Chapter 1: Framing and Context

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Notes:

Table of Contents

Executive Summary........ 4

1.1 Human, ecological, and physical dimensions........ 6
  1.1.1 The challenge of 1.5°C: human rights, ethics and governance........ 6
  1.1.2 1.5°C and Pathways........ 7
  1.1.3 Sustainable Development and 1.5°C........ 8

1.2 Understanding 1.5°C: reference levels, probability, transience, overshoot, stabilization........ 9
  1.2.1 Working definitions of 1.5°C and 2°C for use in this report........ 9
    1.2.1.1 Definition of global average temperature........ 9
    1.2.1.2 Choice of reference period........ 11
    1.2.1.3 Total versus human-induced warming........ 11
    1.2.1.4 Summary........ 12
  1.2.2 Global versus regional and seasonal warming........ 12
    1.2.2.1 Definition of regions........ 13
  1.2.3 Definition of 1.5°C consistent pathways and associated emissions........ 13
    1.2.3.1 Temperature stabilization pathways........ 14
    1.2.3.2 Temperature overshoot pathways........ 14
    1.2.3.3 Continued warming pathways........ 14
    1.2.3.4 Prospective versus adaptive mitigation pathways........ 15
Box 1.1: Scenarios and Pathways........ 16
    1.2.3.5 Impacts at 1.5°C associated with different pathways........ 17
    1.2.3.6 Cumulative budgets for CO_2 and CO_2-forcing-equivalent emissions........ 18
  1.2.4 Definition of 'balance' and net zero emissions........ 18
Box 1.2: Long-lived and short-lived climate forcers, emission metrics and emissions 'balance'........ 19
  1.2.5 Definitions of warming commitment........ 21

1.3 Multiple dimensions of impacts at 1.5° C and beyond........ 23
  1.3.1 Physical Dimensions of Impacts........ 23
    1.3.1.1 Spatial and temporal distribution of impacts........ 23
    1.3.1.2 Implications of 1.5°C for extreme events and associated impacts........ 24
    1.3.1.3 Non-temperature related impacts........ 25
    1.3.1.4 Probability and uncertainty of impacts........ 25
  1.3.2 Different dimensions of ecosystem impacts........ 25
    1.3.2.1 Drivers of ecosystem impacts........ 25
    1.3.2.2 Cumulative impacts, permanence and irreversibility........ 26

1.3.3 Human dimensions of impacts including vulnerability and adaptation 26
1.3.3.1 Sectoral impacts, human settlements, and adaptive capacity 26
1.3.3.2 Poverty, equity, justice and sustainable development 27

1.4 1.5°C in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, with consideration for ethics and equity 27
1.4.1 Justice, equity and ethics 27
1.4.2 Governance 29
1.4.3 Transformation, Transformation Pathways, and Transition 29
Box 1.3: Feasibility and limiting global temperature increases to 1.5°C 30
1.4.4 Trade-offs and synergies of adaptation, mitigation and sustainable development 33
1.4.5 Solar Radiation Management 36
1.4.6 Implementation and policies 37

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development 37
1.5.1 Multidimensional costs and benefits 38
1.5.2 Types of knowledge and evidence used in the report 39
Box 1.4: Experiencing 1.5°C - Opportunities and challenges of visualizing a 1.5°C world: The potential role of community knowledge 39

1.6 Consideration and communication of confidence, uncertainty and risk 40

1.7 Storyline of the report 43

References 45

Technical Annex 1.A 56
Technical Note for Figure 1.1 56
Technical Note for Figure 1.2 57
Technical note for Figure 1.3 58
Technical Note for Box 1.4 Figure 1 60

Executive Summary

This IPCC Special Report of global warming of 1.5°C assesses the conditions under which the global community could limit the rise in global temperatures to 1.5°C above pre-industrial levels; the impacts of a 1.5°C world compared to higher levels of warming; and the feasibility of meeting this target while promoting sustainable development, poverty reduction and increased equity. It is the first in a series of IPCC Special Reports to span all three IPCC working groups, and to include greater social science literature. As a result, this report builds on previous IPCC assessments but also goes beyond them in review existing literature on potential implementation options. The report is global in scope and includes regional analyses. The primary focus is on the 21st century, with some impacts considered on multi-century timescales.

Human-induced warming reached a global average of about 1°C above pre-industrial levels in 2016, increasing at 0.1-0.25 °C per decade. Many regions have already experienced greater warming and significant changes in rainfall. Consistent with the IPCC 5th Assessment Report (AR5), warming relative to pre-industrial levels is defined as the increase in global average temperature averaged over a multi-decadal period relative to the 30-year reference period 1850-1879. This level and rate of warming imply that a 20% reduction of global emissions from their present-day level for every tenth of a degree of warming from now on, or an average compound reduction rate of 2-5% per year, would be required to limit warming to 1.5°C.

Global warming of 1.5°C implies different levels of warming and rainfall change at the local level, and warming in regions with human settlements will often exceed 1.5°C. Local and traditional knowledge of recent climate changes bears direct relevance to the impacts of a 1.5°C climate. Present-day climate changes are not likely to be indicative of climate changes that would be realised in a global mean 1.5°C world. However, large parts of the world have already experienced warming in excess of 1.5°C in at least one season of the year, corresponding to over 50% of the global population for which local warming trends can be calculated.

Currently defined Nationally Determined Contributions (NDCs) specified under the Paris Agreement will not be sufficient to create conditions for a 1.5 °C world. Total global emissions, if expressed in terms that give all climate drivers a similar global temperature impact as CO_2, must be reduced to net zero in order to stabilise global average temperatures. Current patterns of population growth, fossil fuel consumption and exploitation of natural resources present structural impediments to achieving ambitious global emissions reduction targets.

Climate change of 1.5°C above pre-industrial levels will disproportionally exacerbate other global scale problems such as the degradation of ecosystems, disasters, food security, increased disease outbreaks, and access to fresh water. Increases in extreme events (e.g. droughts and floods) that result in resource depletion, conflict and forced migration are impacting economic development worldwide, and present a challenge to addressing the Sendai Framework for Disaster Risk Reduction 2015-2030. Global economic growth has been accompanied by increased life expectancy, educational attainment and income. But many regions are characterised by severe inequity in resource distribution that amplifies vulnerability to climate change.

Justice and equity are central to understanding the ambition of the Paris Agreement, recognising that the impacts of climate change for warming levels beyond 1.5°C could fall disproportionately on the poor and vulnerable. Three key points of connection between climate change and justice are associated with the conditions under which a 1.5°C world can achieved: asymmetry in the contributions to the problem; asymmetry in impacts and vulnerability, such that the worst impacts may fall on those that are least responsible for the problem, including future generations; and asymmetry in the power to decide solutions and response strategies. Mitigation and adaptation policies each have the potential for profound human rights implications of their own, especially if framed without considerations of the complex local-national to regional interlinkages and feedbacks in social-ecological systems.

The connection between 1.5°C warming and ambitions of sustainable development are complex and multifaceted - socially, spatially and over time. AR5 noted that climate change constitutes a moderate threat to current sustainable development and a severe threat to future sustainable development, and that ill-designed responses could offset already achieved gains. However, synergies exist between achieving the UN Sustainable Development Goals (SDGs) and climate responses. SDGs include the specific goals 'Climate action' (SDG13) but also closely related goals, including 'Affordable and clean energy' (SDGl7), 'Sustainable cities and communities' (SDG11), 'Responsible consumption and production' (SDG12), and others such as equality/equity goals for gender, education, income, work, and access to justice.

Limiting global warming to 1.5°C is associated with an opportunity for innovative global, national and subnational governance, enhancing adaptation and mitigation within the framework of sustainable development, poverty eradication, rights, justice and equity, and synergistically linking with global scale trends including increased urbanization and decoupling of economic growth from greenhouse gas forcing. Work on adaptive and flexible governance systems and policy experimentation will provide key information for transitioning to a 1.5°C global warming and reducing further temperature increase. Significant governance challenges include the ability to incorporate multiple stakeholder perspectives in the decision-making process to reach meaningful and equitable decisions, scalar interaction and coordination between the different levels of government, and the capacity to raise financing, and support for technological and human resource development for such actions. Governance capacity includes the wide range of activities and efforts needed to develop coordinated climate mitigation and adaptation strategies in the context of sustainable development taking into account equity, justice and poverty eradication.

Transitioning from climate planning to practical implementation is a major challenge in constraining global temperature to 1.5°C. Barriers include finance, technology and human resource constrains plus institutional capacity to strategically deploy available knowledge and resources. Regional diversity, including highly carbon-invested and emerging economies, are important considerations. Incorporating strong linkages across sectors, devolution of power and resources to sub-national and local governments and facilitating partnerships among public, civic, and private sectors will be key to implementing identified response options.

Mitigation-adaptation linkages, synergies and trade-offs, as well as the different dimensions of feasibility, are important linking elements to sustainable development. Feasibility is considered in this report as the systems-level capacity to achieve a specific goal or target. A complete vision of the feasibility question requires integration of natural system considerations into the human system scenarios, the placement of technical transformations into their political, social, and institutional context, and an indication that feasibility is dynamic across spatial social and temporal scales.

Common tools for making complex policy decisions such as cost-benefit analyses are insufficient for a 1.5°C target. For example, costs may be relatively easily quantifiable in terms of money but the impacts of climate change on humans' lives, their culture and values, or on ecosystem goods and services, may have unpredictable feedback loops and impacts for other regions, making it difficult to quantify and compare. In addition, costs and benefits can occur at very different times, even across different centuries for different regions, in which case standard cost-benefit analyses become difficult to justify.

Incorporating knowledge from different sources, setting a multi-faceted information channel, as well as educating and building awareness at various levels will advance decision making and implementation of context specific responses to 1.5°C of warming and the associated uncertainties. Reliable climate data is insufficient in many areas, especially in low-income countries. Indigenous and local knowledge and experience can complement scientific data with chronological and landscape-specific precision and detail that is critical for verifying climate models and evaluating climate change scenarios for 1.5°C warming.

1.1 Human, ecological, and physical dimensions of 1.5°C: building a knowledge base for this report

Previous IPCC reports have explicitly demonstrated evidence of human interference in the climate system. AR5 found that the average global surface temperature has reached approximately 1°C above pre-industrial levels (IPCC 2013a), and monthly average temperatures of 1.4°C above these same levels have been observed. The warming to date has generated observable impacts, and acts as an amplifier of risks for natural and human systems as noted in Chapter 3 of this report. It is this rising risk that underpins the ambition of the Paris COP21 agreement, to 'pursue efforts to limit' the rise in global temperatures to 1.5°C above pre-industrial levels.

This report assesses the feasibility of re-orienting global society to limit the rise in global temperatures to 1.5°C above pre-industrial levels; the effects and impacts of a 1.5°C world; the challenges of keeping within such a stringent warming target, and the consequences of failing to do so. The report is structured as a scientific assessment of the potential global response to this challenge within the specific context of sustainable development, poverty eradication, justice, equity and ethics as concrete means to articulate the long-standing ethical dilemmas posed by climate justice and the United Nations Framework Convention on Climate Change (UNFCCC) notion of equity.

To seek encompassing solutions to achieving a 1.5°C world, the assessment draws from past global assessments and knowledge of social-ecological systems as defined within the frame of the Anthropocene. The Anthropocene is used as a comprehensive interpretation of the global to local, and past–present-future human-nature interlinkages (Pattberg and Zelli 2016; Delanty and Mota 2017; Olsson et al. 2017). Climate change and other significant human imprints such as ocean acidification, land use change, biodiversity loss, sea level rise are linked to, among others, high population growth, unprecedented fossil fuel consumption and unequal exploitation of natural resources, jointly resulting in degradation of the environment and requirements for more sustainable pathways.

The assessment approach used in the report includes a framework to help the comprehension of the scale and interlinkages of the global environmental, economic, social and technical requirements that climate change raises. Complex ethical issues are brought to the fore that is both climate change and potential responses to it may exacerbate poverty, inequality and injustice, globally and locally and has implications on inter-generational justice. These present profound challenges to path-dependent governance and invites interdisciplinary research and reflection, pointing to a systems approach that takes into account social inequalities, unequal distribution of risks and ability to respond to 1.5°C warming (Dryzek 2016; Pattberg and Zelli 2016; Lövbrand et al. 2017; Bäckstrand et al. 2017). As a result, this assessment builds on the previous IPCC assessments to provide a range of pathways, including implementation strategies, on the feasibility of achieving the required substantive transformation of society to limit global warming to 1.5°C in the context of the 2030 Agenda for Sustainable Development within the complexity of the Anthropocene.

1.1.1 The challenge of 1.5°C: human rights, ethics and governance

This assessment is the response to an invitation extended to IPCC by the UNFCCC as part of the Paris COP21 Agreement that was negotiated by 195 countries. The Paris aspiration to limit warming to 1.5°C is highly ambitious and progress towards achieving this ambition is uncertain (Falkner 2016; Marquardt 2017). In 2014, AR5 identified 'only a limited number' of model-based scenarios that would achieve this target (IPCC 2014a). These few all assumed immediate and rapid scaling up of mitigation technologies, coupled with plunging global energy demand. Those conditions continue not to be met: global decarbonisation now stands at a rate of 1.3% per year, far below the estimated 6.3% required to stay within even a 2°C target (see Figure 2.9). The 1.5°C scenario differs from less ambitious targets in part because of the unusual scale, rapidity and coordination of any global response.

While economic growth has been accompanied by increased life expectancy, educational attainment and income, many regions are characterised by severe inequity in income distribution that amplifies vulnerability to climate change. The world population continues to rise and is projected to reach 9.7 billion by 2050

(United Nations 2015a) with much of this growth occurring in hazard-prone small and medium sized cities in low and moderate-income countries (Birkmann et al. 2016). The urgency of keeping with the Paris agreement is that the threat of 1.5°C above pre-industrial levels will likely exacerbate other global scale problems such as the degradation of ecosystems, food security, increased disease outbreaks, access to fresh water in different regions (FAO et al. 2015; Campbell et al. 2016).

Temperature rise to date has already resulted in profound alterations to human and natural systems, with new shocks and new risks (IPCC 2014a). Many regions of the world have experienced higher warming already, at different periods (Chapter 3, Section 3.3.1). Increases in extreme weather events, droughts, floods, sea level rise and biodiversity loss are already affecting economic development worldwide presenting a challenge to addressing the Sendai Framework for Disaster Risk Reduction (Mysiak et al. 2016) (Chapter 3, Sections 3.4 and 3.5). The most affected are the low and middle income countries where this has led to decline in food security and has been linked to migration and poverty. Small islands and populations residing in megacities, coastal regions and in high mountain ranges are some of the most affected. Efforts to curtail greenhouse gas emissions without incorporating the intrinsic interconnectivity of the Anthropocene world may themselves impact negatively on development ambitions of many nations.

The 1.5°C target thus raises ethical concerns that have been central to the climate debate from the outset, and most recently articulated in the language of human rights (Internatonal Council on Human Rights Policy 2008; Adger et al. 2014). For example, how will an average global temperature rise of 1.5°C impact upon human rights especially of the already vulnerable persons, that is the urban and rural poor, indigenous communities, women and children? As the world advances towards 1.5°C, further deterioration of the human rights may be unavoidable, although a solid knowledge base of the various social-ecological interlinkages may allow for some impacts to be anticipated and pre-empted. Failure to limit warming to 1.5°C will necessarily result in further extensive human rights consequences. In human rights terms, the gap between 1.5°C and 2°C amounts to a greater likelihood of drought, flooding, resource depletion, conflict and forced migration in many parts of the world (FAO et al. 2015; Campbell et al. 2016; Office of the United Nations High Commissioner for Human Rights 2009; Adger et al. 2014). Further, mitigation and adaptation policies each have the potential for profound human rights implications of their own, especially if framed without considerations of the complex local-national to regional interlinkages and feedback loops in social-ecological systems. Without sustained technology transfer, rapid decarbonisation could slow or stall growth and exacerbate poverty, especially in less wealthy countries. Adaptation measures, if they are to be effective and at scale, may be intrusive and so raise questions about participation (Dryzek and Pickering 2017) and respect for existing rights (Knox 2015; United Nations General Assembly 2016).

As a result, achieving the ambitions of the Paris Agreement will require unprecedented political will and highly supportive innovative governance arrangements equipped with an in-depth understanding of the far reaching diversity in spatial, temporal and social interconnectedness and the learning capabilities of society (Delanty and Mota 2017; Olsson et al. 2017; International Bar Association 2014). These arrangements include integrated reflexive policy institutions capable of operating at multiple scales (from local to regional and international), to affect the far-reaching policy change required to bring about reductions in GHGs consistent with a 1.5°C warmer world, while also strengthening global responses to poverty and addressing associated emerging human rights issues (Dryzek and Pickering 2017; Lövbrand et al. 2017; Bäckstrand et al. 2017).

1.1.2 1.5°C and Pathways

Altering or slowing the pace of current warming can be defined through mitigation pathways. Different pathways are more consistent than others with the requirements for sustainable development. The conditions required for achieving the 1.5°C goal include geo-physical, technological, and socio-economic dimensions (described in Box 1.3). Limiting warming to 1.5°C also involves identifying advantageous technology and policy levers, with which it may be possible to accelerate the pace of transformation.

The global commitment to 1.5°C pathways is, in part, defined by nationally determined contributions (NDC) of greenhouse gas reduction. The current NDCs are not ambitious enough to secure the 1.5°C goal and are currently tracking toward a warming of 3-4°C above preindustrial temperatures (Rogelj et al. 2016; UNFCCC 2016). The analysis of pathways also reveals opportunities for greater decoupling of economic growth from the rate of GHG emissions. Movement toward 1.5°C will require an acceleration of this trend.

The challenge is in identifying the best ways to achieve wide reaching policy change with consideration to ethics and justice, the appropriate actors to lead this change, and the most effective arenas for policy action to address adaptation and mitigation for a 1.5°C world within a sustainable development framework (Jordan et al. 2015; Stripple and Bulkeley 2011). An option exists for strong effective earth-system governance for international institutions (Biermann 2014) and 'top-down, treaty-based' approaches to reducing greenhouse gases as opposed to non-binding, 'pledges of intent' with periodic review (Busby 2016). The later approach underpinned the Paris Agreement of 2015 and is consistent with multi-level polycentric or decentralised public and private networked governance (Stevenson and Dryzek 2013; Lövbrand et al. 2017).

The new approach signalled by the Paris Agreement does not leave mitigation entirely to bottom-up efforts or top down directives. Instead, voluntary country pledges are embedded in 'an international system of climate accountability and a "ratchet" mechanism' (Falkner 2016) and allows for actions by non-state actors (Morgan and Northrop 2017).

1.1.3 Sustainable Development and 1.5°C

Despite unprecedented global wealth, the number of people living in extreme poverty and hunger remain close to or around one billion (United Nations Development Programme 2014); global wealth distribution has become increasingly unequal (OECD 2015). The AR5 provided insight into the geographic distribution and trends of poverty patterns and addressed poverty dynamics, for example shifts between transient and chronic poverty, as well as relational aspects of poverty (Olsson et al. 2014). The AR5 concluded that 'climate change and climate variability worsen existing poverty and exacerbate inequalities' (*high confidence*) and that climate change will 'create new poor between now and 2100, in developing and developed countries, and jeopardise sustainable development' (*high confidence*) (Olsson et al. 2014).

The AR5 (IPCC 2014b) concluded that climate change constrains possible development paths, that synergies and trade-offs exist between climate responses and socio-economic contexts, that capacities for effective climate responses overlap with capacities for sustainable development, and that existing societal patterns (e.g., overconsumption) are intrinsically unsustainable (Fleurbaey et al. 2014). As a result, any serious attempt to meet a 1.5°C target, while at the same time reducing poverty, will benefit from attentiveness to the Anthropocene narrative on the past-present and future functioning of national and global economies and their connections that give rise to the need for a sustainable development framework (Delanty and Mota 2017).

In this assessment, the definition of sustainable development is rooted in the 1987 report Our Common Future: ' (…) development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development 1987). The recent UN Sustainable Development Goals (SDGs) are an interlinked network of targets that are crucial to addressing the interconnected challenges of the Anthropocene for systematic wellbeing. Building on the successes and limitations of the Millennium Development Goals, the SDGs acknowledge more integrated systems and lend themselves to inclusive implementation and policy integration across sectors.

SDG13 specifically requires 'urgent action to address climate change and its impacts', but most if not all of the 17 SDGs are directly relevant to climate action. They include, for example, ending poverty and hunger, reducing inequality, making cities resilient and sustainable, encouraging sustainable consumption and production, making energy affordable and clean, promoting 'decent work' and conserving biodiversity on land and sea (United Nations 2015b). The SDGs provide targets and indicators to be assessed periodically at global conferences and thus provide a useful forum in which to monitor and promote efforts to manage climate change sustainably.

Equality and equity expressed under SDGs 5 and 10 are fraught with definitional problems. Equality affords all people the same status, opportunities, and rights, yet people embark from different starting points and thus don't benefit the same way. In the context of global warming, the importance of equality across generations has been articulated in terms of 'growth sustainability' (Llavador et al. 2015). Equity is often seen synonymous with fairness and justice, entailing distributive and procedural equity as well as equity between and within generations (Shelton 2007).

The interdependence of SDGs resonates strongly with the AR5 findings that climate change amplifies conditions of poverty and inequality. SDGs have a strong focus on equity and environment and apply to all countries as global goals (see Box 5.1) that are 'action-oriented, concise and easy to communicate, limited in number, aspirational, global in nature and universally applicable to all countries while taking into account different national realities, capacities and levels of development and respecting national policies and priorities' (United Nations 2015b). Nevertheless, how to achieve these aspirations alongside the transitions needed to secure a 1.5°C world will need careful planning.

An understanding of 1.5°C comes from a variety of established and emergent knowledge bases, such as the Anthropocene (Olsson et al. 2017). These different knowledge bases will, together, be critical to more fully realise the texture and conditions of impact, vulnerability, mitigation and strengthening of the sustainable development agenda. The demands of limiting warming to 1.5°C with meaningful solutions require this approach.

1.2 Understanding 1.5°C: reference levels, probability, transience, overshoot, stabilization

1.2.1 Working definitions of 1.5°C and 2°C for use in this report

While the overall intention is clear, the Paris Agreement does not specify precisely what is meant by 'global average temperature' relative to 'pre-industrial levels'. Whether or when global temperatures reach 1.5°C depends to some extent on these definitions. While the ultimate decision on what definition to adopt is beyond the mandate of this report, working definitions are required to ensure consistency across chapters and figures. Issues affecting the definition include the choice of pre-industrial reference period, whether 1.5°C refers to total or human-induced warming, and which variables and coverage are used to define global average temperature change. In this section, a working definition is proposed and related to various potential alternatives.

1.2.1.1 Definition of global average temperature

The IPCC has traditionally defined changes in observed global mean surface temperature (GMST) as a weighted average of observed near-surface air temperature (SAT) changes over land and sea surface temperature (SST) changes over the oceans (Morice et al. 2012). Modelling studies, with no coverage constraints, have typically used a simple area average of SAT over land, sea-ice and oceans. For relatively low warming levels, the difference can be significant. Cowtan et al. (2015) show that the use of blended SAT/SST data gives approximately 0.1°C less warming to-date in the 5th Climate Model Intercomparison Project (CMIP5) ensemble than the use of area-average SAT, while Richardson et al. (2016) show that incomplete coverage reduces warming to-date by a further 0.1°C (see inset panel in Stocker et al. (2013), Figure TFE8.1 and Figure 1.1). Detection and attribution studies have generally been careful to make a like-for-like comparison, accounting for coverage (Tett et al. 1999; Jones et al. 2003). The simple climate models used in many Integrated Assessment Models do not distinguish SAT and SST, but are typically calibrated to more complex models or observations, and hence could reproduce either a pure SAT or blended SAT/SST metric. Richardson et al. (2016) show that defining global temperature using a blended SAT/SST metric reduces the expected transient warming under rapidly increasing forcing by approximately 10% relative to a pure SAT metric, but has less impact on the equilibrium response.

The three GMST reconstructions used in AR5 differ in their treatment of missing data. GFDL (Vose et al. 2012) estimates low-frequency changes in GMST by, in effect, equating temperature anomalies in unobserved regions with a weighted average of anomalies within ±10° in space or ±15 years in time (decadal and shorter variations are treated separately). GISS (Hansen et al. 2010) equates unobserved temperature anomalies with the average of contemporaneous observations in the corresponding latitude band, while HadCRUT (Morice et al. 2012) equates them with the hemispheric average. Since AR5, considerable effort has been devoted to more sophisticated statistical modelling to infill missing data (Rohde et al. 2013; Cowtan and Way 2014; Jones 2016), the main impact of which is to increase the warming to date by approximately 0.1°C (Richardson et al. 2016) by placing more weight on poorly-observed but rapidly-warming polar regions. Full assessment of the reliability of these infilling methods is beyond the scope of this report, which therefore defines warming to date using blended versions of the GMST datasets with their incomplete coverage, consistent with the use of these datasets in AR5. Compared to AR5, datasets have been extended in time and some have small methodological updates such as bias adjustments (Karl et al. 2015) which affect trends over recent decades, but not warming relative to the 19th century.

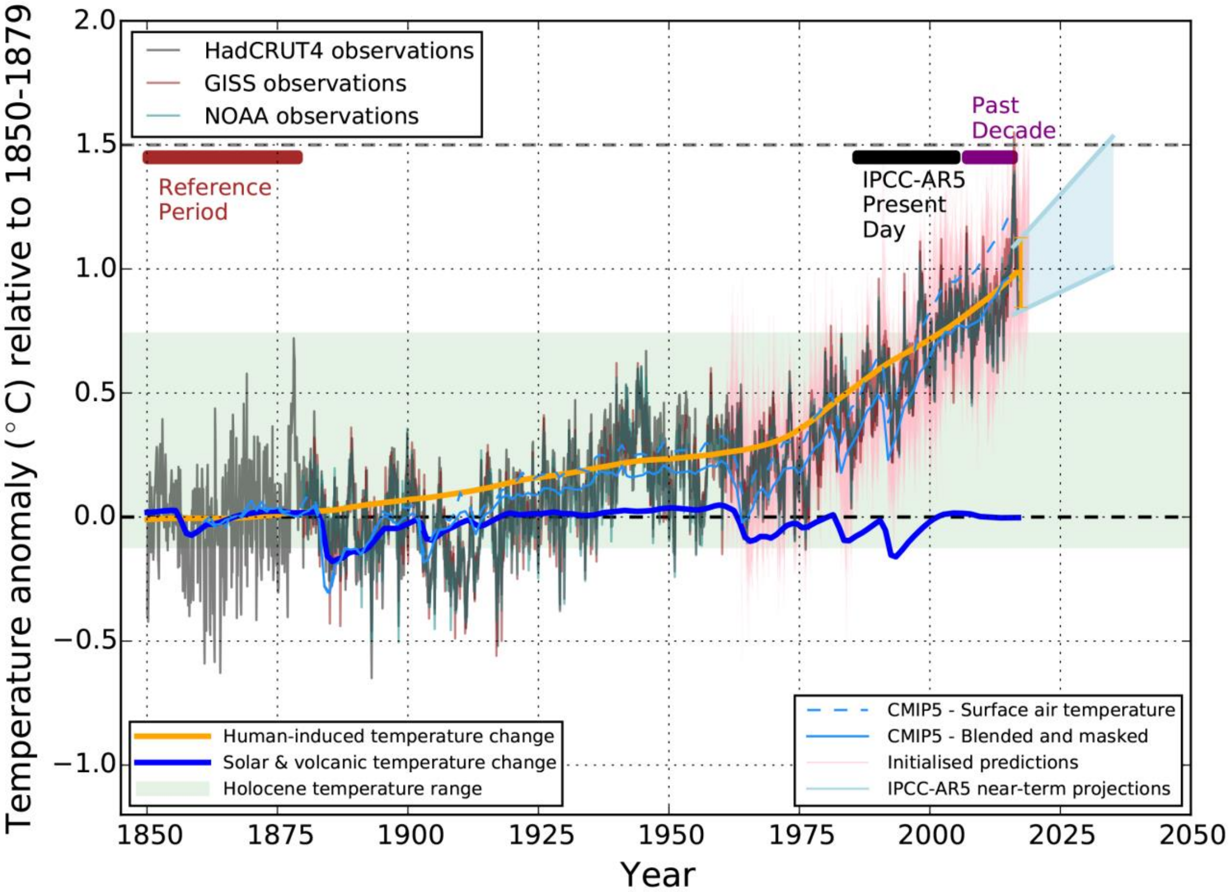


Figure 1.1: Evolution of global warming over the observed period. Warming is expressed as anomalies from the 1850-1879 base period for monthly means of the HadCRUT4, NOAA and GISTEMP datasets, which measure a blended mix of near surface air temperature over land and sea surface temperature over oceans. Human-induced warming (orange) and naturally-forced warming (blue) are calculated using the two time constant response model of Myhre et al. (2013) following Otto et al. (2015). Proportional uncertainty in the final human-attributable warming is set equal to that assessed in Bindoff et al. (2013). The thin blue lines show the modelled global-mean surface air temperature (dashed) and blended surface air and sea surface temperature accounting for observational coverage (solid) from the CMIP5 ensemble under the Historical and RCP8.5 scenario (Cowtan et al. 2015; Richardson et al. 2016). Pink lines show initialised predictions

using a decadal prediction system (Smith et al. 2013a). The green shading indicates a maximum and minimum temperature range from the Holocene (Marcott et al. 2013). Near-term predictions for global mean warming for the 2016-2035 period from Kirtman et al. (2013) are shown in light blue. See Technical Annex 1.A of this chapter for further details.

1.2.1.2 Choice of reference period

Any choice of reference period used to approximate 'pre-industrial' conditions is a compromise between data coverage and representativeness. Carbon budget calculations in the AR5 (e.g., Figure SPM10 of IPCC (2013a) and Table 2.2 of the IPCC (2014a)) used the 1861-1880 reference period, while the evaluation of impacts in Working Group 2 (e.g., Box AR5 TS.5 Figure 1 of (Field et al. 2014)) used 1850-1900. The years 1880-1900 are subject to strong but very uncertain volcanic forcing, complicating their use in a reference period for model-observation comparisons and studies of mitigation pathways focusing on human-induced warming. Hawkins et al. (2017) note that the 1720-1800 period is more representative of pre-industrial forcing conditions, at the cost of increased uncertainty in estimated warming to date.

This report adopts the compromise 30-year reference period, 1850-1879 inclusive. In this period the GMST in HadCRUT4 (the only available observational dataset covering this period) is less than 0.01°C higher than the 51-year 1850-1900 period, and between 0.01 and 0.02°C cooler than the 1861-80 period. The period 1986-2005, extensively used in AR5 as a reference period representing recent climate conditions, was 0.61°C warmer than 1850-1879 (with a 5-95% confidence interval of 0.55-0.67°C), indistinguishable (within rounding) from the warming from 1850-1900. Hence conclusions regarding observed impacts based on the 1850-1900 period will also be applicable to using the 1850-1879 reference period, while the latter has the clear advantage for modelling and mitigation studies of avoiding post-1880 volcanic activity. The use of a consistent reference period for mitigation and impact assessment (not achieved in AR5) is strongly recommended. This report uses a 30-year reference period, for consistency with the WMO definition of climate, and defines 'decades' as starting in years ending in zero, for consistency with public understanding of the term. Thus far, average temperatures of the present decade (i.e., that beginning on 1st January 2010) are 0.89°C warmer than 1850-1879 in the HadCRUT4 dataset. Temperatures rose by 0.0-0.2°C prior to the 1850-1879 reference period (Hawkins et al. 2017; Schurer et al. 2017) relative to earlier centuries, but the anthropogenic contribution to this warming is uncertain (Schurer et al. 2017).

1.2.1.3 Total versus human-induced warming

Total warming refers to the actual temperature change, irrespective of cause, while human-induced warming refers to the component of that warming that is attributable to human activities. Total warming is timescale-dependent: temperatures in individual years can fluctuate substantially around the long-term average temperature or secular temperature trend due to externally driven and internally generated climate variability. Studies of climate change impacts typically refer to warming levels defined by multi-decade average temperatures, recognizing the inevitability of fluctuations about these averages on shorter timescales and smaller spatial scales.

In the absence of strong natural forcing due to changes in solar or volcanic activity, multi-decade average total warming is expected to be very similar to human-induced warming. Figure 1.1 shows, for example, that human-induced warming since the 1850-1879 reference period is close to total observed warming, the net contribution of natural climate variations being small once random interannual variations are averaged out, while monthly temperatures fluctuate substantially around this total.

Mitigation studies focus on human-induced warming because, while past natural drivers may be included in historical simulations, future natural fluctuations are both unpredictable and unaffected by mitigation policy. Hence, for the purposes of this report, a '1.5°C world' is defined as one in which temperatures averaged over a multi-decade timescale are expected to be 1.5°C above the pre-industrial reference period or, equivalently in the absence of a substantial secular trend emerging in natural forcing (for which there is no evidence at present), a world in which human-induced warming has reached 1.5°C.

On this definition, global temperatures would fluctuate equally on either side of 1.5°C in the absence of a large volcanic eruption (which would cause a temporary cooling). Alternative definitions, such as maintaining the probability of temperatures fluctuating over 1.5°C below a specified level, are more ambiguous, since they depend on the averaging timescale used and the properties of future natural or internal variability. For example, the decadal predictions shown in Figure 1.1 indicate there is a substantial chance (probability to be given in the SOD if the relevant publication is available) of monthly temperatures fluctuating over 1.5°C between now and 2020, but this would not constitute temperatures 'reaching 1.5 °C' on our working definition. An indication of the range of natural fluctuations is given by Figure 1.1, which shows observed 20-year-average temperatures varied by ±0.1°C (5-95% range), and monthly temperatures by ±0.2°C, around the human-induced warming trend over the period 1861-2017. Regional fluctuations would be larger still.

1.2.1.4 Summary

For the purposes of this report, warming relative to pre-industrial levels is defined as the increase in expected global average blended surface air temperature changes over land and sea surface temperature changes over oceans, relative to the reference period 1850-1879, noting that incomplete coverage has under sampled polar, southern hemisphere and some tropical regions in the past, but assuming full spatial coverage in future. At the level of precision at which GMST can be defined, this means that 1.5°C relative to pre-industrial means 0.9°C warmer than 1986-2005, or 0.6°C warmer than the present decade 2010-2019.

1.2.2 Global versus regional and seasonal warming

Warming is not observed or expected to be spatially uniform, nor distributed uniformly across all months of the year, and is generally expected to be greater over land than over the oceans (IPCC 2013a). Hence a 1.5°C increase in GMST will be associated with warming substantially greater than 1.5°C in many land regions, and less than 1.5°C in most ocean regions. This is illustrated by Figure 1.2, which shows a best-estimate of the observed change in seasonal average temperatures in the June-August and December-February seasons, associated with the observed 1°C rise in global temperatures relative to the 1850-1879 pre-industrial reference period. Many regions, particularly in northern mid-latitude winter, have already experienced regional warming in excess of 1.5°C or even 2°C. Natural climate fluctuations mean that individual seasons may be substantially warmer, or cooler, than these expected long-term average changes.

There has been considerable research on the 'time of emergence', when the climate change signal becomes significant relative to the noise of internal climate variability (Joshi et al. 2011; Mahlstein et al. 2011; Hawkins and Sutton 2012; Sui et al. 2014; Lyu et al. 2014). While the signal of human influence on seasonal mean temperatures (Mahlstein et al. (2011) and Figure 1.2) and temperature extremes (King et al. 2015; Schleussner et al. 2017) has already emerged above the noise in many regions, particularly in the tropics, the signal-to-noise for precipitation is much lower. Mahlstein et al. (2012) estimate that many regions will not experience statistically significant changes until GMST warming has reached 1.4°C, but substantial changes in the probability of extreme precipitation events may occur much earlier (Mitchell et al. 2016).

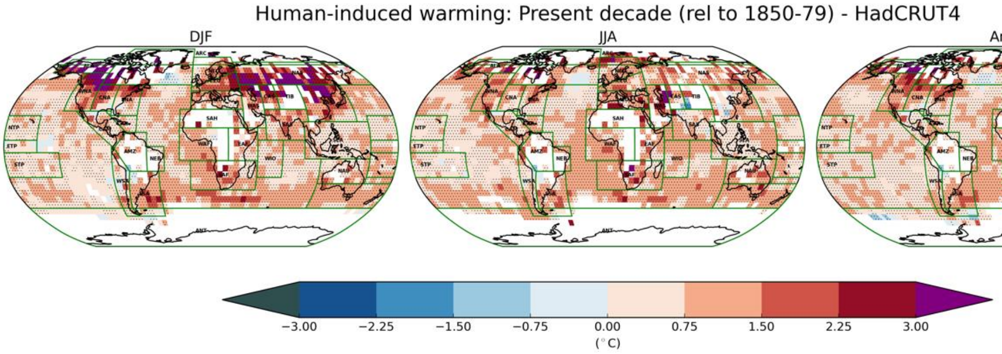


Figure 1.2: Regional human-attributable warming for the most recent decade 2007-2016 relative to 1850-1879 for the average of December, January and February (DJF – left) and for June, July and August (JJA – middle) and for the annual mean (right). Trends are evaluated by regressing regional changes in the HadCRUT4 dataset onto the human-attributable warming (orange line in Figure 1.1). Data is shown where missing data represents less than 50% of the record. Hatching indicates significance at a 10% confidence level assuming Gaussian errors. See Technical Annex 1.A of this chapter for further details.

1.2.2.1 Definition of regions

The report adopts the AR5 definition of regions that included 33 regions of land and sea areas and each of the 33 regions was provided with a name and a label (Christensen et al. 2013). Projections of change in surface temperature and precipitation show large regional variations for example, northern mid-latitude winter, have already experienced regional warming in excess of 1.5°C or even 2°C. Arctic warming is projected to increase more than the global mean, mostly because the melting of ice and snow produces a regional feedback by allowing more heat from the sun to be absorbed (Christensen et al. 2013). The Arctic region experienced its warmest year ever recorded in 2016, consistent with record low sea ice found in that region for most of the year (GISTEMP Team 2017).

1.2.3 Definition of 1.5°C consistent pathways and associated emissions

The Paris Agreement does not associate a timescale or pathway with the long-term temperature goal, so classifying temperature pathways that might be considered consistent with 1.5°C is an important task for this report. Three broad categories of temperature pathways are used in this report, associated with very different impacts and emissions: temperature stabilization, continued warming, and temperature overshoot.

The word ‘scenario’ is often used interchangeably with the word ‘pathway’. This report will not attempt to refine these definitions but, in general, pathway will be used to describe the specific evolution over time of particular climate variables, such as emissions or temperatures, while scenario will be used to refer to the underlying assumptions (see Box 1.1 on scenarios and pathways).

Figure 1.3 relates pathways of (a) temperature and (b) radiative forcing consistent with the temperature pathways shown in (a) for a given value of the Transient Climate Response (TCR), which is the relevant measure of climate response on these timescales (Frame et al. 2006; Gregory and Forster 2008; Held et al. 2010). Additional versions of Figure 1.3 corresponding to higher and lower values of the TCR are provided in Technical Annex 1.A. Panel (c) shows cumulative diagnosed CO_2-forcing-equivalent (CO_2-fe) emissions, meaning the CO_2 emissions (diagnosed with a carbon-cycle model) that would yield these radiative forcing and temperature pathways (Wigley 1998; Zickfeld et al. 2009; Manning and Reisinger 2011; Allen et al. 2017). The similarity between panels (a) and (c) shows that, to a good approximation, cumulative CO_2-fe emissions equal total anthropogenic warming multiplied by the Transient Climate Response to Emissions (TCRE) (Allen et al. 2009; Matthews et al. 2009; Gillett et al. 2013; Collins et al. 2013; Millar et al. 2016). Panel (d) shows annual CO_2-fe emissions, which are simply the time rate of change of (c). A CO_2-fe emission pathway will have approximately the same impact on GMST as a corresponding pure-CO_2 pathway (see Box 1.2 on metrics and balance).

The relationship between different forcing mechanisms and GMST response is further complicated by efficacy considerations (Myhre et al., 2013). The same global mean radiative forcing from different mechanisms (e.g., aerosol and CO_2 change) can have different transient and equilibrium GMST impacts of typically 20-30% (Shindell 2014; Rotstayn et al. 2015; Marvel et al. 2016). This makes the relationship between CO_2-fe emission pathways and GMST temperature somewhat dependent on the nature of the scenario, but this dependence can be minimised through the use of 'Effective Radiative Forcing' (Myhre et al. 2013).

1.2.3.1 Temperature stabilization pathways

The simplest 1.5°C-consistent pathway is one in which human-induced warming rises monotonically to stabilise at 1.5°C. Because of the inertia of the climate, carbon cycle and energy systems, the rate of human-induced warming varies slowly over decades, allowing only smooth temperature pathways if temperature goals are achieved through emission reductions alone (Huntingford et al. 2017). Stabilization also has been used to refer to stabilization of atmospheric greenhouse gas concentrations, which would result in continued warming (see Section 1.2.4). This report will focus on temperature rather than concentration stabilization pathways.

Stabilizing GMST requires net annual CO_2-fe emissions (Figure 1.3, panel d) to decline to near zero or slightly below (depending on the long-term adjustment of the carbon cycle), but does not imply stabilizing other aspects of climate. If other forcings are constant and positive, stable GMST implies gradually declining CO_2 concentrations (panel b, and Solomon et al. (2009)), so ocean pH levels would begin to recover. Sea level, represented in panel (e) by a very simple semi-empirical model (Kopp et al. 2016), would continue to rise, but at substantially lower rates than would be expected under a continued warming scenario. The requirement that CO_2-fe emissions must reach zero to stabilise temperatures also means that the abatement rate must increase (or emissions as a percentage of baseline "no-policy" scenario must decrease) as temperatures rise, to reach 100% reduction from baseline around the time of peak warming. Panel (f) shows how the level and rate of change in this quantity provides an indication of expected peak warming under a smooth mitigation scenario.

1.2.3.2 Temperature overshoot pathways

Under this category of pathway, temperatures rise above 1.5°C before peaking and declining, either to converge on 1.5°C from above or to fall below it. Substantial negative CO_2-fe emissions (corresponding to anthropogenic removals of CO_2) are required to draw temperatures down, so their feasibility and availability limit accessible rates of temperature decline. In this report, consistency with the Paris Agreement temperature goal is interpreted as implying temperatures peaking well below 2°C. Overshoot pathways are referred to in this report as 1.5°C-consistent, but qualified by the amount, duration and timing of the temperature overshoot, which can have a substantial impact on sea level rise (e) and many irreversible climate change impacts such as species extinctions.

1.2.3.3 Continued warming pathways

Under this category, 1.5°C is reached and temperatures then continue to warm. An important sub-category of continued warming pathways are pathways associated with baseline scenarios, in which no climate mitigation policies are assumed at all, or 'current policies' scenarios, in which existing climate mitigation policies and commitments are extrapolated into the future. Triangles in Figure 1.3 show that CO_2-fe concentrations (and hence CO_2 concentrations themselves) and sea level would be very different when temperatures reach 1.5°C on a continued warming pathway than when on a stabilisation pathway. Upward pointing triangles in panels a, b and e show years in which 1.5°C is reached from below, while downward pointing triangles indicate years it is reached from above following an overshoot.

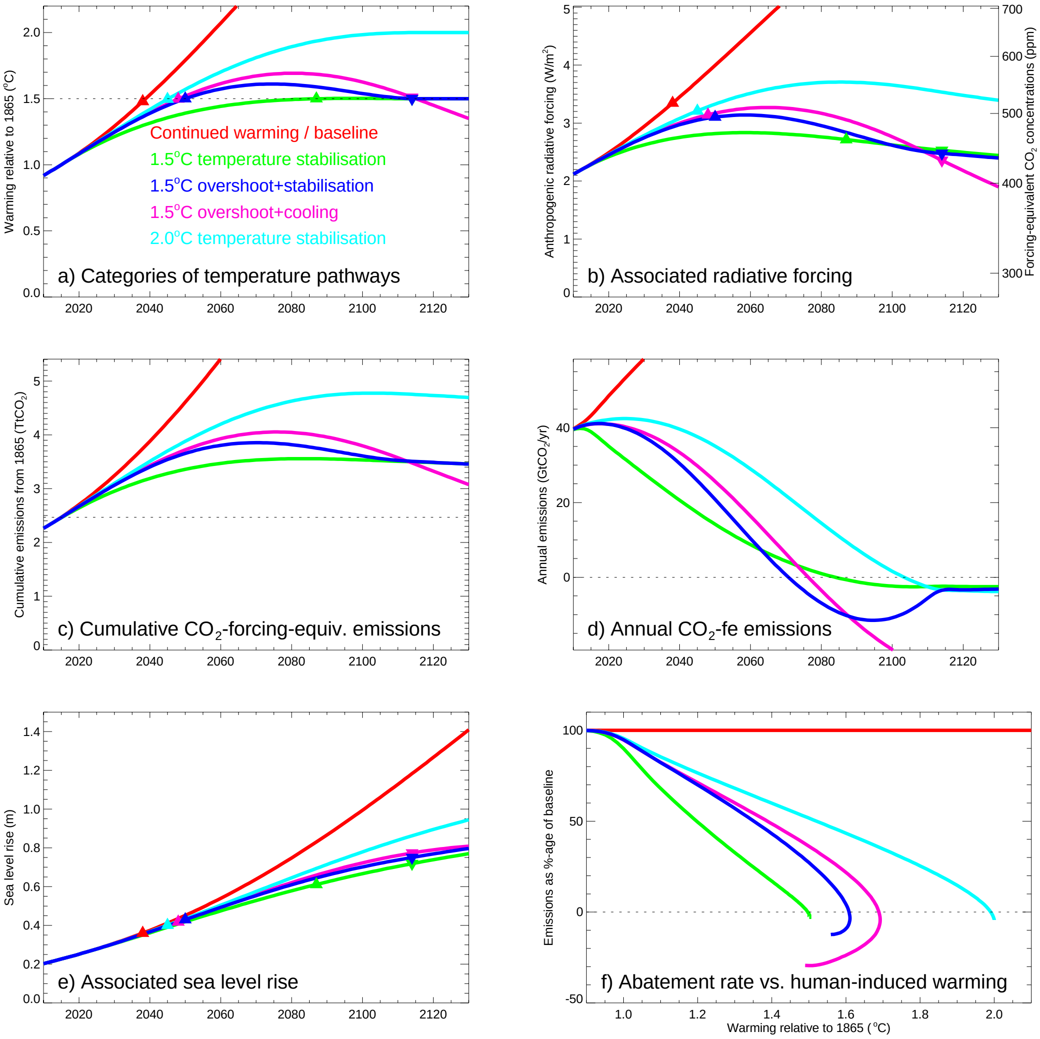


Figure 1.3: Schematic showing a) categories of temperature pathways; b) radiative forcing that would give the temperature responses in (a) with a simple climate model (Myhre et al. 2013; Millar et al. 2017) and a representative value (1.6°C) of the Transient Climate Response; c) cumulative CO_2-forcing-equivalent emissions that would give the radiative forcing in (b) with a simple carbon cycle model (Millar et al, 2017); (d) annual CO_2-fe emissions that would give the cumulative emissions in (c); (e) sea-level-rise in response to temperature pathways from a semi-empirical model (Kopp et al. 2016); (f) Abatement rate (Emissions as a percentage of baseline no-policy scenario (100 minus Abatement Rate) plotted as a function of warming, showing how the level and rate of decrease in this quantity provides an indication of expected peak warming under a smooth mitigation scenario.

1.2.3.4 Prospective versus adaptive mitigation pathways

A useful distinction can be drawn between ‘prospective’ mitigation pathways, in which emissions are prescribed to limit the prospect of temperatures exceeding a given threshold at a given level of probability given current uncertainties in the climate response, and ‘adaptive’ pathways, in which it is assumed that emissions are actively adjusted in future to meet the temperature goal in the light of the emerging climate response. They show that TCR uncertainty alone means that, in a prospective pathway corresponding to two thirds chance of temperatures remaining below 1.5°C, the most likely warming is around 1.2°C while there is still a non-negligible probability of temperatures exceeding 2°C (see Box 1.1 on scenarios and pathways and Section 2.2).

Box 1.1: Scenarios and Pathways

Authors: Mikiko Kainuma, Elmar Kriegler, Joeri Rogelj, Kristie L. Ebi, Sabine Fuss, Keywan Riahi, Rachel Warren

A **scenario** is a comprehensive, plausible, and integrated description of a possible future of the human-environment system, including a narrative with qualitative trends and quantitative projections (Nakićenović et al. 2000). Climate change scenarios provide a framework for developing and integrating emissions, climate change and climate impact projections, including an assessment of their inherent uncertainties. The long-term and multi-faceted nature of climate change requires them to describe how assumptions about inherently uncertain 21st century trends of key driving forces such as population, GDP, technological innovation, governance, and lifestyles influence future energy and land use, resulting emissions and climate change as well as human vulnerability and exposure to climate change. Such descriptions allow climate change scenarios to be used as frameworks for analysing and contrasting climate policy choices.

'Pathway' can have different meanings in the literature. It is often used to describe the temporal evolution of a set of scenario features, such as GHG emissions and socioeconomic development. As such, it can describe individual scenario components or the scenario itself. For example, the **Representative Concentration Pathways (RCPs)** describe greenhouse gas concentration trajectories (van Vuuren et al. 2011) and the **Shared Socio-Economic Pathways (SSPs)** a set of narratives of societal futures augmented by quantitative projections of socio-economic determinants such as population, GDP, and urbanization (O’Neill et al. 2014; Kriegler et al. 2012). Socio-economic driving forces consistent with any of the SSPs can be combined with a set of climate policy assumptions that together would lead to emissions and concentration outcomes consistent with the RCPs (Kriegler et al. 2014). This is at the core of the new scenario framework for climate change research that aims to classify scenarios according to their similarities in the SSP and RCP dimensions (Ebi et al. 2014; van Vuuren et al. 2014).

In other parts of the literature, 'Pathway' implies a solution orientation that is a scenario from today’s world to achieving a set of future goals. **Climate resilient development pathways** describe social and governance/policy dimensions that need to be met to ensure the climate mitigation pathways fulfil the equity and equality dimensions outlined in Agenda 2030 (United Nations 2015b). This includes considering the conditions needed so that poorer nations are enabled to design local solutions and afford externally produced technologies without developing new dependencies or high-risk pathways.

Climate change scenarios have been used in IPCC assessments since the First Assessment Report (Leggett et al. 1992). The **SRES scenarios** (named after the IPCC Special Report on Emissions Scenarios, (Nakićenović et al. 2000)) published in 2000 consists of four scenarios that do not take into any future measures to limit greenhouse gas (GHG) emissions, but many policy scenarios have been developed based on these scenarios (Morita et al. 2001). The SRES scenarios are superseded by a new set of **SSP-RCP based scenarios** (Riahi et al. 2017). The **Representative Concentration Pathways (RCPs)** constitute a set of four GHG concentration trajectories that jointly span a large range of plausible human-caused climate forcing ranging from 2.6 W m^2 (RCP2.6) to 8.5 W m^2 (RCP8.5) by the end of the 21st century (van Vuuren et al. 2011). They were used to develop new climate projections in the 5th Coupled Model Intercomparison Project (CMIP5, Taylor et al. (2012)) and have been assessed in the IPCC 5th Assessment Report. RCP2.6, which in the CMIP5 ensemble provides a better than two in three chance of staying below 2°C and a median warming 1.6°C relative to 1850-1879 in 2100, is often used as representative of a ‘well below 2°C’ pathway.

Recently, the RCPs were complemented by the **Shared Socio-economic Pathways (SSPs)**, which allow to structure the scenario set according to varying socio-economic challenges to adaptation and mitigation. Based on five narratives, the SSPs describe alternative socio-economic futures, comprising sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil-fuelled development (SSP5), and middle-of-the-road development (SSP2) (Riahi et al. 2017; O'Neill et al. 2017). Socioeconomic drivers, comprising population and education (KC and Lutz 2017), economic growth (Crespo Cuaresma 2017; Dellink et al. 2017; Leimbach et al. 2017), and urbanisation (Jiang and O'Neill 2017), are quantified for all SSPs (Riahi et al. 2017). Based on the narratives and the driver projections, SSP-based scenarios were developed for a baseline case without climate policy and mitigation cases aiming to reach, *inter alia*, the end of century forcing levels of the RCPs. These scenarios offer an integrated perspective on socio-economic, energy system (Bauer et al. 2017), land use (Popp et al. 2017), air pollution (Rao et al. 2017) and greenhouse gas emissions developments (Riahi et al. 2017). A subset of SSP-based baseline and mitigation scenarios will be used to drive the next round of climate change projections (CMIP6) to be assessed in the upcoming Sixth Assessment Report of the IPCC (O'Neill et al. 2016). Because of their harmonised assumptions, scenarios developed with the SSPs facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation.

This report focuses on scenarios that could limit the global mean surface air temperature increase to 1.5°C above preindustrial. Other scenarios are also addressed, including baseline scenarios that assume no climate policy; scenarios that assume some kind of continuation of current climate policy trends and plans, many of which are used to assess the implications of the NDCs; and (well below) 2°C scenarios. A distinction must be drawn between 'efficient' baseline scenarios, in which resources are deployed efficiently in the future without regard to their climate impact, and 'business-as-usual' scenarios in which current trends and policies are extrapolated. The distinction is important because mitigation scenarios typically assume efficient resource allocation subject to a climate constraint, so an efficient baseline is needed for a like-for-like comparison. These other scenarios are used to provide context for the mitigation and adaptation actions in a 1.5°C scenario. Even though this report focuses on global mitigation scenarios, regional, national and local scenarios are important to understand the challenges of achieving a 1.5°C target and are thus indispensable when assessing implementation.

Different climate policies result in different temperature pathways, which result in different climate impacts. Temperature pathways are classified into continued warming pathways (in the cases of baseline and reference scenarios), temperature stabilization and temperature overshoot pathways relative to the 1.5°C and 2°C temperature targets. In the case of overshoot, net negative CO_2 emissions are required to remove excess CO_2 from the atmosphere.

Emission scenarios can be classified as 'prospective' or 'adaptive'. Prospective scenarios are estimated by calculating the emissions consistent with a given prospect or probability, such as a 50:50 or two thirds chance, of staying below a temperature limit, given current knowledge of the climate system response. Adaptive scenarios foresee emission plans evolving to stay below the temperature limit as new information about the climate response emerges. The 1.5°C pathways assessed in Chapter 2 of this report are prospective. The differences between climate impacts at different warming levels assessed in Chapter 3 are better related to adaptive pathways. Unless otherwise qualified, the 'impacts of 1.5°C warming' refers to climate impacts in a world that has succeeded in holding warming to 1.5°C, whatever the response, not climate impacts in a world that has simply taken measures required, in the light of current knowledge of the climate response, to limit the prospect of temperatures exceeding 1.5°C to a particular probability. The latter would also include (and might indeed be dominated by) the impacts of other warming levels that might emerge in such a prospective scenario.

1.2.3.5 Impacts at 1.5°C associated with different pathways

Impacts that occur when GMST reaches 1.5°C under a continued warming or overshoot pathway may be very different from those on a 1.5°C temperature stabilization pathway, since surface temperatures are not in equilibrium with atmospheric composition. To illustrate this point, triangles in Figure 1.3, panels (b), (e) and (f) correspond to years in which temperatures reach 1.5°C in panel (a). In particular, CO_2 concentrations will be higher, and sea level and, potentially, mean precipitation (Pendergrass et al. 2015) both lower as temperatures warm past 1.5°C than they are as temperatures stabilise at 1.5°C, leading to very different impacts on agriculture, some forms of extreme weather, and marine and terrestrial ecosystems (James et al. 2017; Mitchell et al. 2016).

1.2.3.6 Cumulative budgets for CO_2 and CO_2-forcing-equivalent emissions

The AR5 noted that there is a simple, near-linear relationship between cumulative CO_2 emissions and CO_2-induced warming (Allen et al. 2009; Matthews et al. 2009; Zickfeld et al. 2009), characterised by the Transient Climate Response to Emissions, or TCRE. At that time, the notion of a cumulative carbon budget could not be extended to non-CO_2 agents because the majority of these are relatively short-lived climate forcers (SLCFs) and hence do not accumulate in the climate system. Shine et al. (2005), Lauder et al. (2013) and Allen et al. (2016), observe that an approximate equivalence can be drawn between cumulative emissions of CO_2 and changes in emission rates of SLCFs, allowing the construction of CO_2-forcing-equivalent (CO_2-fe) emissions (Wigley 1998; Zickfeld et al. 2009; Manning and Reisinger 2011; Allen et al. 2017), defined as the CO_2 emission pathway that results in the same radiative forcing as a multi-gas pathway, assuming efficacies are close to unity (see Section 1.2.3). Because the climate response to CO_2-fe emissions is, by construction, the same as the response to CO_2, the same near-linear relationship holds: total human-induced warming is equal to cumulative CO_2-fe emission multiplied by the TCRE.

This simple relationship helps frame the mitigation challenge. In an exponential temperature stabilization pathway, total future warming is given by the current rate of warming divided by the rate per year at which warming slows down (just as the stopping distance of a car is determined by the current speed divided by the deceleration rate). Human-induced warming is currently approximately 1°C (Otto et al. 2015) and increasing at 0.1-0.25°C per decade (Kirtman et al. 2013; Haustein et al. 2017 and Figure 1.1). To limit total warming to 1.5°C via an exponential stabilization pathway, this rate of warming must decrease by 2-5% yr^{-1} from now on, which would mean the annual rate of CO_2-fe emissions henceforth also being reduced by 2-5% yr^{-1}. The current level and rate of increase of human-induced warming are therefore critically important in determining how fast CO_2-fe emissions need to be reduced to avoid overshooting a temperature goal.

1.2.4 Definition of 'balance' and net zero emissions

Article 4 of the Paris Agreement acknowledges that, 'in order to achieve the long-term temperature goal (…) Parties aim to (…) achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'. This report will examine the scientific basis of what is meant by 'balance' in the context of 1.5°C and how 'balance' relates to the temperature goals articulated in Article 2 of the Agreement. A number of interpretations are possible, but in this report, 'balance' will generally be interpreted in terms of a sustained combination of emissions and removals that results in stable GMST (Fuglestvedt et al. 2017).

On multi-century timescales, natural processes that remove CO_2 permanently from the active carbon cycle are so slow that balance requires net global anthropogenic CO_2 emissions close to zero (Archer and Brovkin 2008; Matthews and Caldeira 2008; Solomon et al. 2009). Hence any remaining anthropogenic CO_2 emissions will need to be compensated for by an equal rate of anthropogenic carbon dioxide removal (CDR), using measures such as bioenergy with carbon capture and sequestration (BECCS), large-scale afforestation, biochar enhanced soil sequestration, direct air capture or ocean alkalinisation (Chapter 4, Section 4.3.6).

For greenhouse gases other than CO_2, 'balance' for temperature stabilization requires net zero total anthropogenic CO_2-fe emissions (by definition, CO_2-fe emissions affect temperatures like CO_2), but this need not imply zero anthropogenic emissions of individual gases or zero total CO_2-equivalent emissions if equivalence is defined using the conventional Global Warming Potential (see Box 1.2). Sustained constant emissions of a short-lived climate forcer (SLCF) such as methane could be consistent with gradually declining atmospheric concentrations (Shine et al. 2005; Rogelj et al. 2015a; Schleussner et al. 2016b) and no additional contribution to warming. Even though equivalent to a zero rate of CO_2-fe emissions, such a constant emission of an SLCF could still represent a mitigation opportunity, since reducing it would lead to cooling.

Changes in anthropogenic emissions of non-greenhouse gas SLCFs, such as sulphur dioxide, black carbon and non-methane ozone precursors also affect the ability to meet temperature goals. Although such emissions are not explicitly covered in Article 4 of the Paris Agreement, they contribute to total anthropogenic CO_2-fe emissions, so changes in all these can be included in the definition of balance.

Another interpretation of Article 4 might be that sources and sinks of greenhouse gases balance in such a way that the equivalent atmospheric CO_2 concentration is stabilised. This, however, implies continued warming (see Section 1.2.5) which is not consistent with a focus on temperature goals. Should temperatures exceed 1.5°C, returning global temperature to 1.5°C would require anthropogenic cooling of the climate system, or net negative CO_2-fe emissions through some combination of anthropogenic removals of long-lived greenhouse gases and falling anthropogenic emissions of SLCFs. Hence achieving 'balance' in the sense of net zero CO_2-fe emissions represents a necessary, but potentially not sufficient, condition for achieving the 1.5°C temperature goal, if net-negative CO_2-fe emissions are required to return temperatures to 1.5°C under an overshoot scenario.

Box 1.2: Long-lived and short-lived climate forcers, emission metrics and emissions ‘balance’

Authors: Piers Forster, Myles Allen, Elmar Kriegler, Joeri Rogelj, Seth Schultz, Drew Shindell, Kirsten Zickfeld

It is often useful to compare emissions of different anthropogenic forcers using simplified indicators, whether in terms of their effects on climate or their socioeconomic impacts (Clarke et al. 2014; Myhre et al. 2013). Metrics such as the Global Warming Potential are used in multi-gas policy frameworks such as the Kyoto Protocol and successive climate agreements, to compare emissions from different sectors and regions (Weyant et al. 2006) and as a measure of exchange within many integrated assessment models (Myhre et al. 2013; Reisinger et al. 2012; Smith et al. 2013b; Klein et al. 2014a). Metrics are also used to represent multi-gas pathways in terms of so-called ‘CO_2-equivalent’ emissions (Clarke et al. 2014). As no two emissions have the same broad range of effects, the choice of metric represents value judgements over what is equated and what time frames are considered. Unified frameworks of GHG metrics have linked metric choice to the intended use and the admissible level of uncertainty about metric values (Richard et al. 2012; Deuber et al. 2013).

Examples of physical impact metrics are the Global Warming Potential (GWP) and the Global Temperature Change Potential (GTP), and of socio-economic impact metrics the Global Cost Potential (GCP) and the Global Damage Potential (GDP). GWP is the ratio between the integrated radiative forcing due to a unit mass emission of a particular gas and the integrated radiative forcing of a unit mass emission of carbon dioxide over a given time period. The GTP compares the endpoint temperature change, the GCP employs a cost effectiveness framework and the GDP compares marginal climate-related damages from emission increases. To date, UNFCCC protocols have adopted GWPs over a 100 year time period to account for a basket of greenhouse gases based on either IPCC SAR or AR4 values. IPCC WG3 reports have used the same metric to evaluate CO_2-equivalent emissions. The GWP can be calculated to a higher degree of certainty than the other metrics but is somewhat removed from both the resultant climate impact of an emission and any policy interventions (Myhre et al. 2013). It is also increasingly misleading as an indicator of impact on GMST under ambitious mitigation scenarios (Allen et al. 2017). Metrics used in policy often lag behind the research-base. For example, the carbon cycle response for non-CO_2 gases was preliminarily included into GWP estimates in IPCC AR5 (Myhre et al. 2013), raising GWP values (which have since been updated in Gasser et al. 2017), but is not yet accounted for in policy.

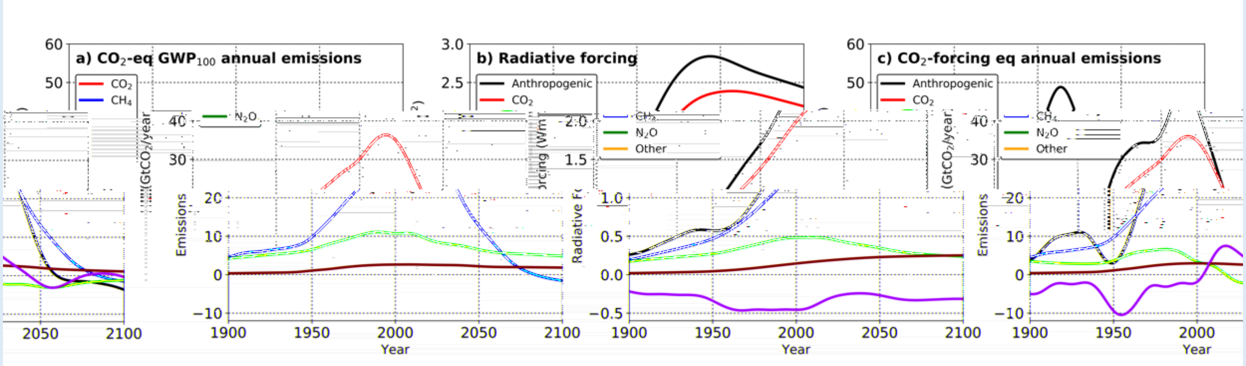
CO_2-forcing-equivalent (CO_2-fe) emissions (Wigley 1998; Manning and Reisinger 2011; Allen et al. 2017) are defined as the CO_2 emissions that give the same radiative forcing pathway that results from a non-CO_2 or multi-gas emission pathway. They are computed directly from radiative forcing using a carbon cycle model. While they are therefore subject to modelling uncertainty, CO_2-fe emissions do not depend on a choice of metric and indicate more directly how different emissions contribute to global mean surface temperature (GMST) change.

A clearly defined policy goal or implementation strategy narrows the range of suitable metrics. A temperature goal as articulated within Article 2 of the Paris Agreement would point to a temperature change metric, although other considerations such as limiting the climate damages up to the temperature goal or during a temporary overshoot of the goal remain relevant. GTP has the limitation of focusing on the temperature at a single point in the future, which may neither reflect the actual policy goal nor the success or failure of staying on track towards this goal. An alternative approach is to use a metric that approximates CO_2-fe emissions, which have (by construction) the same impact as CO_2 on radiative forcing and GMST over all timescales. Allen et al. (2016a) show how the GWP metric can be modified to achieve this approximately. They define a GWP* metric that equates a sustained one-tonne-per-year increase in the emission rate of a short-lived climate forcer (SLCF) with the emission (as a one-off pulse) of $GWP_H \times H$ tonnes of CO_2, where GWP_H is the value of that short-lived component's GWP for a time-horizon H. Both of these have a similar impact on GMST over a broad range of timescales.

It may be desirable to consider more than GMST in the definition of metrics. Even if GMST is stabilised, sea-level rise and associated impacts will continue (Sterner et al. 2014). Within the broader context of sustainable development articulated in the Paris Agreement, there are many possible alternative narratives of impacts. In particular, early action on short-lived climate forcers (including actions that may warm the climate such as reducing SO_2 emissions) may have considerable societal co-benefits such as reduced air pollution and improved public health with associated economic benefits (Shindell et al. 2016; OECD 2016). Valuation of broadly defined social costs is another emission metric that attempts to account for many of these additional non-climate factors along with climate-related impacts (Shindell 2015; Sarofim et al. 2017; Shindell et al. 2017). For any given sector and/or state it may also be more or less economically viable to target mitigation of particular gases over CO_2 mitigation measures. In addition, balanced contributions to global mean temperature change do not imply balanced contributions to many other impacts, such as ocean acidification or agricultural yields even for well-mixed greenhouse gases.

To achieve stable GMST, a combination of emissions that achieves sustained net zero CO_2-fe emissions is required. To a fair degree, this can be approximated by net zero emissions measured by GWP* (Allen et al. 2017). In a steady state, this means near-zero net emissions of long-lived greenhouse gases (CO_2 and gases with lifetimes of a century or more, such as nitrous oxide) and near-constant net emissions of SLCFs. Within the categories of long-lived gases and SLCFs there would still be scope for temporary trade-offs (Smith et al. 2012, and Daniel et al. 2012), but compensating for substantial continued net emissions of long-lived greenhouse gases with continually falling emissions of SLCFs would not be possible, since it is unfeasible to reduce the rate of emission of most SLCFs below zero (with the possible exception of methane – see Boucher and Folberth 2010). To achieve a peak and decline in GMST net CO_2-fe emissions have to become negative, and this also applies in approximation to GWP*.

Box 1.2, Figure 1 shows emissions of and radiative forcing due to CO_2, methane and nitrous oxide under the RCP2.6 mitigation scenario, contrasting CO_2-equivalent computed with AR5 GWP_{100} values (Myhre et al. 2013) with CO_2-fe emissions computed with a simple carbon cycle model (Millar et al. 2017). Note that falling methane emissions over the coming decades equate to negative CO_2-fe emissions, in that only active removal of CO_2 would have the same impact on radiative forcing and GMST as a reduction in methane emissions. Traditional metrics such as GWP_{100} are adequate for representing the GMST impact of long-lived gases but become increasingly unrepresentative of forcing and temperature impact of SLCFs under ambitious mitigation scenarios.



Box 1.2, Figure 1: (a) emissions of CO_2, methane and nitrous oxide under the RCP2.6 mitigation scenario expressed as CO_2-equivalent using GWP_{100}; (b) radiative forcing resulting from these emissions, plus other (primarily aerosols and ozone) and the total anthropogenic forcing; (c) CO_2-forcing-equivalent emissions, defined (Wigley 1998) as the CO_2 emissions that give the radiative forcing pathways shown in the central panel, derived using a simple climate-carbon-cycle model (Millar et al. 2017).

1.2.5 Definitions of warming commitment

The question of whether meeting the 1.5°C target is 'feasible' implicitly includes the notion of warming 'commitment', or unavoidable future warming. This commitment arises due to inertia in the physical Earth system, but also due to technological, economic, institutional and behavioural inertia.

Geophysical warming commitment is defined as the unavoidable future warming resulting from geophysical inertia. The most widely used variant of geophysical warming commitment is the 'constant composition commitment', which is the remaining warming if atmospheric composition and hence radiative forcing were stabilised at the current level (Collins et al. 2013). The former has often been used to illustrate inertia in the physical climate system, primarily associated with slow heat uptake by the ocean (the so-called warming 'in the pipeline' (Hansen et al. 2005)). This type of commitment includes the climate system response to past emissions, as well as the response to future emissions that are required to maintain a constant atmospheric composition, and is therefore ill suited to estimate a lower bound on future warming resulting from geophysical inertia alone.

Another variant of geophysical warming commitment is the 'zero emissions commitment', which defines the remaining warming if future anthropogenic emissions of greenhouse gases and aerosol precursors were eliminated (Collins et al. 2013). The zero emissions commitment, although based on highly idealised assumptions, has value as it allows one to clearly isolate the climate system response to past emissions from socio-economic assumptions about future emissions. The magnitude and sign of the zero emissions commitment depend on the mix of gases considered because of different lifetimes[1] and signs of radiative forcing. For CO_2, where the elevated atmospheric concentration change from an emission has a lifetime of decades to millennia (Eby et al. 2009), the commitment from past emissions ranges from slightly negative (i.e., a slight cooling after emissions cease) to zero (Gillett et al. 2011; Matthews and Zickfeld 2012; Lowe et al. 2009; Frölicher and Joos 2010), implying no future warming from past CO_2 emissions. This near-zero warming commitment for CO_2 arises from the near cancellation between declining radiative forcing in response to the elimination of CO_2 emissions (cooling effect) and the delayed temperature response to previously increasing radiative forcing from CO_2 (warming effect) (Solomon et al. 2009).

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[1] We here refer to the atmospheric lifetime of the atmospheric CO_2 perturbation, rather than the turnover time in the atmosphere.

For greenhouse gases with a short atmospheric lifetime (order of decades or less) such as methane (CH_4) the warming commitment is negative, implying cooling if future emissions of these gases are eliminated (Matthews and Zickfeld 2012; Frölicher and Joos 2010). This cooling arises from a rapid decline in radiative forcing, which dominates over the delayed warming response to previously increasing radiative forcing. Substances with a short atmospheric lifetime and negative radiative forcing such as sulphate aerosols have a positive warming commitment, as elimination of the radiative 'dimming' effect of these aerosols results in rapid warming over about a decade (Frölicher and Joos 2010; Matthews and Zickfeld 2012). Estimates of the warming commitment from eliminating sulphate aerosols is uncertain due to large uncertainties in radiative forcing (Myhre et al. 2013). Using a range of sulphate aerosol radiative forcings consistent with temperature observations, Matthews and Zickfeld (2012) estimate a total geophysical warming commitment from GHGs and sulphate aerosol emissions up to year 2010 of 0.3°C (0.25-0.5°C) over the decade immediately following elimination of emissions. This warming is followed by a cooling due to decline in radiative forcing of non-CO_2 GHGs, with the temperature response converging to that from elimination of CO_2 alone after about a century. The radiative forcing from sulphate aerosols has decreased over the last decade (Myhre et al. 2017) suggesting a lower warming commitment from elimination of sulphate aerosols than estimated in Matthews and Zickfeld (2012).

Geophysical warming commitment can be thought of as the minimum warming commitment, absent inertia in the socio-economic system, and absent active removal of CO_2 from the atmosphere by human activities. However, existing infrastructure, technologies, policies, institutions, and behavioural and social norms constrain the rate and magnitude of future GHG emission reductions. These constraints determine the GHG emissions reductions that are feasible in the near- and medium term and define the warming commitment resulting from socio-economic inertia (referred to as the 'feasible scenario commitment'; (Hare and Meinshausen 2006)).

Three main types of inertia in the socio and techno-economic system have been identified in the literature: infrastructural and technological, institutional, and behavioural (Seto et al. 2016). Infrastructural and technological inertia arises from the long lifetime and large investments associated with energy infrastructure. For instance, unless power plants will be retrofitted with carbon capture and sequestration (CCS) or operable infrastructure decommissioned early, existing infrastructure can be expected to contribute CO_2 emissions and warming for many decades. Davis et al. (2010) estimate 0.2-0.5°C future warming from existing GHG emitting energy infrastructure (as of 2009). Pfeiffer et al. (2016) gave a similar range from present infrastructure.

In contrast to infrastructure and technological inertia, 'institutional inertia is an intended feature of institutional design, not an unintended by-product of systemic forces' (Seto et al. 2016). Institutional inertia arises because 'powerful economic, social, and political actors seek to reinforce a status quo that favours their interests against impending change or to create and then stabilise a new, more favourable, status quo' (Seto et al. 2016). The transition to a low-carbon trajectory is also hampered by behavioural inertia. Two factors contribute to this inertia: psychological processes and social structure. Habits, aversion to take risks and the necessity of collective action to solve the climate change problem (giving the feeling to individuals that they have little control over the problem) can lock in carbon intensive behaviours (Seto et al. 2016). Also, individual behaviour is embedded in social norms and processes that change only slowly in response to changes in the technological and political environment (Seto et al. 2016). The emission pathways and unavoidable warming from such inertia has not yet been quantified.

One way of visualising this commitment is the notion of a 'stopping distance': under a smooth temperature stabilisation pathway, future warming is approximately equal to the current rate of human-induced warming divided by the average compound rate at which warming decreases from now on, or the rate of decrease of CO_2-forcing-equivalent emissions. If emissions decrease by at most 4% per year, for example, (a typical capital turnover time in the energy industry), then a current warming rate of 0.1-0.25°C per decade (Kirtman et al. 2013) implies a stopping distance (committed future warming) of at least 0.25-0.6°C, consistent with Davis et al. (2010) and Pfeiffer et al. (2016).

1.3 Multiple dimensions of impacts at 1.5° C and beyond

The impacts of climate change throughout the world are projected to be uneven and in some instances, very localised. Impacts are consequences not only of rising temperatures, sea level and ocean acidification, but also of shifting rainfall patterns and extreme events such as floods, droughts, and heat waves, all of which occur within the background of natural climate variability (IPCC 2012a, 2014c). Impacts of climate change occur across all continents and across the oceans, affecting many sectors including natural and managed ecosystems, urban and rural areas, economic services, human health, livelihoods and poverty, and human security (IPCC 2014a). Many impacts have been formally attributed to anthropogenic global warming and the increasing greenhouse gas concentrations due to human activities (Hansen et al. 2016; Rosenzweig et al., 2008), but other forcings play major roles, such as land use change (e.g., Pitman et al., 2011; Ward et al. 2014), atmospheric pollution (e.g., aerosols; Menon et al. 2002), and irrigation (Thiery et al. 2017).

The reference to '1.5°C above pre-industrial' is part of the Paris Agreement and thus a target defined in the context of UNFCCC COP21 negotiations; but what do we mean when we say 'impacts of 1.5 °C'? Differentiating the impacts of 1.5°C from those of 2°C does not imply a scientific statement of safe *vs.* unsafe conditions of environmental change. For a number of systems, the differential impacts of 1.5°C and 2°C have been found to reach the upper limit of current natural variability, for example for heat-related extremes in tropical regions (Schleussner et al. 2016a) or for ecosystem change in the Mediterranean Basin (Guiot and Cramer 2016). For this Special Report, we propose that 'impacts at 1.5°C' refers to *the impacts when the expected global average of near-surface air temperature is 1.5°C above the pre-industrial period (1850-1879) subject to similar natural forcing*. The same principle applies to impacts at 2°C, and by examining impacts at 1.5°C *vs.* 2°C, this report quantifies the avoided impacts by maintaining global temperature increase at or below 1.5°C. Chapter 3 presents an in-depth analysis of changes in impacts at 1.5°C *vs.* 2°C and higher levels of warming.

Observed impacts may be attributed formally to various climate drivers. While objective detection and attribution techniques are commonly used within the physical climate sciences to attribute the likelihood of particular events to anthropogenic warming (e.g., Hansen and Stone 2016), detection and attribution can also come from more subjective forms of knowledge, such as community knowledge of impacts. Although a region may not be classified as being impacted from a climatological perspective, local community knowledge of impacts (i.e., subjective knowledge) can be equally important (Brinkman et al. 2016; Kabir et al. 2016). That is, there are many drivers of 'impact experience'.

Impacts are multi-dimensional; hence, there is no universal, value-neutral metric of total or aggregate impact. While some dimensions of impacts are obvious (space, time, sector), others are less so (probability, equity), but all relevant to UNFCCC climate policy. This multi-dimensionality is particularly important because at these levels of warming, impacts may still be comparatively small or even positive when measured along certain dimensions (e.g., expansion of the growing season). The weight assigned to different dimensions could eventually affect the sign of the aggregate or total impact in a particular region or sector.

1.3.1 Physical Dimensions of Impacts

1.3.1.1 Spatial and temporal distribution of impacts

The spatial and temporal distributions of impacts are key considerations in understanding what 1.5°C impacts mean for people. Many regions are already 1.5°C warmer with respect to the pre-industrial period (Figure 1.2). Therefore, local/regional impacts of a global mean warming of 1.5°C can be higher (or, in fewer instances, lower) than 1.5°C. Consequently, the time of occurrence of 1.5°C above pre-industrial levels will vary widely for different regions, depending on different emissions pathways, with some regions, for example parts of Africa, warming faster than others (Niang et al. 2014; Déqué et al. 2016). Also, warming or rainfall changes may differ substantially for different seasons. At global warming of 1.5°C, some seasons will be substantially warmer than 1.5°C above pre-industrial (Seneviratne et al. 2016).

1.3.1.2 Implications of 1.5°C for extreme events and associated impacts

For most regions, any increase in global mean temperature implies substantial increases in the occurrence of some extreme events (Karmalkar and Bradley 2017; Fischer and Knutti 2015; King et al. 2017). Overall, a 1.5°C world as compared to a 2°C world will have very different impacts in terms of extreme events (see Chapter 3). In some regions, warming may also imply decreased occurrence of some extremes, such as cold extremes in high-latitude regions (Seneviratne et al. 2012). Understanding the impact of an additional 0.5°C warming on impacts associated with weather extremes demands an understanding not only of the distribution of the relevant extreme events in the present climate, but also of vulnerabilities and thresholds, and the extent to which human and natural systems may be impacted as certain classes of weather events become more or less frequent.

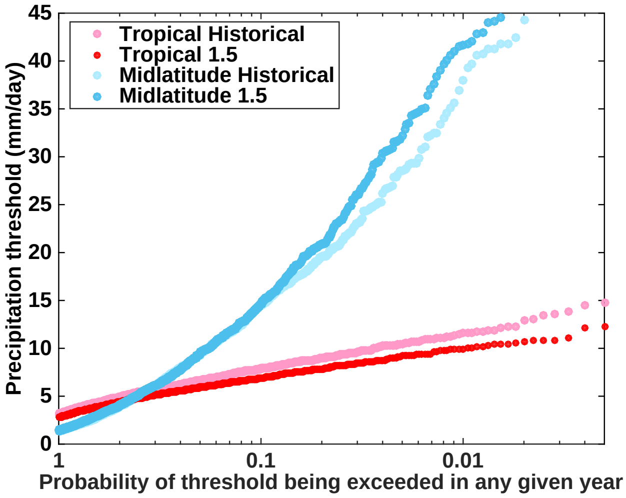

Figure 1.4: Illustration of the variety of impacts of 1.5 degrees of warming on weather extremes. Dots show the probability of daily rainfall exceeding a threshold in any given year in two South American locations, both for the decade 2005-2015 and for a representative decade in a 1.5°C world: it shows how the distribution of rainfall in the present climate, as well as the climate change signal, affects how risks may be expected to change. In the mid-latitude location (blue) the intensity of extreme daily rainfall events increases, by up to 5mm per day for the most intense events, but because this “return-time” graph is relatively steep (corresponding to a ‘fat-tailed’ distribution, with frequent extremes), this increase corresponds to a relatively modest (less than a factor of 2) increase in the risk of any particular threshold being exceeded. In the particular tropical location shown (red), the intensity of extreme precipitation events in this season actually falls by much less than 5mm per day, but because this return-time graph is shallow (a 'thin-tailed' distribution), these changes are associated with much larger changes (in this case reductions) in the probability of thresholds being exceeded.

Figure 1.4 shows the probability of daily rainfall exceeding a threshold in any given year in two South American locations, both for the decade 2005-2015 and for a representative decade in a 1.5°C world: it shows how the distribution of rainfall in the present climate, as well as the climate change signal, affects how risks may be expected to change. In the mid-latitude location (blue) the intensity of extreme daily rainfall events increases, by up to 5 mm per day for the most intense events, but because this ‘return-time’ graph is relatively steep (corresponding to a ‘fat-tailed’ distribution, with frequent extremes), this increase corresponds to a relatively modest (less than a factor of 2) increase in the risk of any particular threshold being exceeded. In this tropical location (red), the intensity of extreme precipitation events in this season actually falls by much less than 5 mm per day, but because this return-time graph is shallow (a ‘thin-tailed’ distribution), these changes are associated with much larger changes (in this case reductions) in the probability of thresholds being exceeded.

1.3.1.3 Non-temperature related impacts

Although the focus of this special report is on 1.5°C of global warming, it is important to note that many impacts do not depend on warming alone. Changes to the hydrological cycle affect rainfall and soil moisture availability and it is estimated that more than two billion people live in highly water stressed areas (Oki and Kanae 2006). Several impacts depend on atmospheric composition, for example, increasing atmospheric carbon dioxide levels leading to ocean acidification (Hoegh-Guldberg et al. 2007). It is also important to contrast impacts which are driven by long-term changes in ocean heat content, for example ice-sheet melt and sea-level rise (Bindoff et al. 2007; Chen et al. 2017), *versus* impacts which depend directly on air temperature, for example heat waves (Matthews et al. 2017; Meehl and Tebaldi, 2004). Impacts may also be triggered by combinations of these factors, including 'impact cascades', that is through secondary consequences of changed systems. Changes in agricultural water availability caused by upstream changes in glacier volume are a typical example. Recent studies also identify compound events, that is when impacts are induced by the combination of several climate events (AghaKouchak et al. 2014; Martius et al. 2016; Zscheischler and Seneviratne 2017).

1.3.1.4 Probability and uncertainty of impacts

Uncertainties in projections of future climate change come from a variety of different sources, including the assumptions made regarding future emission pathways (Moss et al. 2010), the inherent limitations and assumptions of the climate models used for the projections, downscaling methods (Ekström et al. 2015), and the uncertainties in the impact models (e.g., Asseng et al. (2013)). The trajectory of climate change also affects uncertainty with respect to impacts. For example, the impacts of overshooting 1.5°C and later stabilization, compared to stabilization at 1.5°C without overshoot may differ in magnitude as well as uncertainty as some ecosystems may not be able to recover after the overshoot (assessed in detail in Chapter 3). Changes in mean precipitation, for example, are found to be smaller as 1.5°C is passed on a continued-warming pathway than after equilibrium is reached (Pendergrass et al. 2015), so estimation of impacts of 1.5°C on the basis of extrapolation from recent observed impacts, or even from impacts when temperatures reach 1.5°C on a potential overshoot pathway, could yield an underestimation of actual expected impacts at 1.5°C temperature stabilisation (Schleussner et al. 2017)

1.3.2 Different dimensions of ecosystem impacts

Impacts of climate change on most ecosystems occur in addition to the variability caused by growth, phenology, population dynamics and other natural processes, rendering impacts at lower levels of warming more difficult to distinguish from natural variability. The same degree of warming can be lethal during some phase of the life of an organism and irrelevant during another. Many ecosystems (notably forests) undergo long-term successional processes characterised by varying levels of resilience to environmental change over time, including the possibility of abrupt changes, for example as a consequence of unusual drought events. Another specificity with ecosystem consequences of climate change are the important feedbacks which can occur, for example, in terms of changing water and carbon fluxes through impacted ecosystems – these can amplify or dampen atmospheric change. For example, of particular concern, is the response of the world's temperate forests ecosystems, which play key roles as carbon sinks (Luyssaert et al. 2008; Magnani et al. 2007; Pan et al. 2011).

1.3.2.1 Drivers of ecosystem impacts

Besides changes in temperature and (for land ecosystems) rainfall, most ecosystems are influenced by other variables. For example, ecosystem impacts are often driven or exacerbated by heavy weather events such as hurricanes/tropical cyclones (Gardner et al. 2005). As stated in Section 1.3.1.3, ocean acidification is driven by increasing atmospheric CO_2 concentrations (e.g., Hoegh-Guldberg et al., 2007), which then impacts marine ecosystems. In addition to these, human use or other human impacts play a major role which can even dominate over change in climate. Quantifying ecosystem impacts at 1.5°C, 2°C and beyond is therefore particularly challenging.

1.3.2.2 Cumulative impacts, permanence and irreversibility

Impacts can be cumulative (Halpern et al. 2008) and their total impact can be greater than the sum of its parts. For example, in an assessment of cumulative human impacts to the California current marine ecosystems, Halpern et al. (2009) found that climate change was the top threat among several other anthropogenic factors (e.g., nutrient inputs, coastal engineering impacts etc.). In the context of 1.5°C and 2°C worlds (see Box 3.12), these cumulative impacts need to be accounted for.

Another key consideration is the resilience of ecosystems that may decline at higher levels of warming. Ecosystem resilience is generally defined as the ability of ecosystems to resist, or recover after a disturbance, e.g., a heat wave. An example are reef ecosystems, with some studies suggesting that reefs will change, rather than disappear entirely, and particular species showing greater tolerance to coral bleaching than others (Pörtner et al. 2014). A key issue is therefore whether ecosystems such as coral reefs survive an overshoot scenario, and to what extent would they be able to recover after stabilization at 1.5°C or higher.

1.3.3 Human dimensions of impacts including vulnerability and adaptation

There is increasing evidence that climate change is having observable and often disastrous effects on human communities, especially where settlements coincide with climate-sensitive physical conditions and socio-economic/political constraints (IPCC 2014c; World Bank 2013; IPCC 2012a). The character and severity of impacts from climate extremes depend not only on the extremes themselves but also on exposure, vulnerability and adaptive capacity.

1.3.3.1 Sectoral impacts, human settlements, and adaptive capacity

The impact of 1.5°C warming will affect a range of infrastructure systems and the built environment, natural resources development and provisions capacities, as well as agricultural production systems. The impacts on human systems vary temporally and spatially under conditions of a 1.5°C warmer world. Some parts of the globe have already experienced over 1.5°C of regional warming. Given the vulnerability of some locations, these impacts could result in intergenerational consequences.

The magnitude and consequences of climate impacts vary across the range of human settlement types. Density and risk exposure, infrastructure vulnerability and resiliency, and governance capacity drive the differential impacts (Revi et al. 2014; Dasgupta et al. 2014; Rosenzweig et al. 2015). Adaptive capacity to a 1.5°C world will vary markedly for individual sectors and across sectors such as water supply, public health, infrastructure, ecosystems and food supply. Additionally, the adaptive capacity of human settlements, especially in highly populated urban regions poses several equity, social justice and sustainable development issues.

The IPCC (2013) and World Bank (2013) underscored the non-linearity of projected risks and impacts as temperature rises from 2°C to 4°C of warming, in particular in relation to water availability, heat extremes or the bleaching of coral reefs. More recent studies and analysis (James et al. 2017; Schleussner et al. 2016a) deal with the responses and effects of a 1.5°C and 2°C warming, with the same message of non-linearity of effects, although some changes are found to be mostly linear such as changes in the temperature of hot extremes (Seneviratne et al. 2016) (assessed in Chapter 3). For some extremes, non-linearity may ensue from the framing of the investigated question, for instance when using threshold-based indices to define extreme events (Whan et al. 2015).

1.3.3.2 Poverty, equity, justice and sustainable development

Climate change disproportionately affects the most vulnerable segments of society, in both urban and rural areas (Rosenzweig et al., 2015;IPCC, 2014b; World Bank, 2013)). These populations, communities, and institutions often lack adaptive capacity to increased climate risk and new or emerging risks. Climate change is projected to slow down economic growth and make poverty reduction more difficult for a warming of 2°C, a substantial threat to the sustainable development of most of the vulnerable countries. As a corollary, these adverse projected climate impacts 'could still be avoided by holding warming below 2°C' (World Bank 2013). Furthermore, differences in vulnerability and exposure to climate change arise from non-climatic factors and from multi-dimensional inequalities, which are often produced by uneven development processes, leading to differential risks from climate change (Olsson, L. et al. 2014).

1.4 1.5°C in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, with consideration for ethics and equity

The connection between 1.5°C warming and ambitions of sustainable development are complex and multifaceted. Mitigation-adaptation linkages, synergies and trade-offs and the different dimensions of feasibility are important linking elements to sustainable development. The IPCC AR5 acknowledged that 'adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses' (Denton et al. 2014). This report assesses where the key trade-offs and opportunities for synergy are present. Climate mitigation and adaptation measures and actions can be put into place by identifying specific patterns of development and governance that may differ amongst all world regions. This section details the various implementation options, enabling conditions, capacities and types of knowledge that can allow institutions, communities and societies at large to respond to the 1.5°C challenge in the context of sustainable development. Justice, equity and ethics are recognised as issues of paramount importance in reducing vulnerability and eradicating poverty.

Meeting the goal of limiting global temperature rise to 1.5°C is a challenging task, which will be constrained by several dimensions of feasibility. The report defines the feasibility as the systems-level capacity to achieve a specific goal or target (for more discussion see Box 1.3 on feasibility[2]). From an energy balance perspective, certain temperature targets are 'physically feasible', depending on the concentrations of CO_2 and other radiatively important aerosols and gases (IPCC 2013a). In addition, more aggressive pathways will require new technology that may or may not be 'technically feasible' (IPCC 2014c; Rogelj et al. 2015). For policy makers, the 'economic feasibility' is also important, and because of environmental damages from some proposals, some pathways may not be socially acceptable (Smith et al. 2016). A need also exists for a governance structure which allows for appropriate 'institutional feasibility' for any policy to reach a particular temperature target (Schloss 2016; Planton 2013).

1.4.1 Justice, equity and ethics

The 1.5°C target raises ethical concerns that have been central to the climate debate from the outset, most recently articulated in the language of human rights (Adger et al. 2014; Humphreys 2010; Knox 2015). For example, how will an average global temperature rise of 1.5°C impact upon the human rights of specific persons: their rights to water, shelter, food, health and life, the rights of migrants, of refugees, of indigenous

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[2] The term, as used in this report, does not directly incorporate concepts of nested uncertainty across its multiple dimensions. Instead, the term is used to refer to assessments of the possibility of a particular outcome given a set of other assumptions.

persons, of women and children? Poverty, inequity, and injustice, which are intrinsically linked to climate change, are incompatible with sustainable development (O' Brien et al. 2012). As indicated by Stern 2014, climate change is a problem of risk management on an immense scale and the consequences of business-as-usual could significantly threaten human security in a variety of ways including the displacement of hundreds of millions of people that may lead to severe and prolonged conflict (Ionesco et al. 2016). Risks on this scale raise deep questions about ethical perspectives relating to the distribution of impacts associated with climate change and responsibilities for its cause, and preferentially impact on the poor and disenfranchised (Reckien et al. 2017). Focusing on the rights and responsibilities of people as the core policy question may help to clarify the root causes of climate risks, their distribution and management across a range of social groups and geographies[3].

Questions of justice and fairness are central to climate change debates and response efforts across geographies and generations. Mention of human rights by the Paris Agreement is a major step to addressing these questions (Savaresi 2016). Most fundamentally, how can the action to achieve 1.5°C targets be consistent with protection of human rights? Three key points of connection between climate change and justice that need to be attended in the quest for a 1.5°C target have been noted (Okereke 2010; Harlan et al. 2015; Ajibade 2016; Savaresi 2016; Reckien et al. 2017). The first is the asymmetry in contributions to the problem. The second is the huge asymmetry in impact - a problem that is exacerbated because the worst impact tends to fall on those that are least responsible for the problem. Conditions of climate dislocation are an acute example of this inequity and forced migration (Ionesco et al. 2016). Intergenerational equity issues also need to be considered here. The third point of connection in the climate-justice nexus is asymmetry in power to decide solutions and response strategies. This relates to the possibility by the more powerful actors and stakeholders to have greater influence on setting the agenda to their advantage. Hence a justice framing offers a useful organizing framework for understanding the asymmetry between the distributions of benefits and costs in relation to climate change (Aaheim et al. 2016; Schleussner et al. 2016a). In addition, existing multi-level inequalities including in the form of technology, finance, human capital and governance constrain approaches to address the 1.5°C challenge despite INDCs where each country pledges what is possible in its capacity. Concerns around justice are central to the debates about mitigation, adaptation and climate governance as they open up opportunities to discuss who cuts emissions, who pays for the pollution, whose knowledge counts and who has the capability to respond to the problem and benefit most (Schroeder et al. 2012; Ajibade 2016; Reckien et al. 2017). For example, without sustained technology transfer, rapid decarbonisation can be expected to slow or stall growth and exacerbate poverty, especially in less wealthy countries (Humphreys 2017).

Justice considerations need to be an integral part of efforts to mitigate and adapt to a 1.5°C warming, at the global as well as sub-national levels (Shue 2014). Equity and fairness are important elements of the justice framing in climate change research, and relate to both procedural justice (i.e., participation in decision making) and distributive justice (i.e., how costs and benefits of climate actions are distributed) (Savaresi 2016; Reckien et al. 2017). This framing recognises that climate change presents significant threats to future wellbeing in that future generations are likely to be vulnerable to climate impacts and are least represented in current decisions that shape future outcomes. Klinsky and Winkler (2014) draws on Sen and Nussbaum's capabilities approach to argue that differentiated responsibility alone is not sufficient to address the 'trio' of climate equity challenges: unequal climate impacts, development status, and responsibility. They suggest 'operationalizing' equity by including a notion of capabilities in addressing domestic climate policies in the context of carbon constraints and climate impacts.

Ethical consideration also can be extended to the natural world, although different interpretations exist. For example within Environmental ethics. there are those who emphasise nature, argue that ecosystems have a right to exist in their natural state (Attfield 2014). Intergenerational equity argues that we should leave the natural state as much as possible for future generations. However, there other approaches that are linked to social-ecological system view, for instance, the implications of climate change on natural resources with

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[3] Human rights include the right to development, equitable benefits and burdens, participatory, transparent and accountable decisions on climate change, gender equity, and education rights.

respect to indigenous people. Overall, the impacts of climate change onto humans and ecosystems are not equally distributed, because some humans or ecosystems may be more vulnerable to climate change (Agard and Schipper 2014; Savaresi 2016).

1.4.2 Governance

A significant challenge in meeting the 1.5°C target is focused on the governance capacity of institutions to develop, implement and evaluate the needed changes within diverse and highly interlinked global social-ecological systems (Busby 2016). Governance capacity includes the wide range of activities and efforts needed to develop coordinated climate mitigation and adaptation strategies in the context of sustainable development taking into account equity, justice and poverty eradication. Significant governance challenges include ability to incorporate multiple stakeholder perspectives in the decision-making process to reach meaningful and equitable decisions, scalar interaction and coordination between the different levels of government, and the capacity to raise financing, and support for technological and human resource development for such actions.

A systematic review of the literature (Kivimaa et al. 2017) suggests that major policy transformations to low carbon transitions require policy experimentation as an explicit approach to governance. Extensive trials and smaller experiments, strengthen policy and capacity, and help overcome barriers and complex, multidimensional climate challenges. As a result adaptive and flexible governance systems will be key to transitioning to a 1.5°C global warming and reducing further temperature increase.

To date, it is not certain that the voluntary mechanisms of the Paris Agreement will be sufficient to achieve the ambitions of the Paris Agreement (Falkner 2016; Lövbrand et al. 2017). The Agreement’s compliance mechanism is ‘expert based' and 'facilitative in nature’ rather than mandatory (Article 15 (2) cited in (Falkner 2016)). Other international frameworks including the Sendai Framework of Disaster Risk Reduction (UNISDR 2015) provide an opportunity for advancing climate adaptation and resilience since it is assumed that through risk reduction, climate change adaptation can be enhanced (Mysiak et al. 2016).

Policy arenas, governance structures and robust institutions are key enabling conditions for transformative climate action in achieving the global response to 1.5°C warming. A range of high and some middle income cities provide examples of how government and community response can simultaneously make meaningful contribution to adaptation and mitigation goals. Conversely, the risk of climate change will escalate in countries with severe governance failure (IPCC 2012a; Oppenheimer et al. 2014; Revi et al. 2014) and climate change threat may also weaken governance, for example triggering conflict or migration and deepening vulnerability (Voski 2016).

Adaptation incorporates changes on modes of governance (Klein et al. 2014b). It is through governance that justice, ethics and equity within the adaptation-mitigation-sustainable development nexus can be addressed (Stechow et al. 2016). This can be illustrated in cities where different management solutions can have implications for equity as is the case of the privatization of water supply and sanitation services (Revi et al. 2014). Governance is critical to the response to 1.5°C warming given the diversity of organizations and actors at national and global level that have a role in the climate change challenge (Busby 2016). Governance capacity plays a critical role in a range of key contexts including the realization of the Nationally Determined Contributions (NDCs), small island states, highly vulnerable sites, low carbon and zero carbon cities.

1.4.3 Transformation, Transformation Pathways, and Transition

Embedded in the 1.5°C goal is the opportunity for intentional societal transformation. The pace and process of transformation is varied and multifaceted. Fundamental elements of 1.5°C -related transformation will include a decoupling of economic growth from carbon emissions, leap frogging development to new and emerging low and zero carbon technologies, and synergistically linking climate action to global scale trends that will further enhance the prospects for meaningful climate action. The rate of change within systems or its resilience can occur gradually or be punctuated by rapid change, particularly when linked with disruptive technological innovation. Incremental change can set in motion larger scale transformations in systems. Incremental transformation is key when designing, planning, and improving implementation options at local level (e.g., in urban areas, see Box 4.14 on Cities).

System-level analyses of adaptation (Solecki et al. 2017) and mitigation transition pathways highlight the importance of root, contextual, and proximate drivers that when acting together promotes increased opportunity for societal transformation. The connection between transformative climate action and sustainable development illustrates a complex coupling of systems that have important spatial and time scale lag effects and implications for process and procedural equity. Early warning signals of system change including system instability, increased fluctuation, and slowing response rates provide important sign posts for potential transition pathways and of use by decision makers and policy makers to advance climate adaptation and mitigation agendas. Extreme events are associated with windows of transformational change. Historical analogues provide insights into the process of societal transformation coming in response to external and internal system dynamics (IPCC 2012a).

Box 1.3: Feasibility and limiting global temperature increases to 1.5°C

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A central question coming from the Paris Climate Agreement is how achievable or feasible is it to keep warming well below 2°C and pursue efforts to limit it to 1.5°C (Schellnhuber et al. 2016; Schleussner et al. 2016a). This cross-chapter Box assessed the notion of feasibility specifically in the context of limiting temperature increase to 1.5°C above pre-industrial levels. The aim here is to disentangle what is behind this rather abstract idea and to move it toward a more tangible, policy-relevant understanding, and thereby further revealing enabling conditions of making the transition to a 1.5°C world. The Box does not directly address what is feasible and whether limiting warming 1.5°C is possible, generally (or with no overshoot or overshoot, specifically); but, instead focuses on how feasibility could be considered and put in practice.

Three dimensions of feasibility

This approach of the ‘feasibility’ question starts from a given condition - in this case the requirements of 1.5°C world - and aims to reveal the policy implications and enabling conditions of different trajectories compatible with this objective, building on back casting techniques, as theorised in (Robinson 1982). This seminal paper points notably to the need to analyse not only the technical transformation in the system, but also ‘the social, environmental, economic, political, and technological implications of the scenarios’.

A large literature exists on technical feasibility studies of ambitious climate targets, and is primarily based on engineering and economic knowledge with a focus on quantifiable technical, economic and environmental implications (IPCC 2013b, 2014c). A complete vision of the feasibility question requires integration of natural system considerations into the human system scenarios (Robinson 1990) and the placement of technical transformations into their political, social, and institutional context (Nilsson et al. 2011; Schubert et al. 2015; Andrews-Speed 2016). This notably requires a closer synthesis of different perspectives on the ‘feasibility’ question to reflect the societal and governance transitions implied by different visions of low-emission futures (Söderholm et al. 2011). Combining different methods and approaches, like quantitative modelling and more qualitative storylines, is key to build robust and integrated visions useful for stakeholders and practitioners and to inform climate transition pathways governance (Fortes et al. 2015; Turnheim et al. 2015). This integrated approach to ‘feasibility’ is essential to inform on the potential synergies and conflicts between different policy objectives (e.g., investments in near term emissions reduction *vs.* long term emissions reduction) (Hildingsson and Johansson 2016).

To reflect on these different aspects characterizing the pathways to a 1.5°C world, we decompose the feasibility discussion into three dimensions: 1) geophysical and environmental dimensions, which questions the capacities of physical systems (including response to negative implications) to meet the requirements of achieving the condition of 1.5°C; 2) technological and economic dimensions, which investigates the nature of the enabling conditions in technical and economic systems; and 3) social and institutional dimensions, which captures the evolutions in the social and institutional context that are required to create the space for the deep socio-technical changes implied by these scenarios.

Aim of feasibility framing

The assessment of feasibility is not a matter of answering by 'yes' or 'no' regarding the feasibility of limiting warming to 1.5°C; it is rather a frame to organise the different types of enabling conditions for transformations compatible with a 1.5°C world. The above three dimensions of feasibility speak to different disciplines - physical sciences, engineering/economists perspectives, and social sciences - each having their specific approaches to the question and considering different types of base assumptions and requirements corresponding to their entry point into the feasibility discussion.

The purpose of distinguishing these three feasibility dimensions is multiple. Key is to acknowledge a comprehensive set of enabling conditions to limiting temperature increase to 1.5°C above pre-industrial levels, and to understand how different feasibility dimensions are related. These will help clarify the communication of opportunities and challenges associated with the feasibility in each community of interest. One's entry point to the question of feasibility and the conditions in which one is interested will influence who they engage with the concept of feasibility and the associated operational indicators. Another objective is to try to bridge the gap in understanding between different communities, by streamlining the discussion of feasibility along the organizing principle of the three distinct categories. In this way, 'feasible' pathways, including options and limitations, can be articulated and recognised in terms that can be easily understood by a broad spectrum of relevant communities including the policy stakeholders, practitioners, and private sector decision-makers, and serve as a guide for them in what to do to secure feasibility. It will be important to define indicators and metrics of the feasibility dimensions that are transferable as much as possible to within specific communities and across communities including national and sub-national government officials, NGO members, and the private sector.

Process of feasibility framing

Each feasibility dimension and their associated enabling conditions have embedded within system level functions that could include linear and non-linear connections and feedbacks. It is through these systems level mechanisms that conditions of feasibility can be more fully understood. For example, more rapid deployment of technology and larger installations (e.g., new large scale energy mega-projects) implies increased costs and reductions in social acceptability and hence a potential reduction in feasibility. Case studies can demonstrate system level interactions between the feasibility dimensions and conditions for positive or negative feedback effects. System level interactions amongst feasibility of mitigation, climate adaptation, and sustainable development and the sustainable development goals will be especially important to consider. Data quality and scenario and pathway projections are another important elements associated with the application of the feasibility concept. For example, statements of uncertainty, likelihood and risk will influence how feasibility measures and their multiple interactions are defined and interpreted by user communities.

The conditions of feasibility also are highly dynamic and varied across temporal and spatial contexts, especially under potential conditions of overshoot or no overshoot. Guidance on feasibility should elucidate the distinction between the near-term (i.e., within the next several years to decade or two) and long-term (i.e., over the next several decades) dimensions of feasibility. For instance, actions taken to promote a near-term trajectory of emissions reduction consistent with pursuing 1.5°C could negatively impact the opportunity for longer-term feasibility. Some dimensions might be more time sensitive than others (i.e., if conditions are such that it is no longer geophysical feasible to achieve a particular interpretation of a 1.5°C world, social and institutional feasibility will be no longer relevant). This cascading effect will be important for understanding the comparative importance of different metrics or indicators of feasibility.

Feasibility is spatially variable and scale dependent, which has implications for its validity at the global-scale. What could be considered feasible in some regions of the world might be not feasible in others. The spatial variation of feasibility for example will be dependent on regional scale environmental resource limits, social organization and conditions of urbanization, and financial and institutional capacities among other factors. Regional feasibility is not necessarily additive to the global scale and vice versa. System boundaries are especially important here as certain technologies, for instance, may be feasible in one region, but not on a global scale. In Europe, it may be possible that bio-energy with carbon capture and storage (BECCS) technology could be deployed quickly but there is limited biomass available regionally thereby limiting the feasibility of the approach in this regional context. It should be noted that some integrated assessment models (IAMs) do not account for this type of BECCS life cycle assessment footprint and as a result do not translate full system emissions projections. Many other spatial differences that influence regional understanding of feasibility such as economic wealth, institutional and governance capacity and culture are also present and need to be recognised.

The feasibility discussion in this report

The feasibility discussion is one of the organizing principles for this 1.5°C report. The three basic dimensions of feasibility are presented in Box 1.3, Table 1 below. Different dimensions of feasibility are considered in the different chapters, which provide a deeper analysis into specific conditions associated to these specific dimensions. Chapter 2 focuses largely on geophysical and technological feasibility, Chapter 3 on environmental feasibility, Chapter 4 on technological, economic, social and institutional feasibility, Chapter 5 on social and institutional feasibility.

For each dimension in Box 1.3, Table 1, several characteristics and relevant metrics and indicators are listed corresponding to existing measures of geophysical and environmental limits, amount of technology required, investments and institutional arrangements needed, and enhancement of social and economic conditions, among other variables. Each dimension can be distilled down to several characteristics each with a lengthy list of potential empirical measures (e.g., indicators and metrics). The empirical measures provided are but a sample of variables that could be considered. The list includes many variables for which attribute data already are being collected or could be easily collected in the future.

Dimensions	Characteristics	Empirical Measures
Geophysical and Environmental	Geophysical	- Proportion of the change required; warming commitment - Rate of land use change - Is there enough geological storage capacity? - Physical feasible - C geological storage capacity (Is there opportunity in for geophysical capture?)
	Environmental - Ecological	- Capacity of ecological systems - Limits of mitigation/adaptation in ecosystems -Risks of responsive options - Tipping points - reversibility of ecosystems - Are future emissions compatible with 1.5 degrees? At what probability? - Risks associated to irreversible changes
Technological and Economic	Technological	- Has the technology been deployed? - How quickly different types of technologies can be implemented? - Are there technical resources available? - Historical analogues for curves of deployment/implementation - How long does it take to bring immature technologies to large-scale deployment? - What are the needed investment on R&D?
	Economic	- Required investment flows and costs of response options - Transition costs through time and regional dimensions - Availability of financing resources and financial mechanisms to enable transitions - International and national flows/governmental and private flows - *Mal-mitigation* and maladaptation; risks; Unforeseen impacts including stranded assets - Differential effects of competitiveness - Benefits/tradeoffs -e.g.: economic development, GDP, poverty alleviation, employment impacts - Alternative growth models/SSPs
Social and Institutional	Social/cultural	- Social capacity and adaptive capacity - Public acceptability and social disruptiveness - Behavioural responses (communities and private sector) - Equity/social inclusion/distributional impacts - Cultural specificities - Human rights including Inter-generational - Speed of social practices and changes - Regional dimensions - sub-national, national, regional - Health benefits and risks
	Institutional	- Political economy and transparency - Political support - Market structures, market failure and missing markets - Rate of institutional change - Administrative traditions and institutional capacity - Civil society engagement - Interaction between multi-levels of governance

Box 1.3, Table 1: Dimensions of feasibility

1.4.4 Trade-offs and synergies of adaptation, mitigation and sustainable development

Multiple climate responses including mitigation and adaptation often occur simultaneously, each with varying affects (Figure 1.5) and different pathways that would limit warming to 1.5°C (Kainuma et al. 2017) *versus* 2°C. For example, subsistence farmers are more sensitive to precipitation changes than farmers in regions with advanced irrigation techniques. Yet, the ability to adapt to climate change, or adaptive capacity of these advanced irrigation techniques can build resilience to weather or other hazards but also require greater carbon emissions (Agard and Schipper 2014). From the mitigation side, it is important to reduce emissions of CO_2 and other greenhouse gases (IPCC 2014a). Even if low CO_2 trajectories are achieved, impacts of climate change on humans and ecosystems will require adaptation (IPCC 2014c). Extreme measures could be undertaken to avoid climate change. These include carbon dioxide removal (CDR), whereby CO_2 is actively removed and stored (Rockström et al. 2016), or solar radiation management (SRM, see Section 1.4.5), where deliberate changes to the earth's albedo are undertaken (IPCC 2012b) (see Box 4.13). None-the-less, mechanisms exist to respond to climate change that will enhance both mitigation and adaptation and, with appropriate governance, also provide for social justice, equity and ethics (Stechow et al. 2016) (Figure 1.5). Solar radiation management strategies which press against socially acceptable and physical limits, provide a clear example of the constraints and capacities of governance with respect to decision-making equity, and integrating levels of uncertainty into the decision-making process.

Urban areas exemplify how synergies between mitigation and adaptation can be enhanced. There is value in examining the two together since urban areas are balancing between adaptation and mitigation and have to negotiate trade-offs at different scales. 'Based on the content analysis of urban studies, it appears that drivers of conflicts can be understood through the consideration of multiple scales and cross-scale interactions (cf. Cash et al. 2006) on which adaptation and mitigation policies are being implemented and practical actions taken' (Landauer et al. 2015).

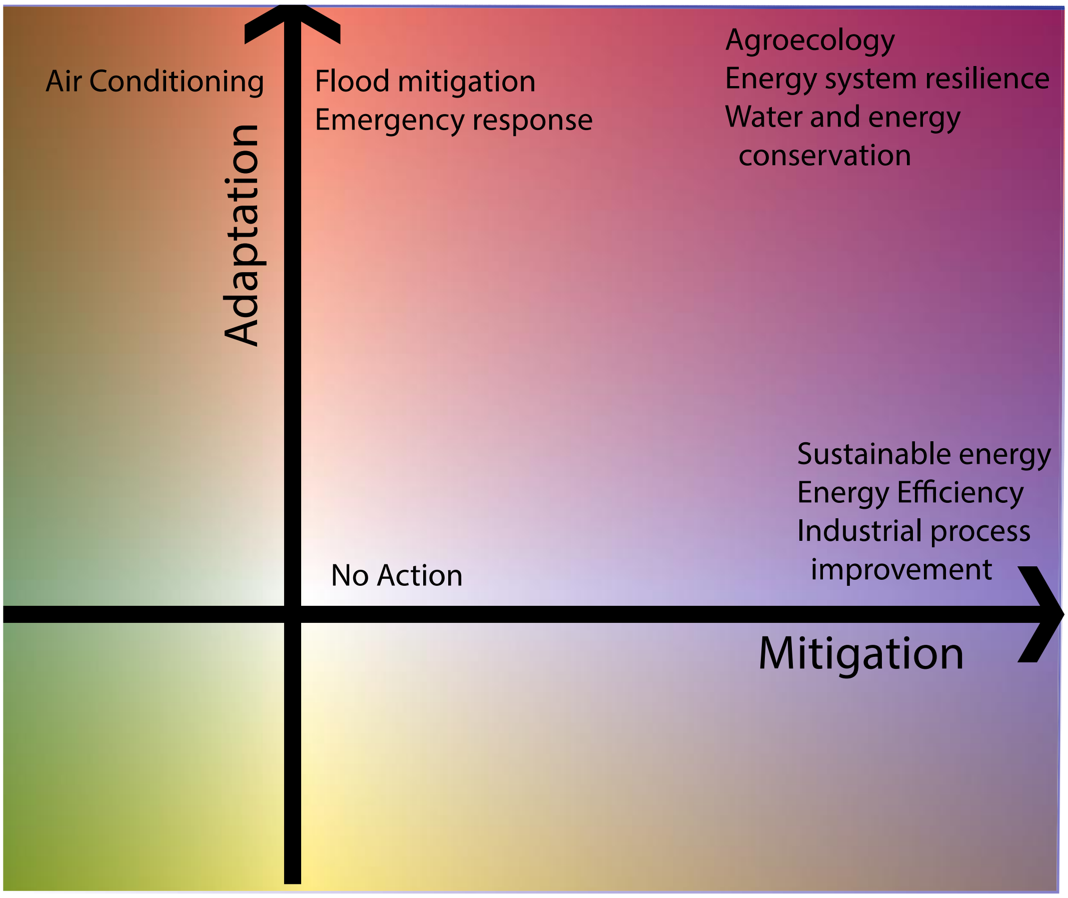

Figure 1.5: Schematic of some adaptation and mitigation options, showing examples of those that serve both to help adaptation (red) and mitigation (blue), as well as those that may only help one or the other (yellow/orange). Hamin and Gurran (2009), quoted in (Landauer et al. 2015)) provide an example: if adaptation can reduce the cost of mitigation or vice versa, or a situation where an adaptation strategy supports the mitigation strategy at the local level. In the upper right zone adaptation-mitigation synergies can be established. For instance, water and energy conservation systems can bring benefits for both. Conserving forest ecosystems in the peri-urban areas of the city can capture CO_2 and rainfall preventing potential floods and landslides within the city. Other measures and actions can only address either adaptation or mitigation goals (upper left and lower right).

In September 2015, the international community endorsed a universal agenda entitled "Transforming our World: the 2030 Agenda for Sustainable Development", widely known as the Sustainable Development Goals (SDGs[4]) which provide a framework for addressing the 1.5°C target. The SDGs include specific goals for climate action (Goal 13), access to affordable and clean energy (Goal 7), sustainable consumption and cities (Goals 11 and 12), and equality/equity goals for gender education, income, work, and access to justice (Goal 5 and transcending several other goals). In addition Denton et al. 2014 noted that climate change constituted "a moderate threat to current sustainable development and a severe threat to future sustainable

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[4] The 17 goals and 169 targets to be met by 2030 were developed with widespread participation and were adopted in 2012 under the rubric of goals for people, prosperity, peace, partnerships and the planet. The preamble to the SDGs announces 'to take the bold and transformative steps which are urgently needed to shift the world onto a sustainable and resilient path'. With their explicit aim to 'leave no one behind', the SDGs provide a promising basis for addressing inclusive growth, shared prosperity, and multidimensional inequalities (UNRISD 2016). They are seen as an 'indivisible' package of goals that need to be pursued in an integrated way (Coopman et al. 2016); yet, the policy challenges to realise this integration are enormous.

development" (*high confidence*) and that "ill-designed responses" could "offset already achieved gains" (Denton et al. 2014).

The Sendai Framework for Disaster Reduction 2015-2030 (UNISDR 2015) focuses on building resilient human settlements to reduce the vulnerability to disaster and enhances the capacity to reach the SDGs. Some of the SDGs are likely to be enhanced by strong climate change response, but some SDGs may be more difficult to achieve with a strong climate mitigation response, and may become less likely with a stronger climate response (1.5 *versus* 2°C) (Figure 1.6). For example, if an intensive land-based approach is used for climate mitigation, this can place pressure on food security (Smith et al. 2016) or many strong mitigation pathways are expensive, thus reducing the likelihood of poverty eradication, depending on the financial burden sharing pathway used (Nilsson et al. 2017; Stechow et al. 2016).

Conversely, multiple examples of synergies exist between achieving SDGs and climate responses. For instance, converting to sustainable energies can enhance the energy security of a society and protect the ecosystem services offered by land and ocean environment (Figure 1.6). In addition, adaptive capacity and resilience is enhanced in societies with a broad access to education and infrastructure. Since urbanization is occurring at an accelerating rate, the interactions between urbanization, sustainable development and climate response needs to be considered (Reckien et al. 2017). Simultaneously considering how to achieve an ambitious low climate trajectory and achieve the SDGs is a centre point of this report (Figure 1.6). Intuitively, it is likely that addressing these multiple goals simultaneously is more likely to achieve a cost-effective and socially acceptable solution, than addressing these goals piecemeal (Stechow et al. 2016), although there may be different synergies and trade-offs between a 2°C (Stechow et al. 2016) and a 1.5°C goal (Kainuma et al. 2017).

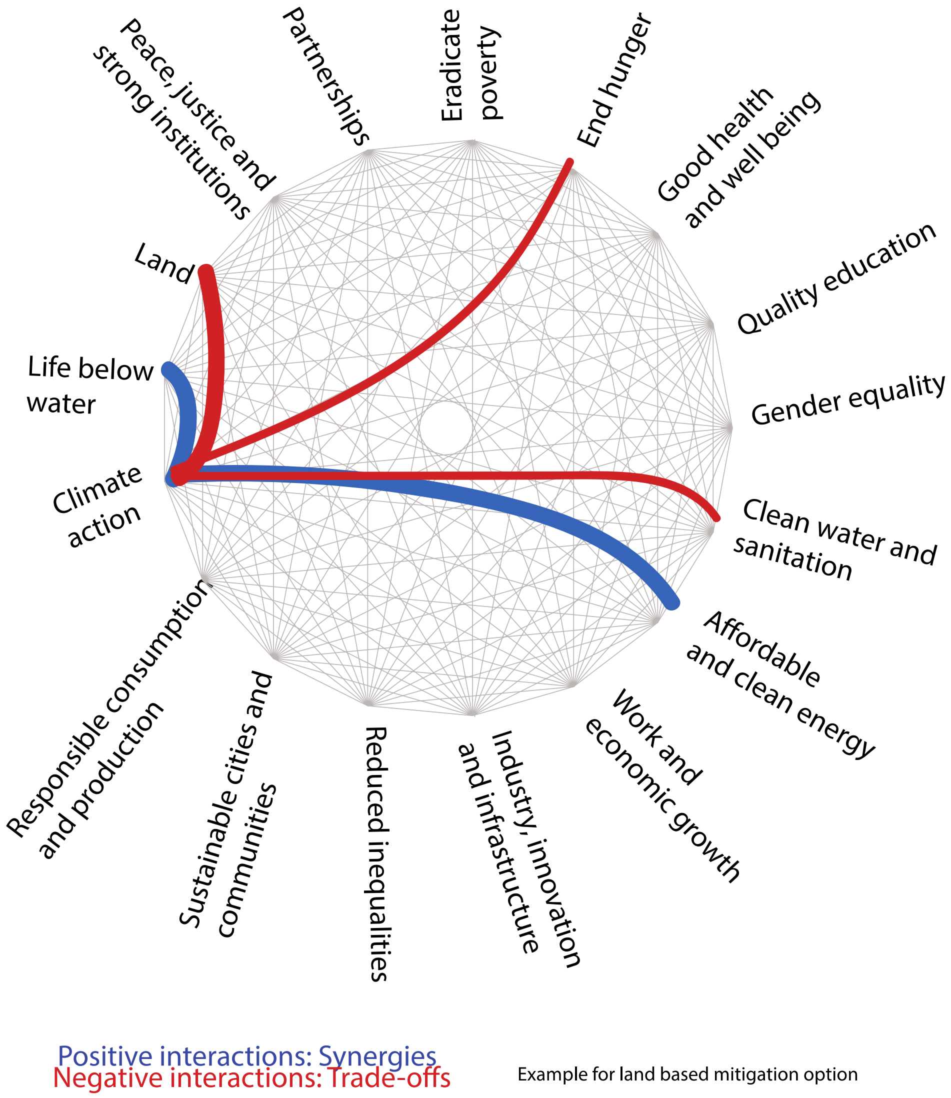


Figure 1.6: A framework for evaluating the impact of different climate response pathways on the multiple dimensions of the Sustainable Development Goals. For each goal, positive or negative impacts for each climate action can be estimated, highlighting the climate response pathways that require trade-offs versus those that have the most synergies. An example is shown of a land-based mitigation strategy for climate change. Positive interactions (synergies) are shown with a blue line, negative interactions (trade-offs) are shown with red, and the strength of the interaction is shown with a bolder line).

1.4.5 Solar Radiation Management

Solar Radiation Management (SRM), also referred to as 'sunlight reduction methods' involves deliberate changes to the albedo of the Earth system, with the net effect of reducing the amount of solar radiation reaching Earth's surface (Smith and Rasch 2013). One of the most commonly proposed SRM techniques involves the artificial emission of aerosols into the stratosphere (Rasch et al. 2008), referred to as Sulphate Aerosol Injections (SAI), to essentially mimic the effect of volcanic eruptions in reducing global average temperatures. Other related approaches exist, which involve increasing the albedo of the land surface, for example *via* changes in the albedo of agricultural land or urban areas (Davin et al. 2014; Hirsch et al. 2017; Irvine et al. 2011). These land-surface radiation management methods have a smaller spatial footprint, because the forcing is more restricted in space (although the same overall radiative principles apply). The land-surface radiation management approaches are potentially better suited than SAI to affect local and regional temperature (Seneviratne et al. 2017) but would have at most only a negligible effect on global temperature, and are thus addressed here separately from other SRM approaches (see also Sections 3.7.2.1

and 3.7.3 in Chapter 3 for more background on this topic). Traditionally considered SRM approaches, such as SAI, would, on the other hand, have a global footprint on climate. While this may make global SRM seem attractive for counteracting increased greenhouse gas forcing, there are serious shortcomings when considering effects on the water cycle and on regional scale, as detailed in Chapter 3.

Consistent with previous IPCC reports (IPCC 2012b), SRM does not fall within the usual definition of adaptation or mitigation. Therefore, SRM is not investigated as a mitigation option in Chapter 2 of this report, which makes use of IAMs, amongst other tools, to investigate different mitigation pathways to achieve the 1.5°C target. SRM is nonetheless sometimes proposed as a means to address climate impacts (Crutzen 2006), and the associated risks and impacts (both biophysical and social) need to be carefully reviewed. This is carried out in Chapter 3, which reviews the direct and indirect impacts of SRM at the regional scale, for example changes in precipitation patterns and ocean acidification. Chapter 4 reviews the social, cost, governance, and ethical issues associated with SRM, and Chapter 5 discusses SRM implications relevant to SDGs, with particular focus on how these relate to food production, ocean acidification, partnerships, and potential health impacts via changes in ozone. Finally, since this by no means covers all aspects of SRM, several related topics are covered in Box 4.2, including, the global impacts of SRM (i.e., changes to the global circulation and associated impacts on precipitation, cloud coverage, etc.), the effectiveness of different SRM techniques in reducing global mean temperatures, and the implications of termination-effects associated with SRM.

1.4.6 Implementation and policies

There is growing literature that suggests the costs of policies that eliminate GHGs may be small or negative, ‘and that policies to expand renewable energy also make them cheaper’, for example in some cases of providing renewable energy compared to fossil fuels (Patt 2017). Transitioning from climate planning to practical implementation is a major challenge identified for constraining global temperature to 1.5°C. This is due to several barriers including finance, technology and human resource constrains plus institutional capacity to strategically deploy available knowledge and resources (Mimura et al. 2014). Uncertainties in climate change at different scales, different capacities to respond coupled with the complexities of social-ecological systems point to a need for diverse implementation options within and among different regions involving different actors. The tremendous regional diversity between highly carbon-invested economies and emerging economies are important considerations for sustainable development and equity in achieving the 1.5°C goal. Key sectors such, as urban systems, food security and water supply also are critical to these connections. Incorporating strong linkages across sectors, devolution of power and resources to sub-national and local governments and facilitating partnerships among public, civic, and private sectors will be key to implementing identified response options. The implementation process of climate policy is not well understood let alone when it comes to integrating other territorial, urban and sectoral policies like disaster risk reduction measures and how also public participation mechanisms can contribute to addressing vulnerabilities to climate-related hazards (Forino et al. 2017).

Implementation options could be informed by Chapter 20 of IPCC AR5 key message that: ‘To promote sustainable development within the context of climate change, climate-resilient pathways may involve significant transformations. Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways’ (Denton et al. 2014).

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development

The information for the report is global in scope and includes regional analysis. The report provides synthesis of municipal, sub-national, and national case studies. Global level statistics including physical science and social science data are presented and as well as detailed and illustrative case study material of particular conditions and contexts. The time scale of the assessment is the 21st century and includes focus on the near-term, medium term, and long term. It is recognised that the occurrence of a 1.5°C world is spatial and temporally uneven with some part of the earth's surface already experiencing that level of annual warming. Similarly, wide spatial variation exists with respect to level of economic development, sustainable development, and adaptation capacity. The spatial and temporal contexts are illustrated throughout the chapters including Chapter 2's assessment tools that include dynamic projections of carbon budgets and mitigation costs, Chapter 4's mitigation potential assessment framework, and Chapter 5's linkage of the share sustainability pathways (SSPs), sustainable development goals (SDGs), and the connection to social innovation.

Depending on policies and investments adopted, emission reductions required for a 1.5°C world and the associated adaptation to resulting impacts present variable multidimensional costs and benefits in different regions and countries at the technological, economic and socio-cultural level as well as with natural systems (Admiraal et al. 2016; Rose et al. 2017). Actions and strategies for a 1.5°C world will be translated from local to global scales and originate from international agreements that could be interpreted at the local level.

1.5.1 Multidimensional costs and benefits

Common tools for making difficult policy decisions include cost-benefit analyses, whereby the costs of impacts are compared to the benefits from different response actions (IPCC 2014c). However, for the case of climate change in the Anthropocene these tools can be difficult to use because of the disparate impacts versus costs and the complex interconnectivity within the global social-ecological system. For example, costs may be relatively easily quantifiable in terms of money, but the impacts of climate change may be on humans' lives, their culture and values or ecosystem goods and services and may have unpredictable feedback loops and impacts on other regions, making it difficult to quantify and compare(IPCC 2014c). In addition, costs and benefits can occur at very different times, even across different centuries for different regions, for which case, standard cost-benefit analyses become difficult to justify (Dietz et al. 2016; IPCC 2014c). For example, the cost of catastrophic events could be unpredictable, and result not only in large impacts on the region directly affected but could also extend to other areas, for example through trade linkages and or increased susceptibility to further impacts, even those less severe (Hsiang et al. 2017; Schleussner et al. 2016a).

Climate change tends to enhance pre-existing inequalities, between regions and within countries, elevating losses in already disadvantaged areas due to low adaptive capacity but also the skewed distribution of risks as is the case for many developing regions (Aaheim et al. 2016; Hsiang et al. 2017; Schleussner et al. 2016a). However, in this case, where a deliberate effort is required to constrain the temperature to 1.5°C, costs and benefits will also be related to transitioning approaches adopted to move from high to low emission investments. This is likely to result in losses and opportunities for different sectors, for example fossil fuel related industries versus green oriented ones, socio-economic groups and locations within a country and or region and stretching beyond due to existing strong global interlinkages and inequalities (Aaheim et al. 2016; Admiraal et al. 2016; Hsiang et al. 2017).

Significant benefits in investing on a low emissions development pathway are more likely to be experienced by future generations requiring sacrificial approach for the current society (Admiraal et al. 2016). While large-scale intervention in the Earth’s climatic system (e.g., geoengineering) could give rise to far reaching costs, some going beyond the current generation, in addition to anticipated benefits. Available higher global welfare losses are indicated for the 2°C post-2030 pathway pointing to a possible rise in cost with further constraining of warming that will be politically challenging (Rose et al. 2017).

Cost and benefits of a 1.5°C world could be estimated taking into account the above noted constraints, for example for desired development framework such as under the Agenda 2030 sustainable development pathways. Flexibility in policy at multiple scales to facilitate appropriate timing, required, innovations and technology as well as conducive economic and socio-cultural environment to emerge will be key to balancing costs and benefits across scales for different systems and sectors (Admiraal et al. 2016).

1.5.2 Types of knowledge and evidence used in the report

Different types of knowledge and evidence within the Anthropocene context are used in this assessment. The Anthropocene, which in earth system science is considered a paradigm that marks a unique geological era strongly defined by human activity, is growing to be a powerful cultural model that contemporary societies can use to interpret social-ecological system in light of on-going major shifts and explore sustainable solutions (Delanty and Mota 2017). Within this framing, the assessment is achieved using two broad sources of knowledge and evidence: peer reviewed scientific literature and grey-unpublished literature.

Peer-reviewed literature includes the following types of knowledge and evidence: 1) State of knowledge on the physical climate system and human induced changes, and associated impacts and vulnerabilities and adaptation options, established from work based on empirical evidence, simulations, modelling and scenarios with emphasis on new information since the publication of the IPCC AR5 to the cut-off date for this report, May 2018; 2) Human and social science theory and knowledge from lived experiences of climate change risks and vulnerability in the context of social-ecological system, development, equity and justice and the role of governance; within this is co-production of local knowledge that incorporates indigenous knowledge systems; and 3) Mitigation pathways based on climate projections in the future.

The grey literature category also extends to empirical observations, interviews and results from models found in, for example, theses, technical and consultancy reports and conference papers, government reports, industries, reports from development agencies and non-governmental organisations (NGOs) and other sources. The assessment does not cover un-written evidence and does not utilise media based reports and newspaper publications. In addition to the overall scarcity of published literature on 1.5°C warming, with exception to Australia and to some extent China, publications from the South, the most vulnerable, are far lower in the geopolitics of documented knowledge (Czerniewicz et al. 2017).

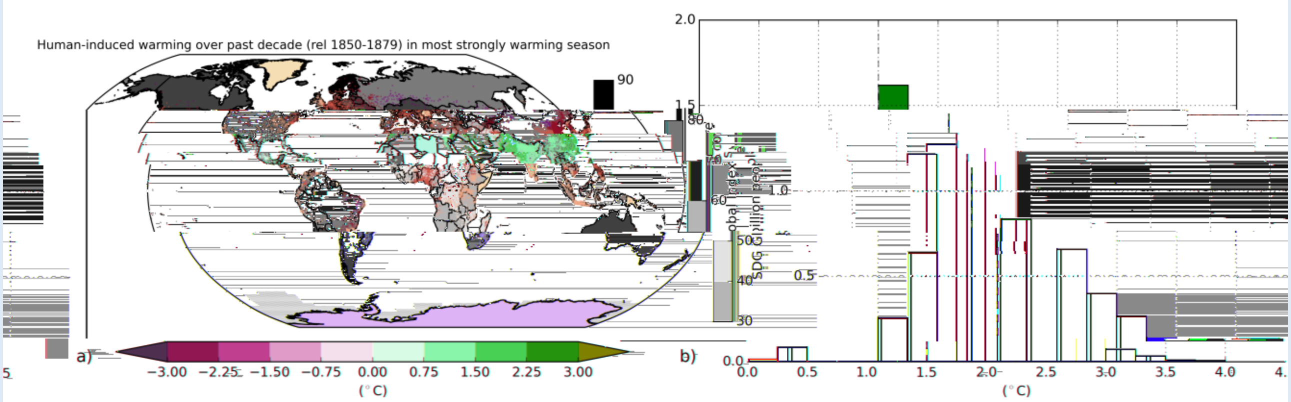
A holistic knowledge base as well as new and adaptable institutional structure at different scales will be required to create, for example, the required policy and legal frameworks, and establish resources for implementing various response options to the 1.5°C warming (James et al. 2017). Incorporating knowledge from different sources and setting a multi-faceted information channel, and educating and building awareness at various levels will advance decision making and implementation of context specific response to 1.5°C warming and associated uncertainties (Somanathan et al. 2014) (see also Box 1.4 on the role of community knowledge).

Box 1.4: Experiencing 1.5°C - Opportunities and challenges of visualizing a 1.5°C world: The potential role of community knowledge

Information about regional climate change impacts is limited and there are large uncertainties where this information is produced in addition to research gaps on the rate of change and regional dimensions on the impacts of 1.5°C (Hulme 2016; James et al. 2017). Indigenous and local knowledge (i.e., traditional ecological knowledge) and experience, though less documented, offers valuable insights and can complement scientific data with chronological and landscape-specific precision and detail that is critical for verifying climate models and evaluating climate change scenarios (Fernández-Llamazares et al. 2015; Reyes-García et al. 2015). Indigenous and local knowledge comprises customary knowledge-practice-belief systems about the relationships of living beings (including humans) with one another and their environment (i.e., social - ecological systems) emerging through adaptive processes and culturally transmitted over generations (McMillen et al. 2014). While scientifically observed climate data tends to be limited in many areas or absent especially in developing countries such as Central Africa and Central America, there are people with relevant data and information in these areas although the accuracy of this information is not always verified (Reyes-García et al. 2015; Czerniewicz et al. 2017).

Local and traditional knowledge of recent climate changes bears direct relevance to the impacts of a 1.5°C climate. Whilst, present-day climate changes are not likely to be indicative of climate changes that would be realised in a global-mean 1.5°C world, particularly when multiple climate variables are considered (Dahinden et al. 2017), large parts of the world have already experienced warming in excess of 1.5°C in at least one season of the year, corresponding to over 70% of the global population for which local warming trends can be calculated (Box 1.4 Figure 1). Since experiences of climate impacts today are heterogeneous (as they will be in a future 1.5°C world), the value of traditional knowledge related to climate is being more widely considered as critical to understanding the climate change impacts at regional and local level and in developing local climate change adaptation plans and strategies that sustain resilience of social-ecological systems at the interconnected local, regional and global scales (Nakashima et al. 2012; Carter et al. 2014). While traditional knowledge is being more widely considered as critical to developing local climate change adaptation plans and strategies, it either exists in grey literature outside of peer-reviewed process or remains in oral form and, in most cases, falls outside the scope of scientific literature on climate change impacts and mitigation (Leon et al. 2015).

Savo et al. (2016) gathered observations covering 137 countries involving more than 90,000 people whose traditional ways of life rely on nature and where weather stations are absent to fill a knowledge gap in climate change science, which is dominated by data and computer models. They found observations from nearly 70 percent of those interviewed generally aligned with data and models developed to predict changes in the climate and this has also been established among the Nepalese community perceptions of changing weather patterns (Ministry of Science Technology and Environment 2015). This is equally so for indigenous people in the Pacific Islands with rich understanding of atmospheric, weather, and seasonal cycles based on long-term observations that have been used to develop customary calendars that include expectations of weather (e.g., wet and dry seasons) in planting and harvest of breadfruit (*Artocarpus altilis*), or the rising and spawning of the palolo sea worm (*Eunice viridis*) (McMillen et al. 2014).



Box 1.4, Figure 1: Realised experience of present-day warming. Panel a): colours indicate human-induced warming in over the past decade (2007-2016) relative to 1850-1879 for the most strongly warming season at any location using the GISTEMP dataset (Hansen et al. 2010b). The density of dots indicates the population (2015) in any 1°x1° grid box. Warming trends are calculated in an identical way to Figure 1.2. The underlay shows SDG Global Index Score ranks at a country level indicating performance across 17 sustainable development goals. Yellow shading indicates missing data. Panel b) shows a histogram for the data shown in panel a). Approximately 50% of the global population have already experienced at least one season with human-attributable warming above 1.5°C for the average of the last decade. See Technical Annex of this chapter for further details.

1.6 Consideration and communication of confidence, uncertainty and risk

Careful consideration and clear communication of levels of confidence and uncertainty is fundamental to the work of the IPCC. This Special Report relies on the IPCC's uncertainty guidance provided in Mastrandrea et al. (2011), building on IPCC (2005), Manning et al. (2004) and Moss and Schneider (2000), that was the basis for the consistent treatment of uncertainty in AR5. Some simplifications and clarifications are proposed to address the specific circumstances of this Report. The AR5 relied on two metrics for communicating the degree of certainty in key findings:

- Qualitative expressions of confidence in the validity of a finding based on the amount of and level of agreement in the evidence available; and
- Quantitative expressions of likelihood or probability of specific events or outcomes.

In both cases, specific terms were adopted to ensure consistency of language across chapters and Working Groups, but differences of practice emerged, with greater use of confidence expressions by Working Groups 2 and 3, and likelihood by Working Group 1. This is a cross-Working Group report with a need for consistent practice spanning physical climate; impacts, vulnerabilities and risks; and mitigation options. For reasons given below, the authors of this Special Report express their key findings using qualitative expressions of confidence and numerical ranges where possible. Following the practice in AR5 Working Groups 2 and 3, and in contrast to Working Group 1, the use of probabilistic (likely, etc.) qualifiers is generally avoided in Executive Summaries and the Summary for Policymakers. Where findings explicitly concern probabilities, or frequency of occurrence within an ensemble, these are given numerically or using phrases such as ‘even chance’ or ‘two in three chance’ to avoid any ambiguity.

Background – confidence scale:

Five qualifiers are used to express levels of confidence in key findings, ranging from very low, through low, medium, high, to very high. The assessment of confidence involves at least two dimensions (see Figure 1.7), one being the type, quality, amount or internal consistency of individual lines of evidence, the second being the level of agreement between different lines of evidence. Very high confidence findings must either be supported by a high level of agreement across multiple lines of mutually independent and individually robust lines of evidence or, if only a single line of evidence is available, by a very high level of understanding of the processes underlying that evidence. High confidence implies either high agreement across different lines of evidence that may be individually less robust, or lower agreement but greater individual robustness. There are multiple ways of supporting a medium confidence qualifier, and further explanation may be required to elaborate whether the issue is lack of agreement between, or the robustness of, different lines of evidence. Findings of low or very low confidence are presented only if they address a topic of major concern.

Background – likelihood scale:

The IPCC uses a calibrated language scale to communicate assessed probabilities of outcomes, ranging from exceptionally unlikely (<1%), extremely unlikely (<5%), very unlikely (<10%), unlikely (<33%), about as likely as not (33-66%), likely (>66%), very likely (>90%), extremely likely (>95%) and virtually certain (>99%). These terms are normally only applied to findings associated with high or very high confidence. Where findings are based on frequencies within model ensembles, calibrated uncertainty language is not used to communicate those frequencies unless these are assessed (with other lines of evidence) to correspond to probabilities in the real world. Figures and text in AR5 normally use 5-95% confidence intervals for observable quantities and the 5-95% frequency interval for ranges of model ensembles.

Challenges in the context of this Special Report:

Three specific challenges arise in the treatment of uncertainty and risk in this report. First, the timetable on which this report is being compiled and the current state of the academic literature on 1.5°C mean that findings based on multiple lines of robust evidence for which quantitative probabilistic results can be expressed may be very few, and those that can be made may not be the most policy-relevant. This introduces a communication challenge: in AR5, whenever a likelihood assessment was given, it could be assumed that it was associated with high or very high confidence, and hence this was not stated. When findings are presented at various levels of confidence, it may not always be clear to the reader that those that omit a confidence qualifier are implicitly high or very high confidence. While stressing that this does not entail a revision to the well-established uncertainty guidance, in this Special Report an effort is made to avoid relying on implicit confidence qualifiers: if a qualifier is intended, then it is stated explicitly. Double-qualified expressions that combine both likelihood and confidence language can, however, easily become impenetrable (e.g., very likely (medium confidence)): hence, where possible, key findings are expressed in this report using confidence qualifiers alone with numerical expressions of frequency or probability as appropriate.

Second, many of the most important findings of this Special Report are highly conditional precisely because they refer to ambitious mitigation scenarios. This also presents challenges in communication with probabilistic language. The risks associated with 4°C of warming may not be very different from the risks associated with a scenario that is expected to result in 4°C of warming, but which might result in 3°C or 5°C depending on the global climate response. This is not true of ambitious mitigation scenarios: the range of risks associated with 1.5°C of global temperature increase may be very different from the risks associated with a scenario that has an even chance of meeting the 1.5°C goal. In the first case, risks are conditioned on the global temperature goal actually being met, while in the second, they also need to allow for a substantial chance of warming exceeding 2°C because of uncertainty in the global temperature response. Such conditional probabilities often depend strongly on how conditions are specified, such as how temperature goals are met, whether through early emission reductions, greater reliance on negative emissions following an overshoot, or later reductions coupled with a low climate response. Hence whether a certain risk is deemed likely or very likely at 1.5°C may depend strongly on how 1.5°C is specified, whereas a statement that a certain risk may be substantially higher at 2°C relative to 1.5°C may be much more robust. Again, this cautions against the use of probabilistic language to convey highly conditional probabilities in situations where the precise specification of the conditions may not be transparent.

Third, the traditional application of probabilistic language in IPCC applies to relatively passive systems, such as the projected response of the climate system to a specific emissions scenario. Achieving ambitious mitigation goals will require active, goal-directed efforts aiming explicitly for specific outcomes and incorporating new information as it becomes available. The focus of uncertainty shifts from the climate outcome itself to the level of mitigation effort that may be required to achieve it. The interpretation of probabilistic statements about future actions, which may in turn be informed by these statements, is clearly a challenge. It may also be unnecessary: in the context of robust decision-making, many near-term policies that are needed to keep open the option of achieving 1.5°C are the same, regardless of the actual probability that the goal will be met.

In the light of these challenges, it is proposed to present summary findings in this report as far as possible using confidence language, using numerical ranges and probabilities where appropriate, avoiding the use of double-qualified statements.

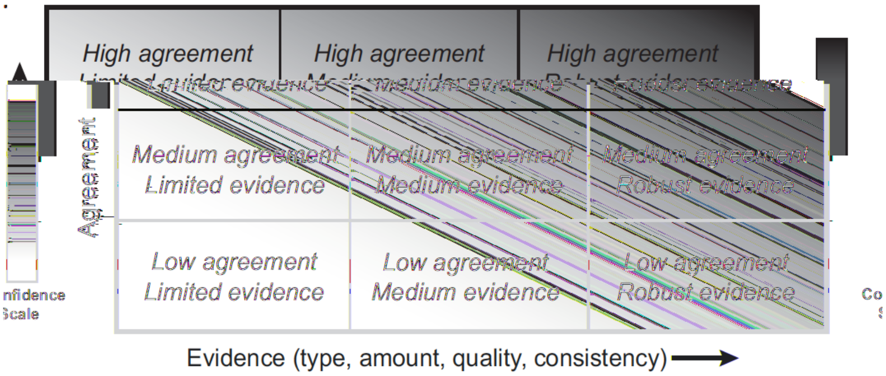


Figure 1.7: The two dimensions of evidence and agreement together determine the level of confidence in a key finding, adapted from Mastrandrea et al. (2011). This figure illustrates how, while there are relatively few ways of supporting a "very high confidence" or "very low confidence" statement, there are multiple ways of supporting a "medium confidence" statement.

1.7 Storyline of the report

The thrust of this report, as illustrated in Figure 1.8, is to establish feasible options for the global community, within the context of the Sustainable Development Goals (SDGs), to limit the global temperature increase to 1.5°C above pre-industrial levels and address adaptation to the associated impacts inclusive of poverty eradication, equity and ethics issues. The report consists of five chapters and a summary for policy makers. The report has a set of Boxes to elucidate specific or cross-cutting themes, frequently asked questions for each chapter and a glossary.

Chapter 1, on Framing and context has seven major sections that are linked to the remaining four chapters forming the body of the report. The introduction section of Chapter 1 serves to situate the assessment within social-ecological systems in the context the Anthropocene. It points to the central role of governance in constraining global temperatures to 1.5°C warming and responding to associated impacts within the sustainable development framework. The next section, key to the whole report, focuses on understanding 1.5°C, global versus regional warming and linkages to 1.5°C -consistent pathways and associated emissions, further developed in Chapter 2. The section on multiple dimensions of impacts at 1.5°C opens the way to Chapter 3 on impacts of 1.5°C global warming on natural and human systems, and coupled social-ecological systems. The section on strengthening the global response to the threat of climate change is the basis for Chapters 4 and 5 and, respectively, cover implementing the global response to the threat of climate change, and sustainable development, poverty eradication and reducing inequalities in the context of 1.5°C global warming. Chapter 1 also provides a framing on assessment methods used in the report and approaches to communicating confidence, uncertainty and risk.

The report flows from this initial framing to Chapter 2 and ‘how 1.5°C global warming could be achieved’, where greenhouse gas emissions consistent with warming of 1.5°C and characterizing mitigation and development pathways that are compatible with a 1.5°C world are covered. Chapter 2 also assesses technological, environmental, institutional and socio-economic opportunities and challenges related to 1.5°C pathways and goes beyond the normal IPCC WGII treatment with an emphasis on sustainable developed in mitigation pathways. In the light of the Chapter 2 assessment, impacts and risks of 1.5°C global warming on social-ecological systems are assessed in Chapter 3. This third chapter is focused on observed and attributable global and regional climate changes and impacts, vulnerabilities and the adaptation experiences to key global and regional impacts and risks at 1.5°C. It links adaptation potential and limits to adaptive capacity. In this context, avoided impacts and reduced risks at 1.5°C compared with 2°C and comparative higher levels of warming. The assessment of system level conditions including timeframes, slow versus fast onset impacts, irreversibility and tipping points are included.

Chapter 4 and 5 focus on development-linked solutions and implications for the near term and longer term. Chapter 4 considers the costs and benefits of 1.5°C warming, synergies, trade-offs and an integration of adaptation-mitigation-development, and addresses governance approaches and implementation strategies cognizant of equity and justice. The chapter has a section on case studies for implementation of adaptation and mitigation options at different scales and circumstances, and lessons learned that will be valuable to strengthening the global response to climate change. Chapter 5 covers linkages between achieving SDGs and 1.5°C. Positive and unintended effects of adaptation and mitigation response measures and pathways for a 1.5°C warmer world are examined, with implications for sustainable development, poverty eradication, and reducing inequalities, as well as for the SDGs. The chapter discusses opportunities and challenges for climate-resilient development pathways, supported through emerging evidence from case studies from national to community scales.

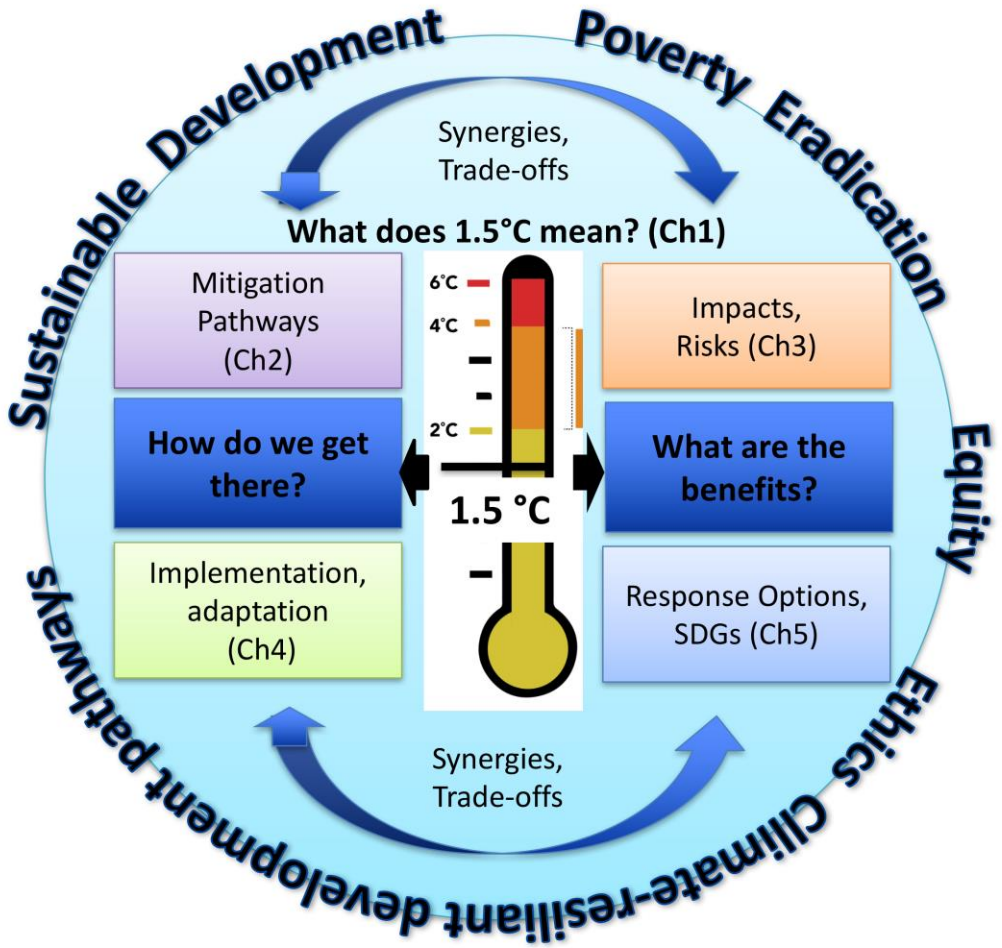


Figure 1.8: Schematic storyline figure for the rest of the report.

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Technical Annex 1.A

Technical Note for Figure 1.1

Observational data is taken from the Met Office Hadley Centre (http://www.metoffice.gov.uk/hadobs/hadcrut4/), National Oceanic and Atmospheric Administration (NOAA) (https://www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp) and NASA's Goddard Institute for Space Studies (https://data.giss.nasa.gov/gistemp/). The GISSTEMP and NOAA observational products (which begin in 1880) are expressed relative to 1850-1879 by first expressing all three time series relative to a common 1961-1990 base period before subtracting off the anomaly between this period and the 1850-1879 average in the HadCRUT4 product. All available data is used, through to the end of 2016, in all cases.

CMIP5 multi-model means, light blue dashed (full field surface air temperature) and solid (masked and blended as in Cowtan et al. (2015)) are expressed relative to a 1861-1880 base period and then expressed relative to the 1850-1879 reference period using the anomaly between the periods in the HadCRUT4 product.

The light green "Holocene" shading is derived from the "Standard5x5Grid" reconstruction of Marcott et al. (2013) (expressed relative to 1850-1879 using the HadCRUT4 anomaly between this reference period and the 1961-90 base period of the data). The vertical extent is determined by the maximum and minimum temperature anomalies in the dataset in the period between 10,000 years before present (present is defined as 1950) and 1850. Marcott et al. (2013) report data with a periodicity of 20 years, so the variability shown by the green shading is not directly comparable to the higher frequency variability seen in the observational products which are reported every month), but this Holocene range can be compared to the emerging signal of human-induced warming.

Pink lines show the first two years of a series of initialised (with prior climate observations) predictions with a multi-model ensemble of decadal prediction systems (Smith et al. 2013a). Model data is reported as anomalies relative to the model climatology over the 1981-2010 period, which is then expressed relative to 1850-1879 using the HadCRUT4 anomalies between these periods. Only the first two years of each integration is shown. Prediction start dates range from 1960-2017.

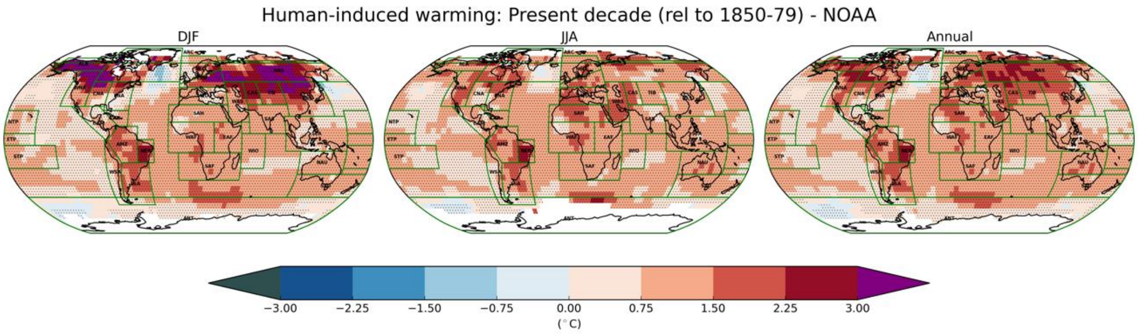
Near term predictions from IPCC-AR5 (Kirtman et al. 2013), for the period 2016-2035 were estimated to be *likely* (>66% probability) between 0.3°C and 0.8°C above the 1986-2006 average, assuming no climatically significant future volcanic eruptions. We construct straight lines that have gradients consistent with the upper and lower ends of this prediction range where the 1986-2006 average is calculated using the HadCRUT4 product. These are shown as the thick turquoise lines, with shading between them.

Best-estimate human-induced temperature change (thick orange line) and solar & volcanic temperature change (thick dark blue line) are estimated using the method of Otto et al. (2015). Best-estimate historical radiative forcings, extended until the end of 2016, are taken from Myhre et al. (2013), incorporating the significant revision to the methane forcing proposed by Etminan et al. (2016). The 2-box thermal impulse-response model used in Myhre et al. (2013), with modified thermal response time-scales to match the multi-model mean from Geoffroy et al. (2013), is used to derive the shape to the global mean temperature response time series to total anthropogenic, and combined volcanic and solar forcing. Both of these time series are expressed as anomalies relative to their simulated 1850-1879 averages and then used as independent regressors in a multi-variate linear regression to derive scale factors on the two time series that minimise the residual between the combined forced response and the HadCRUT4 observations (expressed as anomalies relative to 1850-1879). The error bar on the 2016 attributed human-induced warming is derived using the same proportional uncertainty as the ±0.1°C (*likely*) uncertainty in the 0.7°C best-estimate anthropogenic warming trend over 1951-2010 period assessed in Bindoff et al. (2013).

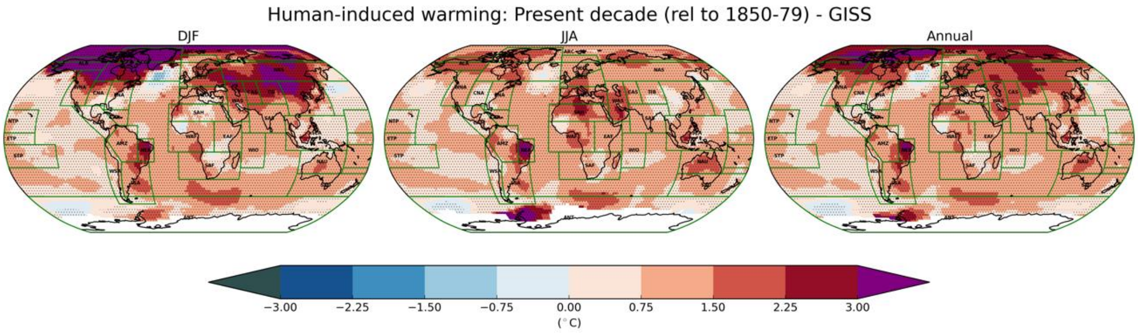
Technical Note for Figure 1.2

Regional attributable human-induced warming shown in Figure 1.2 is derived using a similar method to the calculation of human-induced warming in Figure 1.1. At every grid box location in the native HadCRUT4 resolution, the time series of local temperature anomalies in the HadCRUT4 dataset (expressed relative to the local 1850-1879 average) are regressed onto the global human-induced warming time series shown in Figure 1.1 (assuming a Gaussian error structure) using all available data points. This linear regressed relationship between these two quantities is then used to estimate the human-induced warming relative to 1850-1879 at this location. The maps in Figure 1.2 show the average of local human-induced over the 2007-2016 period. Trends are only plotted only where over 50% of the entire observational record at this location is available. Stippling indicates the linear trend between local warming and global human-induced warming is significant at a 10% level using a one-sided Student-t test. The “JJA” and “DJF” maps take seasonal averages (June/July/August and December/January/February respectively) of the data at every grid box for use in the regressions, whilst the “Annual” map uses annual mean.

Supplementary maps are included below for the NOAA and GISSTEMP observational data, which use infilled data to achieve a higher level of coverage than HadCRUT4. The regression of local temperature anomalies onto the global mean human-induced warming (recalculated using the NOAA and GISS global mean observations respectively), allows local human-induced warming to be expressed relative to 1850-1879 despite these records beginning in 1880.



Technical Annex 1.A, Figure 1: Human-induced warming for the average of 2007-2016 relative to 1850-1879 calculated for the NOAA observational dataset as for Figure 1.2.



Technical Annex 1.A, Figure 2: Human-induced warming for the average of 2007-2016 relative to 1850-1879 calculated for the GISSTEMP observational dataset as for Figure 1.2.

Technical note for Figure 1.3

Construction of figure 1.3

Panel a: Idealised temperature pathways computed by specifying the level of human-induced warming in 2015, $T_{2015} = 1$°C, with temperatures from 1865 to 2015 given by a single-term polynomial: $T = T_{2015}((t - 1865)/150)^{\gamma}$, with γ set to give a rate of human-induced warming in 2015 of 0.17°C/decade. Temperatures from 2016-2115 set by fitting a smooth 4th-order polynomial to prescribed temperatures in 2050 and 2115 and a prescribed gradient in 2115. Gradient is held constant after 2115. Colours are used to illustrate different temperatures pathways, and are consistent in all panels. Upward-pointing triangles indicate years in which 1.5°C is reached from below, and downward-pointing arrows indicate years in which 1.5°C is reached from above.

Panel b: Radiative forcing F that would give the temperature profiles shown in panel a, computed using a 2-time-constant climate response function (Myhre et al. 2013), with Equilibrium Climate Sensitivity (ECS) of 2.7°C and Transient Climate Response (TCR) of 1.6°C and other parameters as given in Millar et al. (2017). Equivalent CO_2 concentrations given by $C = 278 \times \exp(F/5.4)$ ppm.

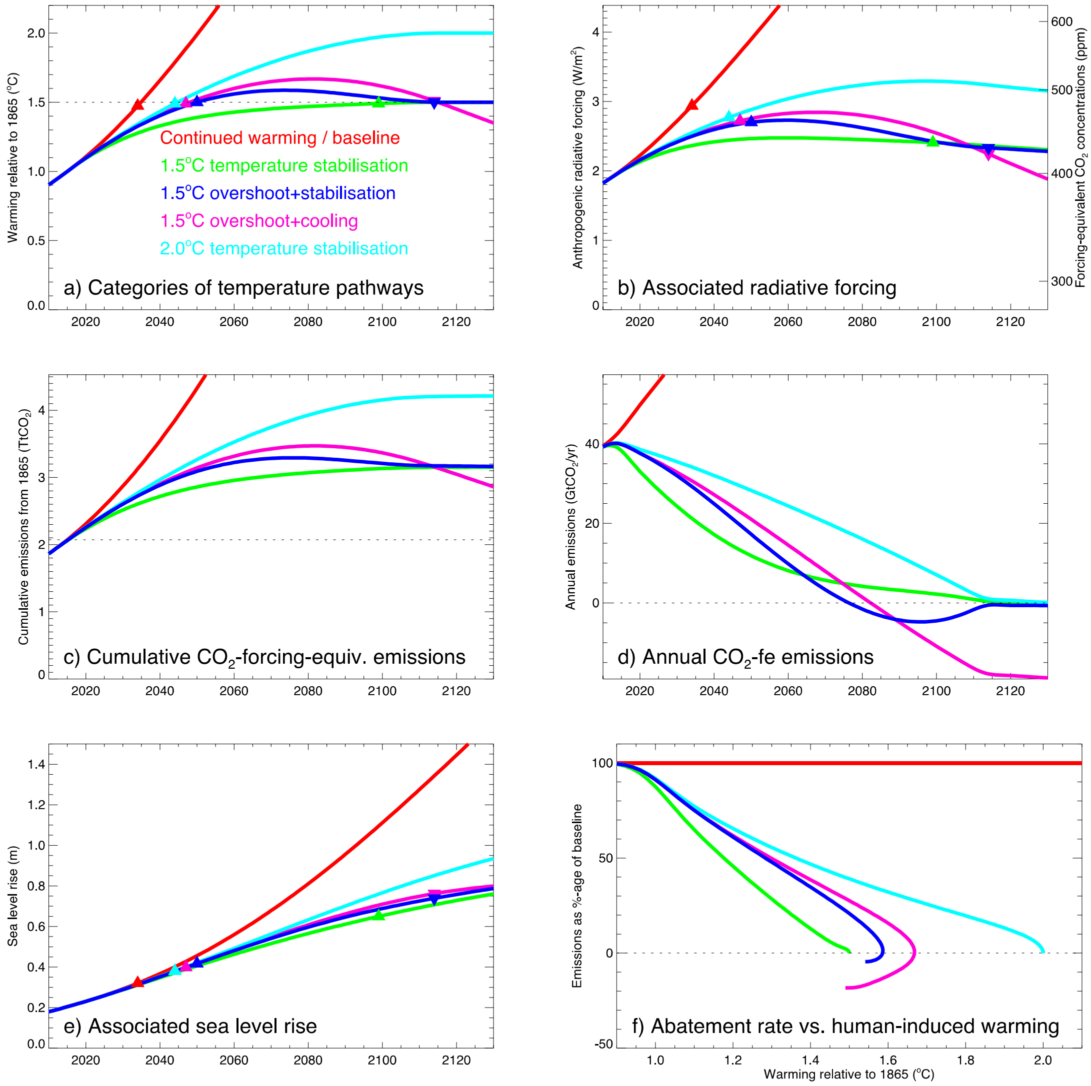
Panel c: Cumulative CO_2-forcing-equivalent emissions, or the CO_2 emission pathways that would give the CO_2 concentration pathways shown in panel b, computed using a simple carbon cycle model (Myhre et al. 2013), modified to account for changing CO_2 airborne fraction over the historical period (Millar et al. 2017).

Panel d: Annual CO_2-forcing-equivalent emissions, or the time-derivative of c.

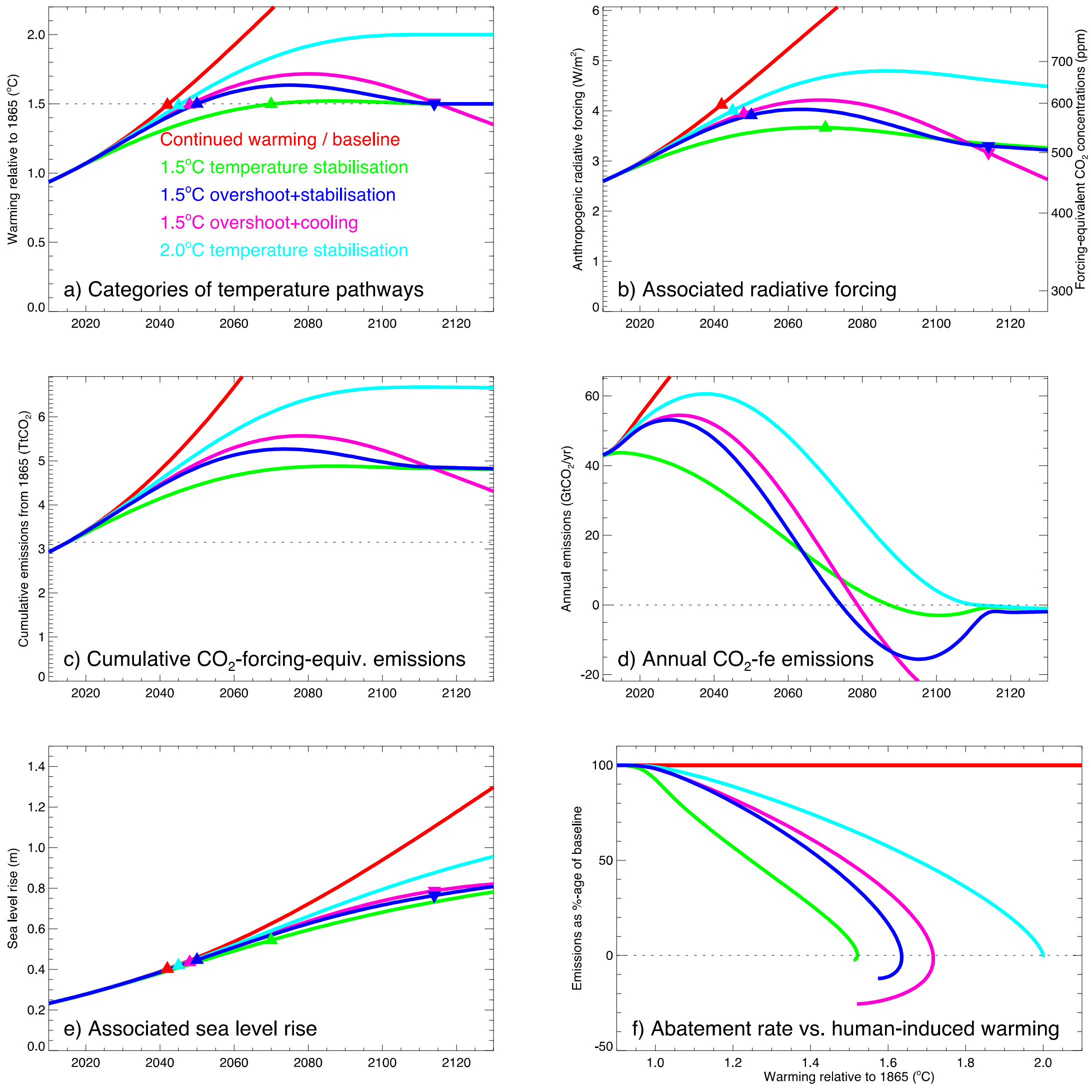
Panel e: Possible pathways of sea level rise computed from temperature pathways shown in panel a using semi-empirical model of Kopp et al. (2016).

Panel f: Emissions as a percentage of baseline emissions for the pathways shown in panel a plotted against temperatures shown in panel a.

Variants of the figure are shown below corresponding to a higher and lower climate response (Higher: ECS=3.1°C, TCR=1.9°C, human-induced warming rate in 2015 of 0.2°C/decade; lower: ECS=2.2°C, TCR=1.3°C, human-induced warming rate in 2015 of 0.13°C/decade). Warming to 2100 and 2050 and temperature gradients in 2100 vary in the baseline pathway in proportion to TCR. All other pathways are specified as in standard version. Note how emissions must fall much faster under a higher climate response to meet a given temperature goal (panel d), but proportionality of cumulative emissions to warming (panel c) still holds, as does the near-straight decline of emissions as a percentage of baseline (panel d).



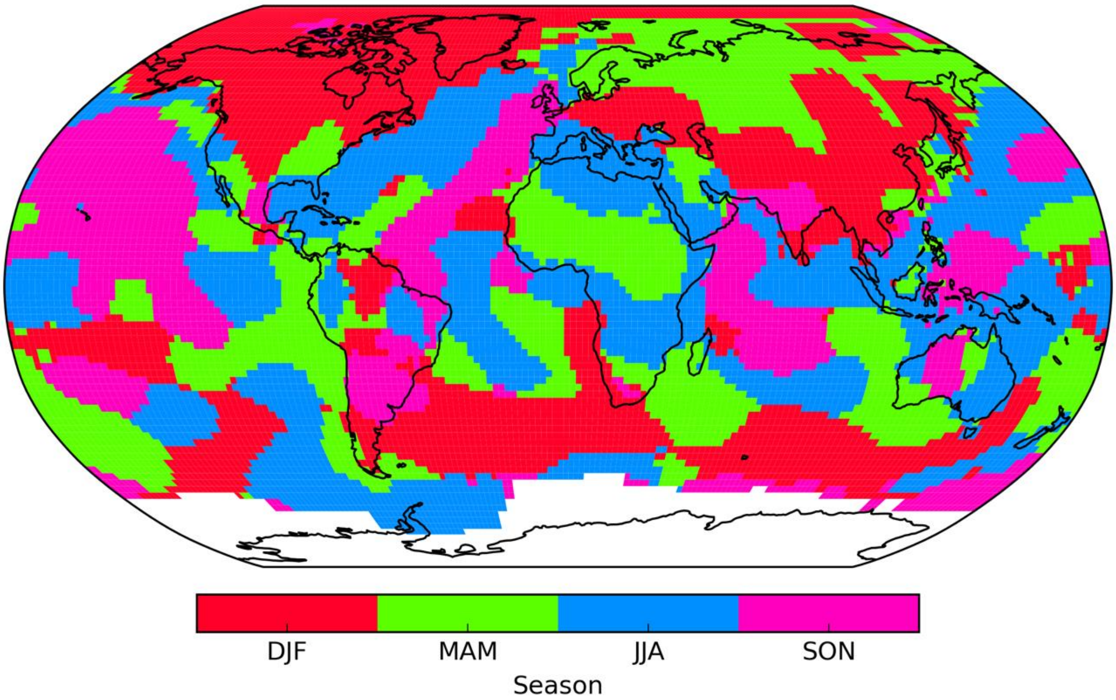
Technical Annex 1.A, Figure 3: Version of figure 1.3 corresponding to a higher climate response.



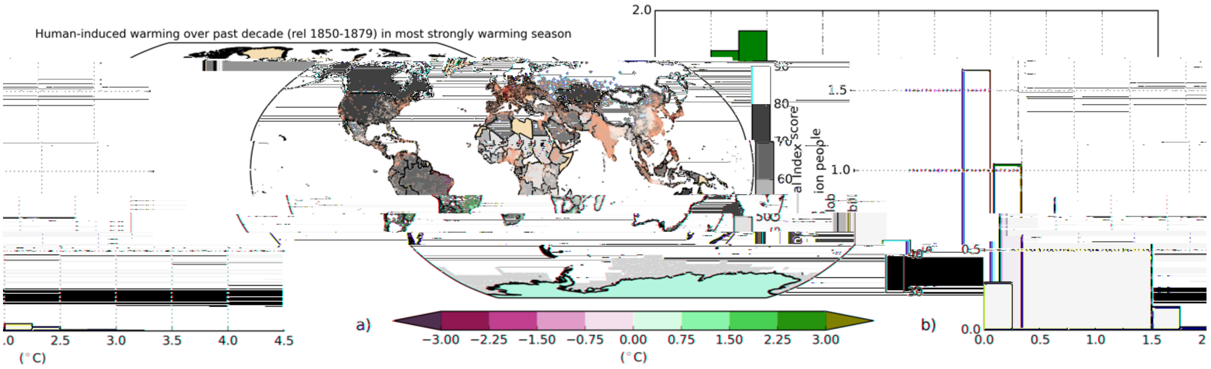
Technical Annex 1.A, Figure 4: Version of figure 1.3 corresponding to a lower climate response

Technical Note for Box 1.4 Figure 1

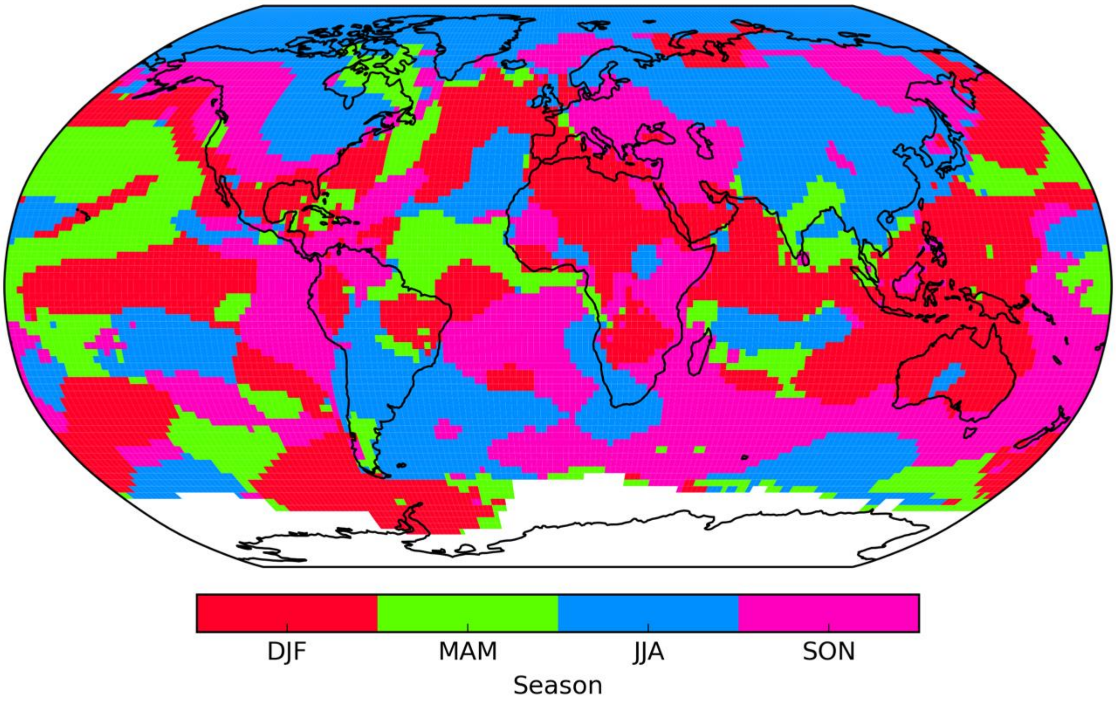
Human-induced warming is calculated for the GISTEMP dataset at every location and for each season as in Figure 1.2. The season with the greatest warming at every location (averaged over the 2007-2016 period) is selected to give the colour of the dots at that grid box. This field is then regridded to the 1°x1° grid of the population density data, taken from Doxsey-Whitfield et al. (2015) for 2015. The density of scatter points in each 1°x1° grid box is proportional to the population in the grid-box, up to a maximum of 50, associated with the greatest population grid box. For grid-boxes below the minimum population threshold to guarantee a point is plotted (approximate 650,000), the probability that a dot is plotted reduces with the population in the grid-box. The SDG Global Index Score ranks country performance across 17 sustainable development goals. The goals cross-cut the three dimensions of sustainable development – environmental sustainability, economic growth, and social inclusion. It has a maximum value of 100. Figure 1.SM.5 shows the month of maximum warming in each grid-box used in Figure 1 of Box 1.4. Figure 1.SM.6 is identical to Figure 1 of Box 1.4, but now shows the season with the least human-induced warming at each location.



Technical Annex 1.A, Figure 5: Season of greatest human-induced warming over the present decade (2007-2016) relative to 1850-1879.



Technical Annex 1.A, Figure 6: As for Figure 1 Box 1.4, but for the least warming season.



Technical Annex 1.A, Figure 7: Season of least human-induced warming over the present decade (2007-2016) relative to 1850-1879.