are unclear in terms of trends detected in the upwelling currents themselves (Lluch-Cota et al., 2014). Projecting the scale of the changes between 1ºC and 1.5ºC, and 1.5ºC and 2ºC is only informed by the changes over the past change in GMST of 0.5ºC (*low confidence*). However, the weight of evidence from GCM projections of future climate change indicates the general strengthening of the Benguela, Canary and Humboldt upwelling systems under enhanced anthropogenic forcing (D. Wang et al., 2015) is *likely* to occur. 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, but at lower latitudes long-shore winds may decrease 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 by 30% since the late 1950s (Srokosz and Bryden, 2015; Caesar et al., 2018). There is only *limited evidence* linking the current anomalously week state of AMOC to anthropogenic warming (Caesar et al., 2018). It is *very likely* that the AMOC will weaken over the 21st century. Best estimates and range for the reduction from CMIP5 are 11% (1 to 24%) in RCP2.6 and 34% (12 to 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 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. Also sea-ice thickness has 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-model simulations of the recent past, and are projected to decrease in the future (Collins et al., 2013). However, the modeled sea-ice loss in most CMIP5 models is much weaker than observed. Compared to observations, the simulations are weak in terms of their sensitivity to both global mean temperature rise (Rosenblum and Eisenman, 2017) and to anthropogenic CO_2 emissions (Notz and Stroeve, 2016). This mismatch between the observed and modeled sensitivity of Arctic sea ice implies that the multi-model-mean response 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. Often based on such bias correction, pre-AR5 and post-AR5 studies agree that for 1.5 °C global warming relative to pre-industrial levels, the Arctic Ocean will maintain a sea-ice cover throughout summer for 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 global warming relative to pre-industrial levels, chances of an 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). The

Arctic is *very likely* to have experienced at least one ice-free Arctic summer after about 10 years of stabilized warming at 2°C compared to after about 100 years of stabilized warming at 1.5°C (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 for 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 achieve an ice-free Arctic Ocean during summer are lower than the ones given in AR5 (about 2.6°C-3.1°C relative to preindustrial or 1.6°C-2.1°C global warming relative to the present day), which was similar to the estimate of 3°C relative to preindustrial levels (or 2°C global warming relative to the present day) by Mahlstein and Knutti (2012) based on bias-corrected CMIP3 models. Rosenblum and Eisenman (2016) explain why the sensitivity estimated by Mahlstein and Knutti (2012) might be too low, estimating instead that September sea ice in the Arctic disappears for 2°C relative to preindustrial (or about 1°C global warming relative to the present day), in line with the other recent estimates. Notz and Stroeve (2016) use the observed correlation between September sea-ice extent and cumulative CO_2 emissions to estimate that the Arctic Ocean would become nearly sea-ice-free during September with a further 1000 Gt of emissions, which also implies a sea-ice loss at about 2°C global warming. Some of the uncertainty in these numbers derives 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 2ºC global warming (Niederdrenk and Notz, 2018).

Regarding the behavior of Arctic sea ice under decreasing temperatures following a possible overshoot of a long-term temperature target, a substantial number of pre-AR5 studies have found that there is no indication of hysteresis behavior of Arctic sea ice (Holland et al., 2006; Schroeder 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 is 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, with for example strongly decreased sea-ice coverage near the Antarctic peninsula and 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, with, however, comparably low ice coverage from September 2016 onwards. Collins et al. (2013) have *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 studies are hence available to robustly assess 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 global warming relative to pre-industrial levels and it is *very likely* that there will be the least one sea-ice-free Arctic summer after about 10 years of stabilized warming at 2°C, while about 100 years are required for a sea-ice-free Arctic summer at 1.5°C. There is *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea-ice coverage.

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 volcanoes (Fasullo et al., 2016). Accounting for the former results in rates (1993 to mid-2014) of 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, as well as freshwater storage on land, are relatively well understood (Church et al., 2013; Watson et al., 2015) and there 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 seen 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, where available. Church et al. (2013) assigned *low confidence* to SEMs because of their assumption 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 overcome this by considering individual GMSL contributors separately and are therefore employed in this assessment. In this subsection, the process-based literature of individual contributors to GMSL is considered for scenarios close to 1.5ºC and 2ºC before assessing emulation-based approaches.

A limited number of processes-based studies are relevant to GMSL in 1.5ºC and 2ºC worlds. Marzeion et al. (2018) force a global glacier model with temperature-scaled scenarios based on RCP2.6 to investigate the difference between 1.5ºC and 2ºC and find little difference between scenarios in the glacier contribution to GMSL at 2100 (54-97 mm relative to present day for 1.5ºC, and 63-112 mm for 2ºC using a 90% confidence interval). This arises because melt during the remainder of the century is dominated by the response to warming from preindustrial to present-day levels (in turn a reflection of the slow response times of glaciers). Fuerst et al. (2015) make projections of 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 obtain an RCP2.6 range of 24-60 mm (1 standard deviation) by the end of the century (relative to 2000 and consistent with the assessment of Church et al. (2013)), however their projections do not allow the difference between 1.5ºC and 2ºC worlds to be evaluated.

The Antarctic ice sheet can contribute both positively and negatively to future GMSL rise by, respectively, increases in outflow (solid ice lost directly to the ocean) and increases in snowfall (due to the increased moisture-bearing capacity of a warmer atmosphere). Frieler et al. (2015) suggest a range of 3.5-8.7 % K^{-1} for this effect, which is consistent with the AR5. Observations from the Amundsen Sea sector of Antarctic 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 change 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 at 2100 is available, it is insufficient to distinguish between emission scenarios associated with 1.5ºC and 2ºC worlds. This literature is, however, consistent with Church et al. (2013) assessment of a *likely* range of 0.28-0.61 m at 2100 (relative to 1986-2005) suggesting that 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 1.5ºC and 2ºC worlds. Table 3.1 presents a compilation of both 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 and 2.0 °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**		**1.5ºC**		**2ºC**	
		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), in particular at their upper limit, however there is *medium agreement* that GMSL at 2100 would be 0-0.2 m higher in a 2ºC world compared to 1.5 ºC with a most likely value of 0.1 m. There is *medium confidence* in this assessment because of issues associated with both 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 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 accounting for spatial differences in ocean heat uptake and circulation. The second maps regional sea level on 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) present a framework to do this and give an example application for nine sites (in the US, Japan, northern Europe and Chile). Of these sites, seven (all except those in northern Europe) 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 no future sea-level rise. Rasmussen et al. (2018)(2018) use this approach to investigate the difference between 1.5ºC and 2ºC worlds up to 2200. They find that the reduction in the frequency of 1-in-100 year floods in 1.5ºC compared to 2ºC worlds is greatest in the eastern US and Europe, with ESL event frequency amplification being reduced by about a half and with smaller reductions for Small Island Developing States (SIDS). This latter 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) emulate the AMOC based on a subset of CMIP-class climate models. When forced using global temperatures appropriate to the CP3-PD scenario (1ºC warming at 2100 relative to 2000 or ~2 ºC relative to preindustrial), the emulation suggests an 11% median reduction in AMOC strength at 2100 (relative to 2000) with 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 less by the end of the century in a 1.5°C compared to a 2ºC warmer world. SLR beyond 2100 is discussed in 3.6, however recent literature strongly supports Church et al. (2013)'s assessment that sea level rise will continue well beyond 2100.

[START BOX 3.3 HERE]

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 (1.5ºC-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 yr and during the Last Glacial Maximum (LGM) has been 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 about10-5 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 millions years BP).

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

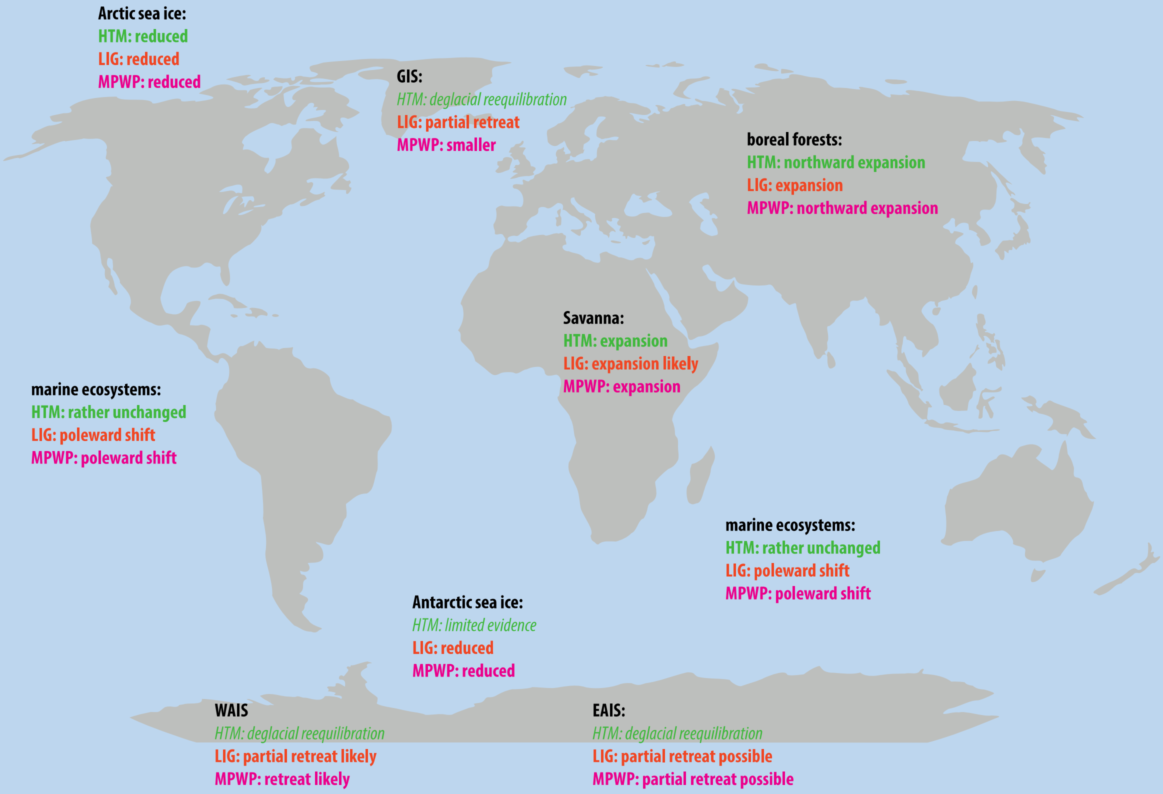
Although imperfect as analogs for the future, these regional changes can inform risk assessments such as the potential for crossing irreversible thresholds or amplifying anthropogenic changes (Box 3.3 Figure 1). For example, HTM and LIG Greenhouse Gas (GHG) concentrations show no evidence of runaway greenhouse gas releases under limited global warming. Transient releases of CO_2 and CH_4 may follow permafrost melting, but may be compensated by peat growth over longer timescales (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).

Ecosystems and biome (major ecosystem types) distributions changed significantly with warming both in the ocean and on land. For example, during past warming events some tropical and temperate forests retreated due to increased aridity, while savannas expanded (Dowsett et al., 2016). Poleward shifts of marine and terrestrial ecosystems, upward shifts in Alpine regions, and reorganisations of marine productivity are also recorded in natural archives (Williams et al., 2009; Haywood et al., 2016).

Past warm events are associated with partial sea ice loss in the Arctic. Limited data on Antarctic sea ice so far preclude 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 > 6m 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 allow for a substantial retreat of the West Antarctic Ice Sheet (WAIS) and parts of East Antarctic Ice Sheet (DeConto and Pollard, 2016), 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). Under modest warming past sea levels rise rates were similar or up to two times larger than observed over the past two decades (Kopp et al., 2013). Given the long timescales involved 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 experienced the high speed of change in atmospheric CO_2 and temperatures that we are experiencing today (Fischer et al., 2018).



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 in Fischer et al. (2018) (all statements relative to pre-industrial. Statements in italic 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, therefore, this figure should not be referred to without reading the source publication in detail. HTM: Holocene Thermal Maximum, LIG: Last Interglacial, MPWP: Mid Pliocene Warm Period

[END BOX 3.3 HERE]

3.3.10 Ocean chemistry

Ocean chemistry includes pH, salinity, oxygen, CO_2, and a range of other ions and gases, which affected by precipitation, evaporation, storms, river run-off, coastal erosion, up-welling, ice formation, and the activities of organisms and ecosystems (Stocker et al., 2013). Ocean chemistry is also changing with global temperature, with impacts projected at 1.5°C and, more so, at 2°C (*high agreement, medium evidence*). Projected changes in the upper layers of the ocean include changes to pH, carbonate ion and oxygen content. 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 ocean where it has combined with water to produce a dilute acid that dissociates and drives ocean acidification (Cao et al., 2007; Stocker et al., 2013). Ocean pH has decreased by 0.1 pH units since the Pre-Industrial Period, which is unprecedented in the last 65 Ma (*high confidence*, Ridgwell and Schmidt, 2010) or even 300 Ma of Earth history (*medium confidence*, Hönisch et al., 2012).

Ocean acidification 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, yet 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 such as Al) which may have impacts although these are poorly understood (Stockdale et al., 2016).

Oxygen varies regionally and with depth, and is highest in Polar regions and lowest in the eastern basins of the Atlantic and Pacific Oceans, and 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 supply of organic carbon to deep areas) has increased the frequency of ‘dead zones’, areas where oxygen levels no longer support oxygenic life (Diaz and Rosenberg, 2008). Drivers are complex and include both climate change and other factors (Altieri and Gedan, 2015) with increases 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. evaporation and inundation). Some regions (e.g. northern oceans and Arctic regions) have decreased salinity (i.e. due to melting glaciers and ice sheets) while others are increasing in salinity due to higher sea surface temperatures and evaporation (AR5 WGII Ch30, Durack et al., 2012). These changes in salinity (density) are also potentially driving changes to large scale patterns of water movement (Section 3.3.8)

3.3.11 Global synthesis

Table 3.2 present a summary of the assessments of global and regional climate changes and associated hazards for this chapter, based on the existing literature. For more detailed observation and attribution in ocean and cryosphere systems please refer to the upcoming IPCC Special Report on the Ocean and Cryophere 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 likehood 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) is given where available. Observed impacts and projected risks in natural and human systems. 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 versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C 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

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Temperature extremes	Overall decrease in the number of cold days and nighs and an 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 day 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 on global scale (*medium confidence*) [Section 3.3.2]	Anthropogenic forcing has contributed to the observed changes in the 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 nearly all inhabited regions *(high confidence)*, with increases of up to 3°C in mid-latitude warm season, and up to 4.5 in high-latitude cold season (*medium confidence*) Highest increase of frequency of unusually hot extremes in tropical regions (*medium 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 nearly all inhabited regions (*high confidence)*, with increases of up to 4°C in mid-latitude warm season, and up to 6°C in high-latitude cold season (*medium confidence*) Highest increase of frequency of unusually hot extremes in tropical regions (*medium 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 rarest and most extreme events (*high confidence*) Particularly large increases in hot extremes in inhabited regions (*high confidence*) [Section 3.3.2]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C 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 global-scale tendency towards increases in the frequency, intensity and/or amount of heavy precipitation events (*medium confidence*) [Section 3.3.3]	Increases in frequency, intensity and/or amount heavy precipitation when averaged on 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 on global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Higher frequency, intensity and/or amount of heavy precipitation when averaded on global on land at 2°C versus 1.5°C (*high confidence)* Several regions are projected to experience increases in heavy precipitation at 2°C warming versus 1.5°C (*high 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]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Drought and dryness	*High confidence* in dryness trends in some regions, especially drying in Mediterranean region (including Southern Europe, Northern Africa and the Near-East) *Low confidence* in drought and dryness trends at global scale. [Section 3.3.4]	*Medium confidence* in attribution of drying trend in 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 dryness index definition [Section 3.3.4]	*Medium confidence* of drying trends in 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 dryness index definition [Section 3.3.4]	*Medium confidence* of drying trends in Mediterranean region and South 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 dryness index definition [Section 3.3.4]	*Medium confidence* of stronger drying trends in Mediterranean region and South Africa at 2°C versus 1.5°C global warming. *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 dryness index definition [Section 3.3.4]
Runoff & river flooding	Streamflow trends mostly non-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 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*) 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]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Tropical & extra-tropical cyclones	*Low confidence* in robustness of observed changes [Section 3.3.6]	Not meaningful to assess given *low confidence* in changes, which are due to large inter-annual variability, heterogeneity of the observational record and contradictory findings regarding trends in the observational record.	*Low confidence* in manifestation of changes in storm tracks under 2ºC global warming *Limited evidence* that the global number of tropical cyclones will be less under 2°C of global warming compared to 1.5 °C of warming, but with an increase in the number of very intense cyclones (low confidence). [Section 3.3.6]		
Ocean temperature and circulation	*High confidence* in observed warming of upper ocean, with slightly lower rates than global warming Increased occurrence of marine heatwaves *(high confidence)* AMOC has been weakening over recent decades (*more likely than not*) [Sections 3.3.7]	*Limited evidence* attributing the weakening of AMOC in recent decades to anthropogenic forcing	Further increases in ocean temperatures, including more frequent marine heatwaves (*high confidence*) AMOC will weaken over 21st century and substantically so under high levels (higher than 2°C) of global warming (*very likely*)		
Sea ice	Continuing the trends reported in AR4, 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	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 *(very likely)* [Section 3.3.8]	At least one sea-ice-free Arctic summer after about 10 years of stabilized warming (*very likely)* [Section 3.3.8]	Probability of sea-ice-free Arctic summer greatly reduced at 1.5°C versus 2°C global warming *(high confidence*) [Section 3.3.8]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
	km^2 per decade) AR5 Chapter 4 (Vaughan et al., 2013)		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 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 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 0.1 pH unit decrease since the pre-industrial period which is unprecedented in the last 35 Ma (*high confidence*) [Section 3.3.10]	It is *very likely)* that oceanic uptake of anthropogenic CO_2 has resulted in acidification of surface waters. [Section 3.3.10]	Ocean chemistry is changing with global temperature with impacts projected at 1.5°C and, more so, at 2°C (*high agreement, medium evidence*) [Section 3.3.10]		

3.4 Observed impacts and projected risks in natural and human systems

3.4.1 Introduction

In Section 3.4, we explore the new literature and update the assessment of impacts and projected risks into the future for a large number of natural and human systems. We also explore adaptation opportunities laying the steps for reducing climate change, preparing the ground for later discussions on the 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 for 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, 2014b). 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 between systems, sectors and regions, many changes over the past 50 years can be attributed to human driven climate change and its impacts. In particular, risks were observed by AR5 to be increasing for natural ecosystems as climate extremes increase in frequency and intensity, as well as those associated with fauna and flora shifting their biogeographical ranges to higher latitudes and altitudes, with consequences for ecosystem services and human dependence. AR5 also reported increasing evidence of changing patterns of disease, invasive species, as well as growing risks for coastal communities and industry, especially important when it comes to sea level rise and human vulnerability.

One of the strong themes that has emerged from AR5 was that previous assessments may have under-estimated how sensitive natural and human systems are to climate change. A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) has 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 those 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 increased by the loss of ecosystem services (e.g. reduced access to safe water) that are supported by biodiversity (Cramer et al., 2014). Limited research on the risks of warming of +1.5 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, socioeconomic 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 has increased the request for greater data and understanding of the projected risks of warming of 1.5°C, and 2°C for reference. This section explores the available literature on the projected risks, impacts and adaptation options, and is supported by additional information and background in Annex 3.1 (S3-4, S3-4-2, S3-4-4, S3-4-7, S3-4-12). 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

WGII 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 (Vörösmarty et al., 2010). UNESCO (2011) concluded that climate change can alter the availability of water and threaten water security.

Although physical changes on 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 incorporating green water, water quality, and environmental flow requirements (J. Liu et al., 2017). Over the past century, substantial growth in population, 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 US (AghaKouchak et al., 2015; Mehran et al., 2015). Due to changes in climate and water consumption behavior, and particularly the effects of spatial distribution of population growth relative to water resources, the population under water scarcity increased from 0.24 billion (14% of global population) in the 1900s to 3.8 billion (58%) in the 2000s. In that last period (2000s), 1.1 billion people (17% of global population) mostly living in South and East Asia, North Africa and Middle East were facing high water shortage and high water stress (Kummu et al., 2016).

Over the next few decades, and for increases in global mean temperature of less than about 2ºC, the 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 in runoff under 1.5ºC and 2ºC, particularly those that are regional, are described in Section 3.3.5. Constraining to 1.5ºC instead of 2ºC warming can mitigate the risks on water availability although socio-economic drivers could affect the availability more than the risks posed by the variation in warming levels, while the risks found in regions are not homogeneous (*medium evidence, medium agreement)* (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 these models, Gerten et al. (2013) reveal that an additional 8% of the world population in 2000 will be exposed to new or aggravated water scarcity at 2ºC warming. This value is almost halved - with 50 % larger reliability - when warming is constrained to 1.5ºC. People inhabiting river basins particularly in the Middle East and Near East become newly exposed to chronic water scarcity even if the warming is constrained under 2ºC warming. Many regions especially in Europe, Australia and southern Africa appear to be affected at 1.5ºC if the reduction in water availability is computed for non-water scarce basins in addition to the reductions in water-scarce regions. From a contemporary population of approximately 1.3 billion exposed to water scarcity, about 3% (North America) to 9% (Europe) are prone to aggravated scarcity at 2ºC warming (Gerten et al., 2013). Under the Shared Socioeconomic Pathway (SSP)2 population scenario, about 8% of the global population are projected to experience a severe reduction in water resources under warming of 1.7ºC in 2021-2040, increasing to 14 % of the population under 2.7ºC in 2043-2071, based on either the criteria of discharge reduction >20% or >1 standard deviation (Schewe et al., 2014). Depending on the scenarios of SSP1 to 5, exposure to the increase of water scarcity in 2050 will be globally reduced by 184–270 million people at about 1.5ºC compared to the impacts at about 2ºC. However the variation between socio-economic differences is larger than the variation between warming levels (Arnell and Lloyd-Hughes, 2014).

On many small developing islands, there will be freshwater stress derived from projected aridity change, however, constraining to 1.5ºC warming can avoid a substantial fraction of water stress compared to 2ºC, especially across the Caribbean region, particularly on the island of Hispaniola (Dominican Republic and Haiti) (Karnauskas et al. (2018). Hanasaki et al. (2013) conclude that the projected range of changes in global irrigation water withdrawal (relative to the baseline of 1971-2000) with human configuration fixing non-meteorological variables at the period of about 2000 are 1.1–2.3% and 0.6–2.0% lower at 1.5ºC than at 2ºC, respectively. The same study, Hanasaki et al. (2013) reports on the importance of water use scenarios in water scarcity assessments, but neither quantitative nor qualitative information regarding water use are available. Hanasaki et al. (2013) conclude that the projected ranges of changes in global irrigation water withdrawal with human configuration fixing non-meteorological variables at about 2000 are 1.1–2.3% at about 1.5ºC, which is projected by Geophysical Fluid Dynamic Laboratory (GFDL) model (Representative Concentration Pathway (RCP)2.6 in 2071-2100 and RCP4.5 in 2011-2040), and 0.6‑2.0% at about 2ºC according to the projection using the Hadley Centre New Global Environmental Model (HadGEM) and Model for Interdisciplinary Research on Climate (MIROC) models (RCP4.5 and RCP8.5 in 2011-2040, respectively).

Comparing the impacts on hydropower production at 1.5°C and 2°C, it is found that mean gross potential increases in northern, eastern and western Europe, and decreases in southern Europe (Tobin et al., 2018; Jacob et al., 2018). The Baltic and Scandinavian countries will have the most positive impacts on production. The most negatively impacted are Greece, Spain, and Portugal, although the impacts can be reduced by limiting warming at 1.5°C (Tobin et al., 2018). It is found that, in Greece, Spain and Portugal, a warming of 2°C will decrease hydropower potential below 10%, while limiting to 1.5°C warming will 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 (Tobin et al., 2018; Jacob et al., 2018), with the magnitude of decreases being about 5% for 1.5°C and 10% for 2°C for most European countries (Tobin et al., 2018). Greece, Spain, and Bulgaria will have the largest reduction at 2°C (Tobin et al., 2018).

Fricko et al. (2016) assess the direct global energy sector water use 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 will be substantial divergence in water withdrawal for thermal power plant cooling under a condition in which the distribution of future cooling technology for energy generation is fixed, whereas adopting alternative cooling technologies and water resources will make the divergence considerably smaller.

3.4.2.2 Extreme hydrological events (floods and droughts)

WG II AR5 concluded that socio-economic losses from flooding since the mid-20th century have increased mainly due to greater exposure and vulnerability (*high confidence*; Jiménez Cisneros et al., 2014). There is *low confidence* due to *limited evidence*, however, that anthropogenic climate change has affected the frequency and the 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 due to increased water demand (Jiménez Cisneros et al., 2014).

Since the AR5, the number of studies related to river flooding and meteorological drought based on long-term observed data have been gradually increasing. There has been progress since the 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, population, their vulnerabilities, the value of assets affected by flooding, and the capacity to cope with flood risks that depend on socio-economic development conditions as well as topography and hydro-climatic conditions (Tanoue et al., 2016). The AR5 assessment 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 modeling evidence are supporting a gathering concensus that human emissions have substantially increased the probability of drought years in the Mediterranean region (Sections 3.3.4, Table 3.2).

WGII AR5 assessed that global flood risk will increase in the future partly due to climate change (*limited evidence*, *medium agreement*), 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 global scale (*high confidence*), and in flood hazard in some regions (*high confidence*), can be expected at warming of 1.5°C level with an overall increase in the area affected by flood hazard at 2°C (*high confidence*) (see Section 3.3.5). There are studies, however, revealing that socio-economic conditions will exacerbate flood impacts more than global climate change, and the magnitude of the impacts can be larger in some region (Arnell and Lloyd-Hughes, 2014; Winsemius et al., 2016; Alfieri et al., 2017; Arnell et al., 2018; Kinoshita et al., 2018) (*limited evidence, medium agreement*). Assuming constant population sizes, countries representing 73% of the world population will experience increasing flood risk with an average of 580% increase at 4ºC compared to the impact simulated over the baseline period 1976-2005. Such impact is projected to be reduced to 100% increase at 1.5ºC and 170% at 2ºC (Alfieri et al., 2017). Alfieri et al. (2017) reveal that the largest increases in flood risks are found in U.S., Asia, and Europe in general, while decreases are found in only few countries in Eastern Europe and Africa. Alfiere et al (2017) report that the projected changes are not homogeneously distributed on the world land surface. Alfieri et al. (2018) studied the population affected by flood events in European states, specifically Central and Western Europe, and found that the population affected can be limited to 86% for 1.5ºC warming compared to 93% at 2ºC. Under the SSP2 population scenario, Arnell et al. (2018) find that 39% (range 36-46%) of impacts on populations exposed to river flood can be globally avoided at 1.5ºC compared to 2 ºC warming.

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

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

Liu et al. (2018) study the changes in population exposure to severe droughts in 27 regions and around the globe for 1.5ºC and 2ºC warming using the SSP1 population scenario, compared to the baseline period of 1986-2005, and conclude that urban population exposure in most regions can be decreased at 1.5ºC (350.2±158.8 million) compared to 2ºC (410.7±213.5 million), respectively. Liu et al. (2018) also suggest that more urban populations will be exposed to severe droughts in Central Europe, Southern Europe, the Mediterranean, West Africa, East and West Asia and Southeast Asia, and the number of the affected people will escalate further in these regions at 2ºC. In the Haihe River Basin in China, the proportion of the population exposed to droughts at 1.5ºC is projected to be reduced by 30.4%, but increased by 74.8% at 2°C relative to 339.65 million people in the 1986–2005 period (Sun et al., 2017) .

Alfieri et al. (2018) estimate expected damage from flood at the European level for the baseline period (1976-2005), in which the reported annual figure is 5 billion euro of losses and reveal that relative changes of flood impacts rise with warming levels from 116% at 1.5°C to 137% at 2°C, respectively.

Kinoshita et al. (2018) study the increase of potential economic loss in SSP3 and project that the smaller loss at 1.5°C compared to at 2°C (0.9%) is marginal regardless of whether the vulnerability is fixed at the current level or not. Winsemius et al. (2016) show adaptation measures have the potential to greatly reduce present and future flood damage, by analyzing the differences in results with and without flood protection standard. They conclude that increases in flood induced economic impacts (% Gross Domestic Product, GDP) in African countries are mainly driven by climate change and Africa's growing assets become increasingly exposed to floods. And hence there is greater need for long-term and sustainable investments in adaptation in Africa.

3.4.2.3 Groundwater

WGII 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 north-eastern central Europe have been affected by climate and land use changes, and show 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 (*robust evidence, high agreement*; 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 due to increasing temperatures over agricultural lands (Wada et al., 2017). Very few studies project the risks of groundwater depletion under 1.5ºC and 2ºC warming. Under 2ºC warming, impacts posed on groundwater are projected to be greater than at 1.5ºC (*limited evidence, low agreement*; Portmann et al., 2013; Salem et al., 2017).

Portmann et al. (2013) indicate that 2.0% (range 1.1-2.6%) of global land area is projected to suffer from an extreme decrease of renewable groundwater resources of more than 70% at 2ºC, which is clearly mitigated at 1.5ºC. The study also projects that 20% of global land surface is affected by more than 10% groundwater reduction at 1.5ºC with the percentage of the land impacted increasing at 2ºC. 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

WGII 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). The AR5 report assessed that climate change is projected to reduce raw water quality, posing risks to drinking water quality with conventional treatment (*medium evidence, high agreement*; Jiménez Cisneros et al. (2014).

Since AR5, studies have detected climate change impacts on several indices of water quality in lakes, watershed and regional (e.g., Patiño et al., 2014; Aguilera et al., 2015; Watts et al., 2015; Marszelewski and Pius, 2016; Capo et al., 2017). Since WGII AR5, the number of studies utilizing RCP scenarios at regional or watershed scale have been gradually increased (e.g., Boehlert et al., 2015; Teshager et al., 2016; Marcinkowski et al., 2017). There are, however, few studies that explore projected impacts on water quality under 1.5ºC versus 2ºC warming. Differences in impacts on water quality between 1.5ºC and 2ºC warming is unclear (Bonte and Zwolsman, 2010; Hosseini et al., 2017) (*limited evidence, low agreement*). The daily probability of exceeding the chloride standard for drinking water taken from Lake IJsselmeer (Andijk, the Netherlands) is projected to increase about five times at 2ºC relative to 1ºC 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 1.5ºC warming (RCP2.6 in 2050-2055) compared to about 2ºC (RCP4.5 in 2050-2055) (Hosseini et al., 2017). In the three river basins (Sekong, Sesan, and Srepok in southeast Asia) about 2ºC warming (1.05 ºC increase in the 2030s relative to the baseline peiod 1981-2008, RCP8.5), impacts posed by land-use change on water quality is projected to be greater than at 1.5ºC (0.89 ºC increase in the 2030s relative to the baseline peiod 1981-2008, RCP4.5)(Trang et al., 2017). Under the same warming scenario, Trang et al. (2017) project annual nitrogen (N) and phosphorus (P) yields change in 2030s at about 1.5ºC and about 2ºC as well as with combinations of two land-use change scenarios: 1) conversion of forest to grassland, and 2) of forest to agricultural land. The projected changes in N (P) yield under 1.5ºC and 2ºC scenarios are 7.3 (5.1)% and -6.6 (-3.6)%, whereas under the combination of land-use scenarios are 1) 5.2 (12.6)% and 8.8 (11.7)%, and 2) 7.5 (14.9)% and 3.7(8.8)%, respectively (Trang et al., 2017).

3.4.2.5 Soil erosion and sediment load

WGII AR5 concluded that there is little or no observational evidence that soil erosion and sediment load have been altered significantly due to climate change (*limited evidence, medium agreement*), (Jiménez Cisneros et al., 2014). As studies of climate change impacts on soil erosion have 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 of vegetation cover due to temperature rise (Potemkina and Potemkin, 2015), and 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 published studies of climate change impacts on soil erosion have increased since 2000 globally (Li and Fang, 2016), few articles have addressed impacts at 1.5ºC and 2ºC warming. The existing studies have found few differences in projected risks posed on sediment load under 1.5ºC and 2ºC (*limited evidence, low agreement*; Cousino et al., 2015; Shrestha et al., 2016). The differences between average annual sediment load under 1.5ºC and 2ºC warmings are not clear because of complex interactions among climate change, land cover/surface and soil management (Cousino et al., 2015; Shrestha et al., 2016). Averages of annual sediment load are projected to be similar under 1.5ºC and 2ºC , in particular in the Great Lakes region in the US as well as in the Lower Mekong region in Southeast Asia (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) boreal, temperate, and tropical regions have been detected (Settele et al., 2014, AR5) and new studies confirm this (e.g. for 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 (Settele et al., 2014, *medium confidence*).

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 warming, but only 4% (range 2-7%) doing so at 1°C; suggesting that about 7% may be transformed at 1.5°C, indicating a doubling of the areal extent of biome shifts between 1.5ºC and 2°C warming (Figure 3.15a). A single ecosystem model LPJmL (Gerten et al., 2013) illustrates that biome shifts in the Arctic, Tibet, Himalayas, South Africa and Australia would be avoided by constraining warming to 1.5°C as compared with 2°C (Figure 3.15b). 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).

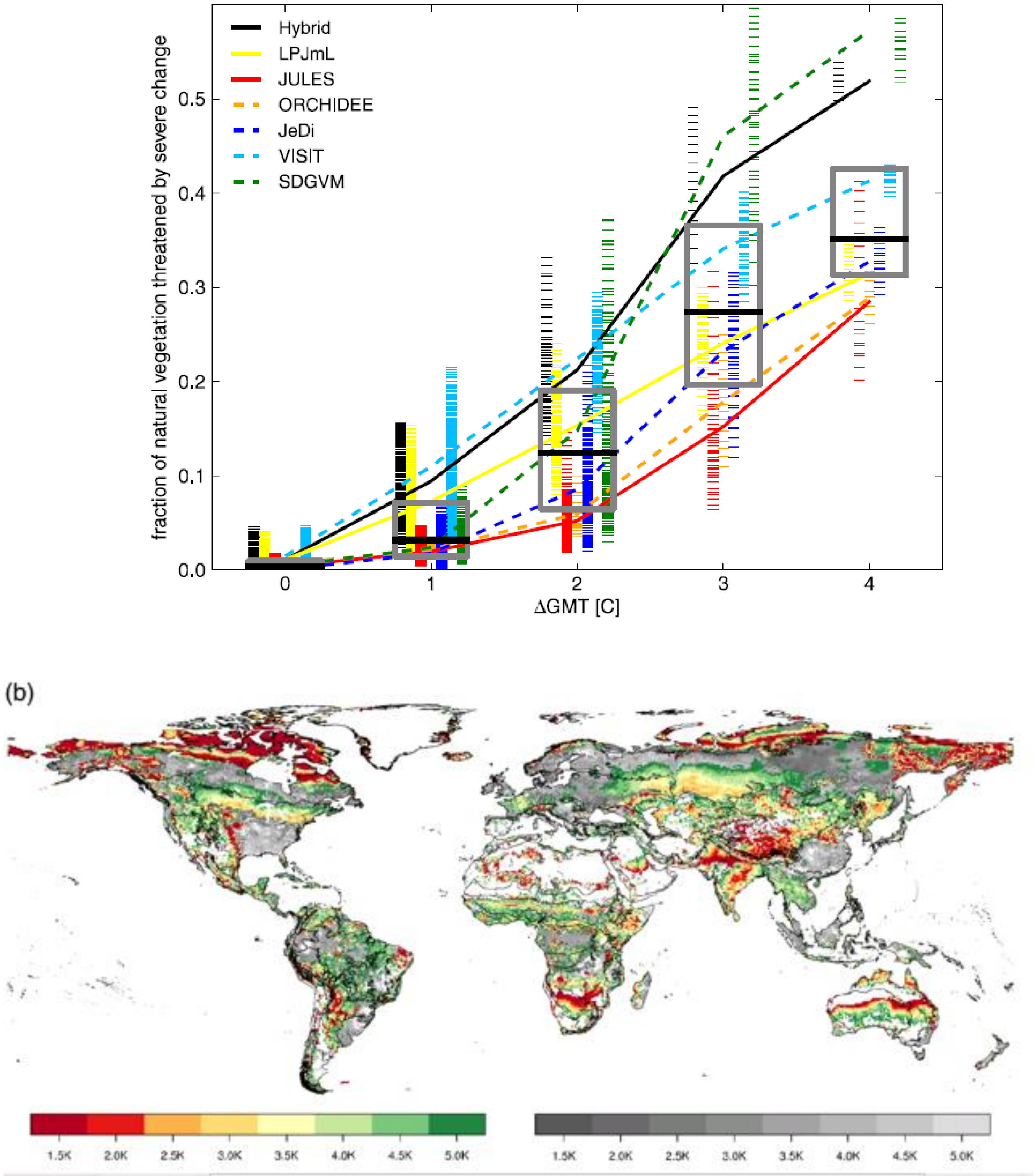


Figure 3.16: (a) Fraction of global natural vegetation (including managed forests) at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems, models, global climate change models

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 colors are used when there is no severe transformation unless global warming exceeds 2°C. Note: 1 K = 1ºC

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 most Northern Hemisphere ecosystems in recent decades (between 30°N and 72°N), and this has been attributed to changes in climate *(high confidence)* (Settele et al., 2014). The rates of change are particularly rapid in the Arctic zone in relation with higher local warming (Oberbauer et al., 2013), but in tropical forests, the phenology changes rather respond 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 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 Normalised Difference Vegetation Index, NDVI, Piao et al., 2015).

The potential for de-coupling of species-species interactions due 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). Now, mid-century projections of plant and animal phenophases in UK (Thackeray et al., 2016) 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), indicating the potential for phenological mismatch and associated risks for ecosystem functionality in the future, associated with global warming of 2.1-2.7°C above pre-industrial; while differing responses could alter community structure in temperate forests (Roberts et al., 2015). Here, the temperate forest phenology is projected to gain 14.3 days in the near term (2010-2039) and 24.6 days in the medium term (2040-2069), so in first approximation the difference between 2°C and 1.5°C global warming is about 10 days (Roberts et al., 2015). This phenological plasticity is not always adaptive and must be taken cautiously (Duputié et al., 2015), due to accompanying changes in climate variability (risk of frost damage for plants or earlier emergence of insects resulting in mortality during cold spells). Another adaptative response for the plants is expanding their range with increased vigor and altered herbivore resistance in their new range, analogous to invasive plants (Macel et al., 2017).

In summary, limiting warming to 1.5°C as compared with 2°C may avoid a few days of advance in spring phenology 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 warming might be limited for plants 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 per decade 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 the 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, is significantly higher in tropical regions, for animals and in freshwater habitats. IUCN (2017) lists 305 terrestrial animal and plant species from Pacific island developing nations as being threatened by climate change and severe weather. Due 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 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 finds that a warming of 2°C by 2100 would lead to projected bioclimatic range losses of >50% in 18 (6-35)% of 19,848 insects species, 8 (4-16)% of 12,429 vertebrate species, and 16 (9-28)% of 73,224 plant species studied (Warren et al., 2018b). At 1.5°C this falls to 6 (1-18) % insects, 4 (2-9)% vertebrates and 8 (4-15)% plants. Hence the number of insect species projected to lose over half their geographic range is reduced by two-thirds when warming is limited to 1.5°C as compared with 2°C, while the number of vertebrate and plant species projected to lose over half their geographic range is halved (Warren et al., 2018b). This is 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 warming (Smith et al., 2018). It should be noted that at 1.5°C warming, and if species' ability to disperse naturally to track their preferred climate geographically is inhibited by natural or anthropogenic obstacles, there still remain 10% amphibians, 8% reptiles, 6% mammals, 5% birds, 10% insects and 8% plants which are projected to lose over half their range, while species on average lose 20-27% of their range (Warren et al., 2018b). Since bird and mammal species can disperse more easily, a small proportion can gain range as climate changes, but even at 1.5°C warming the total range loss integrated over all birds and mammals greatly exceeds the integrated range gain (Warren et al., 2018b).

A number of caveats are noted in studies projecting climatic range change, since the approach does not incorporate the effects of extreme weather events and the role of interactions between species; and trophic interactions may locally counteract range expansion of species towards higher altitudes (Bråthen et al., 2018). Also, there is 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 potential for 1.5°C warming.

Pecl et al. (2017) summarize at the global level the consequences (for economic development, livelihoods, food security, human health and culture) of climate-change induced species redistribution and conclude 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 shown to retain significantly greater geographic ranges under 1.5°C global warming as compared with 2°C (Warren et al., 2018b). In some cases when species (such as pest and disease species) move into areas which become newly 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) estimate that 5.5-14% more of the globe's terrestrial land area can act as climatic refugia for plants under 1.5°C warming as 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 difficult to quantify. However, it is possible to compare the proportions of species at risk of very high range loss in Figure 2 in Warren et al. (2018b) where discernibly lower number of terrestrial species projected to lose over 90% of their range at 1.5°C global warming as compared with 2°C; 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 as compared with 2°C would be expected to reduce both range losses and associated extinction risks in terrestrial species (*medium confidence*).

3.4.3.4 Changes in ecosystem function, biomass and carbon stocks

WGII 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 preindustrial era and that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, yet there is no clear, consistent signal of a climate change contribution. In the northern latitudes, the productivity change has a lower velocity than the warming possibly because of 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 are vulnerable to loss 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). This would contribute to a decrease in the terrestrial carbon sink. Anderegg et al. (2015) show that the total ecosystem respiration, at the global scale, has increased in response to increase of nighttime temperature (1 PgC $year^{-1}$ $°C^{-1}$, $p=0.02$).

The increase of total ecosystem respiration in spring and autumn, in relation with higher temperature, may turn boreal forest from carbon sink to carbon source (Hadden and Grelle, 2016). This is confirmed for the boreal peatlands where increased temperature may diminish the carbon storage and compromise the stability of the peatland (Dieleman et al., 2016). In addition, J. Yang et al. (2015) showed that fires reduce carbon sink of global terrestrial ecosystems by 0.57 PgC yr^{-1} in ecosystems with high carbon storage, 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 is also a key compartment for carbon sequestration (Lal, 2014; Minasny et al., 2017) depending on the net biome productivity and the soil quality (Bispo et al., 2017).

The AR5 assessed that there remains large uncertainty in the land carbon cycle behavior in 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 2100 (Hewitt et al., 2016; Lovenduski and Bonan, 2017). Increased CO_2 will drive further increases in 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 terrestrial carbon cycle response to both CO_2 and 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 decomposition processes (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-tropics and largest spread across model results in the tropics. The 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 little published literature examining modelled land carbon changes specifically under 1.5°C warming, but here existing CMIP5 models and published data are used 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 so are dependent 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 we focus 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 3.16 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 2.0 GtC yr^{-1} K^{-1}. Similarly Gang et al. (2015) also projected a robust increase in Net Primary Productivity (NPP) of temperate forests, however Ahlström et al. (2012) show this could be offset or reversed by increases in decomposition. Globally, GPP increases or remains approximately unchanged in most models (Hashimoto et al., 2013). This is confirmed by Sakalli et al. (2017) for Europe using Euro-Cordex regional models under a 2°C global warming for the 2034-2063 period (storage will increase by +5% in soil and by +20% in vegetation). But 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 of 40-50%.

At the global scale, linear scaling is acceptable for net primary production, biomass burning, and surface runoff and impacts on terrestrial carbon storage will be greater at 2°C than at 1.5°C (Tanaka et al., 2017). If global CO_2 concentrations and temperatures stabilise, 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 reverse (Jones et al., 2016) and so 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 will increase with temperature, reducing soil carbon storage. Soil carbon storage will 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 concentration (i.e. the 'fertilization effect') and higher temperatures, especially at medium and high latitudes (*medium confidence*).

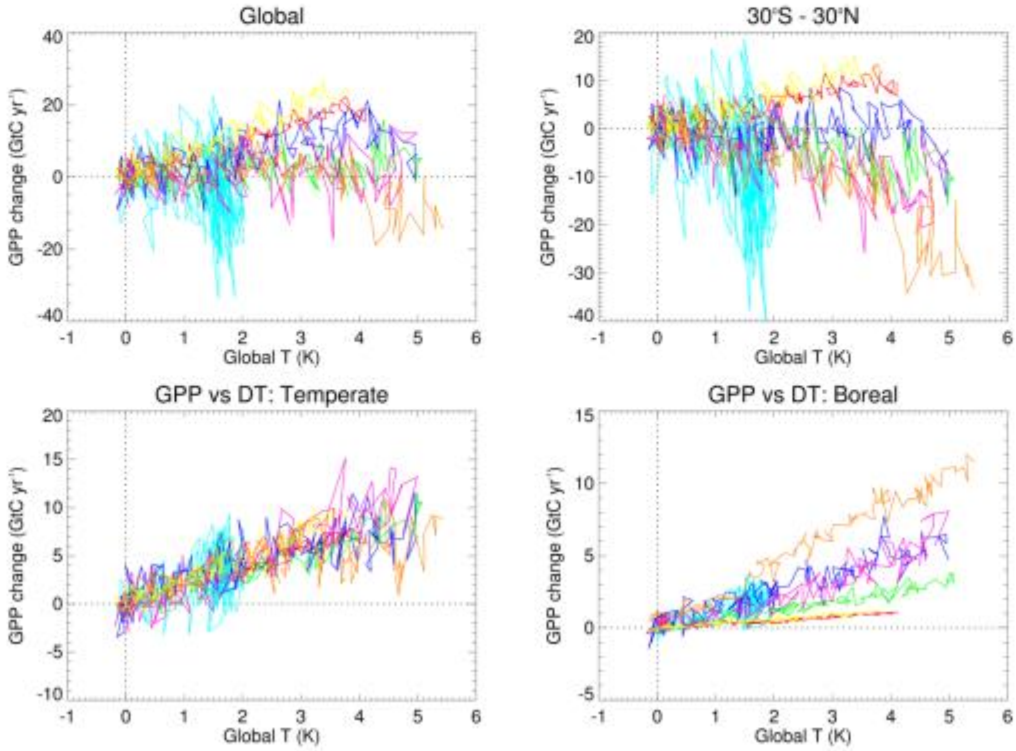


Figure 3.17: The response of terrestrial productivity (Gross Primary Productivity, GPP) to climate change, globally (top left) and for three latitudinal regions: 30°S-30°N; 30-60°N and 60-90°N. Data was used from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (http://cmip-pcmdi.llnl.gov/cmip5/). Seven Earth System Models 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 (pink); Hadley Centre New Global Environmental Model 2-Earth System (HadGEM2-ES, orange); Canadian Earth System Model 2 (CanESM2, green). Results are differences in GPP from model simulations with (‘1pctCO_2’) and without (‘esmfixclim1’) the effects of climate change. Data are plotted against global mean temperature increase above pre-industrial from simulations with 1% per year increase in CO_2 (‘1pctCO_2’).

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 are assessed in the AR5. These include Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succuluent 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 would be expected to be greater than those at 1.5°C (*medium confidence*).

The **High Arctic region**, with tundra-dominated landscapes, has warmed more than the global average over the last century (Settele et al., 2014) (Section 3.3). 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 conditions for 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 (Cooper, 2014) (*high confidence*). Observational constraints suggest stabilisation at 1.5°C would avoid approximately 2 million km^2 of permafrost compared with stabilisation at 2°C (Chadburn et al., 2017), but the timescale for release of thawed carbon as CO_2 or CH_4 is likely to be many centuries (Burke et al., 2017). In Northern Eurasia, the growing season length is projected to lengthen by about 3-12 days for 1.5°C and 6-16 days for 2°C (*medium confidence*) (Zhou et al., 2018). Aalto et al. (2017) predict a 72% reduction of 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 global warming). Long-term absence of snow reduces vascular plant cover in the understorey by 92%, reduces fine root biomass by 39% (Blume-Werry et al., 2016)

Projected impacts on **forests** as climate changes 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 particularly facilitate fire, drought and insect disturbances, while warmer and wetter conditions increase disturbances from wind and pathogens (Seidl et al., 2017). Including disturbances in the simulations may influence productivity changes of European forests in response to climate change (Reyer et al., 2017b). There is additional evidence for attribution of increased forest fire in North America to anthopogenic climate change during 1984-2015, via the mechanism of increasing fuel aridity almost doubling the western US 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 projected fire risks, which indicate that fire frequency would increase over 37.8% of global land areas during 2010-2039 (Moritz et al., 2012), corresponding to a global warming level of approximately 1.2 ºC; as compared with over 61.9% of the global land area in 2070-2099, corresponding to a warming of approximately 3.5ºC[2] (Table 26-1 in Romero-Lankao et al., 2014) also indicated significantly lower wildfire risks in North America for near term warming (2030-2040, which may be considered a proxy for 1.5ºC) than at 2ºC (*high confidence*).

Amazon tropical forest has been shown to be close to its climatic threshold (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 the response of Amazon forest to climate change (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 large scale forest dieback less likely than suggested under early coupled modelling studies (Cox et al., 2000; Jones et al., 2009). Nobre et al. (2016) estimate climate threshold of 4°C and a deforestation threshold of 40%.

In many places around the world the **savanna** boundary is moving into former grasslands with woody encroachment and tree cover and biomass has increased over the past century due to changes in land management, rising CO_2, climate variability and change (often in combination) (Settele et al., 2014). For the plant species in the Mediterranean region, shift in phenology, range contraction, health decline have been observed because of precipitation decrease and temperature increase (*medium confidence*) (Settele et al., 2014). Recent studies using independent complementary approaches now show that there is a regional-scale

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[2] FOOTNOTE: The approximate temperatures are derived from (Figure 10.5 panel A, Meehl et al. 2007), which indicates an ensemble average projection of 0.7 ºC or 3ºC above 1980-1999, which is itself 0.5ºC above pre-industrial) (Figure 10.5 panel A, Meehl et al. 2007).

threshold in the Mediterranean region between 1.5 ºC and 2ºC warming (Guiot and Cramer, 2016; Schleussner et al., 2016b). Guiot and Cramer (2016) finds that only if global warming is constrained to 1.5ºC can biome shifts unprecedented in the last 10,000 years be avoided (*medium confidence*) – whilst 2ºC warming results 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 compared to 1961-1990, respectively (*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 Australian ecosystems and is projected to be amplified (NCCARF, 2013). In Central America, Lyra et al. (2017) showed that with a global warming of 3°C in 2100, the tropical rainforest biomass will be reduced by more than 50% with large replacement by savanna and grassland. With a global warming close to 1.5°C in 2050, a biomass decrease 20% is projected (Lyra et al., 2017). If a linear response is assumed, with a global warming of 2°C, we deduced that the 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). In the Congo Basin (Dargie et al., 2017) and in the Amazonian Basin (Draper et al., 2014), the peatlands store the equivalent of the tropical forest. But this 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, they 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 (Herbert et al., 2015). Settele et al. (2014) find 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 it has been found that the wetland function of the Prairie Pothole region in North America is projected to decline beyond a local warming of 2ºC-3ºC above present (a 1ºC local warming, corresponding to a 0.6ºC global warming) (Johnson and Poiani, 2016). If the ratio of local to global warming remains similar for these small levels of warming, this would indicate a global temperature threshold of 1.2ºC-1.8ºC warming. Hence constraining global warming to approximately 1.5ºC warming would maintain the functioning of the prairie pothole ecosystem in terms of their productivity and biodiversity, but an 20% increase of precipitation can offset a 2°C global warming (*high confidence*) (Johnson and Poiani, 2016).

3.4.3.6 Summary of implications for ecosystem services

In summary, constraining global warming to 1.5ºC rather than 2ºC has strong benefits for terrestrial wetland ecosystems and their services (*high confidence*). These benefits include avoidance of biome transformations, species range losses, increased extinction risks (all *medium confidence*), 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 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, some sources of food, and recreation.

3.4.4 Oceans systems

The Ocean plays a central role in regulating atmospheric gas concentrations, global temperature and climate. It is also provides habitat to a large number of organisms and ecosystems that provide goods and services that are 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. coral reefs: *virtually certain*, WGII AR5) and consequently for many coastal communities who depend on marine resources for food, livelihoods and a safe place to live. Previous sections have described changes in the ocean that include rapid increases in ocean temperature down to at least 700 m (Section 3.3.7). Anthropogenic carbon dioxide has also decreased pH, as well as affected the concentration of ions such as carbonate (Section 3.3.10 and 3.4.4.5), over a similar depth range. Increased ocean temperature has intensified storms (Section 3.3.6), as well as expanded ocean volume and increased sea levels globally (Section 3.3.9) and decreased the extent of polar summer sea ice (Section 3.3.8), as well as 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 at 1.5°C versus 2°C, must be considered in the light of multiple, interactive 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 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^{o}C and, more so, at 2^{o}C above the pre-industrial period (Section 3.3.11). These changes have been accompanied by other changes such as ocean acidification and deoxygenation (Levin and Le Bris, 2015). Risks are already significant at current greenhouse gas concentrations and temperatures, and vary significantly between depths, location 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 gasses have increased, the global mean surface temperature (GMST) has reached about 0.87^{o}C above the pre-industrial period, and oceans have rapidly warmed from the ocean surface to the deep sea (Hughes and Narayanaswamy, 2013; Levin and Le Bris, 2015; Yasuhara and Danovaro, 2016; Sweetman et al., 2017) (*high agreement, robust evidence;* Sections 3.3.1.2 and 3.3.7). Marine organisms are already responding to these changes by shifting their biogeographical ranges to higher, relatively cooler latitudes, at rates that range from 0 to 40 km yr^{-1} (Burrows et al., 2014; Chust et al., 2014b; Bruge et al., 2016; Poloczanska et al., 2016) which has consequently affected the structure and function of the ocean, along with its biodiversity and food webs (*high agreement, robust evidence*). 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 (Woodroffe et al., 2010; Yamano et al., 2011) (*medium agreement, medium evidence*). In the case of 'less mobile' ecosystems (e.g. coral reefs, kelp forests, intertidal communities), shifts in biogeographical ranges may be limited, with mass mortalities and disease outbreaks increasing in frequency as the exposure to extreme temperatures have increased (Hoegh-Guldberg, 1999; Garrabou et al., 2009; Rivetti et al., 2014; Maynard et al., 2015; Krumhansl et al., 2016; Hughes et al., 2017b) (*high agreement, robust evidence*; see also Box 3.4). These trends will become more pronounced at 1.5^{o}C, and more so at 2^{o}C, above the preindustrial period (Hoegh-Guldberg et al., 2007; Donner, 2009; Frieler et al., 2013; Horta E Costa et al., 2014; Verges et al., 2014; Vergés et al., 2016; Zarco-Perello et al., 2017) and are *likely* to result in decreases in marine biodiversity at the equator and correspondingly increases in biodiversity at higher latitudes (Cheung et al., 2009; Burrows et al., 2014).

While the impacts of relocating species are mostly negative for human communities and industry, there are examples 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 agreement, medium evidence;* 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 themselves (Barange et al., 2014; Pörtner et al., 2014; Cheung et al., 2016b; Weatherdon et al., 2016; Section 3.4.4.9). Temporary gains in the productivity of high latitude fisheries are offset against a growing number of examples from low and mid latitudes where increases in sea temperature are driving decreases in NPP, due to the direct effects of elevated temperatures and/or reduced ocean mixing from reduced ocean upwelling (increased stratification; *low to 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 *(low agreement, limited evidence)*. 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 food webs 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, inundation, and coastal run-off

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 ocean has increased although the overall number of tropical cyclones has decreased (Elsner et al., 2008; Holland and Bruyère, 2014) (*medium agreement, limited evidence, hence low confidence;* Section 3.3.6). The direct force of wind and waves associated with larger storms, along with changes in storm direction, increase the risks of physical damage to coastal communities as well as ecosystems such as mangroves (*medium agreement, limited evidence*; 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, Table 3.2). In some cases, this can lead to increased exposure to related impacts (reduced water quality and sediment run-off; *high agreement, medium evidence*) (Brodie et al., 2012; Wong et al., 2014; Anthony, 2016; AR5-Table 5.1).

Sea level rise also amplifies impacts from observed sea level rise (Section 3.3.9) with robust evidence that storm surge and damage are already penetrating farther inland than a few decades ago, changing conditions for coastal ecosystems and human communities, especially Small Island Developing States (SIDS, Box 3.5) and low-lying coastal communities with issues such as storm surges transforming coastal areas (Section 3.4.5; Brown et al., 2018a). Changes in the frequency of extreme events, such as more intense storms, have the potential (along with other factors such as disease, feed web changes, invasive organisms, and heat stress 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, as has recently been seen for centrally important ecosystems such as tropical coral reefs (Box 3.4), which have changed from coral-dominated ecosystems to asemblages dominated by other organisms such as seaweeds, with changes in associated organisms and ecosystem services (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017; Hoegh-Guldberg et al., 2017; Hughes et al., 2017a, 2017b) (*high agreement, medium evidence*). The impacts of storms are amplified by sea level rise (Section 3.4.5) with substantial challenges today and in the future for cities, delta, and small islands in particular (Section 3.4.5.2 - 3.4.5.4) as well as coastlines and ecosystems (Section 3.4.5.5 – 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 as 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 the lack of records that match the long-term nature of these changes in many cases (Lluch-Cota et al., 2014). An assessment of literature since the AR5 (Sydeman et al., 2014), however, has concluded that (overall) upwelling-favourable winds have intensified in the California, Benguela, and Humboldt upwelling systems, but have weakened in the Iberian system, over 60 years of records (1946-2012, Section 3.3.7) (*medium agreement, medium evidence*) and are neutral for the Canary upwelling system. These conclusions are consistent with the developing consensus that wind driving upwelling systems are likely to intensify under climate change for most 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; Verges et al., 2014; Vergés et al., 2016; Zarco-Perello et al., 2017) as well as the arrival of novel disease agents (Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016) (*medium agreement, limited evidence*). For example, the sea urchin, *Centrostephanus rodgersii*, a herbivore, has been able to reach Tasmania, where it was previously unknown, from the Australian mainland due to a strengthening of the East Australian Current (EAC; *high agreement, robust evidence*) (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 likely to become greater at 1.5^{o}C and further so at 2^{o}C (*medium agreement, medium evidence*, Cheung et al., 2009; Pereira et al., 2010; Pinsky et al., 2013; Burrows et al., 2014).

Changes to ocean circulation can have even larger impacts 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. Evidence of a slowdown of AMOC has increased since AR5 (Smeed et al., 2014; Rahmstorf et al., 2015a, 2015b; Kelly et al., 2016) yet a strong causal connecton to climate change is missing (*low agreement, limited evidence*; Section 3.3.7).

3.4.4.5 Ocean acidification

Ocean chemistry encompasses a wide range of phenomena and chemical species of which many are integral to the biology and ecology of the ocean (Section 3.3.10) (Gatusso et al., 2014; Hoegh-Guldberg et al., 2014;

Pörtner et al., 2014; Gattuso et al., 2015). While changes to ocean chemistry are likely to be centrally important, the literature on how climate change might influence ocean chemistry over the short and long term is limited (*high agreement, limited evidence*). 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 have, fundamental and substantial impacts on a wide variety of organisms and hence ecosystem processes (high agreement, robust evidence) Organisms with shells and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a broad number of organisms and processes such as de-calcification, although some taxa that did not show the same 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). These risks vary with latitude (i.e. greatest changes at high latitudes) and depths, with the latter involving the rapid shoaling of 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) as CO_2 penetrates deeper as concentrations in the atmosphere increase over time. Under many models and scenarios, the aragonite saturation reaches the surface from 2030 onwards and with poorly understood impacts and consequences for ocean organisms, ecosystems and people (Orr et al., 2005; Roberts et al., 2008; Hauri et al., 2016).

It is also difficult to reliably separate the impacts of ocean warming and acidification, especially under field settings. Ocean waters have increased in sea surface temperature (SST) by approximately 0.9°C and decreased in pH by 0.11 units since 1870-1899 (‘preindustrial’, 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 linearly with SST, reaching 1.72°C and a decrease of 0.22 pH units (under RCP4.5) relative to the preindustrial period. These changes are likely to continue given the linear correlation of SST 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 agreement, medium evidence*) that include community scale impacts on bacterial assemblages and processes (Endres et al., 2014), coccolithophores (K.L.S. Meier et al., 2014), pteropods and polar food webs (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), 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 (Fabricius et al., 2011; Allen et al., 2017; Box 3.4). Some ecosystems such as bathyal areas (200–3000 m) are likely to undergo significant reductions in pH by the year 2100 (0.29 to 0.37 pH units) yet evidence is currently limited despite the potential importance of these areas (Hughes and Narayanaswamy, 2013; Sweetman et al., 2017) (*medium agreement, limited evidence*).

3.4.4.6 Deoxygenation

Oxygen in the ocean is 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 agreement, robust evidence*) due to three main factors that relate to climate change: (1) heat related stratification of the water column (less ventilation and mixing), (2) reduced oxygen solubility as ocean temperature increases, and (3) impacts of warming on biological processes that produce or consume oxygen such as photosynthesis and respiration (*high agreement, robust evidence*) (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). Similarly, a range of processes (Section 3.4.11) are also acting synergistically, including non-climate change factors such as run-off and coastal eutrophication (e.g. from coastal farming, intensive aquaculture) leading to increased phytoplankton productivity, which increase the metabolic rate of coastal microbial communities by supplying greater amounts of organic carbon (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 experiencing 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 oxygenic 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 due to the complexity of the climate and non-climate change-related processes involved, some impacts related to deoxygenation (*medium agreement, limited evidence*) include the expansion of the 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 oxygenic 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). Deoxygenation interacts with ocean acidification to present substantial and combined challenges for fisheries and aquaculture (*medium agreement, medium evidence*) (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 et al., 2017; Clements and Chopin, 2017; Breitburg et al., 2018). Deoxygenation is expected to have greater impacts as ocean warming and acidification increase (*high agreement, medium evidence*), with most impacts being larger and more numerous than today (e.g. greater challenges for aquaculture and fisheries from hypoxia), and the number of hypoxic areas continue to increase. Risks from deoxygenation are *virtually certain* to increase as warming continues although our understanding of risks at 1.5^{o}C versus 2^{o}C is incomplete (*high agreement, limited evidence*). Reducing coastal pollution and consequently the export of organic carbon into deep benthic habitats is highly likely to reduce the decline in the oxygen concentrations in coastal waters and in hypoxic areas in general (Breitburg et al., 2018).

3.4.4.7 Loss of sea ice

Sea ice has been 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 these regions (e.g. Arctic, Antarctic and Southern Ocean), 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 agreement, robust evidence*) (Larsen et al., 2014). These changes are strongly affecting people in the Arctic who have close relationships with sea ice and associated ecosystems, and 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 from today in average global surface temperature will lead to multiple levels of impact on a variety of organisms - from phytoplankton to marine mammals 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 is 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. Therefore, without intending to be comprehensive, there are a range of responses to the loss of sea ice that are occurring and are likely to increase at 1.5°C and 2°C of global warming. Photosynthetic communities such macroalgae, phytoplankton, and microalgae dwelling on the underside of floating sea ice are changing due 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 (Dalpadado et al., 2014; W.N. Meier et al., 2014) (*medium agreement, medium evidence*). These changes are *very likely* to stimulate fisheries productivity in high latitude regions by mid-century (Cheung et al., 2009, 2010, 2016b; Lam et al., 2014), with evidence of this is already happening for several fisheries species in high latitude regions 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 NPP, there are also direct effects of temperature on fish, which may 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 vaste regions such as the Southern Ocean have substantial implications as far as ocean foodwebs and fisheries are concerned.

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 (*high agreement, robust evidence*). These changes are interacting with other factors such as larger indundation and storms, which may drive greater storm surge, 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 agreement, medium evidence*, 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 a wide range of other non-climate change related risks and impacts, with on-going 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. coastal building, seawalls, and agriculture) can often interrupt shoreward shifts as does reduced sediment supplies down some rivers due to coastal development (Di Nitto et al., 2014; Lovelock et al., 2015; Mills et al., 2016).

The response 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). Available literature largely concludes that these challenges will intensify under a 1.5ºC world but will be higher at 2ºC, especially when considered in the context of changes occuring 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 from rising sea levels, intensifying storms, coastal inundation, and salinization (Section 3.4.5, Box 3.5) (Arkema et al., 2013) although limits of these strategies have been identified (e.g., Lovelock et al., 2015; Weatherdon et al., 2016). These and other issues and options are explored in Section 3.4.5.

3.4.4.9 Projected risks and adaptation options for a global warming of 1.5ºC and 2ºC above pre-industrial levels

Given the space available, it is impossible to be comprehensive, and hence the intention here is to illustrate key risks and adaptation options in the case of the ocean using a number of key examples. This assessment builds on the recent expert consensus of Gattuso and colleagues (Gattuso et al., 2015) by assessing new literature (from 2015-2017) and adjusting the levels of risk in the light of this recent literature. To do this, we use input from the original expert group's assessment (Annex 3.1, S3-4-4) and focus particularly on the implications of global warming of 1.5ºC as compared to 2ºC. A discussion of potential adaptation options is also provided, the details of which will be further explored in later chapters of this special report. This section refers heavily to the review, analysis and literature presented in the Annex 3.1 that accompanies this report.

3.4.4.10 Framework organisms (tropical corals, mangroves and seagrass)

Marine organisms ('ecosystem engineers'), such as seagrass, kelp, oysters, salt marsh species, mangrove 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 large numbers of species (Gutiérrez et al., 2012). These organisms in turn provide food, livelihoods, cultural significance, and services such as coastal protection (Bell et al., 2011, 2017; 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 have recently been assessed by an expert group led by Short et al. (2016). Impacts of climate change were 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 by coastal infrastructure leading to 'coastal squeeze' where coastal ecosystems are trapped between changing ocean conditions and coastal infrastructure (Mills et al., 2016). Projection of the future distribution of seagrasses suggest a poleward shift, with concern that low latitude seagrass communities may contract due to increasing stress levels (Valle et al., 2014).

Present-day risks from climate change (i.e. sea level rise, heat stress, storms and inundation) are medium for seagrass and *high* for reef building corals (Figure 3.20, Annex 3.1 S3-4-4) with evidence of strengthening of concern since the AR5 and the conclusion that tropical corals may be even more vulnerable to climate change than indicated in assessments done in 2014 (Hoegh-Guldberg et al., 2014; Gattuso et al., 2015). The current assessment also took into account the heat wave-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 has under-estimated climate risks for coral reefs. General assessment of climate risks for mangroves prior to this special report concluded that they face greater risks from deforestation and unsustainable coastal development than 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.

With the events of the last past 3 years in mind, risks are now considered to be undetectable to moderate (i.e now moderate risks start at 1.3°C as opposed to 1.8ºC, when assessed in 2015). Consequently, when average global warming reaches 1.3°C above pre-industrial period, mangroves risk from climate change will be *moderate*, while there is very *high confidence* that tropical coral reefs will experience high risks of impacts such as very frequent mass mortalities (at least while populations of corals persist). At global warming of 1.8ºC above the preindustrial period, seagrasses are projected to reach moderate to high levels of risk (e.g. sea level rise, erosion, damage from extreme temperatures, storm damage), while risks to mangroves from climate change will remain medium (e.g. risks of not keeping up with SLR; more frequent heat stress mortality) (Figure 3.17).

Tropical coral reefs will reach a *very high risk* of impact at 2ºC (Figure 3.17; Annex 3.1 3.4.4) with most available evidence suggesting that coral dominated ecosystems will be non-existent at this temperature or higher (e.g., coral abundance near zero in most locations, intensifying storms 'flattening' reefs' 3-dimensional structure; Alvarez-Filip et al., 2009) (*high agreement, robust evidence*). Impacts at this point (coupled with ocean acidification) are likely to undermine the ability of tropical coral reefs to provide habitat for the current high levels of biodiversity as well as a range of ecosystem services important for millions of people (e.g., food, livelihoods, coastal protection, cultural services) (Burke et al., 2011).

Strategies for reducing the impact of climate change on framework organisms include reducing non-climate change stresses (e.g. coastal pollution, overfishing, destructive coastal development) in order to increase 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 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 deep-water communities that experience less extreme conditions and impacts, or variable conditions that lead to more resilient organisms. Given the potential value for promoting the survival of coral communities under climate change, efforts for preventing their loss to non-climate stresses is important (Bongaerts et al., 2010; Chollett et al., 2013, 2014; Fine et al., 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015) but see (Chollett et al., 2010; Bongaerts et al., 2017; Beyer et al., 2018; Hoegh-Guldberg et al., 2018).A full understanding of the utility and feasibility of the role of refugia in reducing the loss of ecosystems has yet to be developed (*medium agreement, limited evidence*). There is also interest in *ex situ* conservation approaches involving the restoration of corals via aquaculture (Shafir et al., 2006; Rinkevich, 2014) and '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 remedies are to be cost effective responses to preserving coral reefs under rapid climate change (Hoegh-Guldberg, 2012, 2014a; Bayraktarov et al., 2016) (*low agreement, limited evidence*).

Integrating coastal infrastructure with ecosystems dependent on mangroves, seagrasses and salt marsh such that they are able to shift shoreward as sea levels rise. Maintaining sediment supply to coastal areas will enable mangroves can keep pace with sea level rise (Shearman et al., 2013; Lovelock et al., 2015; Sasmito et al., 2016). For this reason, reducing interventions such as damming rivers may also maintain the sediment supply needed for mangrove habitat, and hence the ability of mangroves to persist without drowning as sea level increases (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). High levels of adaptation will be required to prevent impacts on food security and livelihoods in general (*medium agreement, medium evidence*). 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 food webs (pteropods, bivalves, krill, and fin fish)

Ocean food webs represent vast interconnected systems that transfer of solar energy and nutrients from phytoplankton to higher trophic levels (including apex predators) as well as through other food web interactions. Here, we take four representative types of marine organisms which are important within food webs across the ocean, and which illustrate the impacts and ramifications of 1.5ºC and 2ºC warming.

Pteropods are small pelagic molluscs that produce a calcium carbonate shell and which are highly abundant in temperate and polar waters, where they form an important link in the food web 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 also filter-feeding invertebrates that underpin important fisheries and aquaculture industries (from the polar to tropical regions) and are important as food sources for a range of organisms including humans. The third group of organisms considered here are a globally significant group of invertebrates known as euphausiid crustaceans (krill), and 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, sea birds). Antarctic krill, *Euphausia superba,* are among the most abundant species in mass and are consequently an essential component of polar food webs (Atkinson et al., 2009). The last group, the fin fishes, are vitally important components of ocean food webs, and contribute to the income of coastal communities, industries and nations, and are important to food security and livelihoods of hundreds of millions of people globally (FAO, 2016). Further background to this section is provided in Annex 3.1 (S3-4-4).

There is a moderate risk to ocean food webs under present day conditions (Figure 3.17, *medium to high confidence*). Changing water chemistry and temperature is affecting the ability of pteropods to produce their shells, as well as swim and survive (Roberts et al., 2008; Bednaršek et al., 2016). Shell dissolution is 19-26% higher, for example, 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 their central importance in ocean food webs (David et al., 2017). Reviewing the literature reveals that pteropods face high risks of impact at 1.5°C and increasing risks of impacts at average global temperatures of 2°C or more above the preindustrial period (*medium agreement, medium evidence*).

As temperatures increase to 1.5˚C and beyond, the risk of impacts from ocean warming and acidification remain moderate to high except in the case of bivalves (mid latitude) where the risks of impacts become high to very high. 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 with larval stages tending to show greater developmental abnormalities and mortality after exposure (Q. Wang et al., 2016; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017) (*medium agreement, robust evidence*). Risks accumulate at higher temperatures for bivalve molluscs, with very high risks at 1.8°C or more. This general pattern continues with low latitude fin fish acquiring medium to high risks of impact (*medium agreement, medium evidence)* when average global surface temperatures reach 1.3^{o}C above the pre-industrial period, and very high risks at 1.8^{o}C (Figure 3.17; *medium agreement, medium evidence*).

Large scale changes to food web structure is occurring in all oceans. For example, record levels of sea ice loss in the Antarctic (Notz and Stroeve, 2016; Turner et al., 2017b) translate as a loss of habitat and hence abundance of krill (Piñones and Fedorov, 2016), with negative ramifications for seabirds and whales which feed on krill (Croxall, 1992; Trathan and Hill, 2016). Other influences such as high rates of ocean acidification, coupled with the 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 non-climate change stresses from human activities. Reducing non-climate change stresses such as pollution and habitat destruction will be important in efforts to maintain these important food web components. Fisheries management (especially for low latitude fin fisheries that include small scale fisheries) at local to regional scales will be important in reducing stress on food web organisms such as those discussed here, as well as helping communities and industries adapt to changing food web structure and resources (see further discussion of fisheries *per se* below; Section 3.4.6.3). One strategy might be to maintain higher population levels of fished species in order to provide more resilient stocks in the face of challenges 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 that include the regulation of atmospheric composition via gas exchange across the boundary between ocean and atmosphere, and storage of carbon in vegetation and soils associated with ecosystems such as mangroves, salt marsh, and coastal peatlands, among other components. These include a series of physicochemical processes which are influenced by ocean chemistry, circulation, oceanography, temperature and biogeochemical components, as well as by non-climate activities (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), with risks becoming high as 2^{o}C is approached and prospects of undersaturation of the ocean carbonate system increase (especially for polar oceans; Bopp et al. 2013). Concern is also growing from observations and models regarding changes in ocean circulation (Rahmstorf et al., 2015b); Sections 3.3.7 and 3.4.4.4). Biological components of carbon uptake by the ocean are also changing with observations of changing NPP in equatorial (*medium agreement, medium evidence*) and coastal upwelling systems (*medium agreement, medium evidence*) (Lluch-Cota et al., 2014; Sydeman et al., 2014; Bakun et al., 2015) as well as subtropical gyre systems (Signorini et al., 2015, *low agreement, limited evidence*). There is general agreement that NPP will decline as ocean warming and acidification increase (Bopp et al., 2013; Boyd et al., 2014; Pörtner et al., 2014; Boyd, 2015) (*medium agreement, medium evidence*).

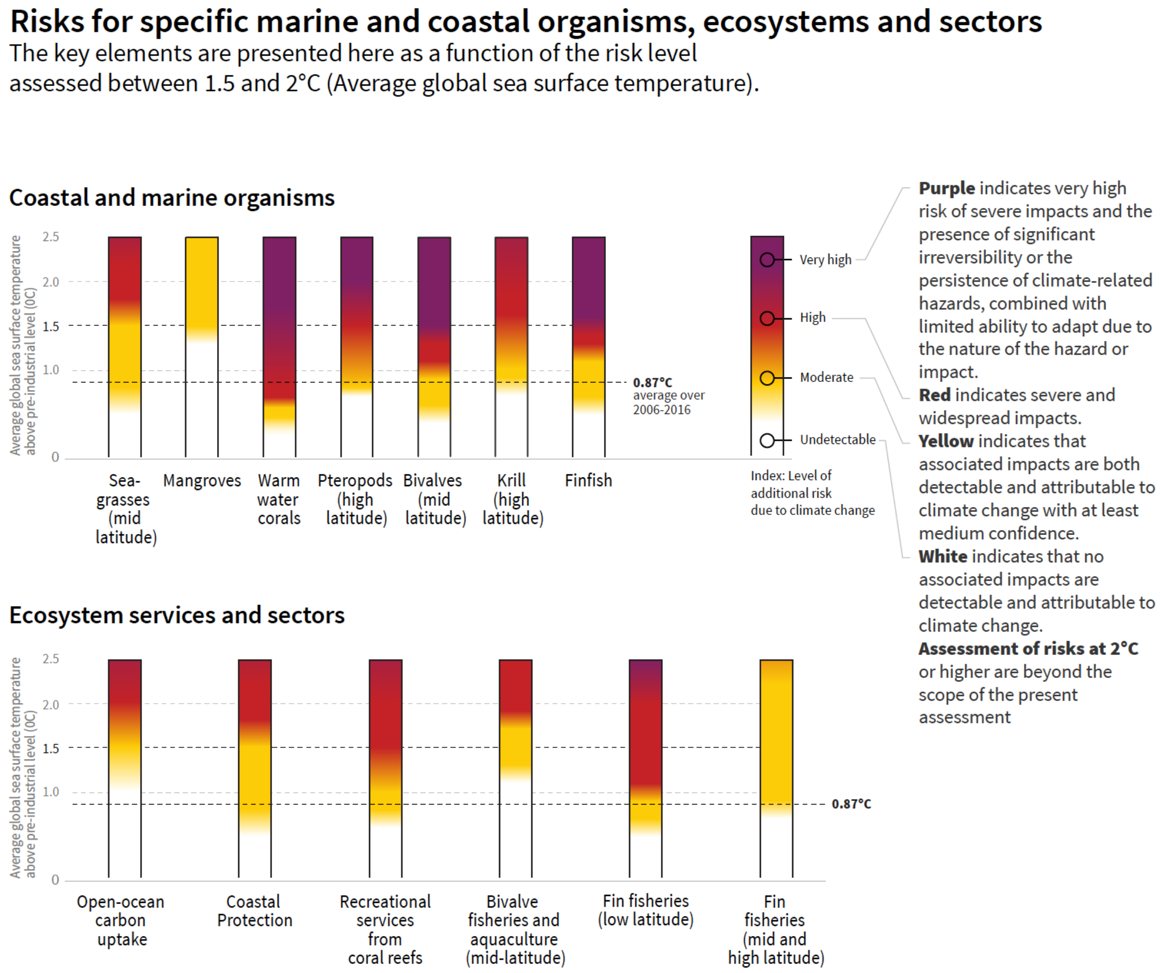
Risks of impacts from reduced carbon uptake, coastal protection, and services contributing to coral reef recreation are moderate at 1.5˚C of warming (*medium agreement, limited evidence*). At 2˚C, risks of impacts associated with changes to carbon uptake remain moderate, while the climate risks associated with reduced coastal protection and recreation on tropical coral reefs are high, especially given the vulnerability of this ecosystem and others (e.g. seagrass, mangroves) to climate change (Figure 3.17). Coastal protection is another service provided by natural barriers such as mangroves, seagrass meadows, coral reefs, and other coastal ecosystems, and which is important for protecting human communities and infrastructure against the impacts associated with rising sea levels, waves and intensifying storms (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 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 play an important role in coastal protection as well as resources for coastal communities but are already under moderate risk of not keeping up with the sea level rise due to climate change and to contributing factors such as reduced sediment supply or obstacles for the shift shoreward (Saunders et al., 2014; Lovelock et al., 2015). This implies that coastal areas currently protected by mangroves may experience growing risks over time.

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). Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries, particularly 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 Annex 3.1 S3-4-4.

Adapting to the broad global changes in carbon uptake by the ocean are limited and are discussed with respect to the changes in NPP and their implications for fishing industries later in this report. These are broad scale and indirect, with the only other solution at scale being reducing the entry of CO_2 into the ocean. Strategies for adapting to reduced coastal protection involve avoidance of vulnerable areas, managed retreat from threatened locations, and/or 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 strategies that involve direct human intervention (e.g. coastal hardening, seawalls and artificial reefs) (Rinkevich, 2014, 2015; André et al., 2016; Cooper et al., 2016; Narayan et al., 2016), while there are others that exploit the opportunities for increasing coastal protection by involving a 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 responses that require constant maintenance (Barbier, 2015; Elliff and Silva, 2017). Recognizing and restoring coastal ecosystems in general may be more cost-effective than human structures such as the installation of seawalls and coastal hardening, where natural adaptation (ecosystem-based adaptation) is limited and the costs of creating and maintaining structures is generally expensive (Temmerman et al., 2013; Mycoo, 2017).

Recent studies have increasingly stressed the need for coastal protection to be considered within the context of new ways of managing coastal land, including protecting and ensuring that coastal ecosystems are able to undergo shifts in their distribution and abundance (Clausen and Clausen, 2014; Martínez et al., 2014; Cui et al., 2015; André et al., 2016; Mills et al., 2016)(André 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 being increasingly 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: (1) Protecting and improving biodiversity and ecological function by minimizing the impact of non-climate change stresses (e.g. pollution, overfishing), (2) Ensuring adequate levels of coastal protection by supporting and repairing ecosystems that protect coastal regions, (3) ensuring fair and equitable access to the economic opportunities associated with recreational activities, and (4) seeking and protecting supplies of water for tourism, industry, and agriculture alongside community needs.

In summary, our understanding of systems has increased significantly since AR5, with multiple lines of evidence supporting very significant changes in the structure and function of the ocean and its resident organisms and ecosystems. These changes are occurring today and will get progressively less manageable as temperatures increase to 1.5°C or higher. There is considerable evidence that avoiding 2°C will avoid very substantial damage to ecosystem services and ultimately impacts on human livelihoods, food resources, communities and industries. Figure 3.17 (and additional online material, S3-3.4.4) summarises the additional risks of impacts from global warming for many of the ocean-based organisms, ecosystems and sectors discussed here.



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).

Purple indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impact.
Red indicates severe and widespread impacts.
Yellow indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence.
White indicates that no associated impacts are detectable and attributable to climate change.
Assessment of risks at 2°C or higher are beyond the scope of the present assessment

Figure 3.17: Summary of additional risks of impacts from ocean warming (and associated climate change factors such ocean acidification) for a range of ocean organisms, ecosystem and sectors at 1.0°C, 1.5°C and 2.0°C warming of average sea surface temperature (SST) relative to the preindustrial period. The dotted line (0.87°C) is a measure of the extent of present day warming. Assessment of changing risk levels and associated confidence were derived from the expert judgement of Gattuso et al., (2015) and the Lead Authors of this Chapter plus the additional input was received from the many reviewers of the ocean systems section of SR1.5. Note: (1) The analysis done here is not intended to be comprehensive. The examples of organisms, ecosystems and sectors discussed here are intended to outline the evidence and projection of impacts and the risks for ocean systems at 1.5° and 2.0°C relative to 0.87°C (today). (2) The evaluation of risks by experts did not consider genetic adaptation, acclimatization, or human risk reduction strategies (mitigation and societal adaptation). (3) As discussed elsewhere (3.3.10, 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 response reported here although partitioning the effects of the two drivers is difficult at this point in time and hence is not attempted. (4) Confidence levels (L=Low, M=Moderate, H=High, and VH=Very high) were assessed for the position of the transitions from one level of additional climate risk to the next successive level (Gattuso et al. (2015). Three transitions 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 (see Figure 3.17).

For each of the 13 Ocean ‘embers’, the levels of confidence for these transitions were assessed (based on level of agreement, extent of evidence) to be: Seagrasses (mid-latitude): W-Y (VH); Y-R (H); R-P(H); Mangroves: W-Y (M); Warm water corals: W-Y (H); Y-R (VH); R-P (VH); Pteropods (high latitude): W-Y (L); Y-R (M); R-P (H); Bivalves (mid-latitude): W-Y (H); Y-R (M); R-P (M), Krill (high latitude): W-Y (M); Y-R (L); R-P (L); Finfish: W-Y (H); Y-R (H); R-P (M); Open ocean carbon uptake: W-Y (H); Y-R (H); Coastal protection: W-Y (M); Y-R (L); R-P (L); Recreational services from coral reefs: W-Y (H); Y-R (M); R-P (M); Bivalve fisheries and aquaculture (mid-latitude): W-Y (H); Y-R (M); Fin fisheries (low latitude): W-Y (H); Y-R (M); R-P (H); and Fin fisheries (high latitude): W-Y (H); Y-R (H); R-P (L)

[START BOX 3.4 HERE]

Box 3.4: Tropical Coral Reefs in a 1.5°C Warmer World

Tropical coral reefs face very high risks (Figure 3.19) of becoming unsustainable as coral dominated ecosystems if warming exceeds 1.5ºC. A 1.5°C world is better for coral reefs than a 2ºC world, in which coral reefs 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 (0.87ºC;Chapter 1), a substantial proportion of coral reefs have experienced large scale mortalities that are causing them to rapidly contract (Hoegh-Guldberg et al., 2014). In the last 3 years alone, 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). These changes are part of a series of heat stress impacts that began in the early 1980s events (Hoegh-Guldberg, 1999).

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

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 (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 (referenced to 1985-1993) over 4-6 weeks being enough to cause mass coral bleaching (loss of the symbiosis) 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 to other benthic organisms such as macroalgae (Dove et al., 2013; Reyes-Nivia et al., 2013, 2014). As corals disappear, so do fish stocks, and many other reef-dependent species, directly impacting industries such as tourism and fisheries, as well as coastal livelihoods for many, often disadvantaged, 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 (Gardner et al., 2005; Dove et al., 2013; Kennedy et al., 2013; Webster et al., 2013; Hoegh-Guldberg, 2014b; Anthony, 2016) (*medium agreement*, *limited evidence*). Ocean acidification also leads to greater 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).

Predictions of back-to-back bleaching events (Hoegh-Guldberg, 1999) have become reality over 2015-2017 (e.g., Hughes et al., 2017b) as have projections of declining coral abundance (*high confidence*). Models have also become increasingly capable, and predict the large-scale loss of coral reefs by mid-century under even low emission 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 emission reduction goals consistent with the ambitious goal of 1.5ºC under the Paris Agreement will result in the further loss of 90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2ºC 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 hypothetical cases, 'optimistic' assumptions in models include the rapid thermal adaptation by corals (0.2-1.0ºC per decade and 0.4ºC per decade; (Donner et al., 2005; Schleussner et al., 2016b), respectively) as well as very rapid recovery rates from impacts (i.e., 5 years; Schleussner et al., 2016b). Adaptation to climate change at these high rates (if at all) has not been documented and rates of recovery from mass mortality tend to be much longer the time between extreme events (> 15 years; Baker et al., 2008). Probability analysis also reveals that the underlying increases in sea temperatures that drive coral bleaching and mortality are 25% less likely under 1.5°C versus 2ºC (King et al., 2017). Differences between 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 coral reefs, especially if these refuges are protected from non-climate change risks. Higher latitude sites are reporting the arrival of reef-building corals, which may deserve focus in terms of limited refugia and coral reef structures, which are likely to be low in biodiversity when compared to tropical reefs today (Kersting et al., 2017). Similar proposals have been made for the potential role of deep water (30 to 150 m) or mesophotic coral reefs (Bongaerts et al., 2010; Holstein et al., 2016) avoiding shallow water extremes (i.e. heat, storms) although the ability of these ecosystems to repopulate 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) will be very challenging to coral reefs. Losing 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 (Spalding et al., 2014; Halpern et al., 2015)(Cross Chapter Box 6). Anticipating these challenges to food and livelihoods for coastal communities will become increasingly important, and 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 coastal 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. Given the scale and cost of these interventions, implementing them earlier rather than later would be expedient.

[END BOX 3.4 HERE]

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 is producing significant impacts (*high agreement, robust evidence*). In this section, impacts and projections of sea level rise are reported at global and city scales (Sections 3.4.5.1-3.4.5.2) and for coastal systems

(Sections 3.4.5.3 – 3.4.5.6). For some sectors, there is a lack of precise evidence of change at 1.5°C and 2°C. Adaptation to sea level rise is discussed in Section 3.4.5.7.

3.4.5.1 Global / sub-global scale

Sea level rise (SLR) and other oceanic climate change will result in salinization, flooding and erosion and affect human and ecological systems, including health, heritage, freshwater, biodiversity, agriculture, fisheries and other services (*very high agreement, robust evidence)*. Due to the commitment to SLR, there is an overlapping uncertainty in projections (Schleussner et al., 2016b; Sanderson et al., 2017; Goodwin et al., 2018; Mengel et al., 2018; Nicholls et al., 2018; Rasmussen et al., 2018) of about 0.1 m difference in Global Mean Sea Level (GMSL) rise between 1.5ºC and 2ºC worlds in 2100 (Section 3.3.9, Table 3.3). Exposure and impacts at 1.5°C and 2ºC 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 higher rises 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 notes the land and people exposed to sea level rise (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); Also see Annex 3.1, Table S4). Thus, even with temperature stabilization, exposure increases. In contrast, land area exposed is projected to at least double by 2300 using a RCP8.5 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 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 sea level rise scenario. Slower rates of rise due to climate change mitigation may provide greater opportunity for adaptation (*medium confidence*), which can substantially reduce impacts.

Agreeing with WGII AR5 Section 5.4.3.1 (Wong et al., 2014), climate change mitigation may reduce or delay coastal impacts and exposure (*very high confidence, robust evidence*). Adaptation has the potential to substantially reduce risk (Nicholls et al., 2007; Wong et al., 2014; Sections 5.5 and 5.4.3.1; Sections 6.4.2.3 and 6.6,). At 1.5°C in 2100, 31–69 million people world-wide could be exposed to flooding assuming no adaptation or protection at all (and 2010 population values), compared with 32–79 million people at 2ºC in 2100 (Rasmussen et al., 2018) (Annex 3.1, Table S4). 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. With a 1.5°C stabilization scenario in 2100, 55-94 million people / year are at risk from flooding increasing to 115-188 million people per year in 2300 (50th percentile, SSP1-5, no socio-economic change after 2100). This assumes there is no upgrade to present protection levels (Nicholls et al., 2018). The number of people at risk increases by approximately 18% using a 2°C scenario and 266% using a RCP8.5 scenario in 2300 (Nicholls et al., 2018). Through prescribed IPCC Special Report on Emission Scenarios (SRES) SLR scenarios, Arnell et al. (2016) also found people flooded increased substantially after 2ºC without further adaptation from present protection levels, particularly in the second half of the twentieth century.

Coastal flooding by the sea is likely to cost thousands on billions of USD annually, with damage costs under constant protection 0.3–5.0% of global GDP in 2100 for a RCP2.6 scenario (Hinkel et al., 2014). Risks are projected to be highest in south and south-east Asia, assuming there is no upgrade to present protection levels, for all temperatures of climate warming (Arnell et al., 2016; Brown et al., 2016) Countries where at least 50 million people exposed to SLR (assuming no adaptation or protection at all) based on a 1,280 Pg C emission scenario (approximately 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 similar countries at high exposure from SLR. Thus there is *high confidence* that SLR will have significant impacts world-wide in this century and beyond.

3.4.5.2 Cities

Observations of the impacts of SLR are difficult to record due to multiple drivers of change in cities. Rather, there are observations of ongoing or planned adaptation to SLR and extreme water levels, and this will continue (Araos et al., 2016; Nicholls et al., 2018), whilst other cities are yet to prepare (see Section Cross-chapter Box 4.1) (*high confidence, medium to robust evidence*). There are limited observations and analysis of how cities will cope with higher and/or multi-centential SLR, with the exception of Amsterdam, New York and London (Nicholls et al., 2018).

Coastal urban areas are projected to see more exteme 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 enhancement through localized subsidence (Wong et al., 2014) causing greater relative SLR. At least 136 mega cities (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 2ºC 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 south-east Asia (Hallegatte et al., 2013; Cazenave and Cozannet, 2014; Clark et al., 2016; Jevrejeva et al., 2016). Jevrejeva et al. (2016) report with 2°C of warming by 2040 (for RCP8.5), more than 90% of global coastlines will experience SLR greater than 0.2 m. However, for scenarios where 2°C is stabilized or occurs later in time, this figure is likely to differ due to the commitment to SLR. Raising exisiting dikes helps to protect against SLR substantially reducing risk (whilst acknowledging other forms of adaptation exist). By 2300, dike heights under an unmitigation scenario (RCP8.5) could be more than 2 m higher (on average for 136 mega cities) than under climate change mitigation scenarios at 1.5°C or 2°C (Nicholls et al., 2018). Thus, rising sea levels commits to long-term adaptation in coastal cities. Thus, rising sea levels commits to long-term adaptation in coastal cities (*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 experienced a 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, robust evidence*), they are also reactive to change. Small islands are impacted by multiple climatic stressers, with SLR being more important a stressor to some islands rather than others (Box 3.5, Section 3.4.10, Section 4.3.5.6, Box 4.3, 5.2.1, 5.5.3.3, Box 5.3).

Observations of adaptation to multiple drivers of coastal change, including SLR, include retreat (migration), accommodate and defend. 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 (as a planned adaptation strategy) just one factor in the choice to migrate (Campbell and Warrick, 2014) (Sections 3.4.10, 4.3.5.6 and 5.3.2). Whilst flooding may result in migration or relocation for example, Vunidogoloa, Fiji, (McNamara and Des Combes, 2015; Gharbaoui and Blocher, 2016) or Soloman Islands (Albert et al., 2017), in-situ adaptation may be have been 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, Phillipines (Jamero et al., 2018) 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 implcations (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014; Section 29.6.22).

There is a lack of precise, quantitative studies of projected impacts of SLR at 1.5ºC and 2ºC. Small islands are projected to be at risk and very sensitive to coastal climate change and other stressors (high agreement, robust evidence) (Nurse et al., 2014; Benjamin and Thomas, 2016; Ourbak and Magnan, 2017; Brown et al., 2018a; Nicholls et al., 2018; Rasmussen et al., 2018; Section 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, Box 3.4, Box 3.5). These can have significant socio-economic and ecological implications, such as on health, agriculture and water resources, which have impacts for livlihoods (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014). Combinations of drivers causing adverse impacts are important: 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, such as temperature. Freshwater 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 of higher elevation are also threatened given there is often a lot of infrastructure located near to the coast (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 for longer time periods at the sea level rise associated with 1.5ºC and 2ºC. In Jamacia and St Lucia, SLR and extreme sea levels threaten transport system infrastructure at 1.5°C unless further adaptation is undertaken (Monioudi et al., 2018). slower rates of SLR will provide greater opportunity for adaptation to be successful (*medium agreement*), but will not reduce it substantially enough on islands of the lowest 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 this (Cross-Chapter Box 12 in Chapter 5). Small islands remain vulnerable to SLR (*high confidence*).

3.4.5.4 Deltas and estuaries

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

Z. Yang et al. (2015) found that USA future climate scenarios (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, 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 as the drivers operate on different time 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 account of SLR, plus surges, tides, bathymetry and local river flows (Brown et al., 2018b). Furthermore increased river salinity and saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C of warming (Zaman et al., 2017). Salinisation could impact agriculture and food security (Cross-Chapter Box 6). For 1.5°C or 2°C stabilization conditions in 2200, or 2300 plus surges, a minimum of 44% of the the Bangladesh Ganges-Brahmaputra, Indian Bengal, Indian Mahanadi and Ghanese Volta deltas land area (without defences) would be exposed unless sedimentation occurs (Brown et al., 2018b). Other deltas are similarly vulnerable. SLR is 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 to reduce 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 world, deltas, which are home to millions of people, are highly threatened from SLR and localised subsidence today, and over long time scales (*high confidence, medium evidence*).

3.4.5.5 Wetlands

Observations indicate that wetlands, such as saltmarshes and mangrove forests are disrupted by changing conditions (Wong et al., 2014; Lovelock et al., 2015; Section 5.4.2.4; Section 3.4.4.8), such as total water levels and sediment availability. For example, observations indicated that saltmarshes in Connecticut and New York 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 stimulated marsh carbon storage, and aided climate change mitigation.

Salinisation may lead to shifts in wetland communities and their ecosystems functions, affecting freshwater wetlands (Herbert et al., 2015). Some projections of wetland change, with magnitudes (but not necessarily rates or timing) of SLR analogous at 1.5°C and 2°C, indicate a net loss (e.g., Cui et al., 2015 with a 2.6 mm yr-1 rise (aligning with AR5) in the Yangtze Estuary; Blankespoor et al., 2014) 1 m rise in multiple countries; Arnell et al. (2016) using an A1 SRES scenario of up to 0.48 m by 2050 on a global scale; drowning of 60% of marshes studied world-wide (with a rate of sea-level rise of 4.4 mm yr^{-1}) by 2100 (Crosby et al., 2016), whilst others report a net gain with wetland transgression ((Raabe and Stumpf, 2016) in the Gulf of Mexico). However, the feedback between wetlands and sea level is complex, with parameters such as lack of accommodation space restricting inland migration, or sediment supply and feedback 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 2oC to 1.5oC will deliver long-term benefits from lower SLR, allowing natural sedimentation rates to more likely keep up with SLR. It remains unclear how wetlands will respond and under what conditions (including other climate parameters) with a rise in 1.5°C and 2°C, simultaneously recognising they have great potential for adaptation and climate change mitigation (medium confidence, medium evidence) (Sections 4.3.2 and 4.3.3.3).

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 (Wong et al., 2014; Section 5.4), such as beaches, barriers, sand dunes, rocky coasts, aquifers, lagoons and ecosystems (for the latter, see Section 3.4.4.12). For example, SLR effects erosion and accretion, and therefore sediment movement, instigating shoreline change (Wong et al., 2014; Section 5.4.2.1) 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 or geological constraints reduces shoreline movement causing coastal squeeze (e.g. in Japan, beach losses due to SLR are projected with a RCP2.6 scenario, and are projected to increase under RCP8.5 (Udo and Takeda, 2017)). Compound flooding (the combined risk of flooding from multiple drivers) 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 SLR rise 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 agreement, robust evidence, 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 (Wong et al., 2014; Section 5.4.2.1). 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 (Hinkel et al., 2014; Wong et al., 2014) (*high agreement, robust evidence*), although there is less certainty for ecosystems (Sections 4.3.2, 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, intensifying storms, coastal inundation and salinization communities (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 the AR5, planned and autonomous adaptation and forward planning has become more wide-spread (Araos et al., 2016; Nicholls et al., 2018), but continued efforts are required as many localities are in the early stages of adapting or not adapting at all (Araos et al., 2016) (See Cross-Chapter Box 9 in Chapter 4). This is regional and sub-sectoral specific, and also linked to non-climatic factors (Ford et al., 2015; Lesnikowski et al., 2015; Araos 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 thinking, but are not widespread practice despite knowledge of long-term risk (Section 4.2.2). Furthermore, retreat and human migration have increasingly being considered as a management 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 (Wong et al., 2014, Section 5.5.8; Nicholls et al. 2015; Section 4.2.2.3). SLR poses a long-term threat (Section 3.3.9), even with 1.5°C and 2°C of warming centennial scale adaptation remains essential (high confidence, robust evidence).

Table 3.3: Land and people exposed to sea level rise (SLR, assuming no protection at all). Extracted from (Brown et al., 2018a; Goodwin et al., 2018). SSP: Shared Socioeconomic Pathway, wrt: with respect to

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 (10^3 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]*

*Population is held static after 2300.

[START BOX 3.5 HERE]

Box 3.5: Small Island Developing States (SIDS)

1.5°C warming is expected to prove a challenging state for Small Island Developing States (SIDS) that are already experiencing impacts associated with climate change. At 1.5°C, compounding impacts from interactions between climate drivers may contribute to loss of, or change in, critical natural and human systems (*high agreement*, *medium evidence*). There are a number of reduced risks at 1.5°C versus 2°C, particularly when coupled with adaptation efforts (*high agreement*, *medium evidence*).

Changing climate hazards for SIDS at 1.5°C

Mean surface temperature is projected to increase in SIDS at 1.5°C (*high agreement*, *robust evidence*). The Caribbean region will experience 0.5°C –1.5°C warming compared to 1971–2000 baseline, with greatest warming over larger land masses (Taylor et al., 2018). Under the Representative Concentration Pathway (RCP)2.6 scenario, the western tropical Pacific is projected to experience warming of 0.5°C –1.7°C relative to 1961–1990. Extreme temperatures will also increase, with potential for elevated impacts as a result of comparably small natural variability (Reyer et al., 2017a). Compared to the 1971–2000 baseline, up to 50% of the year are projected to be under warm spell conditions in the Caribbean at 1.5°C with a further increase by up to 70 days at 2°C (Taylor et al., 2018).

Changes in precipitation patterns, freshwater availability and drought sensitivity differ between small island regions (*high agreement, medium evidence*). Some western Pacific and the northern Indian Ocean islands may see increased freshwater availability, while islands in most other regions are projected to see a substantial decline (Holding et al., 2016; Karnauskas et al., 2016). For several SIDS, approximately 25% of the overall freshwater stress projected under 2°C at 2030 can be avoided by limiting global warming to 1.5°C (Karnauskas et al., 2018). In accordance with an overall drying trend, an increasing drought risk is projected for Caribbean SIDS (Lehner et al., 2017) and moderate to extreme drought conditions are projected to be about 9% longer on average for 2°C versus 1.5°C for islands in this region (Taylor et al., 2018).

Projected changes in the ocean system at higher warming targets (Section 3.4.4), including potential changes in circulation (Section 3.3.7) and increases in both surface temperatures (Section 3.3.7) and ocean acidification (Section 3.3.10) suggest steadily increasing risks for SIDS associated with warming levels close to and exceeding 1.5°C.

Differences in global sea level between 1.5°C and 2°C depend on the time scale considered and will fully materialize only after 2100 (Section 3.3.9). Projected changes in regional sea level are similarly time dependent, but generally found to be above global average for tropical regions including small islands (Kopp et al., 2014; Jevrejeva et al., 2016). Sea level related threats for SIDS, for example, from salinisation, flooding, permanent inundation, erosion and pressure on ecosystems, will therefore persist well beyond the 21st century even under 1.5°C warming (Section 3.4.5.3; Nicholls et al., 2018). Prolonged interannual sea level inundations may increase throughout the tropical Pacific with ongoing warming and in the advent of increased frequency of extreme La Niña events, exacerbate coastal impacts of projected global mean Sea Level Rise (SLR; Widlansky et al., 2015). Changes to frequency of extreme El Niño and La Niña events may also increase the frequency of droughts and floods in South Pacific islands (Cai et al., 2012; Box 4.2; Section 3.5.2)

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., 2017). There are insufficient 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, 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 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 GDP per capita growth for SIDS (Petris et al., 2018, Section 3.4.7.1, Section 3.4.9.1, Section 3.5.4.9). These impacts are reduced considerably under 1.5°C but may be increased by escalating risks from climate related extreme weather events and SLR (Section 3.4.5.3, Section 3.4.9.4, Section 3.5.3)

Marine systems and associated livelihoods in SIDS face higher risks at 2°C as compared to 1.5°C (*high agreement, medium evidence*). Mass coral bleaching and mortality are projected to increase due to interactions between rising ocean temperatures, ocean acidification, and destructive waves from intensifying storms (Section 3.4.4, Box 3.4, Section 5.2.3). 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, increasing to 99% at 2°C (Schleussner et al., 2016b). Warmer 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 population, infrastructure and assets are projected to increase with higher levels of warming (*high agreement, robust evidence*). 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 (Scott et al., 2012; Kumar and Taylor, 2015; Rhiney, 2015; Byers et al., 2018; Section 3.4.9, Section 3.4.5.3). Limiting warming to 1.5°C instead of 2°C spares the inundation of lands currently home to 60,000 individuals in SIDS by 2150 (Rasmussen et al., 2018). However, such estimates do not take into account shoreline response (Section 3.4.5) or adaptation.

Risks of impacts across sectors are higher at 1.5°C as compared to the present, and will further increase at 2°C (*high agreement, medium evidence*). Projections indicate that at 1.5°C there will be increased incidents of internal migration and displacement (Albert et al., 2017, Sections 3.5.5, 4.3.6, 5.2.2), limited capacity to assess loss and damage (Thomas and Benjamin, 2017) and substantial increases in 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 1.5C limits to adaptation will be reached for several key impacts in SIDS resulting in residual impacts and loss and damage (Cross-Chapter Box 12 in Chapter 5, Section 1.1.1). There are a number of reduced risks when limiting temperature increase to 1.5°C versus 2°C, particularly when coupled with adaptation efforts that take into account sustainable development (Mycoo, 2017; Thomas and Benjamin, 2017; Section 3.4.2, Box 4.3, Section 5.6.3.1, Box 5.3). Region-specific pathways for SIDS exist to address climate change (Section 5.6.3.1, Box 5.3, Box 4.6, Cross-Chapter Box 11 in Chapter 4).

[END BOX 3.5 HERE]

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 for 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 geographical area and crop type (Rose et al., 2016). Despite these issues, recent studies confirm that observed climate changes have 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), particularly affecting 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 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), also suggesting the possibility of more than one harvest per year (B. Chen et al., 2014; Sun et al., 2015). Climate variability was 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 variation in the percentage according to crop type and scale (Moore and Lobell, 2015; Kent et al., 2017). Climate trends explain also change in the lengthening of the growing season, where greater modifications were found in the northern 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 ranging from 3% to 16% globally (Van Dingenen et al., 2009). Some studies found that increases in atmospheric CO_2 concentrations would be expected to increase yields by enhancing radiation and water use efficiencies (Elliott et al., 2014; Durand et al., 2017). In open-top chamber experiments at elevated CO_2 and 1.5°C 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 actual crop yield trends indicate that reductions as a result of climate change remain more common than crop yield increases, despite increased atmospheric CO_2 concentration (Porter et al., 2014). For instance, McGrath and Lobell (2013) indicated that production stimulation at increased atmospheric CO_2 concentration 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. However, importantly, the faster growth rates induced by elevated CO_2 often coincided with lower protein values in several important C3 cereal grains (Myers et al., 2014) although perhaps not always for C4 grains such as sorghum under drought conditions (De Souza et al., 2015). Elevated CO_2 concentrations of 568–590 ppm alone (a range that corresponds approximately to RCP6 in the 2080s and hence a warming of 2.3–3.3°C (van Vuuren et al., 2011a, WGI Table 12.2) alone reduced the protein, micronutrient, and B vitamin content of the 18 rice cultivars grown most widely grown in southeast Asia, where it is a staple food source, by an amount sufficient to create nutritional-related health risks for 600 million people (Zhu *et al.* 2018). Overall, the effects of increased CO_2 concentration 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 (Porter et al., 2014; Rosenzweig et al., 2014) (*high confidence*). A few studies since the AR5 have focused on the impacts on cropping systems for scenarios where global mean temperatures increase within 1.5°C. (Schleussner et al., 2016b) projected that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and Central and South America. Ricke et al. (2015) highlighted that cropland stability declines rapidly between 1ºC and 3ºC warming, whilst Bassu et al. (2014) suggested that an increase of air temperature negatively influence the modeled maize yield response of –0.5 t ha^{-1} per degree Celsius, as also reported by Challinor et al. (2014) for tropical regions. Niang et al. (2014) projected significantly lower risks to crop productivity in Africa at 1.5ºC compared to 2ºC warming. Lana et al. (2017) indicated that the impact of temperature increases on crop failure of maize hybrids was much greater as temperatures increase to +2°C compared to 1.5°C (*high confidence*). J. Huang et al. (2017) found that limiting warming at +1.5 °C compared to +2°C, maize yield losses would be reduced 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, these studies generally did find declines in breadbasket regions when the effects of CO_2 fertilization were excluded. Iizumi et al. (2017) found lower maize and soybean yields reduction at +1.5°C than at +2°C, higher rice production at +2°C than at +1.5°C warming and no clear differences for wheat at global mean basis. These results were largely consistent with 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 warming was projected to result in further reduction of maize, sorghum and cocoa cropping areas suitability as well as yield losses especially for C3, only partially compensated by rainfall change (Läderach et al., 2013; World Bank, 2013; Sultan and Gaetani, 2016).

Some studies found a significant reduction in global production of wheat rice, maize, and soybean of 6.0 ± 2.9%, 3.2 ± 3.7%, 7.4 ± 4.5% and 3.1%, respectively, for each degree Celcius 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 by about 10.3% in the greater Mekong sub-region (*medium confidence*). Large rice and maize yield losses are to be expected in China due to climate extremes (Wei et al., 2017; Zhang et al., 2017) (*medium confidence*).

Crop production is also negatively affected also by a factor generally excluded from the aforementioned studies, that is 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 temperature (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), flood (Betts et al., 2018; Byers et al., 2018), chilling damage, (Jiao et al., 2016), while indirect effects include the spread of pest and diseases (van Bruggen et al., 2015, Jiao et al., 2014), which can also have detrimental effects on cropping systems.

Taken together, the findings of studies on the effects of changes in temperature, precipitation, changes in 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 a 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), beside 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 impact of heat stress on dairy cow production over some UK regions, whilst 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); or zoonotic diseases, Njeru et al., 2016; Simulundu et al., 2017).

Future climate change impacts on livestock are expected to increase. In temperate climates, warming is expected to lengthen 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). Similar studies confirmed decrease in forage quality both for natural grassland in France (Graux et al., 2013) and sown pastures in Australia (Perring et al., 2010). Water resources availability for livestock are expected to decrease due to increased runoff and reduced groundwater resource. Increased temperature will likely induce changes in river discharge and basins water amount, leading human and livestock populations to experience water stress especially over the driest areas (Palmer et al., 2008) (i.e., sub-Saharan Africa and South Asia) (*medium confidence*). Elevated temperatures are also expected to increase methane production (M.A. Lee et al., 2017; Knapp et al., 2014). Globally, a decline in livestock of more 7.5-9.6% is expected at about 2°C warming, with associated economic losses of between $9.7 and $12.6 billion (Boone et al., 2017).

3.4.6.3 Fisheries and aquaculture production

Global fisheries and aquaculture contribute a total of 88.6 and 59.8 million tons from capture and aquaculture (FAO, 2016), playing an important role in food security of a large number of countries (McClanahan et al., 2015; Pauly and Charles, 2015) and resulting essential to meet 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-latitude is coincident with increases in temperature, ocean acidification, introduced species, disease and other drivers (Lacoue-Labarthe et al., 2016; Clements et al., 2017; Clements and Chopin, 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). Human actions have reduced the risks from these factors which are expected to be more likely moderated under RCP2.6 and very high under RCP8.5 (Gattuso et al., 2015). The climate related risks 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., 2017). Recent literature (2015–2017) described growing threats from the 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, unsustainable coastal development), drive 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, projections of climate change and the growth in human population increasingly project scenarios that include shortages of fish protein for many regions (e.g., Pacific Ocean, Bell et al., 2013; 2017); Indian Ocean, for example, (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 climate change related impacts on low latitude fin fisheries are low today, but are expected to reach very high levels under all RCPs especially at low latitudes (*high confidence*) by 1.1ºC. 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 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 risk of disease and invasive species). 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), resulting 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 are low up to 1.3ºC, *moderate* at 1.3ºC, and *moderate* to *high* up to 1.9ºC (Figure 3.17). For instance, Cheung et al. (2016a), simulating the loss in fishery productivity at 1.5°C, 2ºC and 3.5°C above the preindustrial period, found that the potential global catch for marine fisheries will *likely* decrease by more than 3 million metric tons for each degree of warming. Low latitude finfish fisheries have higher risks of impacts, with present day risks being moderate and becoming high risks at 1.5˚C and 2˚C. High latitude fisheries are undergoing major transformations, and while production is increasing, present day risk is moderate, and remains at moderate at 1.5˚C and 2˚C (Figure 3.3).

Adaptation measures can be applied to shellfish, large pelagic fish resources and biodiversity and include options such as protecting reproductive stages and brood stock from periods of high Ocean Acidification (OA), stock selection for high tolerance to OA (Ekstrom et al., 2015; Rodrigues et al., 2015; Handisyde et al., 2016; Lee, 2016; Weatherdon et al., 2016; Clements and Chopin, 2017) (*high confidence*), redistribution of highly migratory resources (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 reefs stresses and development of alternative livelihoods (e.g., aquaculture, Bell et al., 2013, 2017).

Cross-Chapter Box 6: Food Security

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

Goal 2 of the SDGs aims to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture by 2030. This builds on the Millennium Development Goal (MDG); efforts to achieve Goal 1 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 possibility of achieving SDG 2 and could reverse the progress made. Food security and agriculture are also critical to other aspects of sustainable development, including eradicating poverty (SDG 1), health and wellbeing (SDG 3), clean water (SDG 6), decent work (SDG 8) and the protection of ecosystems on land and water (SDG 14 and SDG 15) (UN, 2015, 2017; Pérez-Escamilla, 2017).

Increasing global temperatures pose large risks to food security globally and regionally, especially at low latitude areas (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 a global warming of 1.5°C (*high confidence*, Section 3.4.6) owing to the combined effects of changes in temperature, precipitation, and changes in extreme weather events and in CO_2 concentrations. Climate change can exacerbate malnutrition, reducing nutrient availability and quality of food products (Cramer et al., 2014; Springmann et al., 2016); *medium confidence*). Generally, vulnerability to decreases in water and food availability is reduced at 1.5°C versus 2°C (Cheung et al., 2016a; Betts et al., 2018) , whilst at 2°C these are expected to be exacerbated especially in regions such as the African Sahel, the Mediterranean, central Europe, the Amazon, and western and southern Africa (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high confidence*).

Rosenzweig et al. (2018) and Ruane et al. (2018) report that the higher CO_2 concentrations at 2ºC caused positive effects in some regions compared to 1.5ºC. Production can also benefit from warming in higher latitudes with fertile soils, crop, and grassland, 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 alternative regional climate change projections and the assumed strength of CO_2 fertilisation effects (Section 3.6) which are uncertain. For C3 crops, theoretically advantageous CO_2 fertilisation 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 be less accumulated and less available in food (Myers *et al.*, 2014). Together, the impacts on protein availability may take 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 due to climate change (Cheung et al., 2010; Hollowed and Sundby, 2014; Lam et al., 2016; Sundby et al., 2016; Weatherdon et al., 2016) (*high confidence*; Section 3.4.6.3).

Factors affecting projections of food security include variability in regional climate projections, climate change mitigation (where this affects land use; see Section 3.6 and Crosss-Chapter Box 7) and biological responses (McGrath and Lobell, 2013; Elliott et al., 2014; Pörtner et al., 2014; Durand et al., 2017; AR5 6.5.1) (*medium confidence*; Section 3.4.6.1), extreme events (droughts, floods) (Rosenzweig et al., 2014; Wei et al., 2017) (*high confidence*; Sections 3.4.6.1, 3.4.6.2), financial volatility (Kannan et al., 2000; Ghosh, 2010; Naylor and Falcon, 2010; HLPE, 2011) and the distributions of pests and disease (van Bruggen et al., 2015; Jiao et al., 2014). 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 (Asiedu et al., 2017a, b; Utete et al., 2018; Section 3.4.6.3). Human influences on food security include demography, food wastage, diet shift, incomes and prices, storage, health status, trade patterns, conflict, and access to land and government 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 (Lobell et al., 2011; von Lampe et al., 2014; d'Amour et al., 2016; Wei et al., 2017) (*medium confidence*).

Climate change impacts on food security can be reduced through adaptation (Hasegawa et al., 2014). While climate change is very likely to decrease agricultural yield, the consequences could be reduced substantially at 1.5ºC with appropriate investment (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 adaptation via technologies and adaptation strategies for food systems (Lipper et al., 2014; Martinez-Baron et al., 2018; Whitfield et al., 2018) as well as meet mitigation goals (Harvey et al., 2014).

K.R. Smith et al. (2014) concluded that climate change will negatively affect childhood undernutrition and stunting through reduced food availability, and will negatively affect undernutrition-related childhood mortality and increase disability-adjusted life years lost, with the largest risks in Asia and Africa (Ishida et al., 2014; Hasegawa et al., 2016; Springmann et al., 2016; Annex 3.1 Table S11). Studies comparing the health risks associated with food insecurity at 1.5°C and 2°C concluded that risks are 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 were projected to increase mortality due to global reductions in food availability and consumption of fruit, vegetables, and red meat (Springmann et al., 2016). Further, temperature increases are reducing the protein and micronutrient content of major cereal crops, which is expected to further affect food 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 South-East Asia. The Mekong is a major food bowl (Smajgl et al., 2015) yet is also a climate change hotspot (de Sherbinin, 2014; Lebel et al., 2014). It is also a useful illustration of the complexity of adaptation choices and actions in a 1.5˚C world. Climate projections indicate increased annual average temperatures and precipitation (Zhang et al., 2016) and 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 (Renaud et al., 2015). The main climate impacts in the Mekong will be on ecosystem health through salinity intrusion, biomass reduction, and biodiversity losses (Le Dang et al., 2014; 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.

Adaptation imperatives and costs in the Mekong will be higher under increased temperatures via 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), improving water use technologies (e.g., irrigation, pond capacity improvement, 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-rich and land-poor farmers (Chapman et al., 2016). Construction of high dikes for example has enabled triple-cropping with benefits for land-wealthy farmers but increasing debt for land-poor farmers (Chapman and Darby, 2016).

Institutional innovation has happened through the establishment of the Mekong River Commission (MRC) in 1995, an intergovernmental body between Cambodia, Lao PDR, Thailand and Viet Nam. The MRC has facilitated impact assessment studies, regional capacity building, and local project implementation (Schipper et al., 2010), although mainstreaming of adaptation into development policies has lagged behind needs (Gass et al., 2011). Existing adaptation interventions can be strengthened through improving flexibility of institutions dealing with land use planning and agricultural production, improved monitoring of saline intrusion, and setting up 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, 2017; Tran et al., 2018). Critical 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 complexity of environmental, social and economic pressure on people in the Mekong River Basin highlights the complexity of climate impacts and adaptation in this region, and the fact that costs are likely to be much lower at 1.5ºC than 2ºC.

[END BOX X-B 3.1 HERE]

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 intensity of transmission 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 the AR5 provided evidence using multi-step 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 due to more intense heatwaves and fires; increased risks of undernutrition; and consequences of reduced labor productivity in vulnerable populations (K.R. Smith et al., 2014).

3.4.7.1 Projected risk at 1.5°C and 2°C

Annex 3.1, Tables S7, S8 and S9 (based on Ebi et al., 2018) summarize the projected risks to human health of warming of 1.5°C and 2°C from studies of temperature-related morbidity and mortality, air quality and vector borne diseases assessed in and since the AR5. Other climate-sensitive health outcomes, such as diarrheal diseases, mental health 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 for specific temperatures above pre-industrial temperature; Annex 3.1, Table S6 provides the conversions used to translate risks projected at particular time slices to temperature change (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 (*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.T. Li et al., 2016; Chung et al., 2017; Kendrovski et al., 2017; Arnell et al., 2018; Mitchell, 2018). 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 increase varies by region, presumably because of 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; Li et al., 2016b).

In some regions, cold-related mortality is projected to decrease with warmer 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 placed 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 agreement, low evidence*) (Dunne et al., 2013; Kjellstrom et al., 2013, 2017; 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 the difference in economic loss between 1.5°C and 2°C could be approximately 0.3% global 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*) (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); Annex 3.1 Table S.8) reductions in precursor emissions would reduce future ozone concentrations (and associated mortality). Changes in projected PM-related mortality could increase or decrease, depending on climate projections and emissions assumptions (Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016; Table S8).

Malaria: Recent projections of the potential impacts of climate change on malaria globally and for Asia, Africa, and South America (Annex 3.1 Table S9) 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 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 with greater amounts of warming, with regionally variable patterns (*high agreement, medium evidence*). 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 there will be an increase in the number of mosquitos and a larger geographic range at 2° than at 1.5°C and beyond than at present, and suggest more individuals at risk of dengue fever, with regional differences (*high confidence*) (Fischer et al., 2011; Colón-González et al., 2013; Fischer et al., 2013; Bouzid et al., 2014; Ogden et al., 2014a; Mweya et al., 2016). The risks increase with greater warming. Projections suggest that climate change will expand the geographic range of chikungunya, with greater expansions with higher degrees of warming (Tjaden et al., 2017).

Other vector-borne diseases: Increased warming in North America and Europe could result in latitudinal and altitudinal expansions of regions 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 degree of warming (Semenza et al., 2016). Most projections conclude that climate change will 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 changes are larger with greater warming and under higher greenhouse gas emission pathways. Projections of the impacts of climate change on leishmaniosis and Chagas disease indicate climate change could increase or decrease future health burdens, with greater impacts 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, and with a few exceptions (*high confidence*). There is *very high confidence* that each additional unit of warming will increase heat-related morbidity and mortality, and that adaptation would reduce the magnitude of impacts. There is *high confidence* that ozone-related mortality will increase if precursor emissions remain the same, and that warmer temperatures will affect the transmission of some infectious diseases, with increases and decreases projected depending on disease (e.g., malaria, dengue, 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, 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 (Bader et al., 2018; Dawson, et al., 2018; Section 3.4.5). Indirect risks may arise from interactions between urbanization 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, 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 landuse, zoning and building codes (UCCRN, 2018), at 2°C warming, Karachi (Pakistan) and Kolkata (India) could expect annual conditions equivalent to the deadly 2015 heatwaves (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 and Zhai, 2018). Stabilising at 1.5 °C warming could decrease extreme temperature-related mortality compared with stabilisation at 2°C for key European cities, assuming no adaptation and constant vulnerability (Jacob et al., 2018; Mitchell et al., 2018). Holding temperature change to below 2°C, taking Urban Heat Islands (UHI) into consideration, could result in a substantial increase in the occurrence of deadly heatwaves in cities, with the impacts similar at 1.5°C and 2°C, with both substantially larger than under the present climate (Matthews et al., 2017; Yu et al., 2018).

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 differential 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 South East Asia (Schleussner et al., 2016b), with large informal settlements and other vulnerable urban populations, and with vulnerable assets, including 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 1986-2005. Regional dry spells are projected to expand from 7% at 1.5°C to 11% at 2°C. Sea-level rise is expected to be lower for 1.5°C than 2°C, lowering risks for coastal metropolitan agglomerations (Schleussner et al., 2016b).

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).

Climate models are better at projecting implications of greenhouse gas forcing on physical systems than 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), infrastructure sectors (energy, water, transport), levels of poverty and the mix of formal and informal settlements.

3.4.9 Key economic sectors and services

Climate change will 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 across 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 S10 in Annex 3.1 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 the AR5, observed impacts on tourism markets and destination communities continue to be not well analyzed, despite many analogue conditions (e.g., heatwaves, major hurricanes, wild fires, reduced snow pack, coastal erosion, coral reef bleaching) that are anticipated to occur more frequently with climate change. There is some evidence that observed impacts on tourism assets (environmental and cultural heritage) is leading to the development of 'last chance' 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 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 favored by 1.5°C warming, with negative effects projected for Spain, Cyprus (decrease of 8% and 2% overnight stays, respectively) and most coastal regions of the Mediterranean (Jacob et al., 2018). Similar geography of potential tourism gains (central and northern Europe) and reduced summer favorability (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 warming (Jacob et al., 2018). Using an econometric analysis of the relationship between regional tourism demand and climate conditions, Ciscar et al. (2014) projected a 2°C world would reduce European tourism by -5% (€15 billion yr^{-1}), with losses up to -11% (€6 billion yr-1) for southern Europe and a potential gain of €0.5 billion yr^{-1} in the UK.

Growing evidence indicates that the magnitude of projected impacts is temperature-dependent and sector risks will 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 continue to omit snowmaking do not reflect the operating realities of most ski areas and overestimate impacts at 1.5–2°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 number of former Olympic Winter Games host locations that could remain climatically reliable for future Olympic and Paralympic Winter Games was also 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 systems that are critical assets for tourism, including biodiversity, beaches, glaciers, and other environmental and cultural heritage. Limited analyses of projected risks associated with 1.5° versus 2°C are available (Section 3.4.4.12). A global analysis of SLR risk to 720 UNESCO Cultural World Heritage sites projected that about 47 sites could be affected under 1°C warming, 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 in most major tourism destinations and 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 to global scales) has been the lack of integrated sectoral assessments that analyze the full range of potential compounding impacts and their interactions with other major drivers of tourism (Rosselló-Nadal, 2014; Scott et al., 2016b). A global vulnerability index (27 indicators) in 181 countries found that countries with the lowest risk are found in western and northern Europe, central Asia, Canada, and New Zealand, while the highest sector risks are projected in 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 (more than 15% GDP) include many SIDS and least developed countries. Sectoral climate change risk also aligned strongly with regions where tourism growth is projected to be the strongest over the coming decades, including sub-Saharan Africa and South Asia; representing 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 will directly impact climate dependent tourism markets, including sun and 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 will increase risks for coastal tourism, particularly in sub-tropical and tropical regions (*high confidence*).

3.4.9.2 Energy systems

Climate change will likely increase the demand for air conditioning in most tropical and sub-tropical regions (Arent et al., 2014; Hong and Kim, 2015). 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). In the Zambezi River basin, hydropower may fall by 10% by 2030 (about 1.5°C) and by 35% by 2050 under the driest scenario (Strzepek et al., 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 roughly 1.2% cost of GDP per 1°C increase on average under RCP8.5 (Hsiang et al., 2017). Projections of the GDP indicate that negative impacts of energy demand associated with space heating and cooling in 2100 are highest (median: –0.94%) under 4°C (RCP8.5) compared with a GDP change (median: –0.05%) under 1.5°C, depending on the socio-economic conditions (Park et al., 2018). Additionally, total energy demands for heating and cooling at the global scale do not change much with increases in Global Mean Temperature (GMT) up to 2°C. There is, however, a high degree of variability 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 (+2.4% under RCP2.6; +6.3% under RCP8.5 for the 2080s) with the most growth in central Africa, Asia, India, and northern high latitudes (van Vliet et al., 2016). Byers et al. (2018) found energy impacts at 2ºC increase including increased 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, finding a decrease of approximately 40% power capacity is projected for global temperature increase in the range of 1.5°C. At minimum and maximum increases in global mean temperatures of 1.35° 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). Changes are greater at the higher projected temperature. 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 a control scenario with constant temperatures (McFarland et al., 2015). Decreased electricity generation of –15% is projected for Brazil starting in 2040, declining to –28% later in the century (de Queiroz et al., 2016). In large parts of Europe, electricity demand is projected to decrease mainly due to reduced heating demand (Jacob et al., 2018).

In Europe, no major differences in large-scale wind energy resources, inter-annual 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 and increase in Baltic regions (–30% vs. +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 for all climate models). However, wind farm yields will undergo changes up to 15% in magnitude at country and local scales and a 5% change in magnitude at regional scale (Tobin et al., 2015, 2016). Hosking et al. (2018) assessed wind power generation over Europe for 1.5°C warming, finding 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 increases on wind, solar photovoltaic and thermoelectric power generation across Europe. Results 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 limited impacts for 1.5°C 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.

Limited new research since the AR5 supports 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 impacting shipping and reducing transportation cost (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, but more shipping resulting in short-lived pollutants, as well as CO_2 and non-CO_2 emissions associated with additional economic growth enabled by the North Sea Route, is expected to contribute to a mean temperature rise of 0.05% (Yumashev et al., 2017). For a scenario with global mean temperature stabilization of open water vessel transits has the potential to double by mid-century with a season ranging from two to four months (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, and 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 on traditional ecological knowledge (Olsson et al., 2014).

3.4.10.1 Livelihoods and poverty

At approximately 1.5°C (2030), climate change will 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 could force more than 100 million people into extreme poverty, with the numbers attributed to climate change alone between 3 million and 16 million, 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). 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 is challenging with any degree of confidence (Cramer et al., 2014).

No studies specifically explored the difference in risks between 1.5ºC and 2ºC 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 most closely explore the probable impacts of 1.5ºC and 2ºC typically focus on the effects of temperature and precipitation anomalies directly on migration or indirectly through examining migration due to changing agriculture yield and livelihood sources (Mueller et al., 2014; Piguet and Laczko, 2014; Mastrorillo et al., 2016; Sudmeier-Rieux et al., 2017).

Temperature had a positive and statistically significant effect on outmigration over recent decades in 163 countries, but only for agricultural-dependent countries (R. Cai et al., 2016). A 1°C increase in 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 millimeter of precipitation was associated with an increase in migration by 0.5% (Backhaus et al., 2015). An increase in precipitation anomalies, but over a different time period, was strongly associated with an increase in outmigration but 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 or development (Bedarff and Jakobeit, 2017; Speelman et al., 2017; Nicholls et al., 2018). Depending on the situation, changing weather, climatic, or environmental conditions might each be one factor in the choice to migrate (Campbell and Warrick, 2014).

Displacement: At 2°C warming, there is a potential for significant population displacement concentrated in the tropics (Hsiang and Sobel, 2016). Tropical populations may have to move at distances greater than 1000 km if global mean temperature rises by 2 °C from the period of 2011–2030 to the end of the century. A disproportionately rapid evacuation from the tropics could lead 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 cautiousness in relating conflict to climate change due to sampling bias (Adams et al., 2018). Often taking limited consideration of the multiple drivers of conflict, inconsistent associations are 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; Brzoska and Fröhlich, 2016; Burrows and Kinney, 2016; Christiansen, 2016; Reyer et al., 2017c; Waha et al., 2017). Across world regions and the international to micro level, the strength of the relationship between drought and conflict under most circumstances is limited (Buhaug, 2016; von Uexkull et al., 2016). However, drought significantly increases the likelihood of sustained conflict for particularly vulnerable nations or groups due to their livelihood dependance on agriculture. This is particularly relevant among groups in the least developed countries (von Uexkull et al., 2016), sub-Saharan Africa (Serdeczny et al., 2016; Almer et al., 2017) and in the Middle East (Waha et al., 2017). Hsiang et al. (2013) report 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, then rates of human conflict could increase. Some causal associations between violent conflict and socio-political stability were reported from local to global scales and from hours to millennium (Hsiang and Burke, 2014). A temperature increase by one standard deviation in 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 associated in ethnically fractionalized countries, indicating there is no clear signal that environmental disasters directly trigger armed conflicts (Schleussner et al., 2016a).

In summary, average global temperatures that extend beyond 1.5ºC are likely to increase poverty and disadvantage in many populations globally. 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 of temperature and economic productivity is not linear (*high confidence*). Temperature has a positive and statistically significant effect on outmigration for agricultural-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 approximately double between 1.5°C and 2°C, and the land area affected by climate risks increases as warming progresses. For populations vulnerable to poverty, the exposure to climate risks in multiple sectors is an order of magnitude greater (8–32 fold) in the high poverty and inequality scenarios (SSP3; 765–1,220 million) compared to sustainable socioeconomic 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 3.18 shows that moderate and high multi-sector impacts are prevalent where vulnerable people live, predominantly in South Asia (mostly Pakistan, India, and China), at 1.5°C, but spreading 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 are expected to be disproportionately impacted, particularly in cases (SSP3) of high inequality in Africa and southern Asia. Table 3.4 shows the number of exposed and vulnerable people at 1.5°C and 2°C, with 3°C for context, for selected multi-sector risks.

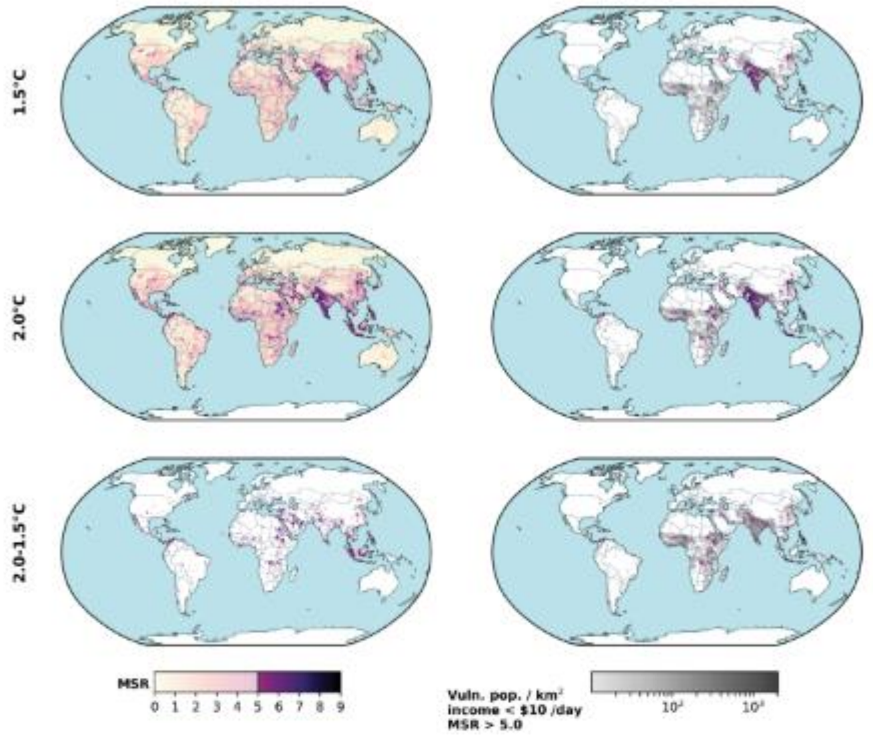


Figure 3.18: Multi-sector risk maps for 1.5, 2°C, and locations where 2°C brings impacts not experienced at 1.5°C (2–1.5°C). The left column shows the full range of the multi-sector risk score (range 0–9) with transparency and the scores >5.0 in full color. Score must be >4.0 to be considered "multi-sector". The right column

greyscale overlays the 2050 vulnerable populations (low income) under Shared Socioeconomic Pathway (SSP)2 with the multi-sector risk score > 5.0 in full color, 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 & Vulnerable	Exposed	Exposed & Vulnerable	Exposed	Exposed & 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	Summarise					
2 indicators	1129 (1019 – 1250)	203 (42 – 487)	2726 (2132 – 2945)	562 (117 – 1220)	3500 (3212 – 3864)	707 (212 – 1545)
3 indicators	66 (66 – 68)	7 (0.9 – 19)	422 (297 – 447)	54 (8 – 138)	1472 (1177 – 1574)	237 (48 – 538)
4 indicators	5 (0.3 – 5.7)	0.3 (0 – 1.2)	11 (5 – 14)	0.5 (0 – 2)	258 (104 – 280)	33 (4 – 86)

3.4.12 Summary of projected risks at 1.5ºC and 2ºC of global warming

The following table summarises the information presented as part of Section 3.4, illustrating the growing of evidence of increasing risks across a broad range of natural and human systems at 1.5°C and 2°C of global warming.

Table 3.5: Summary of projected risks at 1.5ºC and 2ºC of global warming

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
Freshwater	Precipitation, temperature, snowmelt	Water Stress	Additional 8% of the world population in 2000 to new or aggravated water scarcity	Around half compared to the risks at 2.0ºC	~100% increase	M		Europe, Australia and southern Africa		3	L	L	M
		Fluvial flood	170% increase in population affected as compared to the impact simulated over the baseline	100% increase in population affected as compared to the impact simulated over the	70% increase	M	U.S., Asia, and Europe		Africa and Oceania	2	L/M	L/M	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
			period 1976–2005	baseline period 1976–2005									
		Drought	410.7±213.5 million, changes in urban population exposure to severe drought at the globe	350.2±158.8 million, changes in urban population exposure to severe drought at the globe	60.5±84.1 million (±84.1 based on the SSP1 scenario)	M	Central Europe, Southern Europe, the Mediterranean, West Africa, East and West Asia and Southeast Asia			2	L/M	L/M	L
Terrestrial ecosystems	Temperature, precipitation	Species range loss	H (18% insects, 8% vertebrates, 16% plants lose >50% range)	M (6% insects, 4% vertebrates, 8% plants, lose >50% range)	Double or triple	H		Amazon, Europe, South Africa		1, 4	M	L	H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Loss of ecosystem functioning and services	H	M		M							
		Shifts of biomes (major ecosystem types)	13% (range 8–20%) transformed	Around 7% transformed	Around double	H		Arctic, Tibet, Himalayas, South Africa and Australia		4	-	-	-
	Heat and cold stress, warming, precipitation	Wildfire	H	H	L	M	Canada, USA, Mediterranean	Mediterranean	Central and South America, Australia, Russia, China, Africa	1, 2, 4, 5	L	L	M

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
Ocean	Warming and stratification of the surface ocean	Loss of framework species (coral reefs)	very H (*virtually certain*)	H	3	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)	H	M	5	H/very H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; Myanma	1, 2	M	L	M/H
		Loss of framework species (mangroves)	M/H	M	3	M/H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; Myanmar	1, 3	M	L	M/H
		Disruption of marine food webs	M	L	5	M	Global	Global	Deep Sea	4	M	L	M/H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Range migration of marine species and ecosystems	H	M	5	H	Global	Global	Deep Sea	1	M	L	H
		Loss of finfish and fisheries	M/H	M/H	5	H	Global	Global	Deep Sea	4	M	M/L	M/H
	Ocean acidification and elevated sea temperatures	Loss of coastal ecosystems and protection	M	L/M	5	M	Low latitude tropical/subtropical countries	Low latitude tropical/subtropical countries	Most regions - risks not well defined	1	M	M/L	M
		Loss of bivalves and bivalve fisheries	M	M	3	H	Temperate countries with up-welling	Temperate countries with up-welling	Most regions - risks not well defined	4	M/H	L/M	M/H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Changes to physiology and ecology of marine species	M	L/M	3	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/M	L	5	L/M	Temperate countries with up-welling	Temperate countries with up-welling	Deep Sea	4	L	L	M
		Changes to up-welling productivity	M	L	5	L/M	Most upwelling regions	Most upwelling regions	Some up-welling systems	4	L	L	M
	Intensified storm	Loss of coastal ecosystems	H/very H	H	5	H	Tropical/subtropical countries	Tropical/subtropical countries		1, 4	M	L	M

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
		Inundation and destruction of human/coastal infrastructure and livelhoods.	H/very H	H	5	H	Global	Global		1, 5	M/H	M	M/L
	Loss of sea ice	Loss of habitat	very H	H	5	H	Polar regions	Polar regions		1	L	very L	H
		Increased productivity but changing fisheries	M/H	L/M	5	very H	Polar regions	Polar regions		1, 4	L	M/L	H

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
Coastal	Sea level rise, increased storminess	Area exposed (assuming no defences)	590-613 th km^2 when 2.0degC first reached	562-575 th km^2 when 1.5degC first reached	Increasing. 25 -38 th km^2 when temperatures are first reached, 10-17 th km^2 in 2100 increasing to 16-230 th km^2 in 2300	M/H (dependent on population datasets)	Asia. Small islands	Asia. Small islands	Small islands	2,3	M	M	M
		Population exposed (assuming no defences)	141-151 million when 2.0degC first reached	128-143 million when 1.5degC first reached	Increasing. 13 - 8 million when temperatures are first reached, 0-6 million people in	M/H (dependent on population datasets)	Asia. Small islands	Asia. Small islands	Small islands	2,3	M	M	M

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
					2100, increasing to 35-95 million people in 2300								
		People at risk taking account of defences (modelled in 1995)	Between 14.9-52.3 million people / yr if defences are not upgraded from the modelled 1995 baseline	Between 2.3-27.8 million people / yr as defences are not upgraded from the 1995 baseline	Increasing with time, but highly dependent on adaptation.	M/H (dependent on adaptation)	Asia. Small islands. Potentially African nations.	Asia. Small islands	Small islands	2,3, 4	M	M	M

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
Food security and food production systems	Heat and cold stress, warming, precipitation	Changes in ecosystem production	H	M/H	M/H	M/H	Global	Noth 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	Shift and composition change of biomes (major ecosystem types)	H	M/H	M	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/H	M	Risk increased	VH	All regions at risk	All regions	Africa	2,3, 4	H	H	H
		Occupational heat stress	M/H	M	Risk increased	M	Tropical regions	Tropical regions	Africa	2,3, 4	H	M	M

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
	Air quality	Ozone-related mortality	M/H (if precursor emissions remain the same)	M (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, precipitati	Undernutrition	M/H	M	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	Temperature	Tourism (sun and beach, and snow sports)	H	M/H	Risk increased	VH	Coastal tourism, particularly in sub-tropical and tropical regions	Coastal tourism, particularly in sub-tropical 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

3.4.13 Synthesis of key elements of risk

Some elements of the assessment in Section 3.4 are synthesised in a single diagram (Figure 3.19) that indicates the overall risk in five broad categories for natural and human systems as a result of anthropogenic climate change and increases in Global Mean Surface Temperature (GMST). The elements included are supported by a substantive enough body of literature providing at least *medium confidence* in the assessment. The format for figure 3.19 matches that of Figure 19.4 of WGII AR5 Chapter 19 (Oppenheimer et al., 2014) and Figure 3.19) by indicating the levels of the transition of risk from undetectable to moderate (detected and attributed), from moderate to high (severe and widespread) and from high to very high, the latter indicating 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 the 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 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 presented here maps to one or more RFCs, and the figure indicates this relationship. It should be emphasized that risks to the issues assessed here are only a subset of the full range of risks that contribute to the RFCs. This figure is not intended to replace the RFCs but rather to indicate how risks to particular elements of the earth system accrue with global warming, with a focus on levels of warming of 1.5°C and 2°C. Key evidence assessed in earlier parts of this chapter are summarized to indicate the transition points between the levels of risk. A fuller account is in the Annex 3.1 S3-4-12.

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

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 (yellow). At 1.5°C warming, an ice-free Arctic ocean is considered *unlikely* whilst by 2°C warming it is considered *likely* and this unique ecosystem is considered unable to adapt, hence a transition from high (red) to very high (purple) risk is expected between 1.5°C and 2°C warming.

For coral reefs, there is *high confidence* in the transitions between colour assignments, especially in the growing impacts in the transition of warming from 0.4˚C to 0.6˚C, and in projections of change from 0.6ºC to

1.3ºC (Section 3.4.4; Box 3.4). This assessment took into account the heat wave 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 other sites globally. Together with sequential mass coral bleaching and mortality events on the Great Barrier Reef (Hoegh-Guldberg, 1999; Hughes et al., 2017b, 2018), suggest that climate risks are very high for coral reefs. General assessment of climate risks for mangroves prior to this special report concluded that they face greater risks from deforestation and unsustainable coastal development than climate change (Alongi, 2008; Gattuso et al., 2015)(Hoegh-Guldberg et al., 2014). 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, leading to risks considered to be undetectable to moderate, with the transition now starting at 1.3°C as opposed to 1.8ºC as assessed in 2015 (Gattuso et al., 2015). Risks of climate change related impacts 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 by 1.1ºC (*high confidence*) (Section 3.4.4.10).

The transition from white to yellow (related to RFC3, 4) 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, with the current assessment providing further evidence to confirm this (Section 3.4.6). Impacts were detected in the tropics (AR5 WGII Chapter 7, AR5 WGII Chapter 18) and with increasing warming regional risks become high in some regions by 1.5°C warming, and in many regions by 2.5ºC warming, indicating a transition from moderate to high risk between 1.5ºC and 2.5°C 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., socioeconomic conditions; the effect of non-climate stressors). Risks posed by 1.5°C warming continue to increase with warming (Sections 3.4.2, 3.3.5), with projected increases threefold relative to current risk in economic damages due to flooding in 19 countries for a warming of 2°C, indicating a transition to high risk at this level (*medium confidence*). Because few studies assess the potential to adapt to these risks, there was insufficient evidence to locate a transition to very high risk (purple).

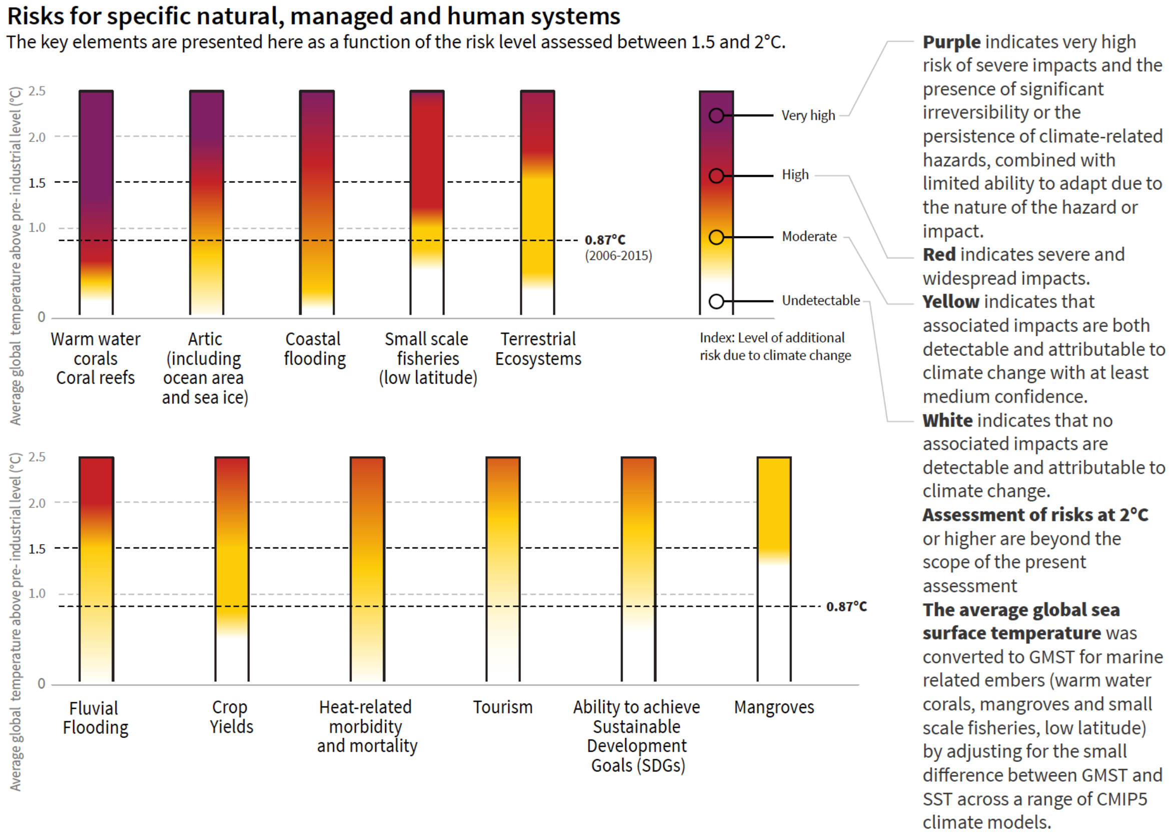
Climate-change induced SLR and associated coastal flooding (related to RFCs 2, 3 and 4) were detectable and attributable since approximately 1970 (Slangen et al., 2016), where temperatures have risen by 0.3°C (Section 3.3.9) (*medium confidence*). Analysis suggests that impacts could be more widespread in sensitive systems such as small islands (Section 3.4.5.3) (*high confidence*) and increasingly widespread by the 2070s (Brown et al., 2018a), even when considering adaptation measures, suggesting a transition to high risk (red) (Section 3.4.5). With 2.5°C warming, adaptation limits would be exceeded in sensitive areas, and hence a transition to purple (very high risk) can be located here (*medium confidence*). Sea level rise could have adverse effects for centuries, posing significant risk to low lying areas (Sections 3.4.5.7 and 3.5.2.5) (*high confidence*).

For heat-related morbidity and mortality (related to RFCs 2, 3 and 4), detection and attribution studies show heat-related mortality in some locations increased due to 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 1ºC and 3°C with *medium confidence*.

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 and environmental and cultural destination assets (Section 3.4.4.12), with ‘last chance’ tourism markets developing based on observed impacts on environmental and cultural heritage (Section 3.4.9.1), indicating a transition from undetected to moderate risk between 0°C and 1.5°C (*high confidence*). Based on limited analyses, risks to the tourism sector are higher at 2°C than at 1.5°C, with greater impacts on climate-sensitive sun, beach, and snow sports tourism markets. The degradation or loss of coral reef systems will increase the risks to coastal tourism, particularly in sub-tropical and tropical regions. A transition in risk from moderate (yellow) to high (red) is located between 1.5 and 3°C (*medium confidence*).

Owing to the existing effects that climate change is already having upon ecosystems, human health and agriculture, climate change is already beginning to make it more difficult to reach goals to eradicate poverty and hunger and protect health and life on land (Sections 5.1 and 5.2.1), suggesting a transition from undetected to moderate risk below recent temperatures at 0.5°C warming *(medium confidence).* Based on limited analyses 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 avoided 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 has not yet begin at this level. At 2°C and higher (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 which are likely to become severe and widespread if warming were increase further to about 3°C *(medium confidence)* (Section 5.2.3).

Disclosure statement: The selection of elements 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.



Risks for specific natural, managed and human systems

The key elements are presented here as a function of the risk level assessed between 1.5 and 2°C.

Purple indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impact.

Red indicates severe and widespread impacts.

Yellow indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence.

White indicates that no associated impacts are detectable and attributable to climate change.

Assessment of risks at 2°C or higher are beyond the scope of the present assessment

The average global sea surface temperature was converted to GMST for marine related embers (warm water corals, mangroves and small scale fisheries, low latitude) by adjusting for the small difference between GMST and SST across a range of CMIP5 climate models.

Figure 3.19 The dependence of risk associated with selected elements of human and natural systems on the level of climate change, adapted from Figure 3.18 and from AR5 WGII Chapter 19, and highlighting the nature of this dependence between 0 and 2ºC warming above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual 'element'. At one end, undetectable risk (white) indicates no detection and attribution of climate change with at least medium confidence. At the other end of the risk spectrum, the transition from red to purple, introduced for the first time in AR4, is defined by very high risk 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 elements indicates the relative sensitivity of elements to increases in Global Mean Surface Temperature (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).

3.5 Avoided impacts and reduced risks at 1.5ºC compared with 2ºC

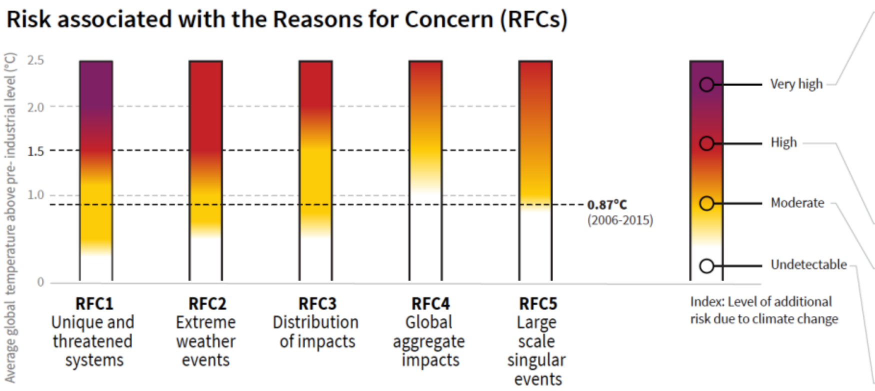
3.5.1 Introduction

Oppenheimer et al. (2014, AR5 Chapter 19) provide a framework that aggregates projected risks from global mean temperature change into five categories known as ‘Reasons for Concern’. Risks are classified as moderate, high, or very high and coloured yellow, red and purple respectively in Figure 19.4 (see AR5 Chapter 19 for details and findings). The framework’s conceptual basis and the risk judgments made in Oppenheimer et al. (2014) were recently reviewed, confirming most judgements made in the light of more recent literature (O’Neill et al., 2017). We adopt the approach of Oppenheimer et al. (2014), with updates in terms of the aggregation of risk as 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 economic benefits to be obtained by achieving the global temperature goal of 1.5°C, as compared to 2°C (or higher) are discussed in Section 3.5.3 in the light of the five reasons for concern explored in Section 3.5.2. Climate change hot spots that can be avoided or reduced by achieving the 1.5°C target are summarised in Section 3.5.4. The section concludes with a discussion of regional tipping points that can be avoided at 1.5ºC 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 RFC 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 to moderate, and from moderate to high, and from high to very high. Figure 3.20 modifies Figure 19.4 from AR5 WGII with the ensuing text in this subsection providing the justification for the modifications. O'Neill et al. (2017) presents a very similar assessment to WGII AR%, but with further discussion of the future potential to create socioeconomic-scenario specific embers. At present, there is insufficient literature to do this so the original simple approach has been used here. Since the focus in the present assessment is on the consequences of warming of 1.5ºC to 2°C, no assessment for global warming of 3°C or more are included, and the embers developed here are discontinued at 2.5˚C.



Purple indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impact.
Red indicates severe and widespread impacts.
Yellow indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence.
White indicates that no associated impacts are detectable and attributable to climate change.
Assessment of risks at 2°C or higher are beyond the scope of the present assessment

Figure 3.20: The dependence of risk 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 0ºC and 2ºC warming above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual 'reason'. The transition from red to purple, introduced for the first time in AR4, is defined by very high risk 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 (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. [Note to reviewers: In WGII AR5 Ch 19 and more recently in O'Neill et al. 2017 the need to detail how these kinds of figures vary with socioeconomic pathway is noted and suggestions are made therein as to how this might be done. That is seen as a task for IPCC AR6, and beyond the scope of what is feasible to do for SR1.5]

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 risk of severe consequences at global warming of 1.6ºC above pre-industrial levels. It was also observed that many species and ecosystems have limited ability to adapt to the very large risks associated with warming of 2.6ºC or more, particularly Arctic sea ice and coral reef systems (*high confidence*). A transition from white to yellow indicating the onset of moderate risk was therefore located below present day global temperatures (*medium confidence*); a transition from yellow to red indicating the onset of high risk was located at 1.6ºC, and a transition to purple indicating the onset of very high risk at about 2.6ºC. This WGII AR5 analysis already implies a significant reduction in risks to unique and threatened systems if warming is limited to 1.5ºC as compared with 2ºC. Since AR5, evidence of present day impacts in these systems has continued to grow (Sections 3.4.2.2, 3.4.2.3, and 3.4.2.5), whilst new evidence has also accumulated about increased risks at 1.5ºC vs 2˚C warming in Arctic ecosystems (Section 3.3.9), coral reefs (Section 3.4.3), some other unique ecosystems (Section 3.4.2) and biodiversity.

New literature since AR5 provides a closer focus on the comparative levels of risk to coral reefs at 1.5ºC versus 2ºC global warming. As assessed in Section 3.4.4 and Box 3.4, reaching 2ºC 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 1.5ºC 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. 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 past climate change. This indicates a transition in risk in this system from high to very high (red to purple) (*high confidence*) at 1.5ºC warming and contributes to a lowering of the transition from high to very high (red to purple) in this RFC1 compared to AR5. Further details of risk transitions for ocean systems are described in Figure 3.20.

Substantial losses of Arctic Ocean summer ice were projected in AR5 WGI for global warming of 1.6ºC, with a nearly ice-free Arctic Ocean being projected for global warming of greater than 2.6ºC. Since AR5, the importance of a threshold between 1ºC and 2ºC has been further emphasized in the literature, with sea ice projected to persist throughout the year for a global warming less than 1.5ºC, yet chances of an ice-free Arctic during summer being high at 2°C warming (Section 3.3.8). Less of the permafrost in the Arctic is projected to thaw (21–37% under 1.5˚C warming as compared with 35–47% for 2˚C warming) (Section 3.3.5.2), which would be expected to reduce risks to both social and ecological systems in the Arctic. This indicates a transition in risk in this system from high to very high (red to purple) between 1.5ºC and 2˚C warming and contributes to a lowering of the transition from high to very high (red to purple) in this RFC1 compared to AR5.

AR5 identifies a large number of threatened systems including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems. These include the Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succuluent Karoo areas of S. Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, impacts accrue with greater warming and impacts at 2ºC being expected to be greater than those at 1.5ºC (*medium confidence*). One study since the AR5 has shown that constraining global warming to 1.5ºC would maintain the functioning of the prairie pothole ecosystem (north America) in terms of its productivity and biodiversity, whilst a warming of 2ºC would not do so (Carter Johnson et al., 2016). The large proportion of insects projected to lose over half their range at 2ºC warming (25%) as compared to 1.5°C warming (9%) also suggests a significant loss of functionality in these systems at 2ºC warming owing to the key role of insects in nutrient cycling, pollination, detritivory, and other key ecosystem processes (Section 3.4.2).

Unique and threatened systems in small island states and in systems fed by glacier meltwater were also considered in AR5 in making a contribution to this RFC, but there is little new information about these systems that pertains to 1.5ºor 2ºC global warming.

Taken together, the evidence suggests that the transition from high to very high risk (red to purple) in unique and threatened systems occurs at a lower level of warming, between 1.5ºC and 2ºC *(high confidence*), than in AR5 where this transition was located at 2.6ºC. The transition from moderate to high risk (yellow to red) would relocate very slightly from 1.6ºC to 1.5ºC.

3.5.2.2 RFC 2- Extreme weather events

In this sub-subsection reduced risks in terms of the likelihood of occurrence of extreme weather events are discussed for 1.5ºC as compared to 2ºC of global warming – for those extreme events where current evidence is available. AR5 assigned a moderate (yellow) level of risk due to extreme weather events at recent temperatures (1986-2005) due to the attribution of heat and precipitation extremes to climate change, and a transition to high (red) beginning below 1.6ºC 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 suggests a significant benefit of limiting warming to 1.5ºC, since this might keep risks closer to the moderate level. New literature since AR5 provides greater confidence in a reduced level of risks due to extreme weather events at 1.5ºC versus 2ºC for some types of extremes (see Section 3.3 and below).

Temperature: It is very likely that further increases in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes will occur under 1.5ºC of global warming compared to present-day climate (1°C warming), with further increases towards 2ºC of warming (section 3.3). As assessed in Sections 3.3.1 and 3.3.2, impacts of a 0.5°C global warming can be identified for temperature extremes at global scales, based on observations and the analysis of climate models. At 2ºC of global warming, it is likely that temperature increases of more than 2°C will occur over most land regions in terms of extreme temperatures (on average between 3 and 8°C depending on region and considered extreme index) (Section 3.3.2). Regional increases in temperature extremes under 1.5°C of global warming, can be reduced to 2–6°C (Section 3.3.2). Benefits to be obtained from this general reduction in extremes depends to a large extent on whether the lower range of increases in extremes at 1.5ºC 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. A recent observations-based study also shows that a 0.5°C increase in global mean temperature has a detectable effect on changes in precipitation extremes at 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 minus evaporation 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 (Section 3.3.4). Regions that are to benefit most include the Mediterranean region and southern Africa (Section 3.3.4). There are also some possible effects in parts of South America and on subregional scale in the Western Sahel (Section 3.3.4). Some possible effects are found in some other regions, mostly for the tails of multi-model projections (Fig. 3.12).

Fire: The increased amount of 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 1.5ºC of global warming relative to the present day (Section 3.4.3). Under 1.2°C of global warming, fire frequency was 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; Romero-Lankao et al., 2014).

In “Extreme Weather Events” (RFC2) the transition from moderate to high risk is located between 1ºC and 1.5ºC global warming, which is very similar to the AR5 assessment but there is greater confidence in the assessment (*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' (red) to 'very high' risk within the context of assessing impacts at 1.5°C vs 2°C 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 to moderate risk below recent temperatures owing to the detection and attribution of regionally differentiated changes in crop yields (*medium to high confidence*) and new literature continues to confirm this finding. Based on 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 highlights that at 2°C warming, new literature shows that risks of food shortage are projected to emerge in the African Sahel, the Mediterranean, central Europe, the Amazon, 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). Reduction in the availability of water resources for less than 2ºC is projected to be greater than 1.5ºC of global warming, although changes in socioeconomics could have a greater influence (Section 3.4.2), with larger risks in the Mediterranean (Box 3.2) but 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 during the 21st century (Hinkel et al., 2014; Hauer et al., 2016), particularly if adaptation is limited. At 2°C of warming, more than 70% of global coastlines will experience sea-level rise 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 warming, being more prevalent vulnerable people live, predominantly in South Asia (mostly Pakistan, India, and China), but these spread to sub-Saharan Africa, the Middle East and East Asia as temperature rises, with the world's poorest disproportionately impacted by 2°C (Byers et al., 2018). The hydrological impacts of climate change in Europe in a 1.5ºC, 2ºC and 3°C warmer world are intense and spatially more extensive (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 an assessment of risks to food security, water resources, drought, heat exposure and coastal submergence *(high confidence)*.

3.5.2.4 RFC 4 - Global aggregate impacts

Oppenheimer et al. (2014) explain 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 acifidification were in general excluded from previous global aggregate economic analyses.

Global economic impacts: WGII AR5 found that overall global aggregate impacts become moderate between 1–2ºC of warming and the transition to moderate risk levels was therefore located at 1.6ºC above pre-industrial levels. This was based on the assessment of literature using model simulations which indicate that the global aggregate economic impact will become significantly negative between 1ºC and 2ºC of warming (*medium confidence*), whilst there will be a further increase in the magnitude and likelihood of aggregate economic risks at 3ºC 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 2ºC than if it is constrained to 1.5ºC. The study of Warren et al. (2018c) uses 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; while Petris et al. (2018) identify several regions in which economic damages are greater at 2°C warming compared to 1.5°C, further estimating that projected damages at 1.5ºC remain similar to today's levels of economic damage. Another study (Burke et al., 2018) uses an empirical, statistical approach and finds that limiting warming to 1.5ºC instead of 2ºC would save 1.5–2.0% of Gross World Product (GWP) by mid-century and 3.5% of GWP by end-of-century (see figure 2A in Burke et al 2018), which under a 3% discount rate corresponds to $8.1-11.6 trillion and $38.5 trillion in avoided damages by mid- and end-of-century, respectively, agreeing closely with the Warren et al. (2018c) estimate of $15 trillion. In the no policy baseline temperature rises by 3.66°C by 2100, resulting in global GDP loss of 2.6% (5-95% percentile range 0.5–8.2%), as compared with 0.3% (0.1–0.5%) by 2100 in 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 world GDP due to reductions in air pollution (Shindell et al., 2018) which is similar to the avoided damages identified for the USA (see below).

Two studies focusing only on the USA (Hsiang et al., 2017; Yohe, 2017) also found that economic damages are projected to be higher by 2100 if warming reaches 2ºC than if it is constrained to 1.5ºC (one study finds a mean difference 0.35% GDP, range 0.2–0.65%, the other identifies 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 1.5ºC case (4%, range 2–7%) compared to the 2ºC 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 2ºC (*medium confidence*), and that there is a possibility that this is below 1.5ºC warming.

Oppenheimer et al. (2014) note 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, a further analysis of the potential economic consequences of triggering these large scale singular events (Y. Cai et al., 2016; Lemoine and Traeger, 2016), also indicates a two to eightfold larger economic impact associated with a warming of 3ºC than most previous analyses, depending on the number of events incorporated: Lemoine includes only three known singular events whereas (Y. Cai et al., 2016) include five.

Biome shifts, risks of species extinction and ecosystem functioning and services: 13% (range 8–20%) of the earth's land area is projected to undergo biome shifts under 2ºC warming compared to approximately 7% at 1.5°C warming (Section 3.4.3, Warszawski et al., 2013), hence implying a halving of biome transformations. Overall levels of species loss at 2ºC warming are similar to previous studies for plants and vertebrates (Warren et al., 2011; Warren et al., 2018b)but insects have been found to be more sensitive to climate change, with 18% (6–35%) projected to lose over half their range at 2ºC warming compared to 6% (1–18%) under 1.5°C warming, which is 66% (Section 3.4.3). The critical role of insects in ecosystem functioning therefore suggests impacts already on global ecosystem functioning at 2ºC warming. Since AR5 new literature indicates that impacts on marine fish stocks and fisheries are lower in 1.5–2°C global warming relative to pre-industrial level when compared to higher warming scenarios (Section 3.4.6) especially in tropical and polar systems.

In AR5, the transition from no impacts detected (white) to moderate impacts (yellow) was considered to occur between 1ºC and 2°C global warming, reflecting the impacts on the economy and on biodiversity globally; whereas high risks (red) were associated with 3°C warming to reflect the high risks to biodiversity and accelerated effects on the global economy. The new evidence suggests moderate impacts on the global aggregate economy and global biodiversity by 1.5°C, suggesting a lowering of the transition to moderate risk (yellow) already by 1.5°C; and higher risks than previously thought on the global aggregate economy and global biodiversity by 2°C global warming warming; suggesting that risks transition to high between 2°C and 3°C warming, as opposed to at 3°C as previously thought (*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 Current, AMOC).
- The El Niño-Southern Oscillation (ENSO) as a global mode of climate variability
- Role of the Southern Ocean in global carbon cycle

AR5 assessed that the risks associated with these events become moderate between 0.6ºC and 1.6ºC above pre-industrial levels due to early warning signs and that risk becomes high between 1.6°C and 4.6ºC due to 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 1.6ºC and 2.6ºC above pre-industrial levels was assessed to be disproprortionately large. New findings since AR5 are detailed below.

Greenland and West-Antarctic ice sheets and Marine Ice Sheet Instability: 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) assess this threshold to be 2°C or higher (relative to pre-industrial temperature).

Robinson et al. (2012) find a range for this threshold of 0.8–3.2°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 range between 1.5ºC and 2ºC. The timescale for eventual loss of the ice sheets varies between millennia and tens of millennia and assumes constant surface temperature forcing during this period. Were temperature to cool 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 plausible to occur over the next two centuries under 1.5–2°C of global warming is estimated to be in the order of several tenths of a meter by most studies (*low confidence*) (Schewe et al., 2011; Church et al., 2013; Levermann et al., 2014; Marzeion and Levermann, 2014; Fuerst 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 suggest that the temperature range of 1.5–2ºC may be regarded as representing moderate risk (it may trigger MISI in Antarctica or irreversible loss of the Greenland ice sheet and it may be associated with sea-level rise as high 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 the cooling of surface waters in the North Atlantic and evidence that the Gulf Stream has slowed by 30% since the late 1950s (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 range for the reduction from CMIP5 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 vs 2°C of global warming, or of a shutdown of the AMOC at these global temperature thresholds. Associated risks are classified as low to medium.

El Niño-Southern Oscillation (ENSO)*:* Extreme El Niño events are associated with significant warming of the usually cold eastern Pacific Ocean, and 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 (G. Wang et al., 2017) indicate 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. This pattern is projected to persist for a century after stabilization at 1.5°C, thereby challenging the limits to adaptation, and thus indicating high risk even at the 1.5°C threshold. La Niña event frequencies are projected to remain similar to that of the present-day under 1.5–2°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 1.5ºC compared to 2ºC of global warming is a priority. Changes in ocean chemistry (e.g., oxygen content, ocean acidification), especially those associated with the deep sea, are associated concerns (Section 3.3.10).

Large scale singular events (RFC5) moderate risk is now located at 1ºC and high risks are located 2ºC, as opposed to 1.9ºC (moderate) and 4ºC (high) risk in AR5 because of new observations and models of the West Antarctic ice sheet (medium confidence), which suggests the ice sheet may be in the early stages of Marine Ice Sheet Instability (MISI). Very-high risk is assessed as lying above 5ºC because the growing literature on process-based projections of the West Antarctic ice sheet predominantly supports the AR5 assessment of a MISI contribution of an additional several tenths of a metre by 2100.

3.5.3 Regional economic benefit analysis for the 1.5°C vs 2°C global temperature goals

This section reviews recent literature that estimates the economic benefits for constraining global warming to 1.5°C as 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, with low-income countries projected to experience the greatest losses (*limited evidence, medium confidence*) (Burke et al., 2018; Petris et al., 2018). A critical issue for developing countries in particular is that advantages in some sectors are projected to be offset by the increasing mitigation costs (Rogelj et al., 2013; 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 (Hasegawa et al., 2016).

Although warming is projected to be the highest in the Northern Hemisphere under 1.5ºC or 2°C of global warming, regions in the tropics and Southern Hemisphere subtropics that are projected to experience the largest impacts on economic growth (*limited evidence, medium confidence*) (Gallup et al., 1999; Burke et al., 2018; Petris et al., 2018). Despite the uncertainties associated with climate change projections and econometrics (e.g., Burke et al., 2016), 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 (Burke et al., 2018; Petris 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 (*limited evidence, 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 (Petris et al., 2018). An important reason why developed countries in the tropics and subtropicas are to benefit substantially from restricting global warming to 1.5°C, relates to present-day temperatures in these regions being above the threshold thought to be optimal for econonomic production (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 to be realized estimated to be 76%, 85% and 81% for the USA, China and Japan, respectively (Burke et al., 2018). Two studies focusing only on the USA (Hsiang et al., 2017; Yohe, 2017) also found that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5ºC (one study finds a mean difference 0.35% GDP, range 0.2–0.65%, the other identifies a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree). Indeed, no statistically significant changes in GDP are projected to occur over most of the developed world (*limited evidence, low confidence*) (Petris et al., 2018).

A caveat of the analysis of Petris et al. (2018) and Burke et al. (2018) is that the effects of sea-level rise are not included in the estimations of damages or future economic growth, implying a potentiall underestimate 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 exceeded at 2°C.

3.5.4 Reducing hot spots of change for 1.5°C and 2°C global warming

This sub-section integrates Sections 3.3 and 3.4 in terms of climate change induced hot-spots 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 temperature goal (as opposed to the 2°C goal). Findings are summarised 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 are even indicative of the entire Arctic Ocean summer period becoming ice-free under 2°C of global warming whilst other more conservatively estimate this probability to be in the order of 50% (Sanderson et al., 2017; Section 3.3.8). The probability for 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)* (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Section 3.3.8). 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). Finally, during winter, only little ice is projected to be lost for either 1.5°C or 2°C global warming (*medium confidence*) (Niederdrenk and Notz, 2018). The losses in sea ice at 1.5ºC 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 due to 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 Actic land regions, the warming of cold extremes and annual minimum temperature at 1.5°C is stronger than the global mean temperature increase by a factor of 2–3, i.e. 3°C -4.5°C regional warming at 1.5°C global warming (e.g., northern Europe, Annex 3.1 Figure S3.6 – also see 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 to 2°C may lead to further temperature increases of 2–2.5°C (Figure 3.3). As a consequence, biome (major ecosystem types) shifts are *likely* in the Arctic, with increases in fire frequencies, degradation in permafrost and increases in tree cover *likely* to occur under at 1.5ºC warming, with further amplification of these changes under 2ºC of global warming (e.g., Gerten et al., 2013; Bring et al., 2016). Rising temperatures, thawing permafrost and changing weather patterns will increasingly impact on people, infrastructure and industries in the Arctic (W.N. Meier et al., 2014), with these impacts larger at 2°C vs 1.5°C of warming (*medium confidence*).

3.5.4.3 Alpine regions

Alpine regions are generally regarded as climate change hotspots given their generally cold and harsh climates in which a rich biodiversity has evolved, but which are 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 with obvious limited by mountain height and habitability. Moroever, many of the world’s Alpine regions are important from a water security perspective through associated glacier melt, snow melt and river flow (Section 3.3.5.2 for a discussion of these aspects). Projected biome shifts are already *likely* to be severe in alpine regions at 1.5ºC warming and increase further for 2ºC warming (Chen et al., 2014a; Gerten et al., 2013; Figure 1b).

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 rise from 1.5°C to 2°C of warming (*medium confidence*), with substantial increases beyond 2°C (Arnell et al., 2016). Southeast Asia displays statistically significant differences in projected changes in heavy precipitation, run-off and high flows at 1.5°C versus 2°C warming (with stronger increase at 2°C; (Wartenburger et al., 2017; Döll et al., 2018; Seneviratne et al., 2018a); Section 3.3.3), and thus is thought to be a hotspot in terms of increases in heavy precipitation between these two global temperature levels (Schleussner et al., 2016b; Seneviratne et al., 2016) (*medium confidence*). For Southeast Asia, a 2°C warming by 2040 indicated a one-third decline in per capita crop production (Nelson et al., 2010) associated with general decreases in crop yields. 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 of warming (*medium confidence*).

3.5.4.5 Southern Europe and the Mediterranean

The Mediterranean is regarded as a climate change hot spot both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature warming (e.g., Seneviratne et al., 2016) and projected substantial decreases in mean precipitation with associated substantial increases in dry spells. The latter is projected to increase from 7% to 11% when comparing regional impacts at 1.5°C versus 2°C of global warming, respectively (Schleussner et al., 2016b). 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 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 are found by (Döll et al., 2018). Overall, there is *high confidence* of strong increases in dryness and decreases in water availability in the Mediterranean and southern Europe from 1.5ºC to 2°C of global warming. Sea-level rise is expected to be lower for 1.5ºC versus 2°C, lowering risks for coastal metropolitan agglomerations. The risks (with current adaptation) related to water deficit in the Mediterranean are high for a global warming of 2°C, but can be substantially reduced if global warming is limited to 1.5°C (Guiot and Cramer, 2016; Schleussner et al., 2016b; Donnelly et al., 2017; Section 3.3.4).

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 heat waves even if the global temperature increase is constrained to 1.5°C, with further increase at 2°C of global warming and beyond (e.g., Weber et al., 2018). Moreover, the daily rainfall intensity and run-off is expected to increase (*low confidence*) towards 2°C and higher global warming scenarios (Weber et al., 2018; Schleussner et al., 2016b), 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 increasingly 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 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). Increase in warming (2°C) by 2040 would result in further yield losses and damages to crops (i.e., maize, sorghum, wheat, millet, groundnut, cassava). Schleussner et al. (2016b) consistently indicate reduced impacts on crop yield for West Africa under 2°C vs 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., 2016b; Betts et al., 2018), and at 2°C these vulnerabilities are expected to be worse (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high evidence).* For global warming greater 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 hot spot 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 numer of hot nights as well as longer and more frequent heat waves are projected even if the global temperature increase is constrained to 1.5°C *(high confidence)*, with further increase at 2°C of global warming and beyond *(high confidence)* (Weber et al., 2018).

Moreover, the region is *likely* to become generally 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 also prominent under 2°C of global warming and even 1.5ºC of warming (Gerten et al., 2013). Risks are significantly reduced, however, under 1.5°C of global warming (Schleussner et al., 2016b). There are consistent and statistically significant projected increases in risks of increased meteorological drought in southern Africa at 2°C vs 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 further amounts of global warming. There is medium confidence that livestock in southern Africa will experience increased water stress under both 1.5ºC and 2°C of global warming, with negative economic consequences (e.g., Boone et al., 2017). 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 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 (Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high confidence*).

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 of global warming versus 2°C of global warming are found in the tropics (Mahlstein et al., 2011). In tropical Africa, increases in the number of hot nights, as well as longer and more frequent heat waves, are projected under 1.5°C of global warming, with further increases 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 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East 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

Small islands are well recognized to be very sensitive to climate change impact such as sea-level rise, oceanic warming, precipitation, cyclones and coral bleaching (high agreement, robust evidence) (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 levels 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 40,000 less people living in SIDS will be inundated in a 1.5°C world than in a 2˚C world

(Rasmussen et al., 2018). Constraining global warming to 1.5ºC would significantly reduce water stress (about 25%) as compared to the projected water stress at 2ºC (e.g., 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 for 1.5°C, with a further increase by up to 70 days for 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 between 20 and 80% for SIDS (Rasmussen et al., 2018). A case study of Jamaica with lessons for other Caribbean SIDS demonstrates that the difference between 1.5ºC 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 have been assessed in AR5. Similar shrublands exists in the semi-arid regions of other continents, 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 will be 3.2–4°C and under 1.5°C of global warming, mean warming in drylands will 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 under 1°C, 2°C and 3°C of warming with respect to present-day climate (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 hot-spots under different degrees of global warming

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-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 ~ 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	Arctic is *very likely* to be ice-free in summer. Critical habitat losses for organsims such as polar bears, whales, seals and sea-birds Benefits for arctic fisheries
Arctic land regions	Cold extremes warm by a factor of 2.5-3, reaching up to 5.5 °C *(high confidence)* Biome shifts in the tundra and	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	Drastic regional warming is *very likely* A collapse in permafrost may

Region and/or Phenomena	**Warming of 1.5ºC or less**	**Warming of 1.5ºC-2°C**	**Warming of 2°C - 3°C**
	permafrost deterioration is *likely*	is *likely*; larger but constrained losses in permafrost are *likely*	plausibly 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*
	Reduced grassland net primary productivity	Increased risks for reduced grassland net primary productivity	Increased risks for significantly reduced grassland net primary productivity
Southeast Asia	Risks for increased flooding related to sea-level rise	Higher risks for increased flooding related to sea-level rise *(medium confidence)*	Substantial increases in risks related to flooding from sea-level rise
	Increases in heavy precipitation events	Stronger increases in heavy precipitation events *(medium confidence)*	Substantial increased in heavy precipitation and high flow events
	Significant risks of crop yield reductions are avoided	One third decline in per capita crop production *(medium confidence)*	Substantial reductions in crop yield
Small Islands	Land of 40,000 less people inundated by 2150 on SIDS	Tens of thousands displaced due to inundation of SIDS	Substantial and wide-spread impacts through indundation of SIDS, coastal flooding, fresh water stress, persistent heat stress and loss of most coral reefs very likely
	Risks for coastal flooding reduced by 20-80% for SIDS	High risks for coastal flooding	
	Fresh water stress reduced by 25%	Fresh water stress from projected aridity	
	Increase in the	Further increase of about 70 warm days per year	

Region and/or Phenomena	**Warming of 1.5ºC or less**	**Warming of 1.5ºC-2°C**	**Warming of 2°C - 3°C**
	number of warm days for SIDS in the tropics Persistent heat stress in cattle avoided Loss of 70-90% of coral reefs	Persistent heat stress in cattle in SIDS Loss of most coral reefs – remaining structures weaker due to ocean acidification	
Mediterranean	Increase (about 7%) in dry-spells Reduction in runoff of about 9% (likely range: 4.5–15.5%) Risk of water deficit	*High confidence* of further increases (11%) in dry spells *High confidence* of further reductions (about 17%) in runoff (likely range 8–28%) Higher risks for water deficit	Substantial reductions in precipitation and reductions in runoff *very likely* Very high risks for water deficit
West African and the Sahel	Reduced maize and sorghum production is *likely,* with suitable for maize production reduced by as much as 40% Increased risks for under-nutrition	Negative impacts on maize and sorghum production *likely* larger than at 1.5 °C Higher risks for undernutrition;	Negative impacts on crop yield may result in major regional food insecurities (*medium confidence*) High risks for undernutrition
Southern African savannahs and drought	*Likely* reductions in water availability High risks for increased mortality from heat-waves; High risk for undernutrition in communities dependent on dryland agriculture and livestock	Even larger reductions in rainfall and water availability *likely*; Higher risks for increased mortality from heat-waves (*high confidence*); Higher risks for undernutrition in communities dependent on dryland agriculture and livestock	Large reductions in rainfall and water availability are *likely* Very high risks for undernutrition in communities dependent on dryland agriculture and livestock

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C
Tropics	Accumulated heat-wave duration up to two months *(high confidence)*; 3% reduction in maize crop yield.	Accumulated heat-wave duration up to three months *(high confidence)*; 7% reduction in maize crop yield.	Oppressive temperatures and accumulated heat-wave duration *very likely* to directly impact on human health, mortality and productivity Substantial reductions in crop yield *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 ecosystems and human systems, is essential for understanding the risks and opportunities from mitigation. 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, how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems is also analysed. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5ºC and 2ºC of global warming – note that tipping points in the global climate system, referred to as large scale singular events, have already been 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) discuss 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 summer sea ice extent can recover after it has been lost (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011). These studies do not find evidence of bifurcation and find 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. Studies do not find evidence of irreversibility or tipping points, and suggest that year-round sea ice could return with years given a suitable climate (*medium confidence*) (Schroeder 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 above 0°C. A potential tipping points exists, where the number of days below 0°C decrease to the extent that 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). Both of these processes facilitate conditions for woody species establishment in tundra areas, and 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 generally indicative that substantial increases will likely occur gradually (e.g., Lenton et al., 2008). Abrupt changes only plausible at levels of warming significantly larger than 2°C (*low confidence*) and are to 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 would lead to further increases in atmospheric carbon dioxide and methane and hence 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 from thawing permafrost is projected to be restricted to 0.12-0.25 Gt C a^{-1} to the atmosphere in a 2ºC world, and to 0.08-0.16 Gt C $a^{-1}$for 1.5ºC (Burke et al., 2006), and thus do not represent 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) suggests 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 timescales of soil carbon accumulation and potentially rapid decomposition in a warming climate implies that the loss of this carbon to the atmosphere is essentially irreversible (Collins et al., 2013).

3.5.5.4 Asian monsoon

It is the pressure gradient between the Indian Ocean and Asian continent that at a fundamental level determines the strength of the Asian monsoon. As land masses warm faster than the oceans, a general strengthening of this gradient, and hence 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 landmass albedo to 0.5 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 emission scenarions are more subtle, with a weakening of the monsoon north of about 25°N in East Asia and a strengthening south of this latitude projected by (Jiang and Tian, 2013) under high and modest emission scenarios. Increases in the intensity of monsoon precipitation is likely under low mitigation (AR5). Given that scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the studies of 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 levels of global warming.

3.5.5.5 West African monsoon and the Sahel

Earlier work has identified 3°C of global warming as a tipping point leading to a significant strengthening of the West African monsoon and subsequent wettening (and greening) of the Sahel and Saharah (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) provide 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 will 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., 2018b)

3.5.5.6 Rain forests

A large portion of rainfall over the world’s largest rainforests are 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 envents 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 productivity being reduced by more than 50%, and 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 and 2°C of global warming.

3.5.5.7 Boreal forests

Boreal forests are likely to experience higher 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 (Gauthier et al., 2015) (*medium confidence*), 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 will 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 and 4°C of global warming (Lucht et al., 2006; Kriegler et al., 2009) (*low confidence*), but given the complexities of the various forcing mechanisms and feedback processes this is thought to be an uncertain estimate.

3.5.5.8 Heat-waves, unprecedented heat and human health

Increases in ambient temperature are linearly related with hospitalizations and deaths (so there isn’t a tipping point per se) once specific thresholds are exceeded. 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, taking into consideration urban heat island effects, there could be a substantial increase in the occurrence of deadly heatwaves in cities, with the impacts similar at 1.5°C and 2°C, but substantially larger than under the present climate (Matthews et al., 2017). At +1.5°C, twice as many megacities as present (such as Lagos, Nigeria, and Shanghai, China) are *likely* to become heat stressed, potentially exposing more than 350 million more people to deadly heat stress by 2050. At +2°C warming, Karachi (Pakistan) and Kolkata (India) could expect annual conditions equivalent to their deadly 2015 heatwaves (*medium confidence*). These statistics imply a tipping point in the extent and scale of heat-wave 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 overall (Akbari et al., 2009; Oleson et al., 2010).

3.5.5.9 Agricultural systems: key staple crops

A large number of studies consistently indicate that maize crop yield will be negatively affected under increased global warming, with negative impacts being higher under 2°C of warming than at 1.5°C of warming (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 more than 2°C of global warming, 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 for the 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) and in particular direct impacts through inceased heat-stress has been less well studied than impacts on crop yield, in particular from the perspective of critical thresholds being exceeded. A case study of Jamaica reveals that the difference in heat stress for livestock between 1.5°C and 2°C is likely to exceed the limits for normal thermoregulation and result in persistent heat stress for livestock 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*) (see Section 3.4.6). It is plausible that under 3°C of global warming, significant reductions in the areas suitable for livestock production occur (*low confidence*) due 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 exist.

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

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-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 ~ 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	Further decreases in number of growing	Potential for an abrupt increase in tree-

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of up to 3°C
	below 0°C Abrupt increases in tree-cover are *unlikely*	degree days below 0°C Abrupt increased in tree cover are unlikely	fraction (*low confidence*)
Permafrost	21-37% reduction in permafrost 2 million km^2 more permafrost maintained than under 2°C of global warming (*medium confidence*) 0.08-0.16 Gt C a^{-1} released Irreversible loss of stored carbon	35-47% reduction in permafrost 0.12-0.25 Gt C a^{-1} released 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 and wettening and greening of Sahel and Saharah *(low confidence)* Negative associated impacts through increase 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 warming, deforestation and fire increases pose uncertain risk to forest dieback	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 for significant dieback of boreal forest (*low confidence*)
Heat-waves, unprecedented heat	Substantial increase in occurrence of potentially	Substantial increase in potentially deadly	Substantial increase in potentially deadly

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of up to 3°C
and human health	deadly heat-waves *likely* More than 350 million more people exposed to deadly heat by 2050 under a midrange population growth scenario	heat-waves *likely* Annual occurrence of heat-waves similar to deadly 2015 heat-waves in India and Pakistan	heat-waves *very likely*
Key staple crops	Global maize crop reductions of about 10%	Larger reductions in maize crop production that under 1.5°C of about 15%	Drastic reductions in maize crop globally and in Africa *(high confidence),* of 20% or more; 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.*

[START BOX 3.6 HERE]

Box 3.6: Economic Damages from Climate Change

Balancing of 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 socioeconomic content) (see Cross-Chapter Box 5 in Chapter 2 for the definition of the social cost of carbon, and 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 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.

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 to \$116 (range 50-166)/tCO_2 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 1.5ºC. These calculations excluded the large health co-benefits that accrue when greenhouse gas emissions are reduced (Shindell 2018; Section 3.4.7.1)

The economic damages of climate change in the USA are projected to be large (Hsiang et al., 2017; Yohe, 2017). Although not specifically related to 1.5˚C warming, Hsiang et al. (2017) concluded that the USA could lose 2.3% Gross Domestic Product (GDP) per degree of global 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 per year by the end of the century (Fawcett et al., 2015), with 1.75˚C per 1000 GtCO_2 as the median estimate (Yohe, 2017). 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 1.5ºC temperature limit along the median-median case is nearly 4% (range 2.0 – 7.0%) by 2100. Avoided damages from achieving a 2ºC temperature limit is lower: 3.5% (range 1.8% - 6.5%). Avoided damages from achieving 1.5ºC vs. 2ºC is modest; it is about 0.35% (range 0.20 – 0.65%) by 2100. The values of achieving either temperature limit 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.

[END BOX 3.6 HERE]

3.6 Implications of different 1.5ºC and 2ºC pathways

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

3.6.1 Gradual vs overshoot in 1.5ºC scenarios

All 1.5°C scenarios from Chapter 2 include some overshoot above 1.5°C global warming during the 21st century (Chapter 2, Cross-Chapter Box 8 in this Chapter). The level of overshoot may also depend on natural climate variability. An overview of possible outcomes of a 1.5°C-consistent mitigation scenarios for changes in physical climate at the time of overshoot and by 2100 is provided in the 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 of all, mitigation of non-CO$_2$ emissions from agricultural production can shift agricultural production between regions via trade of agricultural commodities. Secondly, protection of carbon rich ecosystems such as tropical forests constrains area for agricultural expansion. Thirdly, also demand side mitigation measures such as les consumption of resource intensive commodities (animal products) or food waste reductions 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. Typically, CDR measures that require land can 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 also 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, Smith et al., 2015); potential loss of up to 10% of the current forested lands to biofuels (Yamagata et al., 2018). Other estimates reach 380-700 Mha/21-64% of current arable cropland (Section 4.3.7); while Boysen et al. (2017) find that in a scenario in which emission reductions were sufficient only to limit warming to 2.5ºC, use of CDR to limit warming further to 1.7ºC would result in conversion of 1.1-1.5

Gha of land – implying enormous losses of both cropland and natural ecosystems (Boysen et al., 2017). Newbold et al. (2015) find that biodiversity loss in the scenario Representative Concentation Pathway (RCP)2.6 could be greater than that in RCP4.5 and RCP6.0, 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 explores an extreme mitigation strategy encouraging biofuel expansion sufficient to limit warming to 1.5ºC, which finds that this is more disruptive to land use and crop prices than the climate change impacts of +2.0 ºC 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 would have 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, using BECCS that relies on second-generation (or even third generation) biofuels, or which relies on changes in diet or more generally, management of food demand, or CDR options such as forest restoration (see 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) (see 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 focussing on the conversion of pasture area into both forest area and bioenergy cropland. Some IAMs explored 1.5°C consistent pathways with demand side measures (such as dietary changes) and efficiency gains such as agricultural changes (Sections 2.3.4, 2.4.4) which lead to a greatly reduced CDR deployment and consequently land use impacts (van Vuuren et al., 2018). However, in reality whether this CDR (and more broadly, bioenergy in general) has large adverse impacts on environmental and societal goals depends in large parts on the governance of land use (Obersteiner et al., 2016; Bertram et al., 201; Humpenöder et al. 2018; Section 2.3.4).

Rates of sequestration of 3.3 GtC/ha require 970 Mha of afforestation and reforestation (Smith et al., 2015). Humpenöder et al. (2014) estimates 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 3 to 5 times greater than that required by BECCS, depending on the forest management used. However, not all of the land footprint of CDR need be in competition with biodiversity protection. Where reforestation is the restoration of natural ecosystems, this 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 (Stanturf et al., 2014, Section 4.3.8) and the ability to deliver biodiversity benefits is strongly dependent on the precise nature of the reforestation, which has many 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 is estimated to have the potential to provide 37% of cost-effective CO_2 mitigation needed through 2030 consistent with 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 & Rodríguez-Iturbe, 2016) or may not (Muratori et al., 2016) affect food prices. However, these studies do not consider the deployment of second-generation bioenergy crops (instead of first-generation) 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) as well as protecting the areas where the climate still remains suitable in the future. This implies a need for a considerable expansion of the protected area network (Warren et al., 2018a), 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; whilst in order to meet the rising future food demand of a growing human population, additional land is projected to be needed to be brought into production, unless there are large increases in agricultural productivity (Tilman et al., 2011) yet future rates of deforestation may be underestimated in the existing literature (Mahowald et al., 2017a). Hence, reforestation may be associated with significant co-benefits if implemented so as 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 that 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) or 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 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 harvest (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, both changes induced by modifications in moisture availability and irrigation, or 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 of the order of ca. 1–2°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 (Hirsch et al., 2017, Figure 3.21; Seneviratne et al., 2018a).

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, growing crops for BECCS (Chapter 2), increasing food production to support larger populations or urban expansion (e.g., see review by Smith et al., 2010). In particular, some land management practices may have further implications for food security where some regions may have increases or decreases in yield when ceasing tillage (Pittelkow et al., 2014).

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

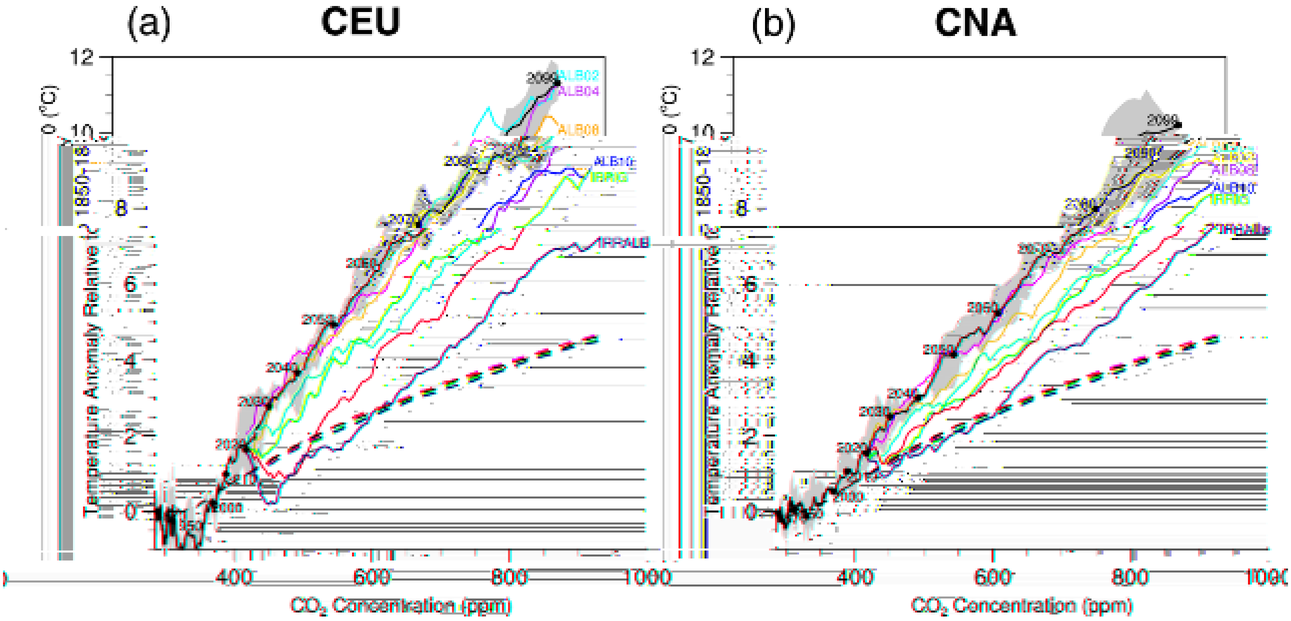


Figure 3.19: Regional temperature scaling with carbon dioxide (CO_2) concentration (ppm) over 1850 to 2099 for two different regions as defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX): Central Europe (CEU) (a) and Central 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 3-member control ensemble mean with the grey shaded regions corresponding to the ensemble range. The colored lines correspond to the 3-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 on (blue), and irrigation with albedo +0.10 (green). Adapted from Hirsch et al. (2017).

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 change the climate impacts on humans and ecosystems. Anthropogenic driven changes in aerosols cause important modifications to 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 aerosols emissions in the next few decades. These aerosol emission reductions may cause a comparable warming to the increase in greenhouse gases by mid-21st century in the low CO_2 pathways (Kloster et al., 2009; Navarro et al., 2017), especially in the low CO_2 pathways (Cross Chapter Box 1; Sections 2.2.2 and 2.3.1). Because aerosol effects on the energy budget are regional, strong regional changes in precipitation changes from aerosols may occur if aerosols emissions are reduced for air quality 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 1.5ºC-consistent pathways (Z. Wang et al., 2017).

Pathways which rely strong on reductions in methane (CH_4) versus CO_2 will reduce warming in the short-term because methane is such a stronger and shorter-lived greenhouse gas, but will be warmer 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 methane is atmospheric photooxidation. This conversion modifies ozone formation and destruction in the troposphere and stratosphere, and therefore modifies the contribution of ozone to radiative forcing, as well as feedbacks onto the oxidation rate of methane itself (Myhre et al., 2013). Focusing on pathways and policies which both improve air quality and reduce climate impacts can serve to provide multiple co-benefits (Shindell et al., 2017), and these pathways are discussed in detail in Sections 4.3.7 and 5.4.1; and Cross Chapter Box 12 in Chapter 5.

Atmospheric aerosols and gases can also modify the land and ocean uptake of anthropogenic carbon dioxide, but some compounds enhance uptake, while others reduce uptake (Ciais et al., 2013) (Section 2.6.2). While CO_2 emissions tend to encourage greater uptake of carbon by the land and the ocean (Ciais et al., 2013), methane emissions can enhance ozone pollution, depending on nitrogen oxides, volatile organic compounds, and other organic species concentrations, and ozone 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 carbon dioxide in land and ocean systems through the deposition of nutrients and modification of climate (Ciais et al., 2013; Mahowald et al., 2017b).

[START BOX Cross-Chapter Box 7]

Cross-Chapter Box 7: Land-Based Carbon Dioxide Removal, in Relation to 1.5°C Warming

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Climate and land form a complex system characterised 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, and 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, fertilisation, irrigation, harvest, 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 $GtCO_2$ per year 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 either limit 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, afforestation and reforestation (AR) (Sections 2.3, 4.3.7); and BECCS (Sections 4.3.2., 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 in IAMs, but their deployment would also necessitate the use of land and/or changes in land management.

IAMs provide a simplified representation of land use and, with only a few exceptions, they 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 (Seneviratne et al., 2018c; section 3.6.2.2). 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 land availability and productivity) (Prestele et al., 2016; Alexander et al., 2017; Popp et al., 2017; Seneviratne et al., 2018d). Despite these limitations, IAM scenarios effectively highlight the extent and nature of potential land-use transitions implicit in limiting warming to 1.5^{o}C .

Cross-Chapter Box 7 Table 1, presents a comparison of the five CDR options assessed in this report. This illustrates that if deployed at a scale -e.g. 12 $GtCO_2yr^{-1}$ in 2100-, BECCS and AR would have a substantial land and water footprint. Wether this footprint results 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 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 recognised to present considerable potential barriers to future deployment (Boucher et al., 2013a; Fuss et al., 2014, 2018; Anderson and Peters, 2016; Williamson, 2016; Vaughan and Gough, 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 implicity or explicity) the use of BECCS and bioenergy (Krey et al., 2014; Bauer et al., 2018; Rogelj et al., 2018), or BECCS and afforestation (Strefler et al., 2018). Alternative strategies to limit future reliance on CDR have also been examined including increased electrification, agricultural intensification, behavioral change and dramatic improvements in energy and material efficiency (Bauer et al., 2018; Grübler, 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 (Krey et al., 2014; Krause et al., 2017; Bauer et al., 2018; Rogelj et al., 2018) (Chapter 2, Box 2.1). 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 postulating that increases in agricultural efficiency and changes in diet can enable land use, for example by postulating that increases in agricultural efficiency and changes in diet can enable land use switching from food crop production to energy crop production without altering the overall agricultural area (Grübler, 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). Yet 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 (Heck et al., 2018; Section 3.6.2.1). The short versus long term carbon impacts of substituting biomass for fossil fuels (in large part determined by feedstock choice) also remain a source of contention (Schulze et al., 2012; Jonker et al., 2014; Booth, 2018; Sterman et al., 2018).

AR can also present trade-offs between biodiversity, carbon sequestration and water use, and has a higher land footprint per ton of CO_2 removed (Cunningham et al., 2015; Naudts et al., 2016; Smith et al., 2018). For example, changing forest management to strategies towards 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 will be further addressed in the IPCC Special Report on Climate Change and Land (SRCCL) due to be published in 2019.

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 agreement, robust evidence*).

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

The impacts of deploying land-based CDR at scale can be reduced if a wider portfolio of CDR options is deployed, and if increased mitigation effort focusses on strongly limiting demand for land, energy and material resources including lifestyle and dietary change (*high agreement, medium evidence*).

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

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 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 & permanence [a]**
	$GtCO_2$ y^{-1}	*$\$ \text{ per } tCO_2$*	*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 time scale

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[1]	Soil sinks saturate and can reverse if poor management practices were to resume

[END BOX Cross-Chapter Box 7]

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 (Schroeder 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) remove sea ice by raising CO_2 concentrations and study subsequent regrowth by lowering CO_2. These studies also suggest changes in Arctic sea ice are neither irreversible nor exhibit bifurcation behavior. It is therefore plausible that the extent of Arctic sea ice may quickly re-equilibrate to end-of-century climate in the event of an overshoot scenario.

3.6.3.2 Sea level

The impacts of 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 timescales, 50 m of sea level rise are potentially 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) find that 28–44% of present-day glacier volume is unsustainable in the present-day climate, so that it would eventually (over the course of a few centuries) melt, even if there were no further climate change. Some components of sea level rise, such as thermal expansion, are only reversible on centennial timescales (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 $°C^{-1}$ falling at higher degrees of warming mostly because of the depletion of glacier mass, with a possible total of ~0.6 m) amount to 0.5–1.2 m and 0.6–1.7 m in 1.5 and 2°C warmer worlds, respectively. The bulk of Sea Level Rise (SLR) on greater than centennial timescales will therefore be contributed by the two continental ice sheets of Greenland and Antarctica, whose existence is threatened on multi-millennial timescales.

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 melt 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 (Gregory and

Huybrechts, 2006) put this threshold about 1.9ºC to 5.1°C above preindustrial period. More recent analyses, however, suggest that this threshold sits between 0.8ºC 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 future climate and varies between about 80% loss after 10,000 years to complete loss after as little as 2000 years (contributing ~6 m to SLR).

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 melt of calved icebergs). The long-term existence of this ice sheet is also 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 (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 has been postulated in which an ice cliff forms at the grounding line which 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 emission scenarios such as Representative Concentration Pathway (RCP)2.6 but that higher-emission 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 as collapse is highly dependent on model details and no consensus yet exists. Current thinking (Schoof, 2007) suggests 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 be anticipated to increase the risk of such irreversible retreat.

The assessment also noted that the collapse of marine sectors of the Antarctic ice sheet could lead to 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' (Church et al., 2013).

The multi-centennial evolution of the Antarctic ice sheet is 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 below 1.0 m. The long-term committed future of Antarctica (and GMSL contribution at 2100) are complex and require further detailed process-based modelling, however a threshold in this contribution may be present close to 1.5ºC.

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 is analyzed by Chadburn et al. (2017). They use an empirical relation between recent mean annual air temperatures and the area underlain by permafrost coupled to 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 eventually permafrost loss by roughly 2 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 of global warming and permafrost loss, leads to the assessment that permafrost extent would be appreciably greater in a 1.5°C world compared to a

2°C world (*medium confidence*, *limited evidence*).

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 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 of global warming at 1.5°C as compared to 2°C and higher.

3.7.1 Gaps in Methods and Tools

- Regional and global climate model simulations for low-emission scenarios such as a 1.5°C 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, 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 ecosystems to climate and models which are increasingly 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

Earth systems and 1.5ºC:

- The cumulative effects of multiple stresses and risks (e.g., increased storm intensity interacting with sea level rise and the effect on coastal people; feedback 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, and biofuel production, Bio-Energy with Carbon Capture and Storage (BECCS), and associated unquantified biophysical impacts.

- The distinct impacts of different overshoot scenarios depending on (a) the peak temperature of the overshoot, (b) the length of the overshoot period, and (c) the associated rate of change in global temperature over the time period of the overshoot.

Physical and chemical characteristics of a 1.5ºC world:

- Critical thresholds for extreme events (e.g., drought, inundation) between 1.5°C and 2°C, 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 worlds, and the impact of changing storminess on storm surge, 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 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.

Terrestrial and freshwater systems

- The dynamics between climate change, freshwater resources, and socioeconomic 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., effect of late frosts), and questions associated with issues such as the consequences of species advancing their spring phenology in response to warming, and the interaction between climate change, range shifts and local adaptation in a 1.5°C world.

- The biophysical impacts of land use in the context of mitigation pathways.

Ocean Systems

- Deep sea processes and risks to deep sea habitats and ecosystems.

- Changes in ocean chemistry in a 1.5˚C world, including how decreasing ocean oxygen content, ocean acidification, and changes to activity of multiple ion species, will affect natural and human systems.

- How ocean circulation is changing towards a 1.5°C and 2°C world, for example, 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 warming on food webs, 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.

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 interactions with surrounding areas. For example, current projections do not integrate adaptation to projected warming by taking into account 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 islands.

- Implications of climate change at 1.5°C on livelihoods and poverty, on rural communities, indigenous groups and marginalised people.

- The changing levels of risk in terms of extreme events (including storms and heat events), 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: 1.5ºC 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 preindustrial period, 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), 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 factoring in.

Key questions[3]:

- **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?** GMST corresponds to the globally averaged temperature of the Earth derived from point-scale ground observations or computed in climate models (Chapters 1 and 3). GMST 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 global mean temperature typically needs to be defined over several decades (typically 20 or 30 years; Chapter 3, Section 3.2). Hence, whether or when global temperature reaches 1.5°C depends to some extent on the choice of preindustrial 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 warming is exceeded, even if the global mean temperature 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 global warming?** The range between single model simulations of projected regional changes at 1.5°C GMST warming can be substantial for regional responses (Chapter 3, Section 3.3). For instance, for the warming of cold temperature extremes in a 1.5°C warmer world, some model simulations project a 3°C warming and others more than 6°C warming in the Arctic land areas (Cross-Chapter Box 8, Figure 2). For warm temperature extremes in the contiguous United States, the range of model simulations includes colder temperatures than pre-industrial (-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., 1–5°C regional warming in hot extremes in Central Europe at 1.5°C warming, Chapter 3, Sections 3.3.1 and 3.3.2). This large spread is due both to modelling

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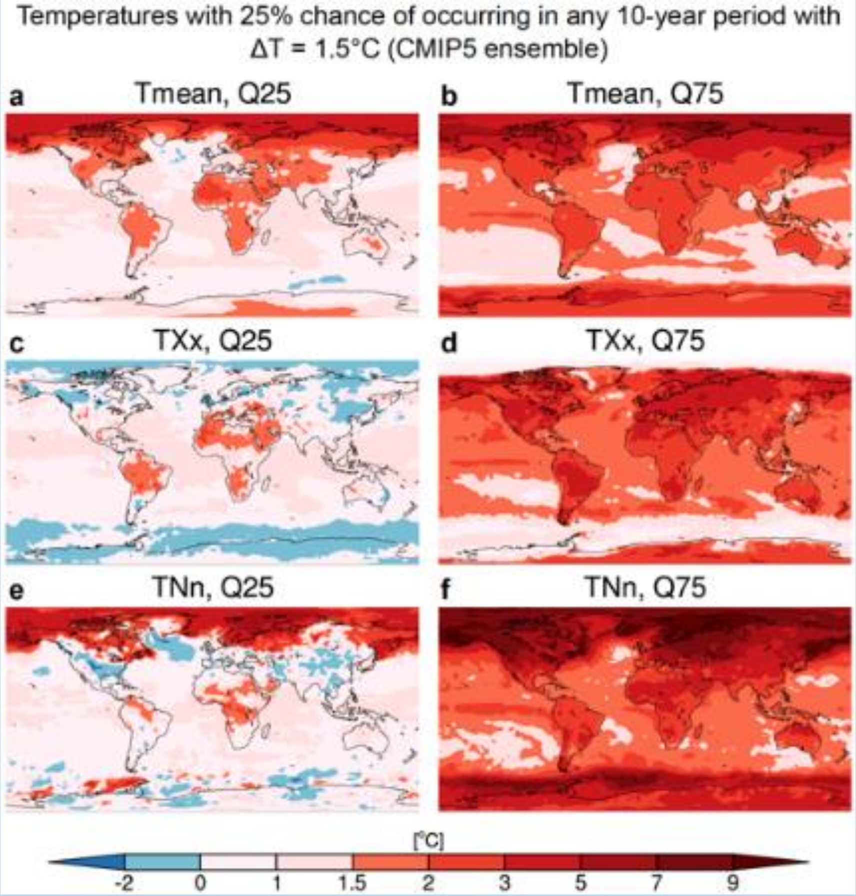
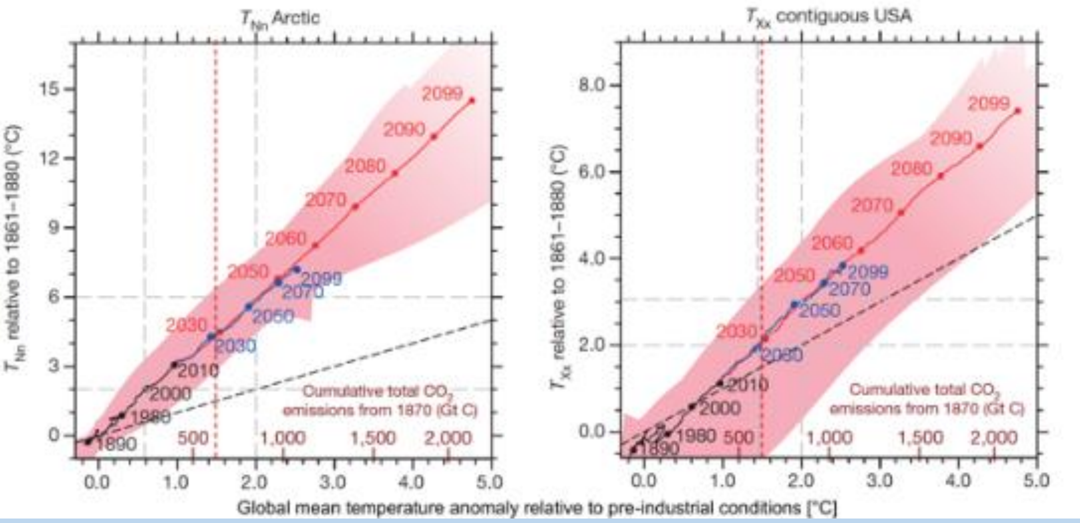
[3] FOOTNOTE: Part of this discussion is based on Seneviratne et al. (2018b)

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 in cold extremes in the Arctic is not reached at 1.5°C global warming in the multi-model ensemble, but could happen at 2°C 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.



Cross-Chapter Box 8, Figure 1: Range of projected realized temperature at 1.5°C (due to stochastic noise and model-based spread). Temperature with a 25% chance of occurrence at any location within 10-year time frames corresponding to GMST anomalies of 1.5°C (Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble). The plots display at each location the 25th percentile (Q25, left) and 75th percentile (Q75, right) values of mean temperature (Tmean), yearly maximum day-time temperature (TXx), 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, Figure 2: Spread of projected multi-model changes in minimum annual night-time temperature (TNn) in the Arctic land (left) and in maximum annual day-time temperature (TXx) in the contiguous United States as a function of mean global warming in climate simulations. The multi-model range (due to model spread and internal climate variability) is indicated in red shading (minimum and maximum value based on climate model simulations). The multi-model 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. [after Seneviratne et al., 2016].

- **What is the impact of emissions pathways with, versus without, an overshoot?** All mitigation pathways projecting less than 1.5°C global warming over or at the end of the 21st century, include some probability of overshooting 1.5°C. These pathways include some time periods with higher warming 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 systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (Chapter 3, Box 3.4). The chronology of emission 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 of most relevance (Loarie et al., 2009; LoPresti et al., 2015) with thus potentially large risks in 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 global warming if emissions compatible with 1.5°C pathway 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 a 1.5°C 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 warming exceeds 1.5°C even under a 1.5°C-consistent pathway, including some possibility of being 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 are those 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 systemic 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 (e.g. 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 for 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).

- **What determines risks and opportunities in 1.5°C warmer worlds?** 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 upon the methods that humanity uses to limit warming to 1.5°C global warming. 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 will depend on development choices over coming decades that will influence 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 (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 1.5°C warmer worlds?** Human-driven warming linked to CO_2 emissions is near irreversible over time frames of 1000 years or more (Matthews and Caldeira, 2008; Solomon et al., 2009). The global mean temperature 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 would be the time at which the net CO_2 budget is zero.

- **Hence, a transition to decarbonisation 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 emission budget. **Most of these use Carbon Capture and Storage (CCS)** in addition to reforestation, to varying degrees (Chapter 4, Section 4.3.7). Some potential pathways to 1.5°C 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 decarbonisation) 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 vs higher levels of warming? Cross-Chapter Box 8, Table 2,** displays 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 either include stabilization at 1.5°C (Scenario 1) or close to 1.5°C (Scenario 2), and one 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'. Important aspects to consider (beside that of global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of global surface temperature at 1.5°C is achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional 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 many ecosystems. In addition, for several types of risks, the rate of change may be of most relevance with thus potentially large risks in 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 to initiate 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, Cross-Chapter Box 8, Table 1). If mitigation pathways are not rapidly activated, much more expensive and complex adaptation measures would have to be taken to avoid the impacts of higher global warming on the Earth system.

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 its set-up used in AR5 WGIII (Clarke et al., 2014), but are uncertain and will be subject to updates and adjustments (see Chapter 2 for details).

		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]	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 (1.66–1.72°C)**	**2.05°C (2.00–2.09°C)**	**2.11°C (2.05–2.17°C)**	**2.67°C (2.59–2.76°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 the 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]	-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[e]	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—1.51°C)**	**1.87°C (1.81—1.94°C)**	**2.06°C (1.99—2.15°C)**	**2.66°C (2.56—2.76°C)**
	Warming in the Arctic[i] (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[i] (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[i] (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[i]	-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[i]	8.38% (4.63, 12.68)	10.34% (6.64, 16.07)	12.02% (7.41, 19.62)	19.72% (11.34, 26.95)

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. These are only a few of possible storylines; their choice is for illustrative purposes.

Scenario 1 [one possible storyline among best-case scenarios]: **Mitigation: Early move to**	**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 of global temperature warming to 1.5°C by 2100.** There is strong participation in all major world regions at national, state and/or city levels. Transport is strongly decarbonized through a shift to electric vehicles, with

decarbonisation, decarbonisation designed to minimise land footprint, coordination and rapid action of world's nations towards 1.5°C goal by 2100 **Internal climate variability: Probable (66%) best-case outcome for global and regional climate responses.**	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 minimised 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 wastage **(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 toward higher latitudes and altitudes resulted 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, and pests and disease, increase **(Cross-chapter Box 6 in Chapter 3)**. Crops are grown on marginal land and no-till agriculture 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, there are 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 5, Box 5.3 and Section 5.3.2; Cross-Chapter Box 12 in Chapter 5; Chapter 4, Section 4.3.2)**, and some respond by moving, in many cases, with consequences for urban areas. In the Tropics, in particular in mega-cities, 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), 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 possible large changes in regional temperature means and hot extremes and the probability of most extreme droughts **(Chapter 3, Sections 3.3.3, 3.3.4 and 3.4.3; Chapter 4, Box 4.3)** as well as through 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 wellbeing **(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 (**3.4.4.7**) and coral reefs having been driven to a low level (10-30% of levels in 2018) have partially recovered after extensive dieback by 2100 **(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, with no efforts to minimize the land and water footprints of bioenergy.** **Internal climate variability: First, 10% worst-case outcome (2020s), then 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 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 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, South Africa and the Western Sahel, 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; Chapter 4, 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 due 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)**. Temperature peaks at 2°C by the middle of the century before decreasing again due to intensive implementation of bioenergy plants with carbon capture and storage **(Chapter 2)**, without efforts to minimize the land and water footprint of the bioenergy production **(Cross-Chapter Box 7 in Chapter 3)**. Reaching 2°C 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, Box 3.4, Box 3.5, 3.4.4.10, 3.4.5)**, leads to much reduced levels of coastal defence from storms, winds and waves increases the vulnerability and risks facing communities in tropical and sub-tropical regions with consequences for many coastal communities **(Chapter 5, 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 **(Section 3.4.4.3)**. The intensive area required for the production of bioenergy combined with increasing water stress sets pressures 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-Chaper 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 due to climate change as well as of land-use change **(Cross-Chapter Box 7 in Chapter 3)**. The ability to implement adaptive action to prevent the loss of ecosystems is frustrated under the circumstances and is consequently minimal **(Chapter 3, Section 3.4.4.10)**. Many natural ecosystems, in particular in the Mediterranean, are lost due to 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, temperature has decreased but is still higher 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; Chapter 4, 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 very significantly **(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 warming in 2100.** **Internal climate variability: First unusual (ca. 10%) best-case scenario for one decade, then 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 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 thus not increasing 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)**. 1.5°C warming 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 temperature 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 forcing **(Chapter 3, Section 3.3.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 11 in Chapter 4)**. Intense floodings occur 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 rain forest **(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 2-year drought in the Great Plains 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 risk and incidence of starvation increase very significantly 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 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 to monsoon rainfall and risks in case of termination **(Cross-Chapter Box 10 in Chapter 5)**. Global and regional temperatures continue to strongly increase while mitigation solutions are being developed and implemented. 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 life-time 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 water resources stress renders agriculture economically un-viable 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; Chapter 5, 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 SLR **(Chapter 3, Section 3.3.9; Chapter 4, Section 4.3.2)**. Several small island states give up hope to survive in their place and look to an increasingly fragmented global community for refuge **(Chapter 3, Box 3.5; Chapter 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 substantially decreased 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. But 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 emission 'pathway' taken. The consequences of temporarily overshooting 1.5°C and returning 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 ~1°C since pre-industrial times, and the impacts of this warming are already been felt in many parts of the world. This warming in global temperature is the average of many thousands of temperature measurements taken over the world's land and oceans. But temperatures aren't changing at the same speed everywhere. Warming is greatest on continents and is particularly strong in the Arctic in the cold season and mid-latitude regions in the warm season. This is due to self-amplifying mechanisms which increase resulting warming, for instance due to snow and ice melt reducing the reflectivity of solar radiation at the surface, or soil moisture drying leading to less evaporative cooling in the interior of continents. This means that some parts of the world have already experienced temperatures above 1.5°C above pre-industrial levels.

Extra warming on top of the ~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 total warming is held at 1.5°C, just half a degree above where we are now, and would be further amplified at 2°C global warming. Reaching 2°C instead of 1.5°C 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 are projected to become drier at 2°C vs 1.5°C global warming, for example the Mediterranean region. 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.

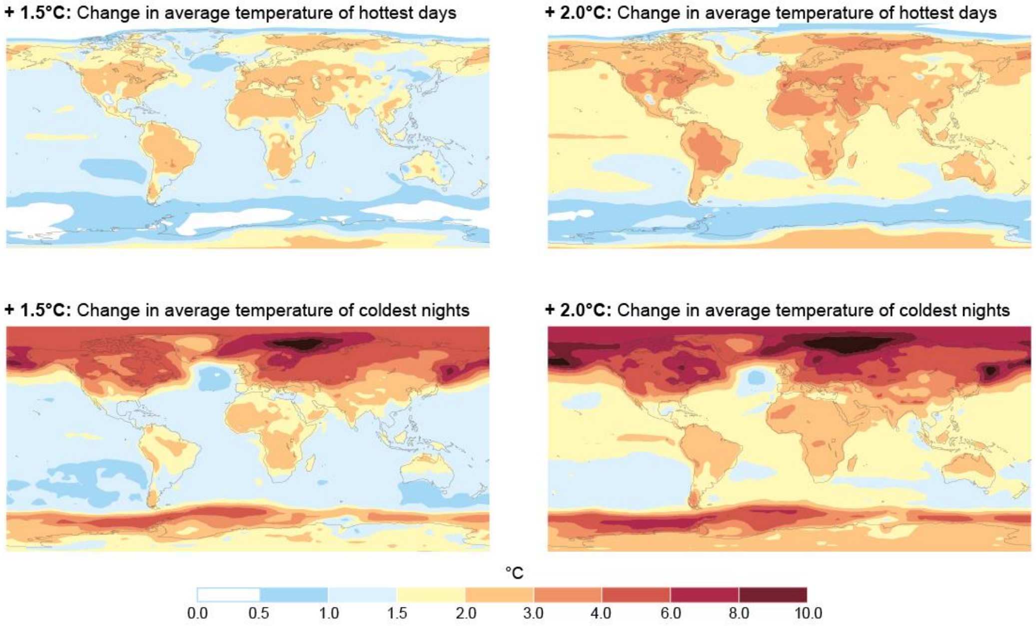
Change in climate means and extremes have knock on effects for the societies and ecosystems living on the planet. Climate change is projected to be a poverty multiplier, which means that its impacts make the poor poorer and increase the total number of people living in poverty. The 0.5°C rise in global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

Essentially, the lower the rise in global temperature above preindustrial 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 oceans, resulting from the delayed ocean mixing, means sea level will continue to rise even if global temperature is limited to 1.5°C, but this would be lower than in a 2°C world. Ocean acidification, the process by which excess CO_2 is dissolving into oceans and making them more acidic, is expected to be less damaging in a world where CO_2 emissions are reduced and warming is stabilised at 1.5°C compared to 2°C. The prospect for coral reefs in a 1.5°C world of less damaging than that of a 2ºC world, too.

The impacts of climate change that we experience in future will also be affected by factors other than the change in temperature. The consequences of 1.5°C 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 preindustrial 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 coming back down later in the century (known as an ‘overshoot’ pathway).

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 example, pathways that overshoot 1.5°C run a greater risk of passing through ‘tipping points’. These are thresholds beyond which certain impacts can no longer be avoided, even if temperatures are brought back down later on. An example is the collapse of the Greenland and Antarctic ice sheets on the time scale of centuries and millennia.



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 hot days and decreases in cold nights than others

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

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