Chapter 1: Framing and Context

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Executive Summary

Warming of the climate system is unequivocal and it is *extremely likely* that anthropogenic greenhouse gas emissions were the dominant cause of the warming observed since the mid-20th-century. At COP21 in 2015, UNFCCC parties expressed the ambition in the resulting Paris Agreement to limit the increase in global average temperature above pre-industrial levels to "well below 2°C" and to "pursue efforts" to limit warming to 1.5°C. This opening chapter provides the framing and context of this Special Report on Global Warming of 1.5°C, outlines the structure that subsequent chapters will follow, and introduces the important underpinning definitions and concepts.

For stabilisation of global temperatures at any level, total net global greenhouse gas emissions, if expressed in terms that give all climate drivers a similar global temperature impact as CO2, must be reduced to zero. CO_2 emissions accumulate in the climate system, so warming will continue until anthropogenic CO_2 emissions reach net zero, with equivalent reductions in other climate drivers. **{1.2}**

Implementation of the current level of Nationally Determined Contributions (NDCs) specified under the Paris Agreement by 2025 or 2030 will not in themselves be sufficient to limit warming to 1.5 °C. Currently-specified NDCs imply stabilisation of global GHG emissions near their current level by 2030 and do not specify total cumulative emissions of long-lived greenhouse gases such as CO_2 before these are reduced to net zero. Continued stable CO_2 emissions after 2030 would result in indefinite warming. **{1.2}**

Current patterns of development and resource consumption, particularly of fossil fuels, present structural impediments to achieving ambitious temperature stabilisation goals. Existing multi-level inequalities between regions, including in technology, finance, human capital and governance constrain approaches to address the challenge of limiting global warming to 1.5°C.**{1.1; 1.4.1}**

Clarity and transparency is important for the interpretation of the Paris Agreement. Quantifying the increase in global average temperature above pre-industrial levels implies choosing the variables and coverage used to define "increase in global average temperature"; and the reference period used to define "pre-industrial". This report adopts a working definition of global average temperature at any given time as the average of land surface air and sea surface temperatures over a 30-year period centred on that time. This average is corrected for the impact of any short-term natural climate drivers, such as volcanoes, in that 30-year period. The 51-year reference period 1850-1900 is considered representative of pre-industrial conditions, consistent with AR5. Using the datasets assessed in AR5, the decade 2006-2015 is estimated to have been 0.87°C (±0.1°C) warmer than 1850-1900, and the best estimate is that all of this warming was human-induced. Hence a warming of 1.5°C relative to pre-industrial conditions corresponds to a warming of 0.63°C (±0.1°C) relative to observed temperatures for the decade 2006-2015. Expressing future changes relative to this more recent decade reduces sensitivity of results to the historical period. **{1.2.2}**

Human-induced warming reached approximately 1°C above pre-industrial in 2017, with greater warming already experienced in many regions and seasons. *[High confidence*] Temperatures were assessed in AR5 to be rising at 0.17°C (±0.07°C) per decade, and hence reached 1°C above pre-industrial (0.13°C above 2006-2015) around 2017/18. Temperatures continue to fluctuate naturally on either side of this externally driven warming trend. A large volcanic eruption could cause a temporary cooling of observed global temperatures without affecting the underlying warming as defined in this report. Most land regions are experiencing greater warming than the global average, with annual average warming already exceeding 1.5°C in many regions. Over one quarter of the global population live in regions that have already experienced more than 1.5°C of warming in at least one season.**{1.2.2 & 1.2.3}**

Past emissions do not commit to substantial future surface warming, but do commit to future sea level rise. If all anthropogenic emissions were reduced to zero immediately, any further warming beyond that already experienced would last at most a decade and be indistinguishable from natural variability over that time. Although a hypothetical scenario, this indicates that future warming depends on future emissions and that substantial warming beyond that which has already been experienced is not geophysically unavoidable. *[High confidence*] Whether or not this occurs depends on future rates of emission reductions. In contrast, impacts that depend on cumulative warming, such as sea level rise, will continue to intensify even after global emissions are reduced to zero.**{1.2.6}**

The cumulative impact of CO2 emissions means that any initial delay in emission reductions requires faster subsequent reductions to meet the same temperature goal, or subsequent active net CO2 removal to reduce temperatures following a temperature overshoot. At the present rate of human-induced warming, global temperatures would reach 1.5°C in the 2040s, or earlier if emissions continue to rise and warming continues to accelerate. *[High confidence*] To avoid temperatures exceeding 1.5°C, the rate of human-induced warming would need to be reduced, starting immediately, by 50% by the 2040s, and subsequently reduced to zero on a similar timescale thereafter.**{1.2.6}**

The concept of pathway provides a valuable conceptual narrative and operational framing for understanding the conditions required to enable limit warming to a 1.5°C. Multiple potential pathways towards the ambition of limiting warming to 1.5°C exist, with different implications for mitigation and impacts. But avoiding exceedance of 1.5°C requires rapid and deep reductions in greenhouse gas emissions. A 50% reduction in the rate of human-induced warming requires halving the annual global emission rate of cumulative greenhouse gases such as CO_2, with corresponding reductions in other climate drivers. **{1.3/1.2}**

Impacts at 1.5°C in this report refer to the projected impacts when the global mean temperature is 1.5°C above pre-industrial levels. Several regions already experience higher levels of warming and associated impacts. For many regions, an increase in global mean temperature of 1.5°C or 2°C also implies substantial increases in the occurrence and/or intensity of some extreme events. Impacts are not all driven by warming. Some are related directly to greenhouse gas concentrations, and some could also result from ambitious efforts to constrain atmospheric greenhouse gas concentrations (e.g. the displacement of land by Bioenergy with Carbon Capture and Storage, or BECCS). Hence impacts at 1.5°C depend on how 1.5°C has been achieved. Finally, the character and severity of impacts depend not only on the hazards (e.g. changes in climate averages and extremes) but also on the vulnerabilities of different communities, and their exposure to climate threats. Adaptive capacity to a 1.5°C warmer world will vary markedly for individual sectors and across sectors such as water supply, public health, infrastructure, ecosystems and food supply.**{1.3}**

Many impacts of transient warming passing through 1.5°C would be very different from the impacts if climate stabilised at 1.5°C, or returned to 1.5°C following an overshoot. For example, some ecosystems may not recover after a temperature overshoot. A 1.5°C warmer world will exacerbate other global scale risks such as the degradation of ecosystems, extreme events such as heat waves, reduced food security, increased disease outbreaks, and reduced access to fresh water. The probability of extreme weather and climate events and irreversible changes increases rapidly at higher warming levels. Extreme weather and climate risks that result in resource depletion, conflict and forced migration are impacting economic development worldwide, and warming of 1.5°C or beyond present increased challenges to addressing the Sendai Framework for Disaster Risk Reduction 2015-2030. Increased exposure to these hazards and severe inequity in resource distribution, chronic poverty and marginality in many global regions amplifies vulnerability to climate change. Many existing risks specific to rural areas and medium to large size urban areas and cities will be magnified **{1.3}**

Links, synergies and trade-offs between mitigation, adaptation and sustainable development, as well as the different dimensions of feasibility, are critical to understanding climate resilient development pathways to limiting global warming to 1.5°C. The connections between limiting global warming to 1.5°C and ambitions of sustainable development are societally and spatially complex and multifaceted. Such connections can be synergistic or involve trade-offs and are best understood holistically, recognising how all aspects of life on Earth are impacted by human decisions in the Anthropocene. AR5 noted that climate change constitutes a moderate threat to current sustainable development and a severe threat to future sustainable development. AR5 also concluded that ill-designed responses could offset already achieved gains. However, important synergies exist between achieving the UN Sustainable Development Goals (SDGs) and climate responses. Positive synergies between mitigation, adaptation and sustainable development can be presented within the narrative of climate resilient development pathways of both rural areas and cities**.** Feasibility is considered in this report as the systems-level capacity to achieve a specific goal or target. A complete vision of feasibility requires integration of natural system considerations into 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.**{1.4.5; 1.4.6; 1.4.7}**

Climatic variability and climate change may exacerbate poverty, particularly in countries and regions where poverty levels are high. Modest changes in rainfall and temperature patterns can push marginalized people into poverty, as they lack the means to recover from shocks. Changes in the frequency of extreme events in an 1.5°C warmer world especially when occurring in a series, plus increased exposure, can significantly erode poor people's already limited resources and adaptation and mitigation capacity, and further undermine their livelihoods in terms of economic assets, housing, infrastructure, and social networks.**{1.4.2}**

Recognising that the impacts of climate change for warming levels beyond 1.5°C and associated response to these impacts could fall disproportionately on the poor and vulnerable, ethics and equity are essential elements of this assessment. Equity—informed by ethics—offers a useful organizing framework for understanding the asymmetry between the distributions of opportunities, benefits and costs in relation to climate change, among present and future generations. Three key points of connection between climate change and equity are associated with the conditions under which a 1.5°C warmer world can be 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 and implement solutions and response strategies. Mitigation and adaptation options also have potentially profound implications for equity, especially if framed without considerations of the complex local-national to regional linkages and feedbacks in socio-ecological and socio-economic systems.**{1.4.1}**

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, ethics and equity. Work on adaptive and flexible governance systems and policy experimentation can provide key insights on decoupling economic growth from greenhouse gas emissions. Significant governance challenges include the ability to incorporate multiple stakeholder perspectives in the decision-making process to reach meaningful and equitable decisions; interaction across scales and coordination between the different levels of government, NGOs, Congressional Budget Offices, academia and the private sector; 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, ethics and poverty eradication.**{1.4}**

Transitioning from climate change mitigation planning to practical implementation is a major challenge in constraining global temperature to 1.5°C. Barriers which also apply to adaptation include finance, education and new innovative knowledge, information, technology, public attitudes, social values, and practices, and human resource constraints, plus institutional capacity to strategically deploy resources. Regional diversity, including highly fossil-fuel-invested and emerging economies, is an important consideration in a limiting global temperature to 1.5°C. Incorporating strong linkages across sectors, devolution of power and resources to sub-national and local governments, especially within cities and areas rapidly urbanizing, with the support of national government and facilitating partnerships among public, civic, private sectors and education institutions are key to implementing identified response options.**{1.4}**

A diverse set of state-of-the-art assessment methodologies provides enhanced capacity to understand and specify potential conditions of a 1.5°C warmer world. Incorporating knowledge from different sources, as well as educating and building awareness at various levels could provide for informed decision making to implement 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. Instrument data along with indigenous and local knowledge and experience are both critical for verifying climate models and for evaluating climate change scenarios for 1.5°C warming. Cost-benefit analyses are by themselves insufficient for assessing a 1.5°C world. Costs and benefits can occur at very different times, even across different centuries for different regions, and often cannot completely describe unpredictable feedback loops and impacts for other regions.**{1.5}**

1.1 Building a knowledge base for a 1.5°C World

Previous Intergovernmental Panel on Climate Change (IPCC) reports have explicitly demonstrated evidence of human interference in the climate system. The IPCC Fifth Assessment Report (AR5) found that the average global surface temperature has reached approximately 1°C above pre–industrial levels (IPCC, 2013), and monthly average temperatures of 1.4°C above these same levels have been observed. The warming to date has generated observable impacts world–wide, and acts as an amplifier of risks for natural and human systems (see 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 in the context of sustainable development and poverty eradication (see Box 1.1 on the Anthropocene).

The present report assesses the enabling conditions and challenges to limit the rise in global temperatures to 1.5°C above pre–industrial levels, and the effects and impacts of a 1.5°C warmer world. The report considers the potential global response to this challenge within the context of achieving sustainable development and poverty eradication while addressing the long–standing ethical dilemmas posed by climate change, with particular reference to the United Nations Framework Convention on Climate Change (UNFCCC) notion of equity. 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 (UN, 2015), with much of this growth occurring in hazard–prone small and medium sized cities in vulnerable low and moderate–income countries (Birkmann et al., 2016).

The spread of material consumption with rising incomes and changing lifestyles is a major driver of global resource use, environmental degradation and pollution, and a contributor to rising greenhouse gas (GHG) emissions (Fleurbaey et al., 2014b). These profound global–scale changes currently underway explain the recognition that we now live in a new era, the 'Anthropocene', in which human influence is the principal agent of change on the planet (see Box 1.1 on the Anthropocene). Climate change is one among numerous other global-scale human imprints such as large scale conversion of Earth's land surface from forest and grassland to croplands, grazing lands and cities; significant biodiversity loss; changes in the global phosphorus and nitrogen cycles; ocean acidification; and sea level rise characteristic of the Anthropocene.

The present report provides an assessment of current knowledge of the extent and interlinkages of the global environmental, economic, financial, social and technical conditions that a 1.5°C warming world represents. Complex ethics questions arise in that both climate change and any potential responses to it that exacerbate poverty and inequality, globally and locally, and carry implications for inter–generational justice. This set of conditions demands interdisciplinary research and reflection, pointing to a systems approach that takes into account social inequalities and the unequal distribution of both, risks in exposure, and ability to respond, to climate change (Bäckstrand et al., 2017; Dryzek, 2016; Lövbrand et al., 2017; Pattberg and Zelli, 2016).

1.1.1 Pathways, Impacts, and Sustainable Development

Limiting global warming to 1.5°C will require substantial societal and technological transformations. This assessment builds on previous IPCC assessments to provide a range of pathways, including implementation strategies to understand the enabling conditions required for such a transformation. These pathways and connected strategies are framed operationally within the context of the United Nations 2030 Agenda for Sustainable Development and conceptually within the Anthropocene. Ways to alter or slow the pace of current warming are illustrated through mitigation pathways (see Chapter 2 of this report). The enabling conditions required for achieving the 1.5°C warming include a range of geo–physical, technological, and socio–economic dimensions of feasibility (described in Cross–Chapter 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 (see Chapter 4 of this report). Some pathways are more consistent than others with the requirements for sustainable development (see Chapter 5 of this report).

Temperature rise to date already has resulted in profound alterations to human and natural systems, bringing new risks for human well–being and economic development (IPCC, 2014a; Chapter 3 of this report). Many regions of the world have experienced local warming above 1.5°C already (see Figure 1.1 and 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 and present a challenge to addressing the Sendai Framework for Disaster Risk Reduction (Mysiak et al., 2016; Chapter 3 Section 3.4). Most affected people live in low and middle income countries, some of which have already experienced decline in food security, linked in turn to rising migration and poverty. Small islands and populations residing in megacities, coastal regions and in high mountain ranges are among the most affected (Albert et al., 2017).

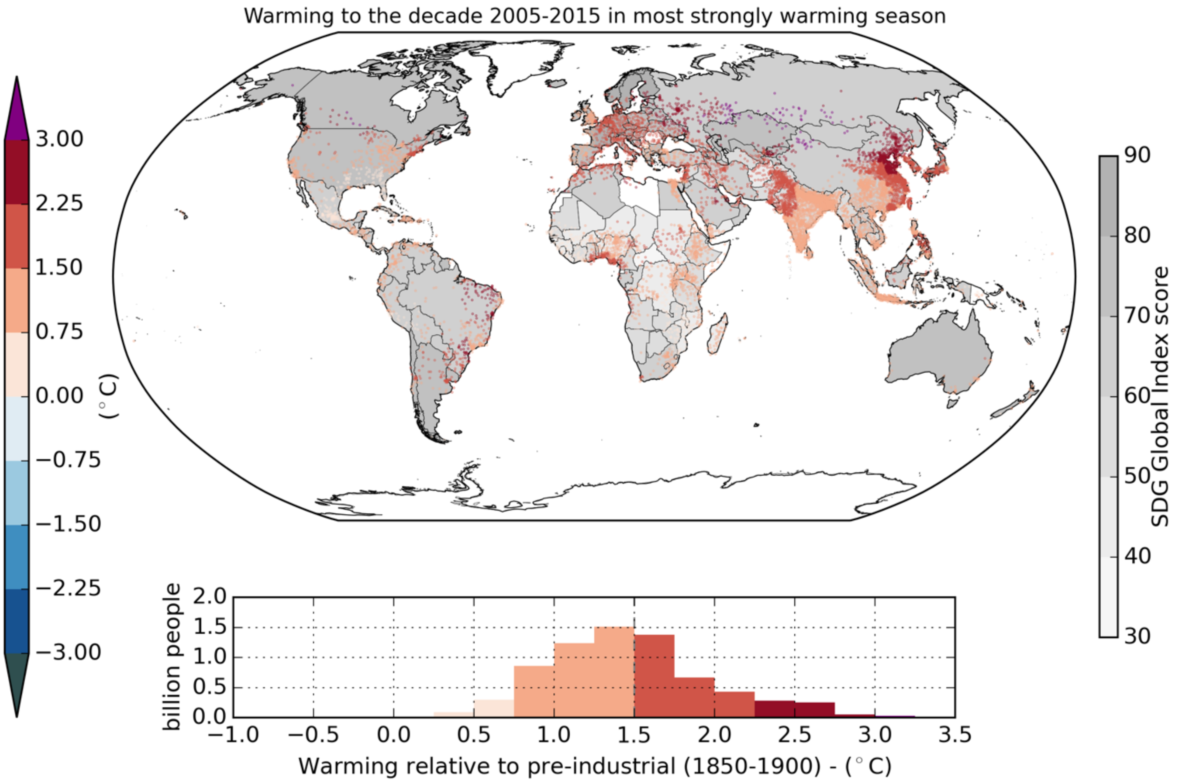


Figure 1.1: Realised experience of present–day warming. Colours externally–forced warming in over the over 2006–2015 relative to 1850–1900 for the most strongly warming season at any location using the GISTEMP dataset (Hansen et al., 2010b). The density of dots indicates the population (2010) in any 1°x1° grid box. Warming trends are calculated in an identical way to Figure 1.3. The underlay shows SDG Global Index Score ranks at a country level indicating performance across 17 sustainable development goals. White indicates missing data. The histogram shows the distribution of warming shown on the map. See Technical Annex of this chapter for further details.

The feasibility of any global commitment to a 1.5°C pathway depends, in part, on the nationally determined contributions (NDCs), committing nation states to specific GHG emission reductions. The current NDCs are not ambitious enough to secure the 1.5°C warmer world and are instead tracking toward a warming of 3–4°C above preindustrial temperatures by 2100, with the potential for further warming thereafter (Rogelj et al., 2016; UNFCCC, 2016). The analysis of pathways in this report reveals opportunities for greater decoupling of economic growth from the rate of GHG emissions. Movement toward 1.5°C requires an acceleration of this trend. Integrated reflexive policy institutions capable of operating at multiple scales (from local to regional and international) will be essential to affect the far–reaching policy change required to bring about reductions in GHGs consistent with a 1.5°C warmer world, while simultaneously strengthening global responses to poverty and addressing associated emerging ethics and equity issues (Bäckstrand et al., 2017; Dryzek and Pickering, 2017; Lövbrand et al., 2017).

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., 2014b). As a result, attempts to limit warming to 1.5°C , while at the same time reducing poverty, will benefit from attentiveness to the Anthropocene narrative on the unprecedented social–ecological and technical change with differential impacts and risks that give rise to the need for a sustainable development framework (Delanty and Mota, 2017) (Box 1.1 on the Anthropocene). A fuller understanding of 1.5°C related impacts, risks, and actions comes from a variety of established or emergent knowledge bases that are also critical to fully realise the conditions for strengthening of the sustainable development agenda (Olsson et al., 2017).

In this assessment, the definition of sustainable development, rooted in the 1987 report *Our Common Future*, includes '… development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). The recent UN Sustainable Development Goals (SDGs) are an interlinked network of targets that are crucial to addressing the interconnected challenges of advancing human 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 (UN General Assembly, 2015). The SDGs require that the achievement of targets be assessed through suitable indicators periodically at global conferences, offering a useful forum in which to monitor and promote efforts to manage climate change sustainably in the context of other global challenges.

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). Nevertheless, how to achieve these aspirations alongside the transitions needed to secure a 1.5°C warming world are associated with innovative planning efforts. 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), encouraging actions also by non–state actors such sub–national entities including cities (Morgan and Northrop, 2017). This extends to the efforts by citizens where individuals take measures to reduce their personal emissions in order to lobby for structural changes through legislative and regulatory measures within their jurisdictions. Limiting the rise in global temperatures to 1.5°C while meeting the ambition of the SDGs will be associated with enabling conditions to adjust current lifestyles, development trajectories, and economic systems, and exploring new ways of facilitating social investment, reducing inequality and deliver ecological and financial stability (Jackson, 2017).

1.1.2 Equity and Ethics Framing for a 1.5°C Warming World

The aspiration to stay within a 1.5°C target raises ethical concerns that have long been central to the climate debate. The UNFCCC process has been guided by ethical consideration articulated in particular through the principle of equity (Kolstad et al., 2014). Article 3 of the UNFCCC establishes that Parties should 'protect the climate system … on the basis of equity' and Article 2 of the Paris Agreement likewise provides that it 'will be implemented to reflect equity… in the light of different national circumstances'. Further, the Paris Agreement Article 4 calls for 'rapid reductions' of greenhouse gases to be achieved 'on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty'. While Article 14 requires that the 'global stocktake' be undertaken 'in light of equity and the best available science'. All of these articles place 'equity' in the context of the relative distribution of the burdens of climate action between different countries.

These considerations of ethics and equity have been most recently articulated in questions of human rights (Adger et al., 2014; Caney, 2010; Fleurbaey et al., 2014b; Humphreys, 2010; IBA, 2014; Knox, 2015; OHCHR, 2009). How, for example, will an average global temperature rise of 1.5°C impact upon human rights especially of the already vulnerable persons, including their rights to water, shelter, food, health and life? How will it affect the rights of the urban and rural poor, indigenous communities, women, children, the elderly and people with disabilities? How will mitigation efforts to meet the 1.5°C target in low and middle income countries affect human development and wellbeing? (Caney, 2010).

This report will examine whether and how failure to limit warming to 1.5°C will result in further human rights consequences. It assesses at the degree to which the gap between 1.5°C and 2°C amounts to a greater likelihood of drought, flooding, resource depletion, conflict and forced migration, each affecting individuals' human rights in many parts of the world and with a potential to negatively affect the global economy (See Chapter 3) (Adger et al., 2014; Campbell et al., 2016; FAO et al., 2015; OHCHR, 2009). The report will also examine whether mitigation and adaptation policies have potentially 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 (Dryzek and Pickering, 2017; Knox, 2015; UNHRC, 2016).

1.1.3 Report Structure

The thrust of this report is to assess enabling conditions 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. It also includes 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 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. While 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 builds upon the IPCC AR5 WGII work with an emphasis on sustainable development in mitigation pathways. Responding to 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. Avoided impacts and reduced risks at 1.5°C are compared with 2°C and comparative higher levels of warming. The assessment of system level conditions such as timeframes, slow versus fast onset impacts, irreversibility and tipping points are included.

Chapters 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 the 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.

Box 1.1: The Anthropocene as Framing

Introduction

The concept of the Anthropocene and the aspiration of the Paris Agreement are linked. The Anthropocene expresses empirical evidence that human impacts on the Earth System have become so large they led to a proposal that the Earth has entered a different geological epoch, the Anthropocene (Crutzen, 2002; Crutzen and Stoermer, 2000; Gradstein et al., 2012). Abundant observational data of this transition exists (Steffen et al., 2016; Waters et al., 2016), among which contemporary rates of change are very fast compared to previous abrupt shifts in Earth's climate. The rate of CO_2 increase, currently at about 20 ppm per decade, is 100 times faster than any sustained rise in CO_2 during the past 800,000 years (Wolff, 2011) and at least an order of magnitude greater than the rates observed in short bursts during the last deglaciation (Marcott et al., 2014; Rhodes et al., 2017). While global average surface temperature is now rising at a rate 170 times faster than the average rate of change since the mid–Holocene (ca. 7,000 years BP) (Marcott et al., 2013).

The physical dimensions of the Anthropocene and 1.5°C global warming

Although the process of formal adoption of the Anthropocene proposal is still subject to debate (Zalasiewicz et al., 2017), a strong majority of the Anthropocene Working Group (AWG) by the Sub–Committee on Quaternary Stratigraphy of the International Commission on Stratigraphy have agreed that (i) the Anthropocene is real from a geological perspective; (ii) it should be formalized as an epoch and included in the Geological Time Scale, following the Holocene; and that (iii) a mid–20th century beginning of the Anthropocene is most appropriate. Markers in the stratigraphic record include an array of novel manufactured materials of human origin, such as aluminium, concrete and plastics; particulates from fossil fuel combustion; radionuclides from the fallout of nuclear tests; and others leading to the conclusion that "these combined signals render the Anthropocene stratigraphically distinct from the Holocene and earlier epochs" (Waters et al., 2016). The literature on the Anthropocene has expanded rapidly beyond the geological science to other earth system sciences, the social sciences and humanities. Increasingly, social science and humanities literature show that the Anthropocene provides a framing to understand pathways through which society could pursue equitable, innovative and responsible approaches for a warming planet.

The underlying narrative of recent IPCC reports and the Paris Agreement embody the intent behind the Anthropocene. Human action is driving global change and that human action can be consciously applied to address this rate of change. The ambition of the Paris Accord to 'pursue efforts to limit' the rise in global temperatures to 1.5°C above pre–industrial levels recognizes that humanity has achieved an unprecedented ability to influence geophysical planetary processes. In this way, the Paris Agreement is better understood and assessed within the context of the Anthropocene.

This assessment report carries this approach forward and employs the Anthropocene as a framing device to advance an understanding of the impacts and risk of the 1.5° C warming world and the multiple pathways that define the trajectory of the physical and societal systems during this transition. The assessment of limiting global warming to 1.5° C above pre–industrial levels, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty require a holistic approach that integrates human–biophysical interconnectivity across multiple scales. This makes this report amenable to the concept of the Anthropocene.

Framing in the Anthropocene

The Anthropocene is emerging as a "boundary concept": a term that can serve to embed critical insights into understanding the drivers, dynamics and specific challenges in responding to the ambition of keeping global temperature well below 2˚C and adapting to a 1.5˚C warmer world (Brondizio et al., 2016). It offers a structured understanding of the culmination of past and present human–environmental relations and provides an opportunity to better visualize the future and minimizing pitfalls (Delanty and Mota, 2017; Pattberg and Zelli, 2016). By acknowledging the dominant influence of human action on planetary functions, society is acknowledging differentiated responsibility and opportunity to probe its capacity to mobilize activities to realize desirable change in ways that will maintain planetary viability and prospects for climate resilient sustainable development (Harrington, 2016). Humanity, while facing high uncertainty and poor control over the trajectory of planetary processes (Shove and Walker, 2007), also has reflexivity, anticipatory capacity and ability to learn in order to alter the climate change trajectory and its impacts (Palsson et al., 2013). As a result a major question for this assessment is how, under the Anthropocene can climate mitigation and adaptation be better integrated with sustainable development to reduce negative environmental impacts and minimize poverty? These climate resilient sustainable development pathways are assessed in the latter chapters of this report (especially Chapter 5).

Human–driven climate change is another expression of the depth of the global interlinkages of the human and nature interactions that are an embodiment of the Anthropocene concept. While human influence over the Earth System has consolidated over the last 60–150 years through accelerated economic and demographic growth and connectivity, the result has not been wholly uniform (Lövbrand et al., 2015; Palsson et al., 2013). The Anthropocene epoch is in fact a manifestation of the differential influence that some populations, specific activities and technologies, and, importantly, worldviews and associated values have on planetary functions (Brondizio et al., 2016; Castree, 2015; Lövbrand et al., 2015; Palsson et al., 2013).

Employed in a nuanced and reflexive manner, the Anthropocene provides an opportunity to raise questions regarding the regional differences, social inequities and uneven capacities and drivers of global social–environmental changes, which in turn motivates the search for solutions as explored in

Chapter 4 (Biermann et al., 2016). It links uneven influence of human actions on planetary functions to an unevenly distribution of impacts (assessed in Chapter 3) as well as the responsibility and response capacity to for example, limiting global warming to no more than a 1.5° C rise above pre–industrial levels. As a result efforts to curtail greenhouse gas emissions without incorporating the intrinsic interconnectivity and disparities associated with the Anthropocene world may themselves negatively affect the development ambitions of some global regions more than others (see Chapter 2 and Chapter 5).

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

1.2.1 Working definitions of 1.5°C and 2°C warming relative to preindustrial levels

What is meant by 'the increase in global average temperature … above pre–industrial levels' referred to in the Paris Agreement depends on the choice of pre–industrial reference period, whether 1.5°C refers to total warming or the human–induced component of that warming, and which variables and geographical coverage are used to define global average temperature change. The cumulative impact of these definitional ambiguities (e.g. Hawkins et al., 2017) is a couple of tenths of a degree, comparable to natural multi–decade temperature variability on continental scales (Deser et al., 2012). Most practical mitigation and adaptation decisions do not depend on quantifying warming to this level of precision, but a consistent working definition is helpful to ensure consistency across chapters and figures in this report.

This report defines the increase in global average temperature above pre–industrial levels at a given point in time as the global average of combined land surface air and sea surface temperatures for a 30–year period centred on that time, excluding the impact of any short–term natural forcing fluctuations and assuming any secular trend continues throughout that 30–year period. On this definition, an explosive volcanic eruption might temporarily reduce observed global temperatures, but would not reduce the estimated overall warming relative to pre–industrial levels. Likewise, if temperatures are warming at 0.2°C per decade (Kirtman et al., 2013), then warming on the definition proposed here at the end of a 30–year period would be 0.3°C higher than the average over that 30–year period, because this definition assumes that this trend would continue. In the context of ambitious mitigation goals, using a traditional definition of "observed climate" using an average over a recent multi–decade period can introduce a substantial bias unless the trend is taken into account. There are multiple ways of estimating this quantity (e.g., Foster and Rahmstorf, 2011; Haustein et al., 2017; Medhaug et al., 2017): this section does not endorse a particular method, but aims to clarify what is being estimated. For consistency with AR5, the reference period 1850–1900 is used to represent pre–industrial conditions. The implications of this choice are discussed in 1.2.1.2 below.

Using the global temperature datasets in AR5, combined and updated, this report therefore considers that 1.5°C relative to pre–industrial conditions corresponds to 0.86°C (±0.05°C 5–95% range) warmer than the period 1986–2005, or 0.63°C (±0.10°C) warmer than the decade 2006–2015, the periods 1986–2005 and 2006–2015 having been 0.64°C and 0.87°C warmer than 1850–1900 respectively, with corresponding uncertainties. This assumes that temperatures in both periods are representative of a 30–year period centred on them. Where possible, the later period is used, because temperatures in the earlier period were affected by the eruption of Mount Pinatubo. These figures are consistent with the overall assessment of the current level and rate of warming in AR5 and the 2013–15 Structured Expert Dialogue. Where possible, estimates of impacts and mitigation pathways are expressed relative to these more recent periods to avoid conflating uncertainty in projections with uncertainty in historical changes

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 have typically used a simple area average of SAT over land, sea–ice and oceans. In the context of ambitious temperature goals, and under conditions of rapid warming, 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 from the 19th century to the present in the 5th Climate Model Intercomparison Project (CMIP5) ensemble than the use of area–average SAT, about half of which emerges in the recent period of rapid sea–ice retreat, while Richardson et al. (2016) show that incomplete coverage reduces this warming by a further 0.1°C (see inset panel in Stocker et al., 2013, Figure TFE8.1 and Figure 1.1). However, Richardson et al. (2017) show that coverage and blending has less impact on future warming relative to the present, particularly under ambitious mitigation scenarios. Hence the choice of blended SAT/SST or global SAT to define GMST is primarily an issue for the interpretation of the historical record for model evaluation and the definition of warming to the present, not for projection of future changes. 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.

The three GMST reconstructions used in AR5 differ in their treatment of missing data. GISTEMP (Hansen et al., 2010a) places the most weight on poorly–observed regions like the Arctic, while NOAA (Vose et al., 2012) and HadCRUT (Morice et al., 2012) are progressively closer to a simple average of available observations, which is equivalent to assuming that the average warming in unobserved regions is the same as that in observed regions. Since AR5, considerable effort has been devoted to more sophisticated statistical modelling to account for the impact of incomplete observation coverage (Cowtan and Way, 2014; Jones, 2016; Rohde et al., 2013). The main impact of statistical infilling is to increase estimated warming to date by about 0.1°C (Richardson et al., 2017). Full assessment of the reliability of these infilling methods is beyond the scope of this report. The 2013–2015 Structured Expert Dialogue relied on the GMST reconstructions used in AR5 and contains the statement: "At the current level of warming of 0.85°C above pre–industrial levels, impacts have been observed on all continents and in all oceans". Redefining GMST to represent a pure SAT metric with fully global coverage could increase this 0.85°C figure to over 1°C, without affecting projected future changes relative to the present, as shown by the difference between the blue dashed and solid lines in Figure 1.2. This would be similar to the impact of adopting different reference periods to 1850–1900. For consistency with the guidance given in the Structured Expert Dialogue, therefore, this report 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 (Karl et al., 2015) which affect trends over recent decades, but not warming relative to the 19th century. Available estimates of warming from various datasets are provided in Table 1.1.

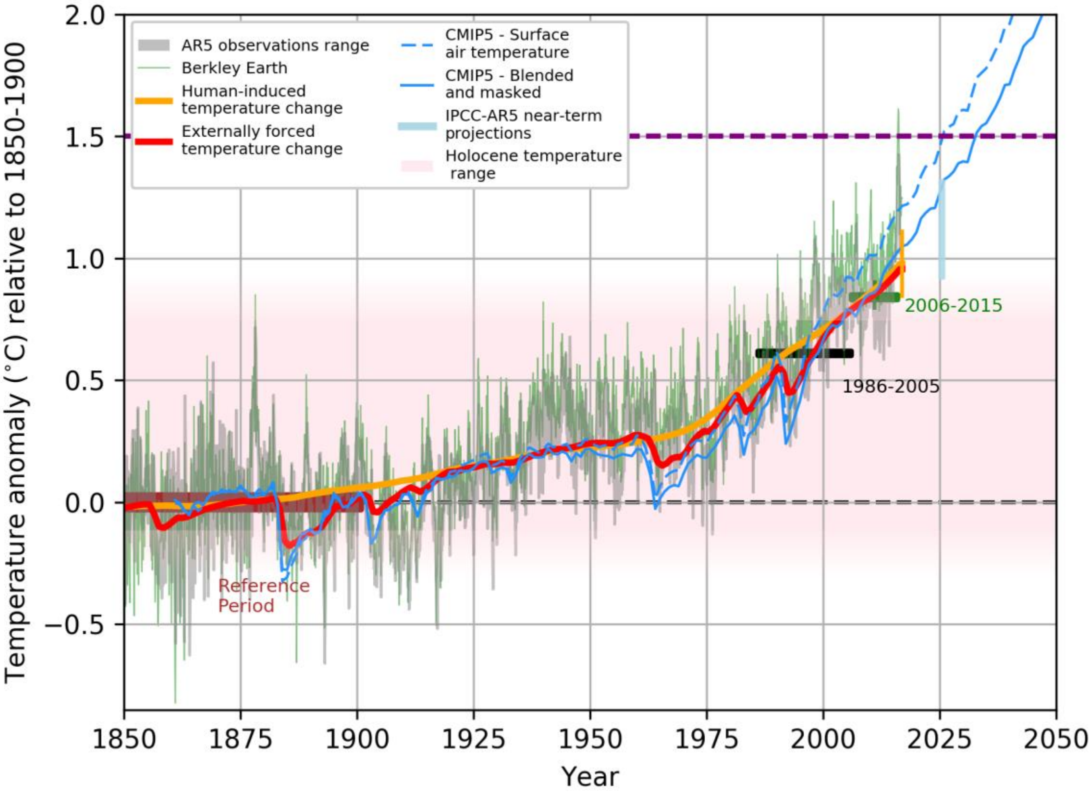


Figure 1.2: Evolution of global mean surface temperature (GMST) over the period of instrumental observations. Grey line shows departures from the 1850–1900 reference period for monthly means of the HadCRUT4, NOAA and GISTEMP datasets assessed in AR5, with line thickness indicating inter–dataset range. Green line shows the Berkeley Earth Surface Temperature as an example of more recent datasets using statistical methods to further account for the impact of incomplete coverage. All observational datasets shown represent GMST as a blended mix of near surface air temperature over land and sea surface temperature over oceans. Human–induced (orange) and total human– and naturally–forced (red) contributions to these GMST changes are shown calculated following Otto et al. (2015) and Haustein et al. (2017). Proportional uncertainty in the level of human–induced warming in 2016 is set equal to that assessed in Bindoff et al. (2013). 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). The pink shading indicates a range for temperature fluctuations over the Holocene (Marcott et al., 2013; Marsicek et al., 2017). 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. This report adopts the 51–year reference period, 1850–1900 inclusive, assessed as representative of pre–industrial conditions in AR5 (e.g., Box TS.5, Figure 1 of Field et al., 2014a). The years 1880–1900 are subject to strong but uncertain volcanic forcing, but the net impact of this forcing on observed temperatures over the full 51–year period appears to be small: in HadCRUT4, average temperatures over 1850–1879 are less than 0.01°C from the average for 1850–1900. Hawkins et al. (2017) argue that the 1720–1800 period is more representative of pre–

industrial forcing conditions, at the cost of increased uncertainty. Temperatures rose by 0.0–0.2°C from 1720–1800 to 1850–1900 (Hawkins et al., 2017; Schurer et al., 2017), but the anthropogenic contribution to this warming is uncertain (Schurer et al., 2017). The 18th century represents a relatively cool period in the context of Holocene temperatures that are estimated to have peaked around 5,000 years ago and declined slightly since (Marcott et al., 2013; Marsicek et al., 2017).

Modelling studies and projections may require different reference periods: for example, carbon budget calculations in the AR5 (e.g. Table 2.2 of the IPCC (2014a)) used 1861–1880 to avoid the volcanic forcing problem. Many impact studies use 1986–2005. The use of a more recent reference period, offset by historical observations, avoids conflating uncertainty in past and future changes, which may have a substantial impact on results (e.g. Millar et al., 2017a). Two recent reference periods will be used in this report: 1986–2005 and 2006–2015. In using a single decade to represent a 30–year average centred on that decade, it is important to consider the potential impact of internal climate variability. The years 2008–2013 were characterised by persistent cool La Niña conditions (Kosaka and Xie, 2013; Medhaug et al., 2017), potentially related to multi–decadal Pacific variability (e.g., England et al., 2014), but these were partially compensated for by El Niño conditions in 2006 and 2015. Figure 1.2 indicates that natural variability (internally generated and externally driven) had little net impact on average temperatures over 2006–2015, in that the average temperature of the decade is similar to the estimated externally–driven warming, while volcanic activity significantly depressed temperatures in 1986–2005. In carbon budget calculations in which emissions are calculated from a particular year, this report recommends using the 2006–2015 reference period and offsetting to the year from which emissions are counted using the AR5 estimate of 0.17°C (±0.07°C) decade^{-1} for the trend from 1996 to 2026.

Table 1.1: Observed increase in global average surface temperature in various datasets

Name of dataset:	1986–2005 vs 1850–1900	2006–2015 vs 1850–1900	2006–2015 vs 1986–2005	Linear trend 1880–2015 (1)
HadCRUT4	0.62 (0.58–0.67)	0.84 (0.79–0.89)	0.22 (0.21–0.23)	0.88 (0.83–0.95)
NOAA	0.63	0.86	0.22	0.91
GISTEMP	0.67	0.91	0.23	0.97
Average (3)	0.64	0.87	0.22	0.92
HadCRUT4–CW (4)	0.65 (0.60–0.72)	0.91 (0.85–0.99)	0.26 (0.25–0.27)	0.93 (0.85–1.03)
Berkeley (4)	0.74	0.99	0.25	1.05
JMA (4)	NaN	NaN	NaN	NaN
Reanalysis (4)	NaN	NaN	NaN	NaN
CMIP5 SAT (5)	0.63 (0.35–0.94)	0.99 (0.72–1.37)	0.36 (0.23–0.62)	0.88 (0.64–1.38)
CMIP5 blend (5)	0.47 (0.27–0.77)	0.83 (0.57–1.16)	0.33 (0.19–0.53)	0.74 (0.52–1.13)

1) In degrees per year multiplied by 135 years.
2) HadCRUT4 estimate scaled by the ratio of linear trends 1880–2015
3) To combine information from all three datasets assessed in AR5 (HadCRUT4, NOAA and GISTEMP), while also using the 1850–1900 reference period adopted as representative of pre–industrial conditions in AR5, this report computes average warming from 1850–1900 to both 1986–2005 and 2005–2015 periods using the HadCRUT4 dataset, updated, and scaled by the ratio of the linear trend 1880–2015 averaged over all three datasets with the corresponding linear trend computed from HadCRUT4.

4) Not included in observational datasets assessed in AR5. JMA and Reanalysis data will be added if possible in the Final Draft.
5) Estimated relative to 1861–80 plus 0.02°C for the offset in HadCRUT4 from 1850–1900. CMIP5 values are the mean of the RCP8.5 ensemble, with 5–95% ensemble range. They are included to illustrate the difference between a truly global surface air temperature record (SAT) and a blended air and water temperature record accounting for incomplete coverage (blend), following Richardson et al. (2016). Note that 1986–2005 temperatures in CMIP5 appear to have been depressed more than observed temperatures by Mount Pinatubo.

1.2.1.3 Total versus human–induced warming in mitigation and impact studies

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. Mitigation studies focus on human–induced warming, while studies of climate change impacts typically refer to total or externally–forced warming, defined by multi–decade averages.

In the absence of strong natural forcing due to changes in solar or volcanic activity, the difference between total and human–induced warming is relatively small. Figure 1.2 shows, for example, that human–induced warming since the 19th century is currently close to total observed warming, the net contribution of natural climate variations being small once they are averaged out: this situation would change were one or more large volcanoes to erupt. Monthly temperatures fluctuate substantially around this externally–driven warming.

Many impacts take time to observe. For example, it may not become clear that the frequency of a particular class of extreme weather event is changing until decades after the change has begun, simply because the events happen infrequently. Hence, although GMST on the working definition adopted here is estimated to have reached 1°C around 2017/18, the statement that ‘we are already experiencing the impacts of 1°C of warming’ needs to be interpreted carefully. Impacts over the past 20 years were associated with temperatures that were, on average, 0.17°C (±0.7°C) colder than the present level of warming, based on the AR5 estimate of the warming trend over this period. Extreme event attribution approaches based on statistical and/or dynamical modelling (e.g. van Oldenborgh et al., 2017) can address this bias, but informal estimates of ‘recent impact experience’ necessarily understate the temperature impact of current warming in a rapidly warming world.

On the definition of a ‘1.5°C warmer world’ proposed in this section, global temperatures would fluctuate equally on either side of 1.5°C over a sufficiently long time period and 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, Figure 1.2 indicates there is a substantial chance of temperatures in a single month fluctuating over 1.5°C between now and 2020, but this would not constitute temperatures ‘reaching 1.5°C’ on our working definition. Observed 20–year–average global temperatures varied by ±0.1°C (5–95% range), while monthly temperatures varied by ±0.2°C, around the human–induced warming trend over the period 1861–2017. Regional temperature fluctuations would be larger on both timescales (Deser et al., 2012).

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, 2013). 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 1.3, which shows an estimate of the observed change in annual and seasonal average temperatures associated with the observed 0.87°C rise in global temperatures in the 2006–2015 decade, relative to the 1850–1900 pre–industrial reference period. Many locations, particularly in northern mid–latitude winter (December–February), have already experienced regional warming in excess of 1.5°C or even 2°C, with warming particularly amplified over land in the northern mid– and high–latitude regions. Natural climate fluctuations mean that individual seasons may be substantially warmer, or cooler, than these expected long–term average changes.

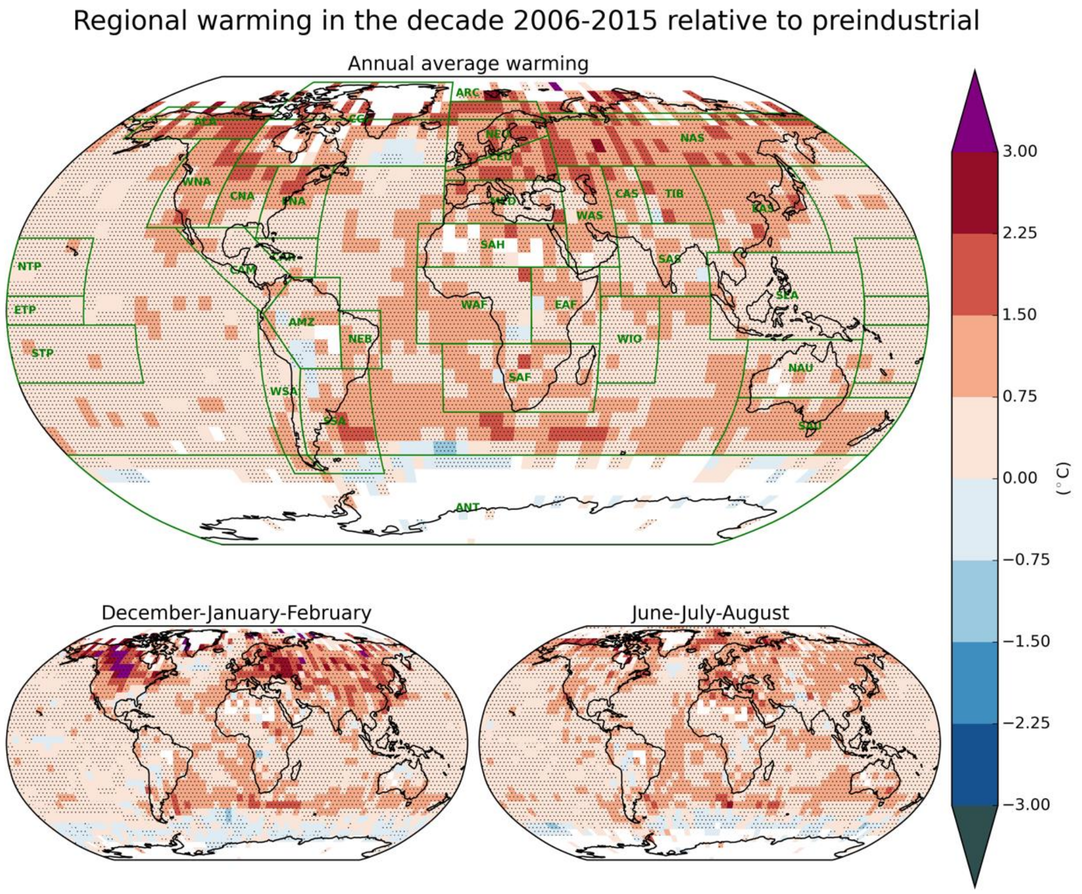


Figure 1.3: Externally–forced warming for the average of the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January and February (bottom left) and for June, July and August (bottom right). Warming is evaluated by regressing regional changes in the HadCRUT4 dataset onto the total (human and natural) externally–forced warming (red line in Figure 1.2). Grid–boxes left white where missing data exceeds 50% of the record. Stippling indicates the regression relationship is statistically significance at the 10% confidence level assuming Gaussian errors. See Technical Annex 1.A of this chapter for further details. The definition of regions (green boxes and labels in top panel) is adopted from AR5 (Christensen et al., 2013).

1.2.3 Trends in emissions and radiative forcing

Figure 1.2 shows a small increase in the estimated rate of human–induced warming since 2000, reaching 0.2°C per decade in the past few years. This is attributed (Haustein et al., 2017) to recent changes in a range of climate forcers, reviewed in this section.

Most studies partition anthropogenic climate forcers into two groups by their lifetime. CO_2 and other long–lived climate forcers (LLCFs) such as nitrous oxide, sulphur hexafluoride and some halogenated gases contribute to forcing over decades and centuries. Other halogenated gases, ozone precursors and aerosols are defined as short–lived climate forcers (SLCF) due to their lifetime of one to several years in the atmosphere. Although methane is either considered as a LLCF or SLCF in published studies or reports (Bowerman et al., 2013; Estrada et al., 2013; Heede, 2014; Jacobson, 2010; Kerr, 2013; Lamarque et al., 2011; Saunois et al., 2016a; WMO, 2015), we assign methane as a SLCF for the purpose of climate assessment, because its lifetime is comparable to or shorter than the thermal adjustment time of the climate system (Smith et al., 2012).

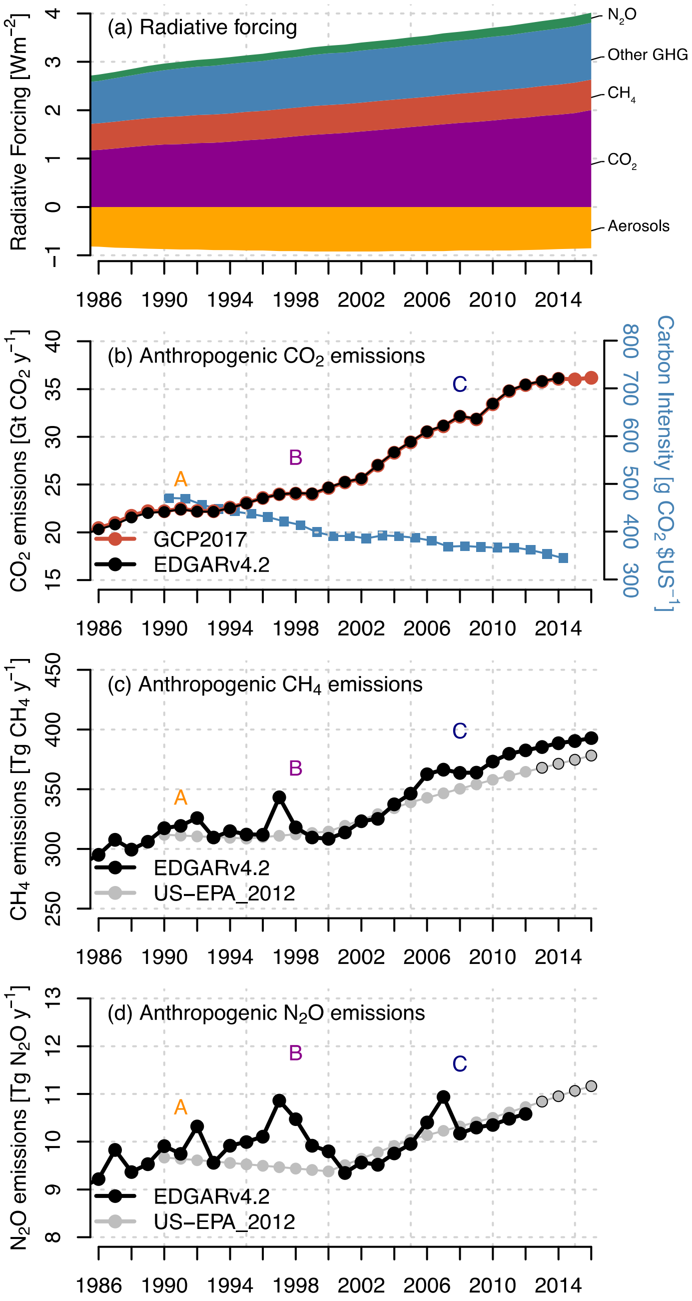


Figure 1.4: Time series of anthropogenic radiative forcing (a), CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions (b–d) for the period 1986–2016. Anthropogenic radiative forcing is estimated according to Etminan et al. (2016) using Dlugokencky and Tans (2016) for greenhouse gases concentrations and ECLIPSE data for aerosols. Anthropogenic CO_2 emissions are from the Global Carbon

Project (GCP; Le Quéré et al., 2017), and EDGAR (Joint Research Centre, 2011) datasets. Anthropogenic emissions of CH_4 and N_2O (e) are estimated from EDGAR (JRC, 2011) and the US Environmental Protection Agency (EPA, 1990). Economic crisis (Former Soviet Union, A; Asian financial crisis, B; global financial crisis, C) are reported following the methodology of (Peters et al., 2011).

CO_2, methane and nitrous oxide are the most prominent contributors of anthropogenic radiative forcing, contributing 63%, 20% and 6% of the anthropogenic radiative forcing in 2016 respectively, as shown in Figure 1.4. Other LLCFs such as the halogenated gases (hexafluoride SF6 and chlorofluorocarbon CFCs) are responsible of about 37% of the anthropogenic radiative forcing. Emissions such as black carbon and sulphur dioxide form different types of aerosol particles, which interact with short – and long – wave radiation and alter clouds. The resulting net aerosol radiative forcing is spatially inhomogeneous and uncertain. Globally averaged, it is estimated to have reduced the globally averaged anthropogenic forcing by about 27% (figures from Myhre et al. (2013), updated).

Since 2013, the growth of CO_2 emissions has slowed down because of changes in the energy mix moving from coal to natural gas and increased renewable energy generation as shown in Figure 1.4b (Boden et al., 2015). This slowdown in CO_2 emission growth has occurred despite global GDP growth increasing to 3%year^{-1} in 2015, implying a structural shift away from carbon intensive activities (Jackson et al., 2015; Le Quéré et al., 2017). In 2016, however, anthropogenic CO_2 emissions are 36.18 CO_2 y^{-1} and have begun to grow again by 0.4% with respect to 2015 (Le Quéré et al., 2017). Global average concentration in 2016 has reached 402.3 ppm, which represents an increase of about 38.4% from 1850–1900 average (290.7 ppm).

Unlike CO_2, methane and nitrous oxide emissions have followed the most carbon–intensive pathways assessed in AR5 (Saunois et al., 2016b; Thompson et al., 2014). However, current trends in methane and nitrous oxide emissions are not driven in the same way by human activities. About 60% of methane emissions are attributed to human activities (e.g. ruminants, rice agriculture, fossil fuel exploitation, landfills and biomass burning, Saikawa et al., 2014; Saunois et al., 2016b), while about 40% of nitrous oxide emissions are caused by various industrial processes and agriculture (Bodirsky et al., 2012; Thompson et al., 2014). It is thus more complicated to link rates of emissions to economic trends or energy demands than is the case with CO_2 (Peters et al., 2011).

Estimates of anthropogenic emissions for methane and nitrous oxide are uncertain as shown by the difference between datasets in Figure 1.4 EDGARV4.2 (JRC, 2011) estimates and US–EPA projections give a global amount of methane emission ranging between 392.87 and 378.29 TgCH_4y^{-1} by 2016 which corresponds to a relative increase of 0.6–1% compared to 2015 emissions. However, livestock emissions in these databases are considered to be underestimated (Wolf et al., 2017). Similar uncertainties exist for anthropogenic N_2O emissions for which only US–EPA projections are available. According to US–EPA projections, anthropogenic N_2O emissions reach 11.2 TgN_2O y^{-1}, representing a relative increase of about 1% compared to 2016. Anthropogenic CH_4 and N_2O emissions also appear to respond to major economic crises.

1.2.4 Definition of 1.5°C consistent pathways and associated emissions and impacts

The Paris Agreement calls for achieving 'balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'. However, it does not associate a specific pathway with the long–term 1.5°C 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: pathways remaining below 1.5°C (which may also include pathways that reach 1.5°C but do not exceed it by a significant margin relative to internal climate variability), pathways temporarily exceeding 1.5°C (where 'temporary' here is with reference to the timescale to 2100, allowing an exceedance duration of at most a few decades), and pathways permanently exceeding 1.5°C (meaning a very low probability of returning to 1.5°C on any policy–relevant timescale). These three categories can be used to broadly characterise mitigation options and impacts associated with 1.5°C pathways over the 21st century, although no classification is exhaustive. For example, the rate of warming in 2100 is highly relevant to impacts such as sea level rise that continue to change after 2100. In general, pathways remaining below or temporarily exceeding 1.5°C show stable or falling temperatures in 2100, but exceptions are possible in principle.

The word 'scenario' is sometimes 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 Cross–Chapter Box 1.1 on scenarios and pathways).

Figure 1.5 is used to illustrate these categories of temperature scenarios and associated annual and cumulative emissions of CO_2, assuming for illustration that the net impact of other climate forcers is either negligible or can be expressed in terms of the equivalent amount of CO_2 emissions that would have the same impact as the non–CO_2 forcing on radiative forcing and GMST (non–CO_2 forcing in discussed in Section 1.2.4.5). While many impacts respond to GMST change shown in the large panel, some such sea level rise respond to cumulative or integrated temperature, meaning the rate of change of the impacted variable scales with GMST. This introduces different timescales of response, shown in the lower right panel.

Cross-Chapter Box 1.1: Scenarios and Pathways

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

The objective of this box is to frame how climate scenarios and pathways are used in this report and not to discuss all definitions of scenarios and pathways presented within the climate research literature (Rosenbloom, 2017).

A **scenario** is a consistent, plausible, and integrated description of a possible future of the human–environment system, including a narrative with qualitative trends and quantitative projections (IPCC, 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 climate scenarios to describe how assumptions about inherently uncertain socio–economic trends in the 21st century could influence future energy and land use, resulting emissions, and climate change as well as human vulnerability and exposure to climate change. Such driving forces include population, GDP, technological innovation, governance, and lifestyles. Climate change scenarios are used for analysing and contrasting climate policy choices.

The notion of a **'pathway'** can have different meanings in the climate 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 sometimes be used interchangeably with the word "scenario". For example, the **Representative Concentration Pathways (RCPs)** describe greenhouse gas concentration trajectories (van Vuuren et al., 2011) and the **Shared Socio–Economic Pathways (SSPs)** are a set of narratives of societal futures augmented by quantitative projections of socio–economic determinants such as population, GDP, and urbanization (Kriegler et al., 2012; O'Neill et al., 2014). Socio–economic driving forces consistent with any of the SSPs can be combined with a set of climate policy assumptions (Kriegler et al., 2014) that together would lead to emissions and concentration outcomes consistent with the RCPs (Riahi et al., 2017). 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 oriented scenario describing a pathway from today’s world to achieving a set of future goals. **Sustainable Development Pathways** (SDPs) describe possible pathways where climate policy becomes part of a larger sustainability transformation resulting in sustainable development within a stable and resilient earth–system (Rockström et al., 2009). The IPCC 5th Assessment Report, Working Group II report presented **climate–resilient pathways** as sustainable development trajectories that combine adaptation and mitigation with the goal to reduce negative impacts from climate change and ensure effective risk management. Such pathways represent a range of future trajectories of development and transformational change; they are negotiated through iterative and participatory processes to evaluate values, preferences, and benefits and risks of climate resilience (Denton et al., 2014). **Adaptation pathways** are understood as a series of adaptation choices involving trade–offs between short–term and long–term goals and values (Reisinger et al., 2014). They are decision–making processes over several potential actions sequenced over time with the purpose of deliberating and identifying socially–salient solutions in specific places (Barnett et al., 2014; Fazey et al., 2016; Wise et al., 2014).

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; IPCC, 2000), published in 2000, consist of four scenarios that do not take into account any future measures to limit greenhouse gas (GHG) emissions; however, 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 RCPs comprise 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 were assessed in the IPCC 5th Assessment Report. Based on the CMIP5 ensemble, RCP2.6, provides a better than two in three chances of staying below 2°C and a median warming of 1.6°C relative to 1850–1900 in 2100 (Collins et al., 2013).

The SSPs were developed to complement the RCPs with 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 a middle–of–the–road development (SSP2) (O’Neill et al., 2017; Riahi et al., 2017). Socioeconomic drivers, including population and education (Samir 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. Based on the narratives and the driver projections, SSP–based scenarios were developed for a range of climate forcing levels, including the end–of–century forcing levels of the RCPs (Riahi et al., 2017) and a level below RCP2.6 to explore pathways limiting warming to 1.5°C above pre–industrial (Rogelj et al., 2017). The SSP–based 1.5°C pathways are assessed in Chapter 2 of this report. The 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 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.

Scenarios and Pathways in this Report

This report focuses on scenarios that could limit global mean surface air temperature increase to 1.5°C above pre–industrial and pathways that align with the goals of sustainable development and poverty eradication. Pace and scale of mitigation and adaptation are assessed in the context of historical evidence to determine where unprecedented change is required (see Chapter 4). Other scenarios are also assessed, primarily as benchmark for comparison for, for example, impacts, mitigation and/or adaptation requirements. These include 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 scenarios holding warming below 2°C above pre–industrial. This report assesses the spectrum from global mitigation scenarios to local adaptation choices – complemented by a bottom–up assessment of individual mitigation and adaptation options and their implementation (policies, finance, institutions, governance, see Chapter 4). Regional, national, and local scenarios as well as decision–making processes over values and difficult trade–offs are important for understanding the challenges of limiting global mean temperature increase to 1.5°C and are thus indispensable when assessing implementation.

This report introduces **Climate resilient development pathways** as low–emission, sustainable development trajectories that promote fair and equitable climate resilience and well–being for all in a 1.5°C warmer world, in alignment with the Agenda 2030 and the Sustainable Development Goals (SDGs, United Nations, 2015, see Chapter 5). They entail priorities about the futures we want and the ethics and equity dimensions of the societal transformation needed to get there.

Different climate policies result in different temperature pathways, which result in different climate risks. Temperature pathways are classified into continued warming pathways (in the cases of baseline and reference scenarios), pathways that keep temperature below a specific limit, and pathways that temporarily exceed or overshoot a specific limit (like 1.5°C or 2°C). In the case of a temperature overshoot, net negative CO_2 emissions are required to remove excess CO_2 from the atmosphere.

Emission pathways also can be classified as 'prospective' or 'adaptive'. Prospective pathways assume emissions will be consistent with a given probability of global mean surface temperature remaining below a temperature target, such as a 50:50 or two–thirds chance of staying below 1.5°C, based on current knowledge of the climate system response. Adaptive pathways assume emissions will evolve to stay below a desired temperature limit, with emissions plans changing as the knowledge about the climate response is updated. The 1.5°C pathways assessed in Chapter 2 are prospective. Their associated risks from climate change would therefore include, and might indeed be dominated by, the risks of warming levels higher than 1.5°C that might emerge with some limited probability. In contrast, the 'risks of warming of 1.5°C'assessed in Chapter 3 refer to risks in a world that held warming to 1.5°C, without considering probabilities (unless otherwise qualified), and therefore can be related more directly to the risks associated with adaptive 1.5°C pathways.

1.2.4.1 Pathways remaining below 1.5°C

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, resulting in smooth temperature pathways if temperature goals are achieved through emission reductions alone (Huntingford et al., 2017). As Figure 1.5 illustrates, annual CO_2 emissions are proportional to the rate of change of CO_2–induced warming. Hence if reductions are delayed until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve very rapid rates of net CO_2 emission reductions, potentially requiring active CO_2 removal combined with rapid reductions in other climate forcers.

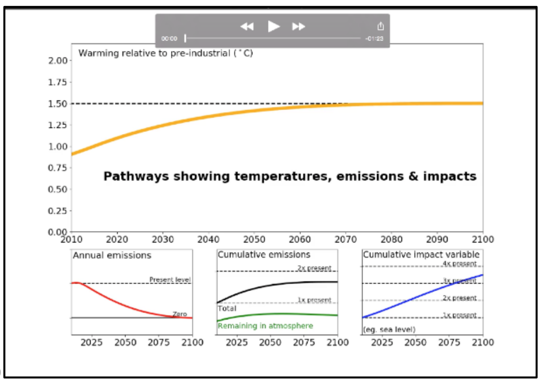
Stabilizing GMST requires net annual CO_2 emissions to decline to near zero or slightly below (depending on the long–term adjustment of the carbon cycle), but does not imply stabilizing other properties of the climate system. If other forcings are constant and positive, CO_2 concentrations and hence radiative forcing need to decline to stabilize GMST (Matthews and Caldeira, 2008; Solomon et al., 2009), as shown by the cumulative emissions remaining in the atmosphere, which is proportional to atmospheric concentrations, green line in the middle lower panel in Figure 1.5. Falling atmospheric CO_2 concentrations mean ocean pH levels would begin to recover, while stabilization of atmospheric greenhouse gas concentrations would result in continued warming, see Section 1.2.6). Sea level would continue to rise after temperatures stabilize (Kopp et al., 2016), but at substantially lower rates than would be expected under a continued warming scenario. The requirement that CO_2 emissions must reach zero to stabilise GMST also provides a simple method of taking stock of progress towards a temperature goal: a minimum requirement for limiting future warming to 0.5°C without overshoot is that CO_2 emissions must fall, on average, by 20% of their present value, or about 8 $GtCO_2$, for every tenth of a degree of warming from now on. This statement is independent of scenario, because it simply states the reductions required to reach net zero before temperatures have risen by more than 0.5°C above present–day.

1.2.4.2 Pathways temporarily exceeding 1.5°C

Under this category, GMST rises above 1.5°C before peaking and declining, either converging on 1.5°C or continuing to fall. Drawing temperatures down requires either negative global CO_2 emissions (net anthropogenic removal of CO_2) or sustained reduction of net non–CO_2 climate forcing. The amount of cooling that can be achieved without active anthropogenic CO_2 removal is limited because most anthropogenic climate forcers cannot be reduced below zero. Hence the feasibility and availability of large–scale CO_2 removal limits accessible rates and amounts of temperature decline. In this report, overshoot pathways are referred to 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 and many irreversible climate change impacts such as coral reef loss, ice–sheet loss and species extinctions.

1.2.4.3 Pathways permanently exceeding 1.5°C

Under this category, 1.5°C is reached and GMST then continues to warm. An important sub–category of continued warming pathways are pathways associated with ‘current policies’ scenarios, in which existing climate mitigation policies and commitments are extrapolated into the future, or ‘no policies’ scenarios, in which no climate mitigation policies are assumed at all. CO_2 concentrations and sea level would be very different when temperatures reach 1.5°C on a continued warming pathway than when on a stabilisation pathway, which has important implications for many impacts.

a)


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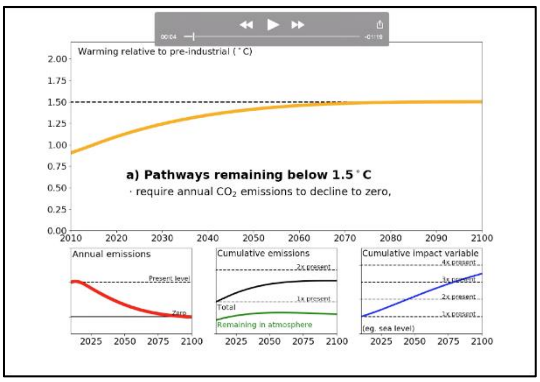
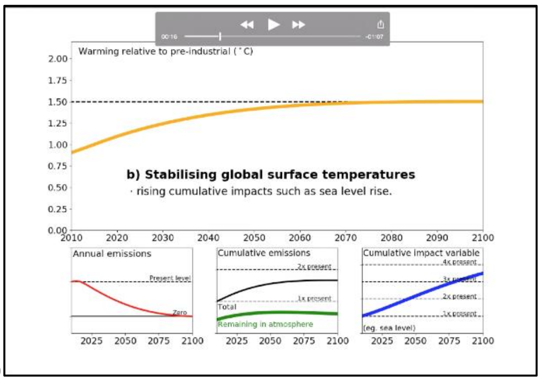
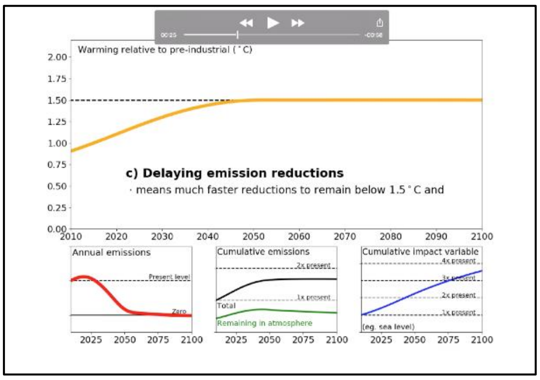
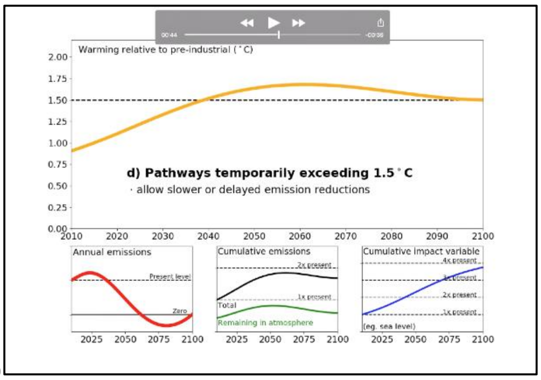




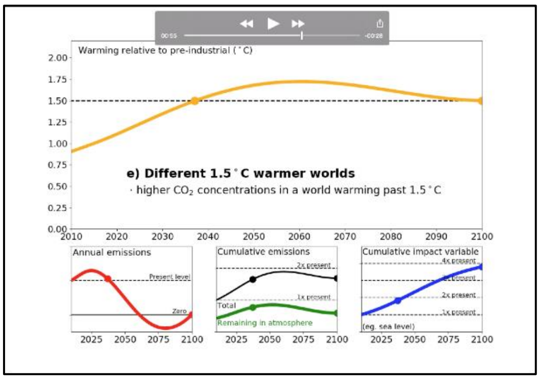
c)



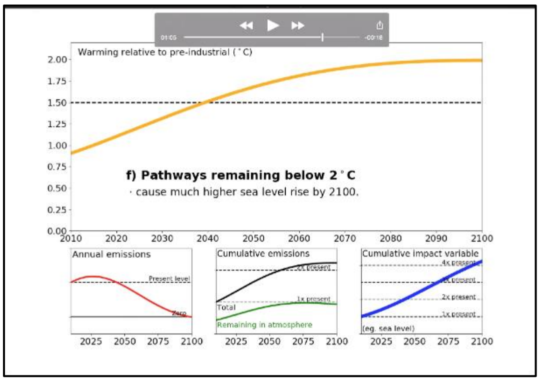
d)



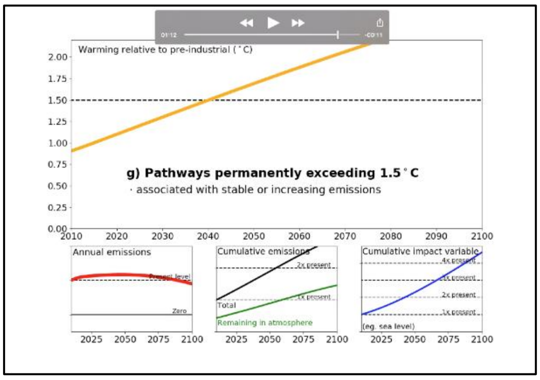
e)



f)



g)



h)

[Figure 1.5 aims to be an interactive animated figure in the final product of this Special Report. A draft animation is available to download with this chapter for review (SR15_SOD_Chapter1_Figure1.5_animation.mp4). Still images from the animation have been provided here for the printed version of the SOD.]

Figure 1.5: Dynamic illustration of the relationship between global temperatures, emissions and impacts. Sequence (a) shows that temperature pathways remaining below 1.5°C require annual CO_2 emissions (red), including the impact of non–CO_2 forcing discussed in 1.2.4.5, to decline to zero, meaning cumulative CO_2 emissions (black) stabilize, before the temperature threshold is reached. Sequence (b) shows that stabilising GMST means declining atmospheric CO_2 concentrations but continued change in cumulative impact variables such as sea level rise. Sequence (c) shows that delaying initiating emission reductions means that much faster reductions would be required to remain below 1.5°C and that 1.5°C with associated impacts is reached earlier. Sequence (d) shows that pathways temporarily exceeding 1.5°C allow slower or delayed emission reductions but require net CO_2 removal after 2050 and imply higher sea levels in 2100. Sequence (e) contrasts conditions when GMST reaches 1.5°C for the first and second time in such an 'overshoot' pathway, showing emissions and atmospheric concentrations of CO_2 are higher as temperature warm past 1.5°C while sea level is higher when temperatures return to 1.5°C after overshooting. Sequence (f) shows that pathways remaining below 2°C but exceeding 1.5°C allow higher cumulative CO_2 emissions but still require annual emissions to be reduced to zero to stabilise

temperatures and cause substantially higher sea level rise by 2100. Sequence (g) shows that pathways permanently exceeding 1.5°C are associated with stable or increasing emissions and continually accelerating sea level rise. Temperatures anchored to 0.87°C above pre–industrial in 2010; emissions–temperature relationship computed using a representative value (1.6°C) of the Transient Climate Response (TCR) with a simple climate model (Millar et al., 2017b; Myhre et al., 2013); cumulative impact variable represented by sea–level–rise computed using a semi–empirical model (Kopp et al., 2016). Figure will provide a link to allow reviewers to view the dynamic illustration that will be embedded in electronic versions of the final report.

1.2.4.4 Impacts at 1.5°C warming associated with different pathways

Impacts that occur when GMST first rises past 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 temperature is not in equilibrium with atmospheric composition. In particular, CO_2 concentrations will be higher, as well as sea level and, potentially, mean precipitation (Pendergrass et al., 2015) will both be lower as temperature warms past 1.5°C than they will be as temperature stabilises at 1.5°C. These differences could lead to very different impacts on agriculture, some forms of extreme weather (Baker et al., 2017), and marine and terrestrial ecosystems (James et al., 2017; Mitchell et al., 2016, Box 3.1). Sea level would be substantially higher when temperatures return to 1.5°C following an overshoot than when temperatures reach 1.5°C on a pathway that remains below 1.5°C before then. Hence it is important to specify the pathway in discussing impacts of 1.5°C of warming.

1.2.4.5 Framing cumulative budgets for CO_2 and non–CO_2 climate forcing using AGWP

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 (TCRE). This makes possible the notion of a "cumulative carbon budget" consistent with a given level of warming: warming over a given time–period is equal to cumulative CO_2 emissions over that period multiplied by the TCRE plus any warming caused by non–CO_2 climate forcing over that period. Under ambitious mitigation scenarios involving limited future cumulative CO_2 emissions, non–CO_2 climate forcing becomes relatively more important.

Most calculations of carbon budgets (e.g. Millar et al., 2017a) have assumed a prescribed scenario for non–CO_2 climate forcing, effectively subtracting warming caused by non–CO_2 forcing from total warming to compute a carbon budget for the remainder. There is a trade–off between non–CO_2 climate mitigation and the size of the cumulative CO_2 budget consistent with any given warming goal (Matthews et al., 2017a). For changes in non–CO_2 forcing that are sufficiently small and gradual to avoid strong non–linearity or transient effects, the Absolute Global Warming Potential (AGWP; Shine et al., 2005) provides a simple and scenario–independent way of quantifying this trade–off. For a long–lived greenhouse gas such as CO_2, the $AGWP_H$ is, by definition, the change in radiative forcing after H years resulting from a $1/H$ tonnes–per–year emission of CO_2 over that period, where H is the AGWP time–horizon (Allen et al., 2017; Shine et al., 2005).

A gradual change in non–CO_2 forcing totalling 1 W m^{-2} over a given period therefore has the equivalent impact on GMST as the cumulative emission of H/AGWP_H tonnes of CO_2 emitted continuously over that period. Hence for smooth emissions and forcing changes, the total change in GMST, ΔT, over a period of H years is given by the following simple formula:

$$\Delta T \approx \mathrm{TCRE} \times \left(G_{\mathrm{CO2}} + \Delta F_{\mathrm{non\text{-}CO2}} \times (H/\mathrm{AGWP}_H)\right) + \mathrm{constant}$$

where G_{CO2} is cumulative CO_2 emissions over the period in question and $\Delta F_{non-CO2}$ is the net change in non–CO_2 radiative forcing over that period. The constant term represents warming or cooling that would occur over this period with zero cumulative CO_2 emissions and constant non–CO_2 forcing, due to previous emissions and forcing in earlier periods, and may also contain a contribution if $\Delta F_{non-CO2}$ departs systematically from a gradual change (for example, if all pathways show an initial increase followed by a decrease). For periods between 20 and 100 years, H/AGWP_H is between 800 and 1090 $GtCO_2/(W\ m^{-2})$ using AR5 AGWP values, while the AR5 gave a likely range for TCRE of 0.22 to 0.68°C per 1000 $GtCO_2$.

The above expression provides a simple indication of the relative importance of cumulative CO_2 emissions and non–CO_2 forcing that may be used to frame the mitigation challenge of meeting ambitious temperature goals in terms of the two key variables affected by policy: cumulative CO_2 emissions and $\Delta F_{non-CO2}$. It is a simplified version of CO_2–forcing–equivalent (CO_2–fe) emissions (Allen et al., 2017; Jenkins et al., 2017; Manning and Reisinger, 2011; Wigley, 1998; Zickfeld et al., 2009) which are defined as the CO_2 emission pathway that results in the same radiative forcing as a given non–CO_2 climate forcing pathway, computed explicitly with a carbon cycle model. The assumption of a constant AGWP value is only valid for relatively small departures of temperature and atmospheric composition from present–day conditions, so the relevance of this expression to higher emission pathways has not been assessed.

1.2.5 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 this means 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 of 'balance', and hence what is meant by 'emissions' and 'removals' of greenhouse gases, 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 on these timescales almost all 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, among others (Chapter 4 Section 4.3.8).

For greenhouse gases other than CO_2, the simplest interpretation of 'balance' for temperature stabilization from a physical climate system perspective is that it requires net zero total anthropogenic CO_2 forcing–equivalent (CO_2–fe) emissions. This follows from the fact that stabilizing CO_2–induced warming requires net zero CO_2 emissions and CO_2–fe emissions, by construction, give the same radiative forcing and hence temperature response as CO_2. Net zero CO_2–fe emissions 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 Cross–Chapter Box 1.2). Sustained emissions of a short–lived climate forcer (SLCF) such as methane could be consistent with gradually declining atmospheric methane concentrations, equivalent to net zero CO_2–fe emissions (recalling that zero CO_2 emissions result in gradually declining atmospheric CO_2 concentrations) and hence no additional contribution to warming (Allen et al., 2017). Even though sustained emissions of a SLCF can be equivalent to a zero rate of CO_2–fe emissions, reducing SLCF emissions would still constitute a mitigation opportunity, with an equivalent impact on future forcing and temperature as active removal of some quantity of CO_2.

While the simplest interpretation of balance, from a physical perspective, is in terms of net zero CO_2–fe emissions, CO_2–fe emissions must be calculated from the full forcing history with a carbon cycle model, and so other interpretations are also helpful. The expression given in Section 1.2.4.5 provides an expression to convert non–CO_2 forcing changes $\Delta F_{\mathrm{non-CO2}}$into approximate CO_2–fe emissions using AGWP. This may provide an adequate approximation provided $\Delta F_{\mathrm{non-CO2}}$ is relatively small and slowly varying. A revised usage of GWP, denoted GWP*, provides a way of approximately calculating CO_2–fe emissions directly from SLCF emissions (Allen et al., 2017, and Cross–Chapter Box 1.2).

Should temperatures exceed 1.5°C, returning global temperature to 1.5°C would require active 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 a pathway temporarily exceeding 1.5°C.

Cross-Chapter Box 1.2: Comparing long–lived and short–lived climate forcers with CO_2–equivalent emissions metrics in the context of 1.5°C pathways

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The IPCC Fifth Assessment Report (Myhre et al., 2013) assessed the use of emission metrics to compare different climate forcing agents, concluding that the most appropriate metric and time–horizon depends on the particular application and which aspects of climate change are considered relevant in a given context. This box assesses the implications of the choice of metrics in the context of ambitious mitigation pathways relevant to 1.5°C.

Policy frameworks such as the Kyoto Protocol employ emission metrics to compare emissions of different greenhouse gases. Metrics are also used to compare across different sectors and regions (Weyant et al., 2006) and to relate different gases within integrated assessment models (Myhre et al., 2013; Reisinger et al., 2012; Smith et al., 2013; Strefler et al., 2014). To date, reporting of GHG emissions under the UNFCCC have adopted Global Warming Potentials (GWPs) evaluated over a 100–year time horizon (GWP_{100}) to account for a basket of greenhouse gases using either IPCC Second Assessment Report or IPCC Fourth Assessment Report values. IPCC Working Group 3 reports have also used GWP_{100} to represent multi–gas pathways in terms of aggregate CO_2–equivalent emissions (Clarke et al., 2014).

Numerous other metrics have been proposed: for illustration, we also consider the Global Temperature–change Potential (GTP; Shine et al., 2005). While GWP is defined in terms of the impact of a one–off 1kg emission of a greenhouse gas on the global energy budget integrated over the GWP time–horizon, GTP refers to the impact of such an emission on global temperatures after a given amount of time (in both cases relative to the corresponding impact of 1kg of CO_2). GTP assigns a lower nominal weight than GWP_{100} to a Short–Lived Climate Forcer (SLCF) such as methane if evaluated over a 100–year time–horizon, but a higher weight than GWP_{100} if evaluated over short (e.g. 20 year) time–horizons (Figure 8.30 of Myhre et al., 2013; Allen et al., 2016). Studies have suggested that policy makers choose a metric that works across a range of policy goals (Edwards et al., 2016; Ekholm et al., 2013) or choose a specific metric that is matched to the intended use and the admissible level of uncertainty about metric values (Deuber et al., 2013; Tol et al., 2012). There is no ideal metric that can be used to compare two or more gases across the full range of physical effects and socioeconomic considerations and timescales. Policy makers hence have to choose metrics based on value judgements, or on pragmatic considerations of simplicity and/or continuity.

Paragraph 17 of the Paris decision to adopt the Paris Agreement specifically requests that this Special Report determines the CO_2–equivalent emission reductions compatible with holding temperatures to 1.5°C above preindustrial levels (see Chapter 2). Calculating aggregate CO_2–equivalent emissions requires a metric, highlighting the need to consider the implications of the choice of metric and time horizon.

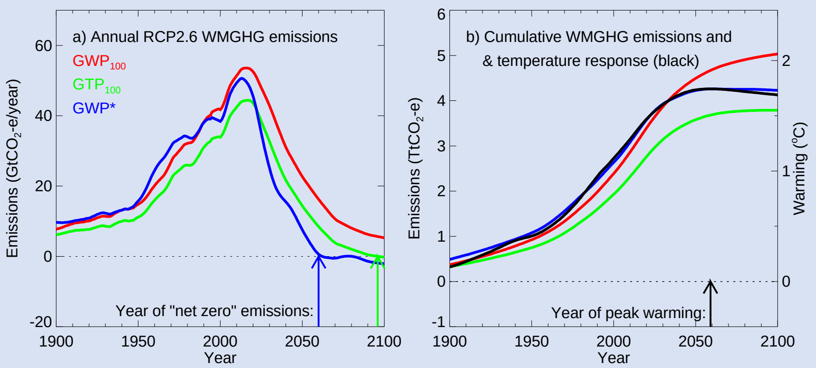
Issues arise with GWP, GTP and similar metrics when comparing the temperature effects of emissions of SLCFs with a long–lived gas such as carbon dioxide(Smith et al., 2012). The warming from long–lived greenhouse gases increases cumulatively with each tonne emitted (i.e. with the emissions “stock”), while on timescales longer than their lifetimes, the warming or cooling from SLCFs is determined by their annual emission rates (or “flow”). Hence a single tonne avoided emission of a long–lived gas like CO_2 has a similar impact on future global mean surface temperature (GMST) over a broad range of timescales as a permanent reduction in the rate of emission of an SLCF like methane (Allen et al., 2016; Lauder et al., 2013; Shine et al., 2005). GWP and GTP, conventionally applied, equate a single tonne of CO_2 with a single tonne of emissions of an SLCF, not a change in SLCF emission rate, and hence typically understate the impact of SLCF emissions on GMST on short timescales, and overstate their impact on long timescales.

Ambitious mitigation scenarios addressing 1.5°C must address both long timescales (temperature stabilisation) and short timescales (rapid emission reductions over decades) simultaneously, posing a challenge for conventional metrics. The usage of the GWP metric can be modified to address this problem approximately by equating a sustained one–tonne–per–year reduction in the emission rate of an SLCF with the (one–off) avoided emission of $GWP_H \times H$ tonnes of CO_2, where GWP_H is the value of that SLCF’s GWP for a time–horizon H (Allen et al., 2016). Both of these have a similar impact on GMST over a broad range of timescales. However, this revised usage (denoted GWP* in Fuglestvedt et al. (2017) and Allen et al. (2017)) would require a modified policy framework to allow different treatment of long–lived and short–lived gases. The Absolute Global Warming Potential of CO_2 (AGWP; Shine et al., 2005) may also be used to relate cumulative CO_2 emissions and non–CO_2 climate forcing in the context of cumulative CO_2 emission budgets (see Section 1.2.4.5 & Section 2.2).

The “stock versus flow” distinction between long–lived gases and SLCFs also affects the definition of emissions “balance”, if interpreted in terms of temperature stabilisation. Achieving a stable GMST requires 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. This may require compensating for residual emissions of long–lived gases with negative CO_2 emissions (active CO_2 removal) as technologies for removing nitrous oxide and ozone depleting halocarbons from the atmosphere remain speculative (de Richter et al., 2017). Compensating for residual CO_2 emissions 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; de Richter et al., 2017). Hence if substantial SLCF emissions continue, stable GMST does not correspond to net zero aggregate CO_2–equivalent emissions measured by GWP_{100}, although it does correspond to net zero emissions aggregated using GWP* (Cross–Chapter Box 1.2, Figure 1). Persistent net zero CO_2–equivalent emissions aggregated using GWP_{100} would result in a steady decline of GMST, while other conventional metrics such as GTP also yield declining GMST, albeit at a slower rate (Fuglestvedt et al., 2017). Whatever metric is used to relate emissions of different greenhouse gases, achieving stable GMST below the Paris Agreement’s thresholds requires both near–zero net emissions of long–lived greenhouse gases and deep reductions in warming SLCFs (Chapter 2).

It may be desirable to consider more than longer–term GMST in the definition of metrics (Deuber et al., 2013; Johansson, 2012; Myhre et al., 2013; Tol et al., 2012). Climate impacts can arise from both magnitude and rate of climate change, and from other variables such as precipitation, which can also be considered in metric definition (Shine et al., 2015). Even if GMST is stabilised, sea–level rise and associated impacts will continue to increase (Sterner et al., 2014), while impacts that depend on CO_2 concentrations such as ocean acidification may begin to reverse. Other climate impacts may persist as well if adaptation options are limited (Chapter 3). All of these could be included in the definition of the climate metric. From an economic perspective, climate metrics should reflect the ratio of marginal economic damages from different GHGs if they are used to determine their exchange ratio under a multi–gas greenhouse gas regulation (Deuber et al., 2013; Kolstad et al., 2014; Tol et al., 2012). Under the assumption of climate damages that increase gradually with increasing temperature, this approach yields the Global Damage Potential (Hammitt et al., 1996; Kandlikar, 1995, 1996; Tol, 1999). Another economic metric, the Global Cost Potential is defined as the price ratio that minimizes the economic costs of maintaining the temperature limit (Manne and Richels, 2001). Studies have found that the effect of metric choice on the median costs of maintaining temperatures below 2°C tends to be modest because all feasible mitigation options are needed (Harmsen et al., 2016; Strefler et al., 2014), implying that a range of metrics might be suitable from a global economic perspective. Metric choice can nevertheless substantially affect carbon prices and consequent mitigation decisions on a regional or sectoral level (see Chapter 2).

Emissions can interact with other dimensions of sustainable development (see Chapters 4 and 5). In particular, early action on some SLCFs (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 (OECD, 2016; Shindell et al., 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 (Sarofim et al., 2017; Shindell, 2015; Shindell et al., 2017). For any given sector and/or state it may also be more or less economically viable or socially acceptable to target mitigation of particular forcers over CO_2 mitigation or vice versa. While they do not, therefore, dictate policy decisions, emission metrics can still provide useful guidance to clarify the implications of such decisions for future GMST.



Cross–Chapter Box 1.2, Figure 1: (a) Aggregate emissions of well–mixed greenhouse gases (WMGHGs) under the RCP2.6 mitigation scenario expressed as CO_2–equivalent using GWP_{100} (red); GTP_{100} (green) and GWP* (blue). Aggregate CO_2–equivalent missions fall more rapidly under GWP* than either of the other metrics, primarily because falling methane emissions are equated with negative CO_2 emissions under GWP*, as only active CO_2 removal would have the same impact on radiative forcing and GMST as a reduction in methane emission rates. (b) Cumulative emissions of WMGHG under the three metrics in panel (a) (red, blue and green & left hand axis) and resulting warming (black line & right hand axis) calculated using a simple climate–carbon–cycle model (Millar et al., 2017b). The temperature response is closely correlated with cumulative WMGHG emissions aggregated using GWP*, but correlated with neither emission rate nor cumulative CO_2–equivalent emissions aggregated using GWP or GTP: these traditional metrics are adequate for representing impact on GMST on specific single time horizons but unrepresentative of the temperature impacts of combined emissions of long–lived gases and SLCFs over multiple time horizons.

1.2.6 Definitions of warming commitment

A central question of this report is whether limiting global mean temperature increase to 1.5°C above pre–industrial is 'feasible' (Cross–Chapter Box 1.3). The feasibility of this temperature goal will depend on the warming 'commitment' that arises due to inertia in the geophysical climate system, but also due to technological, economic, institutional and behavioural lock–in.

Geophysical warming commitment is defined as the unavoidable future warming resulting from physical Earth system inertia. Different variants of geophysical warming commitment are discussed in the literature: the 'constant composition commitment', which is the remaining warming if atmospheric composition and hence radiative forcing were stabilised at the current level and 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 constant composition commitment has been used to illustrate inertia in the physical climate system, primarily associated with slow heat uptake by the ocean (Hansen et al., 2005), and has led to the misconception that substantial future warming is inevitable (Matthews and Solomon, 2013). This variant of commitment includes the warming resulting from past emissions, as well as the warming from the declining but non–zero future emissions that are required to maintain a constant atmospheric composition. It is therefore ill–suited to estimate future warming resulting from geophysical inertia alone.

The zero emissions commitment (ZEC), although based on highly idealised assumptions, allows for a clear separation of the climate system response to past emissions from the effect of future emissions. The magnitude and sign of the ZEC depend on the mix of gases considered because of different atmospheric residence times[1] and signs of radiative forcing. For CO_2, which has an atmospheric residence time of centuries to millennia (Eby et al., 2009), the multi–century warming commitment from emissions to date ranges from slightly negative (i.e., a slight cooling relative to present–day) to slightly positive (Frölicher and Joos, 2010; Gillett et al., 2011; Lowe et al., 2009; Matthews and Zickfeld, 2012). The warming commitment from past CO_2 emissions is close to zero because the warming effect of ocean thermal inertia is approximately balanced by declining radiative forcing due to CO_2 uptake by the ocean (Solomon et al., 2009) Figure 1.6, blue solid line). Thus, although the present–day CO_2–induced warming is irreversible for millennia, past CO_2 emissions do not commit to substantial further warming.

For greenhouse gases and other warming SLCFs with a short atmospheric residence time (order of decades or less) such as methane (CH_4), the ZEC is negative, implying cooling relative to present–day if future emissions of these gases are eliminated (Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Figure 1.6, purple line). This cooling arises from a rapid decline in radiative forcing, which dominates over the warming effect of ocean thermal inertia. Cooling SLCFs (those causing negative radiative forcing) such as sulphate aerosols have a positive ZEC, as elimination of the radiative 'dimming' effect of aerosols results in rapid warming (Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Samset and Myhre, 2017; Smith et al., 2018). Estimates of the warming commitment from eliminating aerosol emissions are uncertain due to large uncertainties in aerosol radiative forcing (Myhre et al., 2013). If present–day emissions of GHGs and aerosols (including sulphate, nitrate and carbonaceous aerosols) are eliminated (Figure 1.6, yellow line), GMST rises over the decade immediately following elimination of emissions (Matthews and Zickfeld, 2012; Smith et al., 2018),

[1]FOOTNOTE We here refer to the adjustment time, rather than the turnover time of a gas in the atmosphere. Adjustment time characterizes the time scale of decay of an instantaneous pulse input of a gas into the atmosphere.

driven by the removal of negative aerosol radiative forcing. This initial warming is followed by a gradual cooling driven by the decline in radiative forcing of short–lived GHGs and in year 2100 ranges from –0.4°C to 0.25°C relative to present–day (Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017; Smith et al., 2018)

Geophysical warming commitment can be thought of as the minimum warming commitment, absent inertia in the socio–economic system. However, existing infrastructure, technologies, policies, institutions, and behavioural and social norms can constrain the rate and magnitude of future GHG emission reductions. These constraints could 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 (Davis et al., 2010; Seto et al., 2016; Unruh, 2000). Infrastructural and technological inertia arises from the long lifetime and large investments associated with GHG–emitting infrastructure (Davis et al., 2010; Davis and Socolow, 2014; Fuglestvedt et al., 2017; Pfeiffer et al., 2016). For instance, unless power plants are retrofitted with carbon capture and sequestration (CCS) or operable infrastructure decommissioned before the end of their technical lifetime, 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 warming in 2060 from existing GHG–emitting infrastructure (as of 2009) in energy, transportation, industrial, residential and commercial sectors. Using the same rates of GHG–emitting infrastructure retirement, Smith et al. (2018) estimate a committed warming of –0.2°C to 0.7°C in 2100. The larger range than in Davis et al. (2010) arises due to their consideration of physical climate system uncertainty.

In contrast to infrastructure and technological inertia, 'institutional inertia is an intended feature of institutional design, not an unintended by–product of systemic forces' (Hughes, 2017; Munck af Rosenschöld et al., 2014; Seto et al., 2016; Taylor, 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). This suggests that overcoming institutional inertia requires efforts on different levels and in various social fields (Hughes, 2017; Munck af Rosenschöld et al., 2014; Seto et al., 2016; Taylor, 2016).

The transition to a low–carbon trajectory is also hampered by behavioural inertia, where the competing concerns and pressures that individuals face in society influence their consumption choices. This creates a self–perpetuating cycle where increasing levels of consumption become normalised (Jackson, 2017; O'Rourke and Lollo, 2015). Habits, risk–aversion and the necessity of collective action to solve the climate change problem (giving the feeling to individuals that they have little control) can lock in carbon–intensive behaviours (Seto et al., 2016). Also, individual behaviour is constrained by the interconnected patterns of social practices that are, in turn, embedded in material arrangements that change only slowly in response to changes in the technological and political environment (Shove et al., 2015). Infrastructure and demand–side solutions and strategies have substantial potential to enable new possibilities to overcome behavioural and habitual barriers (Creutzig et al., 2016). The unavoidable warming from behavioural and institutional inertia has not yet been quantified.

While social, techno–economic and institutional inertia are difficult to quantify, 'pure' geophysical inertia (in the form of the ZEC) is relatively small. Yet there is clearly a profound difference between a state of high emissions and rapid on–going warming and one in which emissions are approaching zero, even though the ZEC in both cases may be small. Leach et al. (2017) introduce a simple way of visualising this 'trajectory commitment' (a communication device, not an actual commitment) through the notion of an 'action timescale' implied by a given temperature stabilisation goal. This is defined as the time GMST would take to reach the target temperature at the current warming rate: if temperatures are now at 1°C and increasing at 0.02°C per year (Haustein et al., 2017) then the action timescale for 1.5°C is 25 years, in that GMST would reach 1.5°C in the early 2040s if the current rate of warming continues.

More relevant to mitigation, this '1.5°C action timescale' is also the timescale over which the rate of warming would need to fall by 50% under a linear decline over time (or 63% under exponential decline) to limit peak warming to 1.5°C. The rate of CO_2–induced warming is proportional to the CO_2 emission rate (Matthews et al., 2009; Zickfeld et al., 2009), while total non–CO_2 warming is approximately proportional to total non–CO_2 radiative forcing (Gregory and Forster (2008) and Section 1.2.4.5). Hence both the annual rate of CO_2 emissions, and the rate of increase in non–CO_2 forcing would have to fall by a similar fraction over the same action timescale to be consistent with temperatures remaining below the 1.5°C goal, assuming a steady decline starting immediately. Present rates of CO_2 emissions and rates of increase of non–CO_2 radiative forcing do not commit to absolute future warming, but they do commit to minimum future reduction rates if specific levels of future warming are to be avoided.

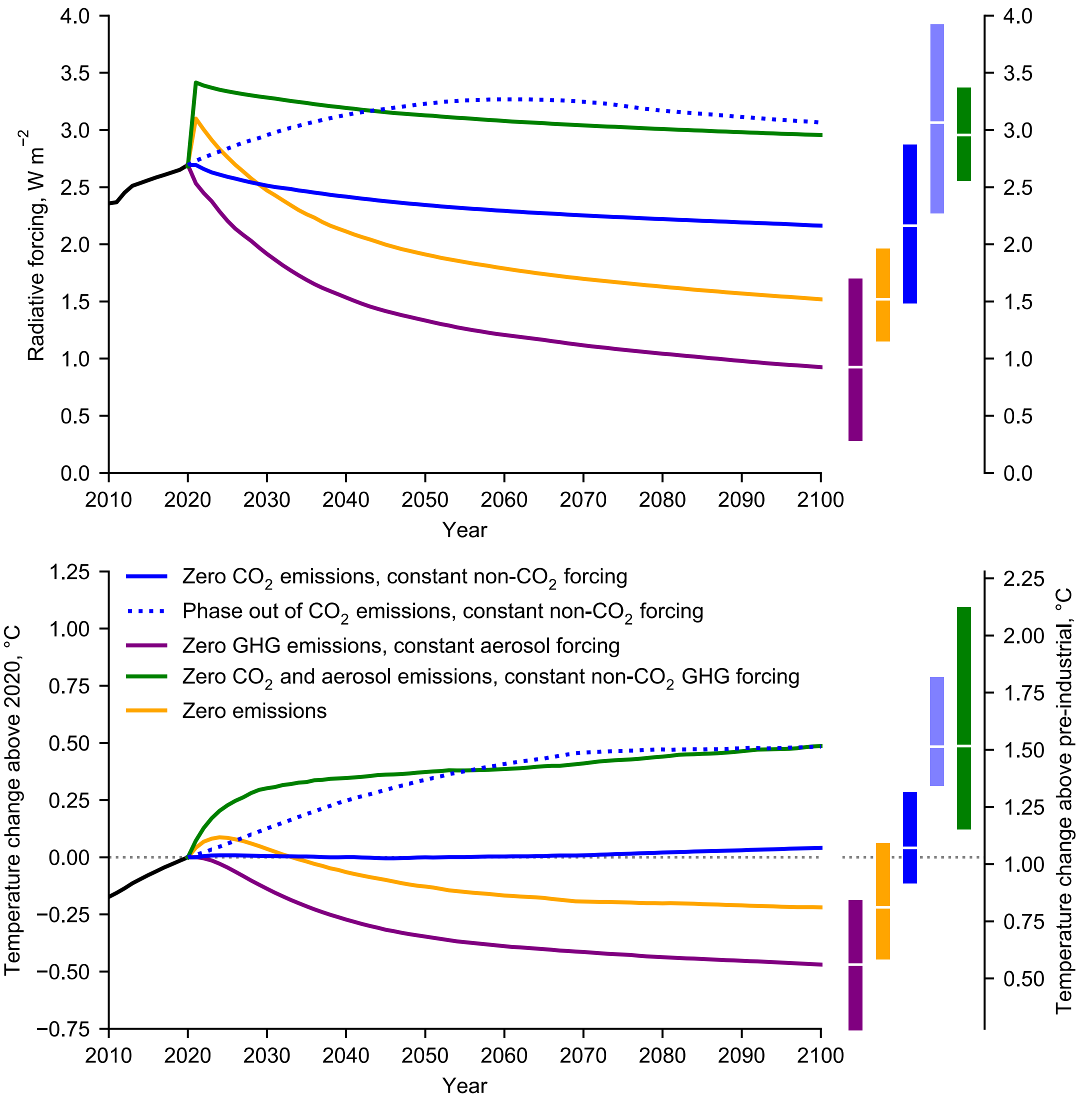


Figure 1.6: Radiative forcing (top) and global mean surface temperature change (bottom) for scenarios with different combinations of greenhouse gas and aerosol precursor emissions reduced to zero in 2020. Variables were calculated using a simple climate–carbon cycle model (Millar et al., 2017b)

with a simple representation of atmospheric chemistry (Smith et al. 2017; Smith et al. 2018). Bars on the right–hand side indicate the median and 5–95% percentiles of a model ensemble generated by taking into account uncertainty in climate sensitivity, transient climate response, effective radiative forcing, ocean heat uptake and carbon cycle response. Dotted blue lines show a hypothetical case where CO_2 emissions are reduced linearly to zero over 56 years, with constant non–CO_2 forcing, to illustrate the response to idealised linear decline over an action timescale of 28 years, chosen to stabilize temperatures at 1.5°C. Dotted blue line in top panel shows that stable temperatures are associated with declining radiative forcing.

1.3 Multiple dimensions of impacts at 1.5° C and beyond

This section discusses the multi–dimensionality of the impacts of climate change at 1.5°C and beyond, to explain in particular why it is not possible to arrive at a single global number comparing impacts at 1.5°C, 2°C or any other level. It also provides context in terms of observed impacts over recent decades, as temperatures have been approaching 1°C. Examples are given to clarify the concepts introduced, but for a detailed assessment of impacts, the reader is referred to Chapter 3 of this report.

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 (IPCC, 2014c). Impacts can be direct, for example, coral bleaching due to ocean warming, and indirect, for example, reduced tourism due coral bleaching at a particular site. Impacts can also be a consequence of mitigation (Section 1.3.2.4) as well as remedial options such as solar radiation management (Cross–Chapter Box 4.2 and Section 4.3.9). Impacts of climate change have already been observed 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, 2014c). Several impacts are now formally attributed to anthropogenic global warming and associated rainfall changes (Cramer et al., 2014; Hansen et al., 2016; Rosenzweig et al., 2008), but other forcings play major roles, such as land use change (e.g., Hosonuma et al., 2012) and atmospheric pollution (e.g., tropospheric ozone; Sitch et al., 2007).

The terms impact and risk are used differently, sometimes interchangeably, and inconsistently within and across disciplines, with different explicit or implicit definitions. The term 'impacts' can refer to observed consequences of climate change for human and natural systems; or can be used as a synonym for projected risks. Risk can refer to the probability of a projected change in the climate system; can be defined within a traditional risk management context as probability times consequence; or can be defined as a function of hazard, exposure, and vulnerability (IPCC, 2014c).

To promote clarity and consistency, this report uses these definitions:

- Consistent with the definition used in the AR5, *impact* refers to observed consequences or outcomes (positive or negative) of climate change on human and natural systems;
- *Projected impact* refers to the projected consequences of climate change for physical (e.g. air, water, energy) and biogeochemical (e.g. carbon cycle, ecosystems, chemistry) systems where there is high confidence in the change and that other drivers would not alter the projection (e.g. projected impact of climate change on the frequency and intensity of heat waves); and
- Consistent with the definition used in the AR5, *risk or projected risk* refers to the projected consequence(s) of climate change for human–influenced systems where drivers of vulnerability and exposure (e.g., demographic change, urbanization pathways, changes in income, progress in research and development) can influence the magnitude and pattern of the projection (e.g., changes in heat–related mortality or crop yields in future decades).

The reference to '1.5°C and 2°C above pre–industrial' is based on the objectives of the Paris Agreement, thus defined in the context of the UNFCCC; but what do we mean when we say 'impacts of 1.5°C and 2°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. An additional 0.5°C (i.e., a 2°C warming world versus 1.5°C) for heat–related extremes in the tropics marks the difference between events at the upper limit of current day natural variability and a new climate regime (Schleussner et al., 2016b). For Mediterranean land ecosystems, an additional 0.5°C is expected to result in changes that are unmatched during the last 10,000 years (Guiot and Cramer, 2016). For this Special Report, 'impacts at 1.5°C' refers to *the projected impacts when the expected global average of near–surface air temperature is 1.5°C above the pre–industrial period* (the same principle applies to impacts at 2°C). By examining impacts at 1.5°C *vs.* those at 2°C, this report discusses the avoided impacts by maintaining global temperature increase at or below 1.5°C as compared to 2°C, noting that these also depend on the pathway taken to 1.5°C (see Section 1.2.4 and Cross–Chapter Box 3.2 on 1.5°C warmer worlds). 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 caused by various climate drivers. While formal detection and attribution techniques and numerical models now are commonly used to attribute impacts to a particular level of (anthropogenic) warming (e.g., Hansen and Stone 2016), indigenous and local knowledge can be equally important. Although a region may not be classified as being impacted from a climatological perspective, due to a lack of scientific climate data, local community knowledge of impacts can be equally important in assessing impacts (Brinkman et al., 2016; Kabir et al., 2016). The challenge is that a community's perception of loss due to the impacts of climate change, is often defined via lived, embodied and place–based experiences, which are felt rather than tangible or empirical, and therefore exceedingly hard to predict (Tschakert et al., 2017).

Impacts are multi–dimensional; hence, there is no universal metric of total or aggregate impact. While some dimensions of impacts are obvious (space, time, sector), others are less well defined (equity), but are all relevant to society. Attributing observed impacts as well as assessing risks for future impacts requires information about both, the amount of physical change in the environment (temperature, rainfall, extreme events), and the sensitivities and possible thresholds of resilience in impacted systems, which differ widely from one system to another and which may be non–linear.

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. In the context of this assessment, *local* consequences of global warming at 1.5°C and 2°C are assessed (Chapter 3). Many regions experience higher than average rates of warming and some are already now 1.5°C warmer with respect to the pre–industrial period (Figure 1.3). For example, some parts of Africa are warming much faster than others (Déqué et al., 2016; Niang et al., 2014). Temperature and precipitation 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). Therefore, local/regional impacts of a global mean warming of 1.5°C will differ from those of local warming by 1.5°C. The "*warming experience at 1.5°C*" in this report will be that of local climate change (temperature, rainfall and other changes) at the time when global average temperatures, as defined in Section 1.2.1, reach 1.5°C above pre–industrial.

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

For many regions, an increase in global mean temperature by 1.5°C or 2°C implies substantial increases in the occurrence and/or intensity of some extreme events (Fischer and Knutti, 2015; Karmalkar and Bradley, 2017; King et al., 2017), generating different impacts (see Chapter 3). In cold regions, warming may also imply decreased occurrence of some extremes, however, these changes could still imply increased risks, due to warm anomalies affecting cold–adapted systems (Seneviratne et al., 2012).

Changes in most extreme events in 1.5°C versus 2°C warming worlds are likely to be region specific. An example is changes in extreme precipitation in the mid–latitudes, where high–precipitation events are common, versus tropical regions, where precipitation is less variable, with higher total precipitation but fewer extremes. Li et al. (2017) show that at mid–latitude locations in South America, there is a relatively modest, almost monotonic increase in the probability of heavy precipitation when comparing historical climate to 1.5°C and 2°C warming worlds. For tropical locations, they show that there is a much larger decrease in the intensity of heavy–precipitation when comparing historical climate to a 1.5°C warming world, but very little change between historical climate and a 2°C warming world, indicating a non–monotonic response. Hence, changes in frequency of some extremes may not only be of the opposite sign in different regions, but scale differently from 1.5°C warming worlds to 2°C warming worlds, and the magnitude of the change can vary markedly.

1.3.1.3 Non–temperature related impacts

Although the focus of this special report is on 1.5°C global warming, it is important to note that many impacts do not depend on warming alone. For example, changes in rainfall affect the hydrological cycle and water availability (Schewe et al., 2014). Several impacts depend on atmospheric composition, for example, increasing atmospheric carbon dioxide levels leading to ocean acidification (Hoegh–Guldberg et al., 2007). Other impacts are driven by changes in ocean heat content, for example the destabilization of coastal ice–sheets and sea–level rise (Bindoff et al., 2007; Chen et al., 2017), whereas impacts due to heatwaves depend directly on ambient air or ocean temperature (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 (e.g., droughts and heat waves), that is, when impacts are induced by the combination of several climate events (AghaKouchak et al., 2014; Le Quéré et al., 2016; Leonard et al., 2014; Martius et al., 2016; Zscheischler and Seneviratne, 2017).

1.3.1.4 Probability, uncertainty and non–linearity 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, for example, their limitations in simulating regional climate variability (James et al., 2017), 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 stabilization at a later stage, compared to stabilization at 1.5°C without overshoot may differ in magnitude (Schleussner et al., 2017). Additionally, the capacity of some ecosystems to recover after an overshoot may not be well known (assessed in detail in Chapter 3).

The IPCC (2014) and World Bank (2013) underscored the non–linearity of projected risks and impacts as temperature rises from 2°C to 4°C of warming, particularly in relation to water availability, heat extremes, bleaching of coral reefs, and more. Recent studies (James et al., 2017; Schleussner et al., 2016a) assess the impacts of 1.5°C versus 2°C warming, with the same message of non–linearity. For some extremes, non–linearity of impacts may ensue when using threshold–based indices such as those for extreme temperature events as a result of dry soils amplifying hot temperature extremes (Whan et al., 2015) and for projected abrupt changes in rainfall, as a response to future increases in temperature (Schewe and Levermann, 2017).

1.3.2 Dimensions of Ecosystem Impacts

1.3.2.1 Sensitivity of organisms and ecosystems to climate change

Impacts of climate change on natural and managed ecosystems can imply loss or increase in growth, biomass or diversity at the level of species populations, landscapes or entire biomes. They occur in addition to the natural variation in growth, ecosystem dynamics, disturbance, succession and other processes, rendering attribution of impacts at lower levels of warming difficult in certain situations. 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 (Settele et al., 2014).

Organisms and ecosystems may adapt to environmental change to a certain degree, for example., through changes in physiology, ecosystem structure, species composition or evolution. Large–scale shifts in ecosystems may cause important feedbacks, for example, in terms of changing water and carbon fluxes through impacted ecosystems – these can amplify or dampen atmospheric change at regional to continental scale. For example, of particular concern, is the response of most of the world's forest ecosystems and many seagrass ecosystems, all of which play key roles as carbon sinks (Marbà et al., 2015; Settele et al., 2014).

1.3.2.2 Drivers of ecosystem impacts

Mean temperature and (for land ecosystems) precipitation are the main drivers of ecosystem processes, any change in them will at some point change the ecosystem. In addition, other environmental variables, such as the frequency or intensity of extreme weather events such as storms, floods or droughts, also play a major role (Seneviratne et al., 2012). Marine ecosystems are also affected by ocean acidification caused by increasing atmospheric CO_2 concentrations (e.g., Hoegh–Guldberg et al., 2007 and see Section 1.3.1.3). In addition to the combination of these drivers of change, human use (agriculture, forestry, fisheries) or other direct human impacts (urbanization, pollution) play a major role which can even dominate over change in climate (e.g., Hosonuma et al. 2012). Quantification of ecosystem impacts, and their attribution to climate change is therefore particularly challenging, notably at moderate levels of warming (Settele et al., 2014).

1.3.2.3 Resilience and irreversibility

The resilience of ecosystems, that is, their ability to resist to change, or to recover after a disturbance, may change, and often decline, in a non–linear way. 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 (see Box 3.6).

1.3.2.4 Impacts of climate change mitigation efforts on ecosystems

Some ambitious efforts to constrain atmospheric greenhouse gas concentrations may themselves impact ecosystems. In particular, changes in land use, potentially required for massively enhanced production of biofuels (either as simple replacement of fossil fuels, or as part of Bioenergy with Carbon Capture and Storage (BECCS)) will impact all other land ecosystems through competition for land (e.g., Creutzig 2016). Depending on earlier use, transformation of land area to biofuel plantations is likely to reduce the availability of other services from these areas, including food provisioning and storage of carbon in soils (for estimates of potentially affected land area, see Box 3.10).

1.3.3 Human dimensions of impacts including vulnerability and adaptive capacity

There is increasing evidence that climate change is having observable and often severely negative effects on people, especially where climate–sensitive biophysical conditions and socioeconomic/political constraints on adaptive capacities combine to create high vulnerabilities (IPCC, 2012c, 2014c; World Bank, 2013). The character and severity of impacts depend not only on the hazards (e.g. changed climate averages and extremes) but also on the vulnerabilities of different communities, and their exposure to climate threats. The impacts of 1.5°C global warming will vary temporally and spatially as different parts of the globe warm unevenly (Ebi et al., 2016). These will affect a range of natural and human systems such as natural resources development and provisions capacities, coastal zones, agricultural production systems, infrastructure systems, the built environment, human health and other socio–economic systems (Rosenzweig et al., 2017).

Adaptive capacity to a 1.5°C warming world will vary markedly for individual sectors and across sectors such as water supply, public health, infrastructure, ecosystems and food supply. For example, density and risk exposure, infrastructure vulnerability and resilience, governance and institutional capacity all drive different impacts across a range of human settlement types (Dasgupta et al., 2014; Revi et al., 2014; Rosenzweig et al., 2015). Additionally, the adaptive capacity of communities and human settlements in both rural and urban areas, especially in highly populated regions, poses several equity, social justice and sustainable development issues. Vulnerabilities due to gender (Arora–Jonsson, 2011; Resurrección, 2013), age, level of education and culture among others, act as compounding factors.

Climate change already disproportionately affects the most vulnerable segments of society, in both urban and rural areas (IPCC, 2014d; Rosenzweig et al., 2015; World Bank, 2013). These populations, communities, and institutions often lack adaptive capacity to increased climate risk and to new or emerging risks. Climate change is also projected to slow down economic growth and make poverty reduction more difficult (Arent et al., 2014), a substantial threat to the sustainable development of most of the vulnerable countries. Furthermore, differences in vulnerability and exposure to climate change arise from non–climatic factors and from multi–dimensional inequalities, which are often a result of uneven development processes, leading to different risks from climate change (Olsson 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 the enabling conditions for limiting global warming to 1.5°C and ambitions of UN sustainable development goals are complex and multifaceted. Climate mitigation–adaptation linkages, synergies and trade–offs are important when considering opportunities for 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). Climate mitigation and adaptation measures and actions can reflect and enforce specific patterns of development and governance that differ amongst the world's regions. This report also assesses where limited adaptation and mitigation capacity, limits to adaptation and mitigation, and conditions of mal–adaptation and mal–mitigation are present. This section details the framing of various implementation options, enabling conditions (for more discussion see Cross–Chapter Box 1.3 on feasibility[2]), capacities and types of knowledge and their availability (Blicharska et al., 2017) that can allow institutions, communities and societies at large to respond to the 1.5°C challenge in the context of sustainable development, as well as integrating other direct relevant international agreements such as the Sendai framework for disaster risk reduction. Equity and ethics are recognised as issues of paramount importance in reducing vulnerability and eradicating poverty.

1.4.1 Equity, rights and responsibilities

Equity and ethics are important framing elements of this report. Climate change raises a set of equity and ethical issues. For example, poverty and inequity are worsened by climate change and constitute barriers to achieving sustainable development (O' Brien et al., 2012). As indicated by Stern (2014), climate change poses a problem of risk management on an immense scale. The consequences of business–as–usual significantly threaten human security in a variety of ways, including the possible displacement of hundreds of millions of people, which in turn may contribute to prolonged conflict (Adger et al., 2014; Ionesco et al., 2016). Risks on this scale disproportionately affect the poor and disenfranchised, raising ethical concerns about the distribution of climate change impacts and the responsibility for its occurrence and scale (Reckien et al., 2017). A focus on rights and responsibilities help to clarify the root causes of climate risks, and assist in their distribution and management.

The principle of equity is a central hinge of climate response efforts across geographies and generations (Kolstad et al., 2014). The Paris Agreement mentions the principle of equity on five separate occasions, and the preamble in particular provides several examples of matters that fall within the broad ambit of ethics and equity, including sustainable development, poverty eradication, and human rights.[3] As IPCC AR5 made clear, these various elements are best understood as mutually supportive and co–achievable within the context of climate action (Fleurbaey et al., 2014b), and are underpinned by various other international hard and soft law instruments (Klein et al., 2014). Success in the effort to mitigate sufficiently to achieve, and to adapt to, a 1.5°C warming world, at the global as well as sub–national levels will depend on a shared capacity to marshal accumulated experience in

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[2]FOOTNOTE 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.

[3]FOOTNOTE Internationally protected human rights include rights to life, self-determination, non-discrimination, public participation, 'adequate food' and housing, water and sanitation, the 'highest available standard of physical and mental health', education, and 'the benefits of scientific progress'. Widely ratified human rights treaties relevant to climate change include the International Covenant on Civil and Political Rights, the International Covenant on Economic Social and Cultural Rights, and the UN Convention on the Rights of the Child (ratified by all but one of the world's states).

applying these instruments to achieve development, climate, and human rights objectives together (Shue, 2014).

As also noted in IPCC AR5, the principle of equity invokes notions of fairness and justice, comprising both procedural justice (i.e. participation in decision making) and distributive justice (i.e. how the costs and benefits of climate actions are distributed) (Kolstad et al., 2014; Reckien et al., 2017; Savaresi, 2016). Concerns regarding equity are central to the debates about mitigation, adaptation and climate governance as they open up opportunities to discuss who must cut emissions, who must pay for pollution, who has benefitted most, and who has the capability to respond (Ajibade, 2016; Reckien et al., 2017; Schroeder et al., 2012; Caney, 2005). Hence, equity 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).

Four key asymmetries in approaching the 1.5°C target have been noted by scholars, all foreshadowed in the UNFCCC (Ajibade, 2016; Harlan et al., 2015; Okereke, 2010; Reckien et al., 2017; Savaresi, 2016). The first is the asymmetry in contributions to the problem. Shue (2013) argues that while industrialization has benefitted humanity generally, the benefits have been unevenly distributed and those who benefited most historically have also contributed most to the current climate problem and so bear greater responsibility. The second asymmetry concerns differential impact; it is exacerbated because the worst impacts tend to fall on those least responsible for the problem. Conditions of climate disruption leading to forced migration provide an acute example of this asymmetry (Ionesco et al., 2016). Intergenerational equity also warrants consideration here. The third point of connection in the climate–justice nexus is asymmetry in the power to take decisions regarding solutions and response strategies. Powerful actors and stakeholders have greater influence on setting the climate action agenda to their advantage. Fourth there is an asymmetry in future–response capacity: some states and places are at risk of being left behind as the world progresses to a low–carbon economy (Fleurbaey et al., 2014b; Shue, 2014).

Klinsky and Winkler (2014) argue that responsibility is differentiable with regard to a ‘trio’ of climate equity challenges: inequality of climate impacts, of development status, and of 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. A number of scholars have suggested that human rights provide a robust framework for such operationalization, since they comprise internationally agreed treaty norms providing minimal standards that embed universally agreed values (Caney, 2010; Fleurbaey et al., 2014b; OHCHR, 2009) – and these already align with the Paris goals of poverty eradication, sustainable development, and the reduction of vulnerability. Human rights comprise both substantive rights and procedural rights (IBA, 2014; Knox, 2015; OHCHR, 2009, 2015; UN General Assembly, 2015).

How can action to limit warming to 1.5°C be consistent with the protection of human rights? Nation states already have several human rights obligations to their own populations that are relevant to the implementation of climate policy. These include obligations of due diligence to assess harm, to inform affected persons of potential risks, to take steps to protect vulnerable persons and to investigate failures of policy resulting in harm (Cedervall Lauta and Rytter, 2016; Knox, 2015). Internationally, according to some scholars, states have obligations of assistance or, at a minimum, a duty to cooperate in meeting climate–related challenges (Knox, 2015). Human rights obligations dovetail with UNFCCC obligations in the areas of adaptation, finance and technology (ICHRP, 2008; OHCHR, 2009, 2015). For example, without sustained technology transfer and stable access to finance, rapid decarbonisation can be expected to slow or stall growth and exacerbate poverty, especially in less wealthy countries (Humphreys, 2017).

In contrast ethical considerations in relation to the natural world assume a temporal dimension to capture the implication of climate change for natural ecosystem. Many argue that human activity is pushing the Earth's systems beyond sustainable boundaries. One response is to focus policy concretely on intergenerational equity and environmental sustainability (McAlpine et al., 2015; Steffen et al., 2015). Further, the impacts of climate change on natural systems are not equally distributed, for example. some ecosystems may be more vulnerable to climate change (Agard and Schipper, 2014; Savaresi, 2016). These specific issues are assessed in Chapter 3.

1.4.2 Eradication of Poverty

A wide range of definitions for *poverty* exist AR5 discussed 'poverty' in terms of its multidimensionality, referring to 'material circumstances' (e.g. needs, patterns of deprivation, or limited resources), as well as to economic conditions (e.g. standard of living, inequality, or economic position), and/or social relationships (e.g. social class, dependency, lack of basic security, exclusion, or lack of entitlement, Olsson et al., 2014). Recognizing that poverty has many dimensions, the UNDP now uses a Multidimensional Poverty Index, and estimates that about 1.5 billion people globally live in multidimensional poverty, especially in rural areas of South Asia and Sub–Saharan Africa, with an additional billion at risk to fall into poverty (UNDP, 2016).

A large and rapidly growing body of knowledge, exploring connections between climate change and poverty has been developed. While climatic conditions are not seen as a sole cause of poverty, climatic variability and climate change are widely recognized as factors that may exacerbate poverty, particularly in countries and regions where poverty levels are high (Leichenko and Silva, 2014). AR5 discussed that climate change–driven impacts often act as a threat multiplier in that the impacts of climate change compound other drivers of poverty (Olsson et al., 2014). Most vulnerable and poor people are highly dependent on climate sensitive activities such as agriculture that are highly susceptible to temperature increases and variability in precipitation patterns (Miyan, 2015; Shiferaw et al., 2014). Even modest changes in rainfall and temperature patterns can push marginalized people into poverty as they lack the means to recover from shocks. Extreme events, such as floods, droughts, and heat waves, especially when they occur in a series, can significantly erode poor people's assets and further undermine their livelihoods in terms of labor productivity, housing, infrastructure, and social networks (Olsson et al., 2014).

The three–pronged emphasis on development, resilience, and transformation laid out in the Agenda 2030 – Transforming our World – are now seen to represent a real opportunity to reduce societal vulnerabilities, address entrenched inequalities, and break the circle of poverty. This is explored in some detail in Chapter 5.

1.4.3 Classifying Response Options

Humans undertake multiple responses to the climate change problem. The key categories of responses are framed here. **Mitigation** refers to efforts to cut or prevent the emission of greenhouse gases – limiting the magnitude of future warming. It also may encompass attempts to remove greenhouse gases from the atmosphere. Mitigation requires the use of new technologies, clean energy sources, change people's behaviour, or make older technology more energy efficient. Switching to low–carbon energy sources such as wind power, solar, geothermal, hydroelectric or nuclear represents strategies for lowering the emissions of greenhouse gases in the atmosphere. Proven approaches for limiting climate change also include enhancing energy efficiency, decreasing deforestation, and reducing industrial and agricultural emissions. These approaches are increasingly cost–competitive, consistent with large–scale use, and largely supported by public sentiment. Many renewable energy technologies have made progress in both performance and cost (IPCC, 2014e) and that their role in reducing air pollution and providing energy security outweighs possible disadvantages (Chapter 2 and 4).

Carbon dioxide removal (CDR) or 'negative emissions' strategies involve reducing the amount of carbon dioxide already in the atmosphere (different from reducing the amount of carbon dioxide emitted). Technologies for carbon removal are mostly in their infancy despite their importance to ambitious carbon mitigation pathways (Herzog, 2001; Minx et al., 2017). Though some carbon removal techniques such as reforestation and ecosystem restoration are well understood, many technologies are immature and the feasibility of massive–scale deployment remains a question (IPCC, 2014e; Leung et al., 2014). For this report, CDR is considered part of mitigation options (Chapter 2 and 4).

Climate change **adaptation** refers to the actions taken to manage the unavoidable impacts of climate change (IPCC, 2014c). The goal is to reduce vulnerability to the harmful effects of climate change (e.g. sea–level rise, more intense extreme weather events or food insecurity). It also includes exploring the potential beneficial opportunities associated with climate change (for example, longer growing seasons or increased yields in some regions). While climate change is a global issue, the impacts are felt locally. Cities and municipalities are at the frontline of adaptation and focusing on addressing their own climate–related challenges by strengthening agricultural systems, building flood defenses, reducing and managing disaster risks due to extreme and slow onset weather/climate events; installing flood and drought early warning systems and, improving water storage and use (Chapter 3 and Chapter 4; and Cross–Chapter Box 5.1)

Remedial options are distinct from mitigation or adaptation, as the aim is to temporarily reduce or offset warming (IPCC, 2012b). One of the most extensively discussed remedial options is **Solar Radiation Management** (SRM, which involves deliberate changes to the albedo of the Earth system, with the net effect of increasing the amount of solar radiation reflected from the Earth in order to reduce the peak temperature from climate change (Schäfer et al., 2015; Smith and Rasch, 2013; The Royal Society, 2009). One of the most commonly proposed SRM techniques involves the artificial emission of aerosols into the stratosphere (Crutzen, 2006; Rasch et al., 2008), referred to as Stratospheric Aerosol Injection (SAI), to essentially mimic the effect of volcanic eruptions in reducing the global average temperature. Another method is Marine Cloud Brightening (MCB), which involves increasing the number of salt particles in low–level marine clouds by spraying sea water into the lower parts of the atmosphere. The larger number of salt particles increases cloud albedo, which increases the amount of solar radiation reflected (Latham et al., 2008). Other related approaches exist, which involve increasing the albedo of the land surface, for example *via* changes in the albedo of agricultural land (e.g., higher albedo crops/soil) or urban areas (e.g., reflective roofing material) (Davin et al., 2014; Hirsch et al., 2017; Irvine et al., 2011). Methods which change local surface albedo only have an effect on regional temperature, with negligible effects on global temperature (Seneviratne et al., 2017; Cross–Chapter Box 3.10). Methods such as SAI could potentially be used for "peak shaving" in over–shoot scenarios to keep the global mean temperature below 1.5°C and temporarily reduce the severity of near–term impacts (Section 3.6.3, Section 4.3.9 and Cross–Chapter Box 4.2). However, other than simulations using climate models and small scale field trials, SRM is largely theoretical and un–tested, and the unintended impacts (both biophysical and societal), technical feasibility, governance and ethical issues associated with SRM need to be carefully considered (Schäfer et al., 2015; Section 4.3.9 and Cross–Chapter Box 4.2). The social aspects, costs and ethical issues associated with SRM also need to be considered carefully (Section 4.3.9).

1.4.4 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 (Lövbrand et al., 2017), 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 at all 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).

One of the outcomes of the Paris Agreement is the recognition of the need to link the multilateral treaty–regime with the bottom–up world of national and sub national climate action. To ensure that global mean warming does not exceed 2°C, and even stays toward 1.5°C, many have suggested that the voluntary pledges submitted by states and non–state actors to the Paris Agreement will need to be more firmly coordinated, evaluated and upscaled (Lövbrand et al., 2017).

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 (Hughes, 2017). Conversely, the risk of climate change will escalate in countries with severe governance failure (IPCC, 2012c; 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., 2014). It is through governance that justice, ethics and equity within the adaptation–mitigation–sustainable development nexus can be addressed (Stechow et al., 2016).

1.4.5 Transformation, Transformation Pathways, and Transition

Embedded in the 1.5°C goal is the opportunity for intentional societal transformation (see Box 1.1 on the Anthropocene). The pace and process of transformation are varied and multifaceted (O' Brien et al., 2012; O'Brien and Selboe, 2015; Pelling, 2011; Pelling et al., 2015). 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 and carbon sequestration technologies, and synergistically linking climate mitigation and adaptation to global scale trends (e.g., global urbanization) that will enhance the prospects for meaningful climate action, as well as enhanced poverty reduction and greater equity (Patterson et al., 2017; Rogelj et al., 2015; Tschakert et al., 2013). 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 including intergenerational equity and for non–human species. Adaptation and mitigation transition pathways highlight the importance of cultural norms and values, sector specific context, and proximate (i.e. occurrence of an extreme event) drivers that when acting together enhance the conditions for societal transformation (Rosenzweig et al., 2018; Solecki et al., 2017). Historical analogues as described in the archaeological, anthropological, geographical, and historical research, provide 1.5°C–related insights into the process of societal transformation and the relative role of external and internal system dynamics (Cooper and Sheets, 2012; IPCC, 2012a; Revi et al., 2014).

The rate of change within environment–related policy systems can occur gradually or be punctuated by rapid change, particularly when linked with extreme disaster events, social crises, or technological innovation (Kates et al., 2012; Pelling et al., 2015). Extreme disaster events that have significant impacts are associated with windows of transformational change but can be interpreted in a variety of ways by impacted communities that can either help or hinder action (Capstick and Pidgeon, 2014; Carmichael et al., 2017; Kates et al., 2006). Potential precursor conditions or early warning conditions associated with significant climate policy shifts have been identified (Solecki et al., 2017).

Incremental change can set in motion larger scale transformations in systems but often is not sufficient (Kates et al., 2012). Even so, incremental transformation is key when designing, planning, and improving implementation options at local level to avoid infrastructure path dependency and facilitate flexible adaptation (Revi et al., 2014; Cross–Chapter Box 5.1 on Cities and Urban Transformation). Disaster and engineering resilience efforts when focused on infrastructure hardening and short–term risk reduction may limit future incremental and transformation change because of infrastructure dependency (Rosenzweig et al., 2018; Solecki et al., 2017).

1.4.6 Implementation and policies

Transitioning from climate change mitigation and adaptation planning to practical policy implementation is a major challenge identified for constraining global temperature to 1.5°C. This is due to several barriers including finance, information, technology, public attitudes, social values and practices (Corner and Clarke, 2016; Whitmarsh et al., 2011) and human resource constraints plus institutional capacity to strategically deploy available knowledge and resources (Mimura et al., 2014). Regional diversity, including highly carbon–invested and emerging economies, is an important consideration. Incorporating strong linkages across sectors, devolution of power and resources to sub–national and local governments with the support of national government and facilitating partnerships among public, civic, private sectors and higher education institutions (Leal Filho et al., 2018) will be key to implementing identified response options.

Implementation challenges of 1.5ºC pathways are larger than for well below 2ºC particularly concerning scale and speed of the transition and the distributional impacts on socio–economic actors. Barriers to implementation can be overcome, for instance, by mainstreaming adaptation into existing policy domains (Uittenbroek et al., 2013). Also, conflicts may arise when it comes to implementing either mitigation or adaptation policies, in particular related to the sources of conflicts – such as unclear allocation of responsibilities for carrying out measures between different actors –, the nature of both policies and the lack of financial resources or cost of measures when choosing between adaptation and mitigation (Landauer et al., 2015).

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 1.5°C warming. 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.

In this regard, some studies indicate that public participation and the engagement of different civil society actors are key to urban climate adaptation planning and implementation (Chu et al., 2016) as well as participatory bottom–up urban development strategies (ADB, 2013). 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).

Cross-Chapter Box 1.3: Framing feasibility: Key concepts and enabling condition for limiting global temperature increases to 1.5°C

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A central question coming from the Paris 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 above pre–industrial levels. The aim of this cross–chapter box is to disentangle what is behind this rather abstract idea and to move it toward a more tangible, policy–relevant understanding, thereby further revealing enabling conditions of making the transition to a 1.5°C warmer world that will include both climate mitigation as well as climate adaptation and compatible with sustainable development objectives. The box does not directly assess what is feasible and whether limiting warming to 1.5°C is possible, generally or with no overshoot or overshoot, specifically; but, instead focuses on how feasibility could be framed and put in practice.

Three dimensions of feasibility and associated enabling conditions

Framing 'feasibility' starts from a given condition – in this case the requirements of a 1.5°C warmer world – and aims to reveal the enabling conditions and policy implications of different trajectories compatible with this objective, building on back casting techniques (Robinson, 1982).

A large literature exists on the technological feasibility of ambitious climate targets. It is primarily based on engineering approaches analysing the feasibility of specific technological solution such as 100% renewables electricity production (Heard et al., 2017) or techno–economic model–based analysis of least–cost pathways (IPCC, 2014a; Iyer et al., 2015; Loftus et al., 2015). To be comprehensive, not only the technical transformation in the system needs to be analysed, but also 'the social, environmental, economic, political, and technological implications of the scenarios'(Robinson, 1982, 1990). This is required to put the technical transformations into their political, social, and institutional context (Andrews–Speed, 2016; Nilsson et al., 2011; Schubert et al., 2015), to clarify the potential synergies and conflicts between different policy objectives (Hildingsson and Johansson, 2016) and to reflect the societal and governance transitions implied by ambitious low–emission pathways (Söderholm et al., 2011).

To illustrate the diverse elements of the pathways to a 1.5°C warmer world, we deconstruct the feasibility concept as three dimensions associated to different types of enabling conditions:
1) Geophysical and environmental–ecological dimension, that addresses the capacities of physical systems (including response to negative implications) to meet the requirements of achieving the condition of 1.5°C and adapting to its impacts;
2) Technological and economic dimension, that investigates the engineering and economic systems as well as financial markets; and

3) Cultural, social and institutional dimension, that captures the evolutions in the social and institutional context required to create the space for the deep socio–technical changes implied by these scenarios and to facilitate adaptation options.

The challenges of feasibility

Systemic effects. Each feasibility dimension and its associated enabling conditions have embedded within them 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, renewable or low carbon mega–projects) can be associated with large initial costs or heightened societal concerns and reduced social acceptability and hence a potential reduction in economic or social feasibility (e.g., Sovacool et al. 2015). Case studies can demonstrate system level interactions between the feasibility dimensions and conditions for positive or negative feedback effects (Heard et al., 2017; Jacobson et al., 2015; Loftus et al., 2015). System level interactions amongst feasibility of mitigation, adaptation, and the sustainable development goals will be especially important to consider.

Dynamic effects. The conditions of feasibility are highly dynamic and vary across temporal and spatial contexts, especially under potential conditions of overshoot or no overshoot. Guidance on feasibility could elucidate the distinction between the near–term (i.e., within the next several years to two decades) 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 low carbon transitions such as actively pursuing replacement of coal with natural gas could negatively impact the opportunity for longer–term feasibility because of energy infrastructure path dependency (Section 1.2.6). Some dimensions might be more time sensitive or sequential than others (i.e., if conditions are such that it is no longer geo–physically feasible to achieve a particular interpretation of a 1.5°C warmer world, social and institutional feasibility will be no longer relevant). Such cascading effects will be important for understanding the comparative importance of different metrics or indicators of feasibility.

Spatial effects. Feasibility also is spatially variable and scale dependent. What could be considered feasible in some regions of the world might be not feasible in others. The spatial variation of feasibility will be dependent on regional scale environmental resource limits, social organization, cultural beliefs and worldviews and conditions of urbanization, and financial and institutional capacities. 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 (see Section 4.3.8 for further BECCS discussion). Many potential spatial differences that influence regional understanding of feasibility such as economic wealth, institutional and governance capacity and culture also need to be recognized.

Defining indicators for the assessment of “feasibility” against enabling conditions

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 organize the different types of enabling conditions for transformations compatible with a 1.5°C warmer world, given the three challenges presented above. The different feasibility dimensions acknowledge the comprehensive and interlocking set of enabling conditions needed to limiting temperature increase to 1.5°C, and adapt to its impacts. They help clarify the opportunities and challenges associated with the feasibility in each community of interest including national and sub–national policy stakeholders, practitioners, and private sector decision–makers. Clearly, the entry point to the question of feasibility and the conditions in which stakeholders are interested will influence who is engaged with the concept of feasibility, their values and biases, and what they consider to be associated operational indicators. Data quality and scenario and pathway projections are other important elements associated with the application and usefulness 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.

Each dimension builds on a different discipline – physical sciences, engineering/economics perspectives, social sciences, and humanities (i.e. ethics – each having their specific approaches to the question and considering different types of base assumptions and requirements that correspond to their entry point into the feasibility discussion. Combining multiple methods and approaches to 'feasibility', including quantitative modeling and more qualitative storylines, is key to building robust and integrated visions useful for climate transition pathways stakeholders and practitioners (Flynn et al., 2018; Fortes et al., 2015; Turnheim et al., 2015).

Streamlining the discussion of feasibility along the organizing principle of the three distinct dimensions should help define and bridge the gaps between these different communities. Defining quantitative and/or qualitative indicators and metrics of feasibility dimensions that are transferable as much as possible within specific communities and across communities is key to enable the dialogue between these different communities (See Cross–Chapter Box 1.3 Table 1.1 below). Each indicator and metric reflect data already are being collected or could be easily collected in the future. The empirical measures provided are but a sample of variables that could be considered.

Different dimensions of feasibility are considered and assessed in the report's chapters. In Chapter 1 Section 1.2.6, focuses on geophysical feasibility (warming commitment), Chapter 2 on geophysical and technological feasibility, Chapter 3 on environmental and social feasibility, Chapter 4 on technological, economic, social and institutional feasibility, and Chapter 5 mostly on social and institutional feasibility yet attempts to integrate all aspects

Dimensions	Characteristics	Indicators and Metrics
Geophysical and Environmental	Geophysical	- Proportion of the emissions change required; warming commitment - Rate of land use change related to emissions growth and reduction - Geological carbon storage capacity
	Environmental - Ecological	- Limits of mitigation/adaptation in ecosystems; capacity of ecological systems - Risks of response options - Risks associated with irreversible changes and tipping points
Technological and Economic	Technological	- Speed of which different types of technologies can be implemented - Technical resource availability - Current and brining immature technologies to large-scale deployment and intellectual property conflicts - Historical analogues for curves of deployment/implementation and technology lock-in
	Economic	- Required investment flows and costs of response options including time and regional dimensions - International and national financing resources and mechanisms available to enable transitions - *Mal-mitigation* and maladaptation; unforeseen impacts and risks including stranded assets - Benefits and trade offs; economic development, GDP, poverty alleviation, employment impacts - Alternative growth models/SSPs including rates of urbanization
Social and Institutional	Social/cultural	- Social and cultural adaptive capacity including speed of changes in values, norms, and practices - Public acceptability, social disruptiveness, and behavioural responses (communities and private sector) - Human rights and equity/social inclusion/distributional impacts including Inter-generational - Regional dimensions - sub-national, national, regional - Health benefits and risks
	Institutional	- Political support, transparency, civil society engagement - Market structures and failures and missing markets - Administrative traditions and institutional capacity and rate of institutional change - Governance capacity and promotion of new legal frames including carbon tax, burden sharing - Interaction between multi-levels of governance

Cross–Chapter 1.3, Table 1: Dimensions of feasibility

1.4.7 Trade–offs and synergies of adaptation, mitigation and sustainable development

Development is multidimensional and its sustainability entails the coevolution of several objectives including the social, economic and environmental (Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014; Fleurbaey et al., 2014a). Denton et al. (2014) noted that climate change constituted ‘a moderate threat to current sustainable development and a severe threat to future sustainable development’ (*high confidence*) and that ‘ill–designed responses’ could ‘offset already achieved gains’ (Denton et al., 2014). 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) which includes specific goals for climate action (Goal 13; Box 1.2). The Sendai Framework for Disaster Reduction 2015–2030 (UNISDR, 2015) focuses on building resilient human settlements to reduce the vulnerability to disaster and enhance the capacity to reach the SDGs. Multiple connections between sustainable development, poverty eradication, reducing inequalities and pathways to limit global warming to 1.5°C versus 2°C above preindustrial levels are present (Kainuma et al., 2017; Nilsson et al., 2016; Stechow et al., 2016). The linkages between sustainable development for intergenerational wellbeing and the risks posed from a changing climate apply in perpetuity, up to and beyond 2030. The challenge is to ensure that the gains from sustainable development are not eroded by climate impacts (Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014; Dasgupta et al.) by managing risks within a 1.5°C warmer world through mitigation and adaptation responses.

There is diversity and flexibility in the implementation choices for adaptation and mitigation, and a potential for trade–offs and synergies between these choices (Chapter 5). For example, in the health sector, trade–offs occur when adaptation to heat stress includes increased air conditioning, which leads to higher energy use and thus higher emissions. Synergies between the two also exist. For example, demand–side measures that increase conservation through efficiency and behavioural change make human settlements more resilient to drought and heat waves, as well as reduce emissions of greenhouse gases (Stechow et al., 2016). In addition to mitigation and adaptation, the response to climate change could include carbon dioxide removal (CDR), whereby CO_2 is actively removed and stored (Rockström et al., 2016), or solar radiation management (SRM), where deliberate changes to the earth’s albedo are undertaken (IPCC, 2012b; see Section 1.4.3 and Cross–Chapter Box 4.2). While pathways aiming at 1.5°C are associated with high co–benefits for some SDGs (i.e., health and air pollution), the magnitude and fast pace of the transitions lead to increased risk for negative side–effects for a number of other SDGs, particularly risk of hunger, poverty, inequality and energy access.

Achieving the SDGs can also enhance the ability to adapt and mitigate the risks of climate change. For example, adaptive capacity and resilience is enhanced in societies with a broad access to education, good governance, and infrastructure (Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014). Eradicating poverty which is widespread in many rural communities, can enhance the resilience of agrarian communities (Eriksen and Brien, 2007), since the vulnerability of food production systems is heavily influenced by socioeconomic conditions (Antwi–agyei et al., 2012). 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). Urban areas exemplify how synergies between mitigation and adaptation and SDGs can be enhanced (e.g. Rao et al., 2013). There is value in examining the climate response and SDGs together since urban areas have to negotiate trade–offs at different scales, including the rural–urban interface (Landauer et al., 2015).

Simultaneously considering how to achieve an ambitious low climate trajectory and achieve the SDGs is a central point of this report and discussed in detail in Chapter 5. 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 1.5°C warming (Kainuma et al., 2017). Climate resilient development pathways (Box 5.1) are defined as sustainable–development pathways that combine adaptation and mitigation to reduce climate change and its impacts, including an iterative process to ensure effective risk management (IPCC, 2014c). Climate resilient pathways can be considered at different scales, including cities, regions or global (Denton et al., 2014; Chapter 5).

Box 1.2: The Sustainable Development Goals (SDGs)

In September 2015, international community endorsed a universal agenda entitled ‘Transforming our World: the 2030 Agenda for Sustainable Development’, widely known as the Sustainable Development Goals (SDGs). 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 realize this integration are enormous and countries are addressing subsets of SDGs in relation to their priorities and national capacities. Commitments to the SDGs are reviewed and reaffirmed at annual high level forums at the United Nations based on voluntary country reports, and will be reviewed at the UN General Assembly in 2019 (https://sustainabledevelopment.un.org/hlpf/2017/news/07/21).

Goal 1 No Poverty: End poverty in all its forms everywhere (defined as less than $1.25/day and multidimensional as defined locally)
Goal 2 Zero Hunger: End hunger, achieve food security and improved nutrition and promote sustainable agriculture
Goal 3 Good Health and Wellbeing: Ensure healthy lives and promote well–being for all at all ages
Goal 4 Quality Educati0n: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
Goal 5 Gender Equality: Achieve gender equality and empower all women and girls
Goal 6 Clean Water and Sanitation: Ensure availability and sustainable management of water and sanitation for all
Goal 7 Affordable and clean energy: Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8 Decent work and Economic Growth: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
Goal 9 Industry, Innovation and Infrastructure: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
Goal 10 Reduced inequalities: Reduce inequality within and among countries
Goal 11 Sustainable Cities and Communities: Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12 Responsible Consumption and Production: Ensure sustainable consumption and production patterns
Goal 13 Climate action: Take urgent action to combat climate change and its impacts

Goal 14 Life below water: Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 15 Life on Land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Goal 16 Peace, Justice and Strong Institutions: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
Goal 17 Partnerships for the Goals: Strengthen the means of implementation and revitalize the global partnership for sustainable development

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

The information and data for this report is global in scope and includes region–scale analysis. The assessment report provides the state of knowledge in a balanced way, including an assessment of confidence and uncertainty to ensure it is policy relevant. A synthesis of municipal, sub–national, and national case studies is included as well. Global level statistics including physical science and social science data are used and as well as detailed and illustrative case study material of particular conditions and contexts. The main time scale of the assessment is the 21st century and the time is separate into the near–term, medium term, and long term. 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 3's methods for assessing observed impacts and projected risks at 1.5°C and higher levels of warming in natural and managed ecosystems and human systems, Chapter 4's mitigation potential assessment framework and the connection to social innovation, and Chapter 5's linkage of the shared socioeconomic pathways (SSPs) and sustainable development goals (SDGs).

1.5.1 Multidimensional costs and benefits

Depending on policies and investments adopted, emission reductions required for a 1.5°C warming 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 warming world will originate from international agreements that must be translated to national and sub–national levels.

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, 2014a; IPCC, 2014b). 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; even though some basic cost–effectiveness estimates are part of integrated assessment models reviewed in Chapter 2 of this report. Some costs are relatively easily quantifiable in terms of monetary measures, but the impacts of climate change are on humans' lives and livelihoods, their culture and values or ecosystem goods and services and have unpredictable feedback loops and impacts on other regions, making it difficult to quantify and compare (IPCC, 2014c). Other costs such as indirect, secondary and tertiary costs and opportunity costs are typically even more difficult to quantify. The complexity of estimating is further complicated through development and application of discount rates of future costs and benefits. In addition, costs and benefits can occur at very different times, even across different centuries for different regions, and as a result, 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 through trade linkages and or increased susceptibility to further impacts, even those less severe (Hsiang et al., 2017; Schleussner et al., 2016a). Full accounting of recovery costs and longer–term secondary and tertiary costs also are very challenging to define. The cumulative impacts from small, recurrent disasters can, over time, equal or even exceed those from larger catastrophes (Campos Garcia et al., 2011).

Climate change tends to enhance pre–existing inequalities, between and within affected regions , elevating losses in already disadvantaged areas (Aaheim et al., 2016; Hsiang et al., 2017; Schleussner et al., 2016a). However, in cases where a deliberate effort is taken to constrain the temperature to 1.5°C, costs and benefits also will be related to transitioning approaches adopted to move from high to low emission investments. These transitions pathways are likely to result in losses and opportunities for different sectors, for example fossil fuel–related industries versus low emissions–oriented ones, specific socio–economic groups and locations and beyond due to existing strong global interlinkages and inequalities (Admiraal et al., 2016; Hsiang et al., 2017).

The significant benefits to future generations from low emissions development pathways are likely to be experienced by current society in part as intergenerational investments although there may be several direct and indirect benefits to present society for example in terms of health and quality of life (Admiraal et al., 2016). Large–scale intervention in the Earth's climatic system for example, solar radiation management (see Cross–Chapter Box 4.2 on solar radiation management) could give rise to far reaching costs and obligations to sustain the efforts, some going beyond the current generation, in addition to anticipated benefits. Available higher global welfare losses also are indicated for the 2°C post–2030 pathway (Rose et al., 2017).

Costs and benefits of a 1.5°C warming world could be estimated by taking into account the above noted constraints and applied to desired development frameworks such as under the Agenda 2030 sustainable development pathways (Fuss et al., 2016; Honegger and Reiner, 2017). Flexibility in policy at multiple scales to facilitate appropriate timing, innovations and technology as well as conducive economic and socio–cultural environment are 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

This report is based on a comprehensive assessment of documented evidence of the enabling conditions to maintain the global temperature at 1.5°C and adapt to this level of warming in an Anthropocene epoch (Delanty and Mota, 2017). Two sources of evidence are used; peer reviewed scientific literature and grey literature, with the former being the by–far dominant source.

The peer–reviewed literature includes the following types of knowledge: 1) State of knowledge regarding 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 actual human experiences of climate change risks and vulnerability in the context of the social–ecological systems, development, equity and justice and the role of governance; within which is body of local knowledge that incorporates indigenous knowledge systems; and 3) Mitigation pathways based on climate projections into the future.

The grey literature category also extends to empirical observations, interviews, and results from models found in theses, technical and consultancy reports and conference papers, government reports, reports from development agencies and non–governmental organisations (NGOs) and other sources. The assessment does not cover non–written evidence and does not use oral evidence nor media reports or newspaper publications. In addition to the overall scarcity of published literature on 1.5°C warming, with the exception of Australia and to some extent China, publications from the Global South, the most vulnerable part of the world, are far lower in the geopolitics of documented knowledge (Czerniewicz et al., 2017).

A holistic knowledge base and new and adaptable institutional structures at different governance scales will be required to create the policy and legal frameworks for societal transformation and to establish resources for implementing various response options to a 1.5°C warming world (James et al., 2017). Incorporating knowledge from different sources, settings and information channels while building awareness at various levels will advance decision making and motivate implementation of context specific responses to 1.5°C warming and associated uncertainties (Somanathan et al., 2014).

1.5.3 Climate models and associated simulations available for the present assessment

Climate models allow for policy–relevant calculations including the assessment of the levels of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions compatible with 1.5°C or 2°C global warming levels, as well as the associated changes in climate means and variability. Climate models are numerical models that can be of varying complexity and resolution (e.g. Le Treut et al., 2007). Presently, global climate models are typically Earth System Models (ESMs), in that they entail a comprehensive representation of Earth system processes, including biogeochemical processes.

Various sources of climate model information are used for the present assessment. First, there are global simulations that have been used in previous IPCC assessments and which were computed as part of the World Climate Research Programme (WCRP) Coupled Models Intercomparison Project (CMIP). The IPCC AR4 and SREX reports were mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. We note that the simulations of the CMIP3 and CMIP5 experiments were found to be very similar (e.g. Knutti and Sedláček, 2012; Mueller and Seneviratne, 2014). In addition to the CMIP3 and CMIP5 experiments, there are results from coordinated regional climate model experiments (CORDEX), which are available for different regions (Giorgi and Gutowski, 2015). For instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et al., 2014; Jacob and Solman, 2017) are newly available for 1.5°C projections. Recently, also simulations from the “Half a degree Additional warming, Prognosis and Projected Impacts” (HAPPI) multi–model experiment have been performed to specifically assess climate changes at 1.5°C vs 2°C global warming (Mitchell et al., 2016). The HAPPI protocol consists of coupled land–atmosphere initial condition ensemble simulations with prescribed sea surface temperatures (SSTs), sea–ice, GHG and aerosol concentrations, solar and volcanic activity that coincide with three forced climate states: present–day (2006–2015), and future (2091–2100) either with 1.5°C or 2°C global warming (prescribed from the modified SST conditions).

Beside climate models, other models are available to assess changes in regional and global climate system (e.g. models for sea level rise, models for floods, droughts, and freshwater input to oceans, cryosphere/snow models, models for sea ice, as well as models for glaciers and ice sheets). Analyses on impacts of a 1.5°C and 2°C climate using such models include for example, Schleussner et al. (2016) and publications from the Inter–Sectoral Impact Model Intercomparison Project (ISI–MIP) Project (Warszawski et al., 2014), which have recently derived new analyses dedicated to 1.5°C and 2°C assessments.

1.5.4 Detection and attribution of change in climate and impacted systems

Formalized scientific methods are available to detect and attribute impacts of greenhouse gas forcing on observed changes in climate (e.g. Hegerl et al., 2007; Seneviratne et al., 2012; Bindoff et al., 2013) and impacts of climate change on natural and human systems (e.g. Hansen et al., 2016; Hansen and Cramer, 2015; Stone et al., 2013). The reader is referred to these past IPCC reports for more background on this topic. It is noted that attribution of GHG on climate requires different techniques, as does attribution of climate change on natural and human systems. In particular, for a specific impact in a specific location, some part of it could be due to natural variability and another part to anthropogenic forcing on the climate system.

Attribution is an important field of research for these assessments. Indeed, global climate warming has already reached approximately 1°C compared to pre–industrial conditions, and thus 'climate at 1.5°C global warming' corresponds to approximately the addition of only half a degree warming compared to present–day warming. This means that methods applied in the attribution of climate changes to human influences are relevant for assessments of changes in climate at 1.5°C warming, especially in cases where no climate model simulations or analyses are available for the conducted assessments. Impacts of 1.5°C global warming can be assessed in parts from regional and global climate changes that have already been detected and attributed to human influence (e.g., Schleussner et al., 2017). This is because changes that could already be attributed to anthropogenic greenhouse gas forcing are related to components of the climate system that are most responsive to this forcing, and thus will continue to be under 1.5°C or 2°C global warming. For this reason, when specific projections are missing for 1.5°C global warming, some of the assessments provided in Chapter 3 build upon joint assessments of a) changes that were observed and attributed to human influence up to present, i.e. for °C global warming and b) projections for higher levels of warming (e.g., 2°C, 3°C or 4°C) to assess the most likely changes at 1.5°C. Such assessments are for transient changes only (see Section 3.3).

Impacted systems respond to natural short– and long –term variability as well as to specific local conditions which may imply particularly high or low rates of human–induced climate change. It is important to remember that local impacts of global climate change may already be due to higher warming than 1.5°C locally, because of the geographical variations in responses to GHG forcing. Many natural and human systems are strongly impacted by non–climatic forcings such as pollution or land use change. To distinguish the climatic forcing in any given case therefore requires first the recognition of a change in the system which goes beyond natural dynamics (such as forest growth after plantation). Once detected, this change must be attributed to climatic or non–climatic forcings, a process that usually requires expert knowledge and the understanding of the physical or ecological dynamics of the impacted system. From this follows that impact attribution usually has the nature of stating that the climate forcing has been "high" or "low", with an associated uncertainty (Hansen et al., 2016).

1.6 Consideration and communication of confidence, uncertainty and risk

Careful consideration and clear communication of levels of confidence and uncertainty are 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). The AR5 relied on two metrics for communicating the degree of certainty in key findings:

i. Qualitative expressions of confidence in the validity of a finding based on the amount of and level of agreement in the evidence available; and
ii. 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. 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 aiming for consistent practice spanning physical climate, impacts, vulnerabilities, risks, and mitigation options, within the constraints of the available literature.

1.6.1 Confidence

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, one being the type, quality, amount or internal consistency of individual lines of evidence, and 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.

1.6.2 Likelihood

A calibrated language scale is used 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%) to 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 actual probabilities of outcomes (frequency of occurrence within a model ensemble does not correspond actual probability of occurrence unless the ensemble is judged to capture and represent the full range of relevant uncertainties). Figures and text normally use 5–95% confidence intervals for observable quantities and the 5–95% frequency interval for ranges of model ensembles.

1.6.3 Challenges in the context of this Special Report

Three specific challenges arise in the treatment of uncertainty and risk in this report.

First, the timeline on which this report is being prepared and the current state of the scientific 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 particular challenge for the current assessment: 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. Although allowed by the Uncertainty Guidance, double–qualified expressions that combine both likelihood and confidence language may be difficult to understand (e.g., “very likely (medium confidence)”). To avoid such double–qualified statements, many key findings are expressed in this report using confidence qualifiers alone – but this should not be interpreted as implying they are less robust or policy–relevant than statements using likelihood qualifiers.

Second, many of the most important findings of this Special Report are highly conditional precisely because they refer to ambitious mitigation scenarios. The risks associated with 1.5°C of global warming (meaning risks conditioned on the assumption that global temperatures are at 1.5°C) may be very different from the risks associated with a scenario that has an even chance of remaining below 1.5°C. In the second case, risks also need to allow for a substantial chance of warming exceeding 2°C because of uncertainty in the global temperature response. 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.

Third, the traditional application of probabilistic language in IPCC reports 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. Probabilistic statements about human decisions, which may in turn be informed by these statements, are always problematic, but they 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 may be the same, regardless of the actual probability that the goal will be met.

1.7 Storyline of the report

The storyline of this IPCC Special Report on 1.5° C, as illustrated in Figure 1.7, includes a set of interconnected assessment components. Taken together, these develop a story line of limiting the global temperature increase to 1.5°C above pre–industrial levels and addressing associated impacts and adaptation opportunities while being inclusive of SDGs–related conditions for poverty eradication, equity and ethics.

At a time of unequivocal and rapid warming, the report’s initial position emerges from the long–term temperature goal of the Paris Agreement; the strengthening the global response to the threat of climate change by pursuing efforts to limit warming to 1.5°C through reducing emissions to restore balance between sources and sinks of greenhouse gases. The assessment focuses first, in Chapter 1, on defining the character of the key report element – 1.5°C itself, and how 1.5°C is defined and understood, what is the current amount of climate change to date, and the present trajectory of change.

Next, in Chapter 2, the assessment explores the enabling conditions of a 1.5°C warmer world, the feasibility of limiting warming to 1.5°C and the associated pathways. All pathways begin now, and involve rapid and unprecedented societal transformation, in an Anthropocene already experiencing extraordinary technological, social and environmental changes. An important framing device for this report is the recognition that choices that determine emissions pathways, whether ambitious mitigation or ‘no policy’ scenarios, do not occur independent of these other changes and are, in fact, highly interdependent. Technology choice, for example, has significant impact on how future emissions are understood and experienced.

While the emission pathways present key thematic elements of possible futures, projected impacts that emerge with a 1.5°C warmer world and beyond also are dominant narrative threads of the report. The assessment examines the diverse and uneven human, economic and ecological impacts of a global warming of 1.5°C that will be felt within, and last at least, a generation. Projected impacts will have a variety of complex spatial, temporal, and system–level manifestations. Central to the assessment is the reporting of opportunities for and limits to adaptation, potential impacts avoided through limiting warming to 1.5°C and comparing impacts at 1.5°C and 2°C of global warming.

With better understanding of emission pathways and impacts, response options emerge next in the account, in Chapter 4. Attention is directed to exploring questions of implementation and of profound transformation within a highly inter–dependent world. Emission pathways, in particular, are broken down into a set of specific questions and answers. The role of technological choices, institutional capacity and large–scale global scale trends like urbanization are assessed. Discussion of enabling conditions and feasibility help set the stage.

The storyline is resolved in Chapter 5 through the vehicle of climate resilient development pathways, developed to define the links between the trajectory towards 1.5°C, associated impacts, emissions pathways and the context of transformation. The report focuses on identifying opportunities and challenges, and implications for ethics and equity, for communities, institutions, countries and the world to transition to climate resilient development pathways. Progress along these pathways will involve learning, adjustment, and reflexivity to maximize the benefits of pursuing climate stabilisation at 1.5°C and the goals of sustainable development.

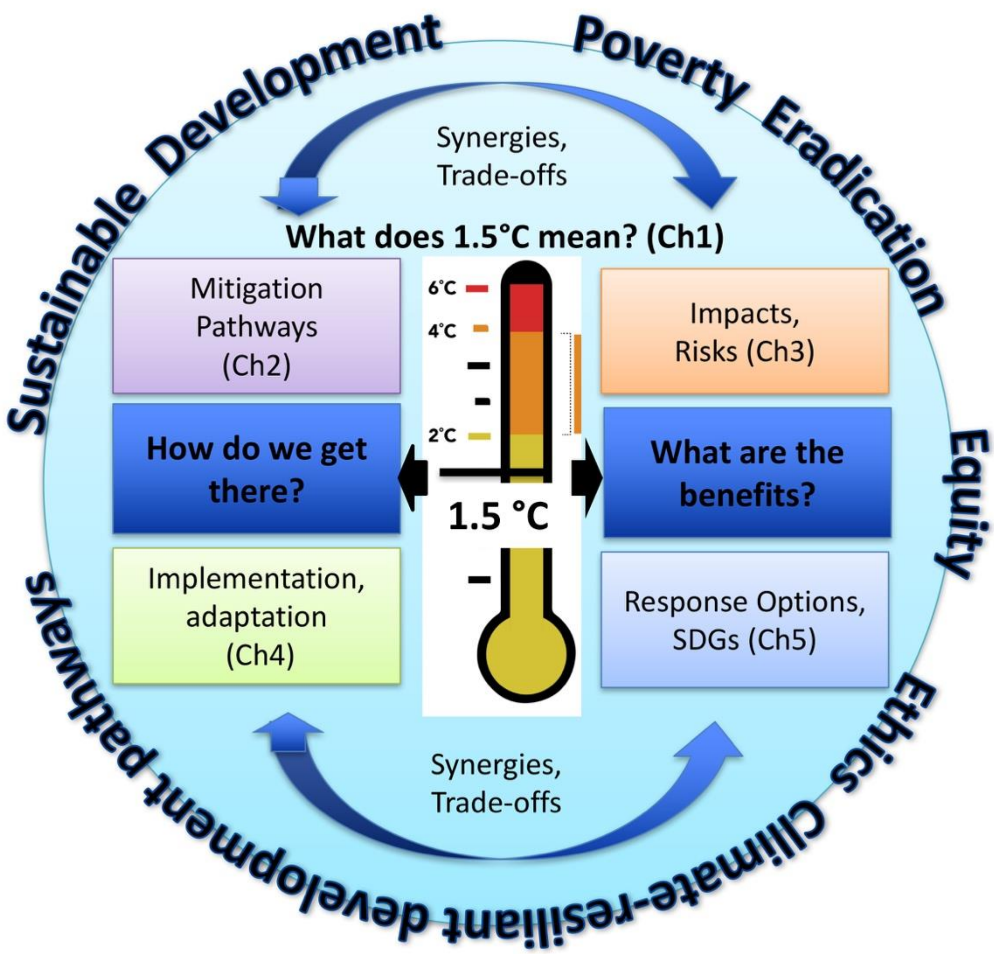

Figure 1.7: Placeholder schematic storyline figure for the rest of the report.

FAQ 1.1: Why are we talking about 1.5°C?

In recognition of the fact that climate change already poses a rising risk in many parts of the world , the Paris Agreement aimed to hold temperatures to "well below 2°C", with efforts to limit the increase to 1.5°C. Recognising limits to scientific knowledge available at the time the Agreement was signed, the UNFCCC invited the IPCC to publish a Special Report on 1.5°C global warming. In particular, countries of the world needed more information on the impacts of 1.5°C warming, global greenhouse gas emission pathways available to achieve 1.5°C, and how transitioning to a 1.5°C world ties in with global efforts to strengthen sustainable development and eradicate poverty, with consideration of ethics and equity.

At the 21st Conference of the Parties (COP21) in December 2015, government representatives from 196 countries negotiated the Paris Agreement. This agreement, the first of its kind, aimed to strengthen the global response to the threat of climate change by holding global temperature rise to "well below 2°C" above pre–industrial levels, and to pursue efforts to limit this increase to 1.5°C.

Before COP21, there had been little focus on global warming of 1.5°C in the scientific world. In an effort to address this, the United Nations Framework Convention on Climate Change (UNFCCC) invited the IPCC to publish a Special Report on global warming of 1.5°C above pre–industrial levels. The request was that the report, known as SR1.5°C, should not only assess what a 1.5°C warmer world would look like but also the different pathways available to achieve 1.5°C. The Special Report also looks at the wide–ranging implications of those different pathways and what actions would be necessary to transition to a 1.5°C world while promoting sustainable development and efforts to eradicate poverty.

The mention of 1.5°C in the Paris Agreement recognises that the impacts of climate change are already being felt in many parts of the world and that as the temperature rises, so do associated risks. The probability of extreme weather events and irreversible changes increases rapidly at higher warming levels. Compared to present day, warming of 1.5°C will also exacerbate other global risks, such as the degradation of ecosystems, food insecurity, disease outbreaks, and lack of access to fresh water. The risks posed by global warming of 1.5°C are greater than present day but substantially lower than at 2°C.

Ethics and equity are essential to understanding the ambition of the Paris Agreement. An asymmetry in vulnerability to climate change means that the impacts of warming levels beyond 1.5°C could fall disproportionately on poor and vulnerable people, and those least responsible for the problem. The combination of increasing exposure and limited capacity to adapt to climate change impacts can amplify the risks posed by 1.5°C and 2°C of warming, particularly for developing countries in the tropics.

***[Figure suggestion**: A general schematic that shows the different factors that need to be considered when looking at 1.5°C? Impacts, differences compared to other temps, knock–on effect, synergies and trade–offs.]*

FAQ 1.2: How close are we to 1.5°C?

Human–induced warming has already reached about 1°C above preindustrial levels at the time of writing of this report. By the decade 2006–2015, human activity had warmed the world by 0.87°C (±0.1°C) compared preindustrial times (1850–1900). If the current warming rate continues, scientists expect the world would reach human–induced global warming of 1.5°C in the 2040s, but this could be earlier if emissions increase and warming continues to accelerate.

Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions to hold the rise in global average temperature to 'well below 2°C' above pre–industrial levels, and to pursue efforts to limit the increase to 1.5°C. While the overall intention is clear, the Paris Agreement does not specify precisely what is meant by 'global average temperature', or what period in history should be considered 'pre–industrial'. To answer the question of how close are we to 1.5°C of warming already, scientists need to first define what both of these terms mean.

In principle, 'pre–industrial levels' could refer to any period of time before the start of the industrial revolution, but fewer direct observations exist the further back in time you go. Defining a "preindustrial" reference period is a compromise between the reliability of the data and how representative it is of truly preindustrial times. Some preindustrial periods are cooler than others for purely natural reasons.

The definition of the pre–industrial reference period, along with the method used to estimate global average temperature, can make a couple of tenths of a degree difference to estimates of historical warming. While this may not affect the big picture of how human activity is influencing the climate, a few tenths of a degree becomes important once we are considering a global temperature limit that is just half a degree above where we are now.

The Special Report on 1.5°C uses the reference period 1850 to 1900 to represent pre–industrial conditions. This is the earliest period with near–global observations, and any warming experienced before 1850 is partly compensated for by volcanic activity in the 1880s. The period 1850–1900 was also the reference period used in the IPCC 5th Assessment Report (AR5), which provided the scientific context of the negotiations leading up to the Paris Agreement, including that the world was already experiencing the impacts of 0.85°C of warming above pre–industrial conditions.

Once scientists have decided on the definition of 'pre–industrial', the next step is to calculate the amount of warming at any given time relative to that reference period. The amount of warming is, in turn, defined as the change in the combined average temperature over land and the oceans.

Scientists don't usually compare conditions between single years since natural variability can cause temperatures to fluctuate considerably either side of the long term warming trend. For example, 2015 and 2016 were both substantially warmer than 1°C, but also affected by the strong El Niño event that took place at that time. Instead, scientists compare the average global temperature over at least a decade, correcting for the impact of natural factors that can affect the climate for short periods of time, such as volcanic eruptions.

By the decade 2006–2015, human activity had already raised global average temperature by 0.87°C (±0.1°C), relative to 1850–1900. This means an additional 0.63°C (±0.1°C) would reach global warming of 1.5°C relative to 1850–1900. The recent rate of increase of 0.2°C per decade, suggests human–induced warming reached 1°C around 2017 and would reach 1.5°C above preindustrial levels in the 2040s**.** 1.5°C could be reached earlier if emissions increase and warming continues to accelerate.

While the change in global average temperature tells scientists about the rate at which the planet is changing, looking far more closely at specific regions and countries reveals some important details. Most land regions are warming faster than the global average, for example. This means that warming in many regions already exceeds 1.5°C. Over a fifth of the global population live in regions that have already experienced more than 1.5°C of warming in at least one season.

*[**Figure suggestion**: Simple schematic with time on x–axis and global average temperature on y–axis, highlighting relative positions of pre–industrial reference level, where we are now and 1.5°C.]*

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