

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

## Chapter 1: Framing and Context

**Coordinating Lead Authors:** Myles Allen (UK), Opha Pauline Dube (Botswana), William Solecki (USA)

**Lead Authors:** Fernando Aragón–Durand (Mexico), Wolfgang Cramer (France/Germany), Stephen Humphreys (UK/Ireland), Mikiko Kainuma (Japan), Jatin Kala (Australia), Natalie Mahowald (USA), Yacob Mulugetta (UK/Ethiopia), Rosa Perez (Philippines), Morgan Wairiu (Solomon Islands), Kirsten Zickfeld (Canada)

**Contributing Authors:** Purnamita Dasgupta (India), Haile Eakin (USA), Bronwyn Hayward (New Zealand), Diana Liverman (USA/UK), Richard Millar (UK), Graciela Raga (Argentina), Aurélien Ribes (France), Mark Richardson (USA/UK), Maisa Rojas (Chile), Roland Séférian (France), Sonia Seneviratne (Switzerland), Christopher Smith (UK), Will Steffen (Australia), Peter Thorne (Ireland/UK)

**Review Editors:** Ismail Elgizouli Idris (Sudan), Andreas Fischlin (Switzerland), Xuejie Gao (China)

**Chapter Scientist:** Richard Millar (UK)

**Date of Draft:** 4/06/18

**Notes:** TSU compiled version. Copy editing not done.

1	<b>Table of Content</b>	
2		
3	<b>Executive Summary</b> .....	<b>4</b>
4	1.1 Assessing the knowledge base for a 1.5°C warmer world .....	7
5	<b>Box 1.1: The Anthropocene: Strengthening the global response to 1.5°C global warming</b> .....	<b>8</b>
6	1.1.1 Equity and a 1.5°C warmer world.....	9
7	1.1.2 Eradication of poverty.....	10
8	1.1.3 Sustainable development and a 1.5°C warmer world .....	11
9	1.2 Understanding 1.5°C: reference levels, probability, transience, overshoot, stabilization.....	12
10	1.2.1 Working definitions of 1.5°C and 2°C warming relative to pre-industrial levels.....	12
11	1.2.1.1 Definition of global average temperature .....	12
12	1.2.1.2 Choice of reference period.....	14
13	1.2.1.3 Total versus human-induced warming and warming rates .....	15
14	1.2.2 Global versus regional and seasonal warming .....	16
15	1.2.3 Definition of 1.5°C-consistent pathways: probability, transience, stabilization and	
16	overshoot.....	17
17	1.2.3.1 Pathways remaining below 1.5°C .....	18
18	1.2.3.2 Pathways temporarily exceeding 1.5°C .....	19
19	1.2.3.3 Impacts at 1.5°C warming associated with different pathways: transience versus	
20	stabilisation .....	19
21	<b>Cross-Chapter Box 1: Scenarios and Pathways</b> .....	<b>21</b>
22	1.2.4 Geophysical warming commitment .....	23
23	<b>Cross-Chapter Box 2: Measuring progress to net zero emissions combining long-lived and</b>	
24	<b>short-lived climate forcings</b> .....	<b>26</b>
25	1.3 Impacts at 1.5°C and beyond .....	28
26	1.3.1 Definitions.....	28
27	1.3.2 Drivers of Impacts.....	29
28	1.3.3 Uncertainty and non-linearity of impacts.....	30
29	1.4 Strengthening the global response .....	31
30	1.4.1 Classifying Response Options .....	31
31	1.4.2 Governance, implementation and policies .....	32
32	<b>Cross-Chapter Box 3: Framing feasibility: Key concepts and conditions for limiting global</b>	
33	<b>temperature increases to 1.5°C</b> .....	<b>33</b>
34	1.4.3 Transformation, transformation pathways, and transition: evaluating trade-offs and	
35	synergies between mitigation, adaptation and sustainable development goals.....	35
36	<b>Cross-Chapter Box 4: Sustainable Development and the Sustainable Development Goals</b> .....	<b>36</b>
37	1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation	
38	and adaptation with sustainable development.....	38
39	1.5.1 Knowledge sources and evidence used in the report .....	38
40	1.5.2 Assessment frameworks and methodologies .....	39

1 1.6 Confidence, uncertainty and risk .....40

2 1.7 Storyline of the report .....41

3 **Frequently Asked Questions .....43**

4 **FAQ 1.1: Why are we talking about 1.5°C? .....43**

5 **FAQ 1.2: How close are we to 1.5°C? .....45**

6 **References.....47**

7

## 1 **Executive Summary**

2  
3 This chapter frames the context, knowledge-base and assessment approaches used to understand the  
4 impacts of 1.5°C global warming above pre-industrial levels and related global greenhouse gas  
5 emission pathways, building on the IPCC Fifth Assessment Report (AR5), in the context of  
6 strengthening the global response to the threat of climate change, sustainable development and efforts  
7 to eradicate poverty.  
8

9 **Human-induced warming reached approximately 1°C ( $\pm 0.2^\circ\text{C}$  likely range) above pre-industrial**  
10 **levels in 2017, increasing at 0.2°C ( $\pm 0.1^\circ\text{C}$ ) per decade (*high confidence*).** Global warming is  
11 defined in this report as an increase in combined surface air and sea surface temperatures averaged  
12 over the globe and a 30-year period. Unless otherwise specified, warming is expressed relative to the  
13 period 1850-1900, used as an approximation of pre-industrial temperatures in AR5. For periods  
14 shorter than 30 years, warming refers to the estimated average temperature over the 30 years centered  
15 on that shorter period, accounting for the impact of any temperature fluctuations or trend within those  
16 30 years. Accordingly, warming up to the decade 2006-2015 is assessed at 0.87°C  
17 ( $\pm 0.12^\circ\text{C}$  likely range). Since 2000, the estimated level of human-induced warming has been equal to  
18 the level of observed warming with a likely range of  $\pm 20\%$  accounting for uncertainty due to  
19 contributions from solar and volcanic activity over the historical period (*high confidence*). {1.2.1}  
20

21 **Warming greater than the global average has already been experienced in many regions and**  
22 **seasons, with average warming over land higher than over the ocean (*high confidence*).** Most land  
23 regions are experiencing greater warming than the global average, while most ocean regions are  
24 warming at a slower rate. Depending on the temperature dataset considered, 20-40% of the global  
25 human population live in regions that, by the decade 2006-2015, had already experienced warming of  
26 more than 1.5°C above pre-industrial in at least one season (*medium confidence*). {1.2.1 & 1.2.2}  
27

28 **Past emissions alone are unlikely to raise global-mean temperature to 1.5°C above pre-**  
29 **industrial levels but past emissions do commit to other changes, such as further sea level**  
30 **rise (*high confidence*).** If all anthropogenic emissions (including aerosol-related) were reduced to zero  
31 immediately, any further warming beyond the 1°C already experienced would likely be less than  
32 0.5°C over the next two to three decades (*high confidence*), and likely less than 0.5°C on a century  
33 timescale (*medium confidence*), due to the opposing effects of different climate processes and drivers.  
34 A warming greater than 1.5°C is therefore not geophysically unavoidable: whether it will occur  
35 depends on future rates of emission reductions. {1.2.3, 1.2.4}  
36

37 **1.5°C-consistent emission pathways are defined as those that, given current knowledge of the**  
38 **climate response, provide a one-in-two to two-in-three chance of warming either remaining**  
39 **below 1.5°C, or returning to 1.5°C by around 2100 following an overshoot.** Overshoot pathways  
40 are characterized by the peak magnitude of the overshoot, which may have implications for impacts.  
41 All 1.5°C-consistent pathways involve limiting cumulative emissions of long-lived greenhouse gases,  
42 including carbon dioxide and nitrous oxide, and substantial reductions in other climate forcers (*high*  
43 *confidence*). Limiting cumulative emissions requires either reducing net global emissions of long-  
44 lived greenhouse gases to zero before the cumulative limit is reached, or net negative global emissions  
45 (anthropogenic removals) after the limit is exceeded. {1.2.3, 1.2.4, Cross-Chapter Boxes 1 and 2}  
46

47 **This report assesses projected impacts at a global average warming of 1.5°C and higher levels of**  
48 **warming.** Global warming of 1.5°C is associated with global average surface temperatures  
49 fluctuating naturally on either side of 1.5°C, together with warming substantially greater than 1.5°C in  
50 many regions and seasons (*high confidence*), all of which must be taken into account in the  
51 assessment of impacts. Impacts at 1.5°C of warming also depend on the emission pathway to 1.5°C.  
52 Very different impacts result from pathways that remain below 1.5°C versus pathways that return to

1 1.5°C after a substantial overshoot, and when temperatures stabilize at 1.5°C versus a transient  
2 warming past 1.5°C. (*medium confidence*) {1.2.3, 1.3}

3  
4 **Ethical considerations, and the principle of equity in particular, are central to this report,**  
5 **recognising that many of the impacts of warming up to and beyond 1.5°C, and some potential**  
6 **impacts of mitigation actions required to limit warming to 1.5°C, fall disproportionately on the**  
7 **poor and vulnerable** (*high confidence*). Equity has procedural and distributive dimensions and  
8 requires fairness in burden sharing, between generations, and between and within nations. In framing  
9 the objective of holding the increase in the global average temperature rise to well below 2°C above  
10 pre-industrial levels, and to pursue efforts to limit warming to 1.5°C, the Paris Agreement associates  
11 the principle of equity with the broader goals of poverty eradication and sustainable development,  
12 recognising that effective responses to climate change require a global collective effort that may be  
13 guided by the 2015 United Nations Sustainable Development Goals. {1.1.1}

14  
15 **Climate adaptation refers to the actions taken to manage impacts of climate change by reducing**  
16 **vulnerability and exposure to its harmful effects and exploiting any potential benefits.**

17 Adaptation takes place at international, national and local levels. Subnational jurisdictions and  
18 entities, including urban and rural municipalities, are key to developing and reinforcing measures for  
19 reducing weather- and climate-related risks. Adaptation implementation faces several barriers  
20 including unavailability of up-to-date and locally-relevant information, lack of finance and  
21 technology, social values and attitudes, and institutional constraints (*high confidence*). Adaptation is  
22 more likely to contribute to sustainable development when policies align with mitigation and poverty  
23 eradication goals (*medium confidence*) {1.1, 1.4}

24  
25 **Ambitious mitigation actions are indispensable to limit warming to 1.5°C while achieving**  
26 **sustainable development and poverty eradication** (*high confidence*). Ill-designed responses,  
27 however, could pose challenges especially—but not exclusively—for countries and regions  
28 contending with poverty and those requiring significant transformation of their energy systems. This  
29 report focuses on ‘climate-resilient development pathways’, which aim to meet the goals of  
30 sustainable development, including climate adaptation and mitigation, poverty eradication and  
31 reducing inequalities. But any feasible pathway that remains within 1.5°C involves synergies and  
32 trade-offs (*high confidence*). Significant uncertainty remains as to which pathways are more  
33 consistent with the principle of equity. {1.1.1, 1.4}

34  
35 **Multiple forms of knowledge, including scientific evidence, narrative scenarios and prospective**  
36 **pathways, inform the understanding of 1.5°C.** This report is informed by traditional evidence of the  
37 physical climate system and associated impacts and vulnerabilities of climate change, together with  
38 knowledge drawn from the perceptions of risk and the experiences of climate impacts and governance  
39 systems. Scenarios and pathways are used to explore conditions enabling goal-oriented futures while  
40 recognizing the significance of ethical considerations, the principle of equity, and the societal  
41 transformation needed. {1.2.3, 1.5.2}

42  
43 **There is no single answer to the question of whether it is feasible to limit warming to 1.5°C and**  
44 **adapt to the consequences.** Feasibility is considered in this report as the capacity of a system as a  
45 whole to achieve a specific outcome. The global transformation that would be needed to limit  
46 warming to 1.5°C requires enabling conditions that reflect the links, synergies and trade-offs between  
47 mitigation, adaptation and sustainable development. These enabling conditions have many systemic  
48 dimensions—geophysical, environmental-ecological, technological, economic, socio-cultural and  
49 institutional—that may be considered through the unifying lens of the Anthropocene, acknowledging  
50 profound, differential but increasingly geologically significant human influences on the Earth system  
51 as a whole. This framing also emphasises the global interconnectivity of past, present and future

- 1 human–environment relations, highlighting the need and opportunities for integrated responses to
- 2 achieve the goals of the Paris Agreement. { 1.1, Cross-Chapter Box 1 }
- 3

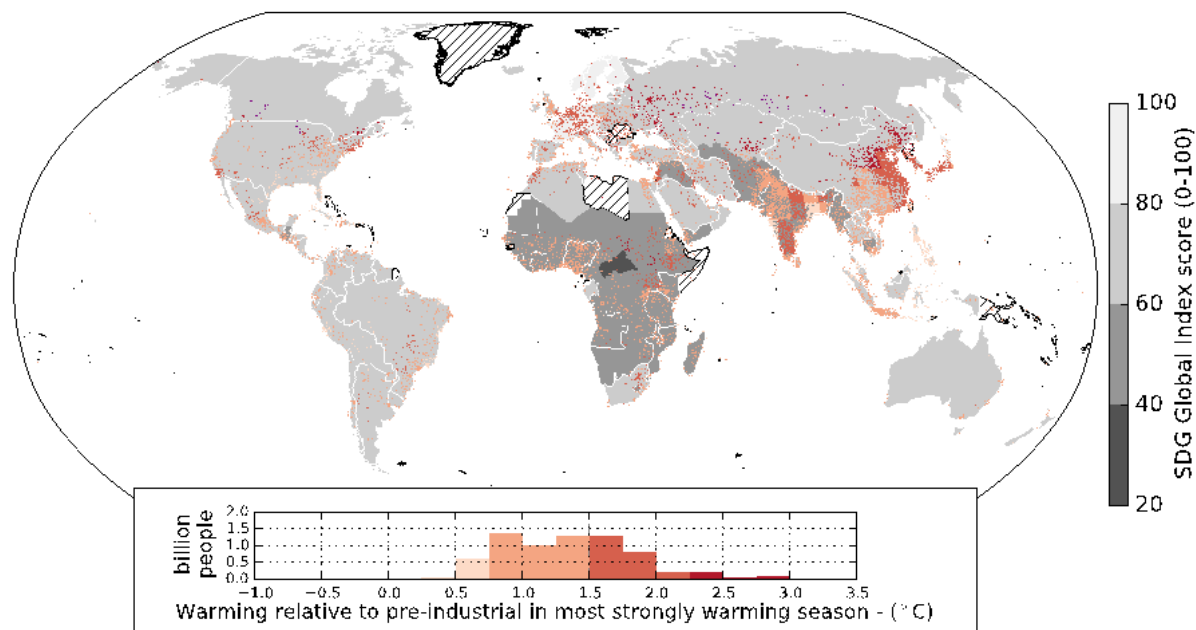
## 1.1 Assessing the knowledge base for a 1.5°C warmer world

Human influence on climate has been the dominant cause of observed warming since the mid-20th century, while global average surface temperature warmed by 0.85°C between 1880 and 2012, as reported in the IPCC Fifth Assessment Report, or AR5 (IPCC, 2013b). Many regions of the world have already experienced greater regional-scale warming, with 20–40% of the global population (depending on the temperature dataset used) having experienced over 1.5°C of warming in at least one season (Figure 1.1 and Chapter 3 Section 3.3). Temperature rise to date has already resulted in profound alterations to human and natural systems, bringing increases in some types of extreme weather, droughts, floods, sea level rise and biodiversity loss, and causing unprecedented risks to vulnerable persons and populations (IPCC, 2012a, 2014b; Mysiak et al., 2016), Chapter 3 Section 3.4). The most affected people live in low and middle income countries, some of which have already experienced a decline in food security, linked in turn to rising migration and poverty (IPCC, 2012a). Small islands, megacities, coastal regions and high mountain ranges are likewise among the most affected (Albert et al., 2017). Worldwide, numerous ecosystems are at risk of severe impacts, particularly warm-water tropical reefs and Arctic ecosystems (IPCC, 2014d).

This report assesses current knowledge of the environmental, technical, economic, financial, socio-cultural, and institutional dimensions of a 1.5°C warmer world (meaning, unless otherwise specified, a world in which warming has been limited to 1.5°C relative to pre-industrial levels). Differences in vulnerability and exposure arise from numerous non-climatic factors (IPCC, 2014b). Global economic growth has been accompanied by increased life expectancy and income in much of the world - but in addition to environmental degradation and pollution, many regions remain characterised by significant poverty, severe inequity in income distribution and access to resources, amplifying vulnerability to climate change (Dryzek, 2016; Pattberg and Zelli, 2016; Bäckstrand et al., 2017; Lövbrand et al., 2017). World population continues to rise, notably in hazard-prone small and medium-sized cities in low- and moderate-income countries (Birkmann et al., 2016). The spread of fossil-fuel-based material consumption and changing lifestyles is a major driver of global resource use, and the main contributor to rising greenhouse gas (GHG) emissions (Fleurbaey et al., 2014).

The overarching context of this report is this: human influence has become a principal agent of change on the planet, shifting the world out of the relatively stable Holocene period into a new geological era, often termed the Anthropocene (Box 1.1). Responding to climate change in the Anthropocene will require approaches that integrate multiple levels of inter-connectivity across the global community.

This chapter is composed of seven sections linked to the remaining four chapters of the report. The introductory section 1.1 situates the basic elements of the assessment within the context of sustainable development, considerations of ethics, equity and human rights, and their link to poverty. Section 1.2 focuses on understanding 1.5°C, global versus regional warming, 1.5°C-consistent pathways and associated emissions. Section 1.3 frames the impacts at 1.5°C and beyond on natural and human systems. The section on strengthening the global response (1.4) frames different responses, governance and implementation, and trade-offs and synergies between mitigation, adaptation and the Sustainable Development Goals (SDGs) under transformation, transformation pathways, and transition. Section 1.5 provides assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development. Section 1.6 defines approaches used to communicate confidence, uncertainty and risk, while 1.7 presents the storyline of the whole report.



**Figure 1.1: Human experience of present-day warming.** Colours indicated by the inset histogram show estimated warming for the season that has warmed the most at a given location between the periods 1850-1900 and 2006–2015, during which global average temperatures rose by 0.91°C in this dataset (Cowtan and Way, 2014), and 0.87°C in the multi-dataset average (Table 1.1 and Figure 1.3). The density of dots indicates the population (in 2010) in any 1°x1° grid box. The underlay shows national SDG Global Index Scores indicating performance across the 17 Sustainable Development Goals. Hatching indicates missing SDG index data (e.g., Greenland). The histogram shows the number of people of the 2010 global population living in regions experiencing different levels of warming (at 0.25°C increments). See Supplementary Material 1.SM for further details.

### Box 1.1: The Anthropocene: Strengthening the global response to 1.5°C global warming

#### Introduction

The concept of the Anthropocene can be linked to the aspiration of the Paris Agreement. The abundant empirical evidence of the unprecedented rate and global scale of impact of human influence on the Earth System (Steffen et al., 2016; Waters et al., 2016) has led many scientists to call for an acknowledgement that the Earth has entered a new geological epoch: the Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002; Gradstein et al., 2012). Although rates of change in the Anthropocene are necessarily assessed over much shorter periods than those used to calculate long-term baseline rates of change, and therefore present challenges for direct comparison, they are nevertheless striking. The rise in global CO<sub>2</sub> concentration since 2000 is about 20 ppm/decade, which is up to 10 times faster than any sustained rise in CO<sub>2</sub> during the past 800,000 years (Lüthi et al., 2008; Bereiter et al., 2015). AR5 found that the last geological epoch with similar atmospheric CO<sub>2</sub> concentration was the Pliocene, 3.3 to 3.0 Ma (Masson-Delmotte et al., 2013). Since 1970 the global average temperature has been rising at a rate of 1.7°C per century, compared to a long-term decline over the past 7,000 years at a baseline rate of 0.01°C per century (NOAA 2016, Marcott et al. 2013). These global-level rates of human-driven change far exceed the rates of change driven by geophysical or biosphere forces that have altered the Earth System trajectory in the past (e.g., Summerhayes 2015; Foster et al. 2017); even abrupt geophysical events do not approach current rates of human-driven change.



## **The geological dimension of the Anthropocene and 1.5°C global warming**

The process of formalising the Anthropocene is on-going (Zalasiewicz et al., 2017), but a strong majority of the Anthropocene Working Group (AWG) established by the Sub-Committee on Quaternary Stratigraphy of the International Commission on Stratigraphy have agreed that: (i) the Anthropocene has a geological merit; (ii) it should follow the Holocene as a formal epoch in the Geological Time Scale; and, that (iii) its onset should be defined as the mid-20th century. Potential markers in the stratigraphic record include an array of novel manufactured materials of human origin, and “these combined signals render the Anthropocene stratigraphically distinct from the Holocene and earlier epochs” (Waters et al., 2016). The Holocene period, which itself was formally adopted in 1885 by geological science community, began 11,700 years ago with a more stable warm climate providing for emergence of human civilisation and growing human-nature interactions that have expanded to give rise to the Anthropocene (Waters et al., 2016).

## **The Anthropocene and the Challenge of a 1.5° C warmer world**

The Anthropocene can be employed as a “boundary concept” (Brondizio et al., 2016) that frames critical insights into understanding the drivers, dynamics and specific challenges in responding to the ambition of keeping global temperature well below 2°C while pursuing efforts towards and adapting to a 1.5°C warmer world. The UNFCCC and its Paris Accord recognize the ability of humans to influence geophysical planetary processes (Chapter 2, Cross-Chapter Box 1 in this Chapter). The Anthropocene offers a structured understanding of the culmination of past and present human–environmental relations and provides an opportunity to better visualize the future to minimize pitfalls (Pattberg and Zelli, 2016; Delanty and Mota, 2017), while acknowledging the differentiated responsibility and opportunity to limit global warming and invest in prospects for climate-resilient sustainable development (Harrington, 2016) (Chapter 5). The Anthropocene also 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 inform the search for solutions as explored in Chapter 4 of this report (Biermann et al., 2016). It links uneven influences of human actions on planetary functions to an uneven 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. 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 regions more than others and negate sustainable development efforts (see Chapter 2 and Chapter 5).

### ***1.1.1 Equity and a 1.5°C warmer world***

The AR5 suggested that equity, sustainable development, and poverty eradication are best understood as mutually supportive and co-achievable within the context of climate action, and are underpinned by various other international hard and soft law instruments (Denton et al., 2014; Fleurbaey et al., 2014; Klein et al., 2014; Olsson et al., 2014; Porter et al., 2014; Stavins et al., 2014). The aim of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) to ‘pursue efforts to limit’ the rise in global temperatures to 1.5°C above pre-industrial levels raises ethical concerns that have long been central to climate debates (Fleurbaey et al., 2014; Kolstad et al., 2014). The Paris Agreement makes particular reference to the principle of equity, within the context of broader international goals of sustainable development and poverty eradication. Equity is a long-standing principle within international law and climate change law in particular (Dinah, 2008; Bodansky et al., 2017).

The AR5 describes equity as having three dimensions: intergenerational (fairness between generations), international (fairness between states), and national (fairness between individuals) (Fleurbaey et al., 2014). The principle is generally agreed to involve both procedural justice (i.e.

1 participation in decision making) and distributive justice (i.e. how the costs and benefits of climate  
2 actions are distributed) (Kolstad et al., 2014; Savaresi, 2016; Reckien et al., 2017). Concerns  
3 regarding equity have frequently been central to debates around mitigation, adaptation and climate  
4 governance (Caney, 2005; Schroeder et al., 2012; Ajibade, 2016; Reckien et al., 2017; Shue, 2018).  
5 Hence, equity provides a framework for understanding the asymmetries between the distributions of  
6 benefits and costs relevant to climate action (Schleussner et al., 2016; Aaheim et al., 2017).

7 Four key framing asymmetries associated with the conditions of 1.5°C warmer world have been noted  
8 (Okereke, 2010; Harlan et al., 2015; Ajibade, 2016; Savaresi, 2016; Reckien et al., 2017) and are  
9 reflected in the report’s assessment. The first concerns differential contributions to the problem: the  
10 observation that the benefits from industrialization have been unevenly distributed and those who  
11 benefited most historically also have contributed most to the current climate problem and so bear  
12 greater responsibility (Shue, 2013; Otto et al., 2017; Skeie et al., 2017). The second asymmetry  
13 concerns differential impact: the worst impacts tend to fall on those least responsible for the problem,  
14 within states, between states, and between generations (Fleurbaey et al., 2014; Shue, 2014; Ionesco et  
15 al., 2016). The third is the asymmetry in capacity to shape solutions and response strategies, such that  
16 the worst-affected states, groups and individuals are not always well-represented (Robinson and  
17 Shine, 2018). Fourth, there is an asymmetry in future response capacity: some states, groups and  
18 places are at risk of being left behind as the world progresses to a low-carbon economy (Fleurbaey et  
19 al., 2014; Shue, 2014; Humphreys, 2017).

20  
21 A sizeable and growing literature exists on how best to operationalize climate equity considerations,  
22 drawing on other concepts mentioned in the Paris Agreement, notably its explicit reference to human  
23 rights (OHCHR, 2009; Caney, 2010; Adger et al., 2014; Fleurbaey et al., 2014; IBA, 2014; Knox,  
24 2015; Duyck et al., 2018; Robinson and Shine, 2018). Human rights comprise internationally agreed  
25 norms that align with the Paris ambitions of poverty eradication, sustainable development and the  
26 reduction of vulnerability (Caney, 2010; Fleurbaey et al., 2014; OHCHR, 2015). In addition to  
27 defining substantive rights (such as to life, health and shelter) and procedural rights (such as to  
28 information and participation), human rights instruments prioritise the rights of marginalised,  
29 children, vulnerable and indigenous persons, and those discriminated against on grounds such as  
30 gender, race, age or disability (OHCHR, 2017). Several international human rights obligations that are  
31 relevant to the implementation of climate actions and consonant with UNFCCC undertakings in the  
32 areas of mitigation, adaptation, finance, and technology transfer (Knox, 2015; OHCHR, 2015;  
33 Humphreys, 2017).

34  
35 Much of this literature is still new and evolving (Holz et al., 2017; Dooley et al., 2018; Klinsky and  
36 Winkler, 2018), permitting the present report to examine some broader equity concerns raised both by  
37 possible failure to limit warming to 1.5°C and by the range of ambitious mitigation efforts that may  
38 be undertaken to achieve that limit. Any comparison between 1.5°C and higher levels of warming  
39 implies risk assessments and value judgements, and cannot straightforwardly be reduced to a cost-  
40 benefit analysis (Kolstad et al., 2014). However, different levels of warming can nevertheless be  
41 understood in terms of their different implications for equity – that is, in the comparative distribution  
42 of benefits and burdens for specific states, persons or generations, and in terms of their likely impacts  
43 on sustainable development and poverty (see especially sections 2.2.2.3, 2.3.3.1, 3.4.5-3.4.11, 3.6,  
44 5.4.1, 5.4.2, 5.6 and Cross-Chapter boxes 6 in Chapter 3 and 12 in Chapter 5).

### 45 46 47 **1.1.2 Eradication of poverty**

48  
49 This report assesses the role of poverty and its eradication in the context of strengthening the global  
50 response to the threat of climate change and sustainable development. A wide range of definitions for  
51 *poverty* exist. The AR5 discussed ‘poverty’ in terms of its multidimensionality, referring to ‘material  
52 circumstances’ (e.g. needs, patterns of deprivation, or limited resources), as well as to economic

1 conditions (e.g. standard of living, inequality, or economic position), and/or social relationships (e.g.  
2 social class, dependency, lack of basic security, exclusion, or lack of entitlement – Olsson et al.,  
3 2014). The UNDP now uses a Multidimensional Poverty Index, and estimates that about 1.5 billion  
4 people globally live in multidimensional poverty, especially in rural areas of South Asia and Sub-  
5 Saharan Africa, with an additional billion at risk of falling into poverty (UNDP, 2016).

6  
7 A large and rapidly growing body of knowledge explores the connections between climate change and  
8 poverty. Climatic variability and climate change are widely recognized as factors that may exacerbate  
9 poverty, particularly in countries and regions where poverty levels are high (Leichenko and Silva,  
10 2014). The AR5 noted that climate change-driven impacts often act as a threat multiplier in that the  
11 impacts of climate change compound other drivers of poverty (Olsson et al., 2014). Many vulnerable  
12 and poor people are dependent on activities such as agriculture that are highly susceptible to  
13 temperature increases and variability in precipitation patterns (Shiferaw et al., 2014; Miyan, 2015).  
14 Even modest changes in rainfall and temperature patterns can push marginalized people into poverty  
15 as they lack the means to recover from shocks. Extreme events, such as floods, droughts, and heat  
16 waves, especially when they occur in series, can significantly erode poor people’s assets and further  
17 undermine their livelihoods in terms of labour productivity, housing, infrastructure, and social  
18 networks (Olsson et al., 2014).

### 21 **1.1.3 Sustainable development and a 1.5°C warmer world**

22  
23 AR5 noted with *high confidence* that ‘equity is an integral dimension of sustainable development’ and  
24 that ‘mitigation and adaptation measures can strongly affect broader sustainable development and  
25 equity objectives’ (Fleurbaey et al., 2014). Limiting global warming to 1.5°C will require substantial  
26 societal and technological transformations, dependent in turn on global and regional sustainable  
27 development pathways. A range of pathways, both sustainable and not, are explored in this report,  
28 including implementation strategies to understand the enabling conditions and challenges required for  
29 such a transformation. These pathways and connected strategies are framed within the context of  
30 sustainable development, and in particular the United Nations 2030 Agenda for Sustainable  
31 Development (UNGA, 2015) and Cross-Chapter Box 4 on SDGs (in this Chapter). The feasibility of  
32 staying within 1.5°C depends upon a range of enabling conditions with geophysical, environmental-  
33 ecological, technological, economic, socio-cultural, and institutional enabling conditions. Limiting  
34 warming to 1.5°C also involves identifying technology and policy levers to accelerate the pace of  
35 transformation (see Chapter 4). Some pathways are more consistent than others with the requirements  
36 for sustainable development (see Chapter 5). Overall, the three-pronged emphasis on sustainable  
37 development, resilience, and transformation provides Chapter 5 an opportunity to assess the  
38 conditions of simultaneously reducing societal vulnerabilities, addressing entrenched inequalities, and  
39 breaking the circle of poverty.

40  
41 The feasibility of any global commitment to a 1.5°C pathway depends, in part, on the cumulative  
42 influence of the nationally determined contributions (NDCs), committing nation states to specific  
43 GHG emission reductions. The current NDCs, extending only to 2030, do not limit warming to 1.5°C.  
44 Depending on mitigation decisions after 2030, they cumulatively track toward a warming of 3-4°C  
45 above preindustrial temperatures by 2100, with the potential for further warming thereafter (Rogelj et  
46 al., 2016a; UNFCCC, 2016). The analysis of pathways in this report reveals opportunities for greater  
47 decoupling of economic growth from GHG emissions. Progress towards limiting warming to 1.5°C  
48 requires a significant acceleration of this trend. AR5 (IPCC, 2014a) concluded that climate change  
49 constrains possible development paths, that synergies and trade-offs exist between climate responses  
50 and socio-economic contexts, and that opportunities for effective climate responses overlap with  
51 opportunities for sustainable development, noting that many existing societal patterns of consumption  
52 are intrinsically unsustainable (Fleurbaey et al., 2014).

## 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 pre-industrial 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; Pflieger et al., 2018) is comparable to natural multi-decadal temperature variability on continental scales (Deser et al., 2012) and primarily affects the historical period, particularly that prior to the early 20<sup>th</sup> century when data is sparse and of less certain quality. Most practical mitigation and adaptation decisions do not depend on quantifying historical warming to this level of precision, but a consistent working definition is necessary to ensure consistency across chapters and figures. We adopt definitions that are as consistent as possible with key findings of AR5 with respect to historical warming.

This report defines ‘warming’, unless otherwise qualified, as an increase in multi-decade global mean surface temperature (GMST) above pre-industrial levels. Specifically, warming at a given point in time is defined as the global average of combined land surface air and sea surface temperatures for a 30-year period centred on that time, expressed relative to the reference period 1850-1900 (adopted for consistency with Box SPM.1 Figure 1 of IPCC (2014e) ‘as an approximation of pre-industrial levels’, excluding the impact of natural climate fluctuations within that 30-year period and assuming any secular trend continues throughout that period, extrapolating into the future if necessary. There are multiple ways of accounting for natural fluctuations and trends (e.g., Foster and Rahmstorf, 2011; Hausteine et al., 2017; Medhaug et al., 2017), but all give similar results. A major volcanic eruption might temporarily reduce observed global temperatures, but would not reduce warming as defined here (Bethke et al., 2017). Likewise, given that the level of warming is currently increasing at 0.3-0.7°C per 30 years (Kirtman et al., 2013), the level of warming in 2017 is 0.15-0.35°C higher than average warming over the 30-year period 1988-2017.

In summary, this report adopts a working definition of ‘1.5°C relative to pre-industrial levels’ that corresponds to global average combined land surface air and sea surface temperatures either 1.5°C warmer than the average of the 51-year period 1850-1900, 0.87°C warmer than the 20-year period 1986–2005, or 0.63°C warmer than the decade 2006–2015. These offsets are based on all available published global datasets, combined and updated, which show that 1986-2005 was 0.63°C ( $\pm 0.06^\circ\text{C}$  5–95% range based on observational uncertainties alone), and 2006-2015 was 0.87°C ( $\pm 0.12^\circ\text{C}$  likely range also accounting for the possible impact of natural fluctuations), warmer than 1850–1900. Where possible, estimates of impacts and mitigation pathways are evaluated relative to these more recent periods.

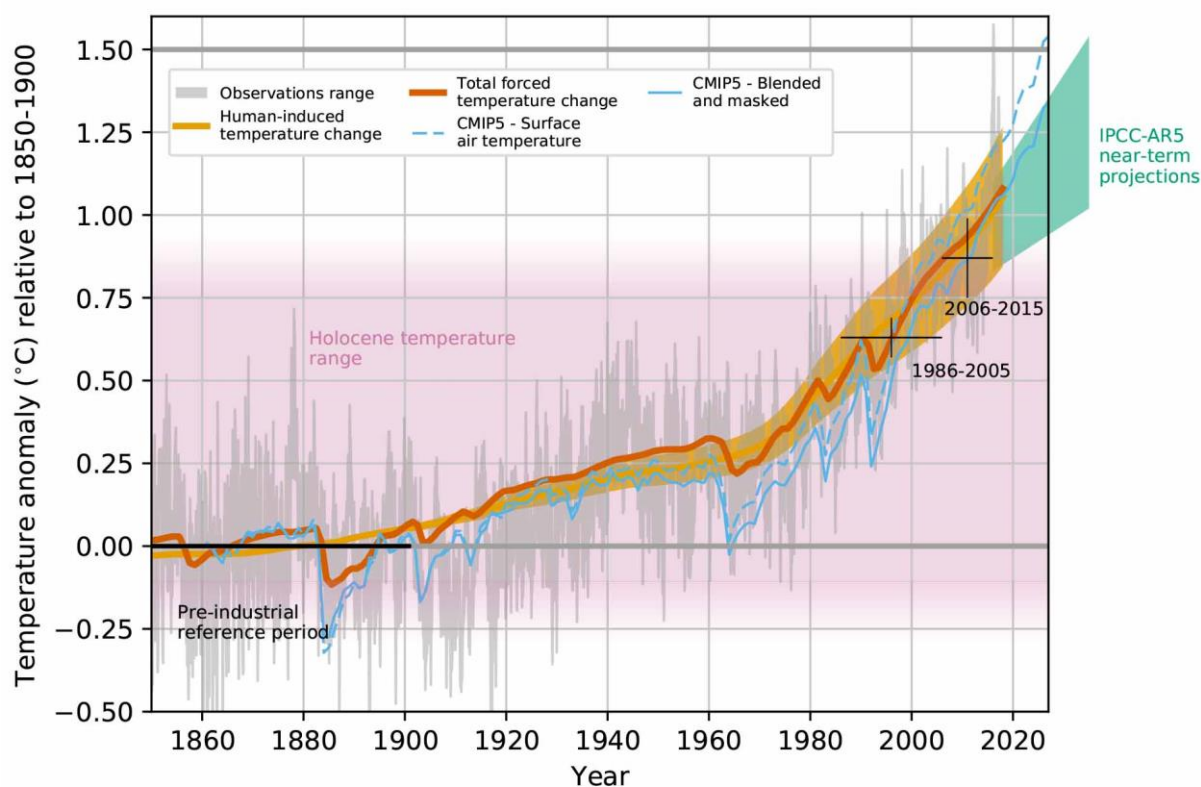
#### 1.2.1.1 Definition of global average temperature

The IPCC has traditionally defined changes in observed GMST as a weighted average of near-surface air temperature (SAT) changes over land and sea surface temperature (SST) changes over the oceans (Morice et al., 2012; Hartmann et al., 2013), while modelling studies have typically used a simple global average SAT. For ambitious mitigation goals, and under conditions of rapid warming, the difference can be significant. Cowtan et al. (2015) and Richardson et al. (2016) show that the use of blended SAT/SST data and incomplete coverage together can give approximately 0.2°C less warming from the 19th century to the present relative to the use of complete global-average SAT (Stocker et al., 2013), Figure TFE8.1 and Figure 1.2). However, Richardson et al. (2018) show that this is primarily an issue for the interpretation of the historical record to date, not for projection of future changes or

1 for estimated emissions budgets consistent with future changes, particularly under ambitious  
2 mitigation scenarios.

3  
4 The three GMST reconstructions used in AR5 differ in their treatment of missing data. GISTEMP  
5 (Hansen et al., 2010) uses interpolation to infer trends in poorly-observed regions like the Arctic  
6 (although even this product is spatially incomplete in the early record), while NOAA (Vose et al.,  
7 2012) and HadCRUT (Morice et al., 2012) are progressively closer to a simple average of available  
8 observations. Since the AR5, considerable effort has been devoted to more sophisticated statistical  
9 modelling to account for the impact of incomplete observation coverage (Rohde et al., 2013; Cowtan  
10 and Way, 2014; Jones, 2016). The main impact of statistical infilling is to increase estimated warming  
11 to date by about 0.1°C (Richardson et al., 2018 and Table 1.1).

12  
13 We adopt a working definition of warming over the historical period based on an average of the four  
14 available global datasets that are supported by peer-reviewed publications: the three datasets used in  
15 the AR5, updated (Karl et al., 2015), together with the Cowtan-Way infilled dataset (Cowtan and  
16 Way, 2014). A further two datasets, Berkeley Earth (Rohde et al., 2013) and JMA, are provided in  
17 Table 1.1. This working definition provides an updated estimate of 0.86°C for the warming 1880-  
18 2012 based on a linear trend that was quoted as 0.85°C in the AR5. Hence the inclusion of the  
19 Cowtan-Way dataset does not introduce any inconsistency with the AR5, whereas redefining GMST  
20 to represent global SAT could increase this figure by up to 20%, (Table 1.1, Figure 1.2 Richardson et  
21 al., 2016).



22  
23 **Figure 1.2: Evolution of global mean surface temperature (GMST) over the period of instrumental**  
24 **observations.** Grey line shows monthly mean GMST in the HadCRUT4, NOAA, GISTEMP and  
25 Cowtan-Way datasets, expressed as departures from 1850–1900, with line thickness indicating  
26 inter-dataset range. All observational datasets shown represent GMST as a weighted average of  
27 near surface air temperature over land and sea surface temperature over oceans. Human-induced  
28 (yellow) and total (human- and naturally-forced, orange) contributions to these GMST changes

1 are shown calculated following Otto et al. (2015) and Haustein et al. (2017). Fractional  
2 uncertainty in the level of human-induced warming in 2017 is set equal to  $\pm 20\%$ . Thin blue lines  
3 show the modelled global-mean surface air temperature (dashed) and blended surface air and sea  
4 surface temperature accounting for observational coverage (solid) from the CMIP5 historical  
5 ensemble average extended with RCP8.5 forcing (Cowtan et al., 2015; Richardson et al., 2018).  
6 The pink shading indicates a range for temperature fluctuations over the Holocene (Marcott et al.,  
7 2013). Light green plume shows AR5 prediction for average GMST over 2016–2035 (Kirtman et  
8 al., 2013). See Supplementary Material 1.SM for further details.  
9

### 11 1.2.1.2 Choice of reference period

12  
13 Any choice of reference period used to approximate ‘pre-industrial’ conditions is a compromise  
14 between data coverage and representativeness of typical pre-industrial solar and volcanic forcing  
15 conditions. This report adopts the 51-year reference period, 1850–1900 inclusive, assessed as an  
16 approximation of pre-industrial conditions in AR5 (Box TS.5, Figure 1 of Field et al., 2014). The  
17 years 1880–1900 are subject to strong but uncertain volcanic forcing, but in the HadCRUT4 dataset,  
18 average temperatures over 1850–1879, prior to the largest eruptions, are less than  $0.01^\circ\text{C}$  from the  
19 average for 1850–1900. Temperatures rose by  $0.0\text{--}0.2^\circ\text{C}$  from 1720–1800 to 1850–1900 (Hawkins et  
20 al., 2017), but the anthropogenic contribution to this warming is uncertain (Schurer et al., 2017). The  
21 18th century represents a relatively cool period in the context of temperatures since the mid-Holocene  
22 (Marcott et al., 2013; Marsicek et al., 2018), as indicated by the pink shaded region in Figure 1.2.  
23

24 Projections of responses to emission scenarios, and associated impacts, may use a more recent  
25 reference period, offset by historical observations, to avoid conflating uncertainty in past and future  
26 changes (e.g. Hawkins et al., 2017; Millar et al., 2017b; Simmons et al., 2017). Two recent reference  
27 periods are used in this report: 1986–2005 and 2006–2015. In the latter case, when using a single  
28 decade to represent a 30-year average centred on that decade, it is important to consider the potential  
29 impact of internal climate variability. The years 2008–2013 were characterised by persistent cool  
30 conditions in the Eastern Pacific (Kosaka and Xie, 2013; Medhaug et al., 2017), related to both the El  
31 Niño / Southern Oscillation (ENSO) and, potentially, multi-decadal Pacific variability (e.g., England  
32 et al., 2014), but these were partially compensated for by El Niño conditions in 2006 and 2015.  
33 Likewise, volcanic activity depressed temperatures in 1986–2005, partly offset by the very strong El  
34 Niño event in 1998. Figure 1.2 indicates that natural variability (internally generated and externally  
35 driven) had little net impact on average temperatures over 2006–2015, in that the average temperature  
36 of the decade is similar to the estimated externally-driven warming. When solar, volcanic and ENSO-  
37 related variability is taken into account following the procedure of Foster and Rahmstorf (2011), there  
38 is no indication of average temperatures in either 1986–2005 or 2006–2015 being substantially biased  
39 by short-term variability (see Supplementary Material 1.SM). The temperature difference between  
40 these two reference periods ( $0.21\text{--}0.27^\circ\text{C}$  over 15 years across available datasets) is also consistent  
41 with the AR5 assessment of the current warming rate of  $0.3\text{--}0.7^\circ\text{C}$  over 30 years (Kirtman et al.,  
42 2013).  
43

44 On the definition of warming used here, warming to the decade 2006–2015 comprises an estimate of  
45 the 30-year average centered on this decade, or 1996–2025, assuming the current trend continues and  
46 that any volcanic eruptions that might occur over the final seven years are corrected for. Given this  
47 element of extrapolation, we use the AR5 near-term projection to provide a conservative uncertainty  
48 range. Combining the uncertainty in observed warming to 1986–2005 ( $\pm 0.06^\circ\text{C}$ ) with the *likely* range  
49 in the current warming trend as assessed by AR5 ( $\pm 0.2^\circ\text{C}/30$  years), assuming these are uncorrelated,  
50 and using observed warming relative to 1850–1900 to provide the central estimate (no evidence of  
51 bias from short-term variability), gives an assessed warming to the decade 2006–2015 of  $0.87^\circ\text{C}$  with  
52 a  $\pm 0.12^\circ\text{C}$  *likely* range. This estimate has the advantage of traceability to the AR5, but more formal  
53 methods of quantifying externally-driven warming (e.g., Bindoff et al., 2013; Jones et al., 2016;

1 Haustein et al., 2017; Ribes et al., 2017), which typically give smaller ranges of uncertainty, may be  
 2 adopted in future.

3  
 4 **Table 1.1: Observed increase in global average surface temperature in various datasets.** Numbers in  
 5 square brackets correspond to 5-95% uncertainty ranges from individual datasets, encompassing  
 6 known sources of observational uncertainty only.  
 7

Diagnostic / dataset	1850-1900 to (1) 2006-2015	1850-1900 to (2) 1986-2005	1986-2005 to (3) 2006-2015	1850-1900 to (4) 1981-2010	1850-1900 to (5) 1998-2017	trend (6) 1880-2012	trend (6) 1880-2015
HadCRUT4.6	0.84 [0.79–0.89]	0.60 [0.57–0.66]	0.22 [0.21–0.23]	0.62 [0.58–0.67]	0.83 [0.78–0.88]	0.83 [0.77–0.90]	0.88 [0.83–0.95]
NOAA (7)	0.86	0.62	0.22	0.63	0.85	0.85	0.91
GISTEMP (7)	0.89	0.65	0.23	0.66	0.88	0.89	0.94
Cowtan-Way	0.91 [0.85–0.99]	0.65 [0.60–0.72]	0.26 [0.25–0.27]	0.65 [0.60–0.72]	0.88 [0.82–0.96]	0.88 [0.79–0.98]	0.93 [0.85–1.03]
Average (8)	<b>0.87</b>	0.63	0.23	0.64	0.86	0.86	0.92
Berkeley (9)	0.98	0.73	0.25	0.73	0.97	0.97	1.02
JMA (9)	0.82	0.59	0.17	0.60	0.81	0.82	0.87
ERA-Interim	N/A	N/A	0.26	N/A	N/A	N/A	N/A
JRA-55	N/A	N/A	0.23	N/A	N/A	N/A	N/A
CMIP5 global SAT (10)	0.99 [0.65–1.37]	0.62 [0.38–0.94]	0.38 [0.24–0.62]	0.62 [0.34–0.93]	0.89 [0.62–1.29]	0.81 [0.58–1.31]	0.86 [0.63–1.39]
CMIP5 SAT/SST blend—masked	0.86 [0.54–1.18]	0.50 [0.31–0.79]	0.34 [0.19–0.54]	0.48 [0.26–0.79]	0.75 [0.52–1.11]	0.68 [0.45–1.08]	0.74 [0.51–1.14]

8  
 9 Notes:

- 10 1) Most recent reference period used in this report.  
 11 2) Most recent reference period used in AR5.  
 12 3) Difference between recent reference periods.  
 13 4) Current WMO standard reference periods.  
 14 5) Most recent 20-year period.  
 15 6) Linear trends estimated by a straight-line fit, expressed in degrees yr<sup>-1</sup> multiplied by 133 or 135 years  
 16 respectively, with uncertainty ranges incorporating observational uncertainty only.  
 17 7) To estimate changes in the NOAA and GISTEMP datasets relative to the 1850–1900 reference period,  
 18 warming is computed relative to 1850–1900 using the HadCRUT4.6 dataset and scaled by the ratio of the  
 19 linear trend 1880–2015 in the NOAA or GISTEMP dataset with the corresponding linear trend computed  
 20 from HadCRUT4.  
 21 8) Average of diagnostics derived – see (7) – from four peer-reviewed global datasets, HadCRUT4.6, NOAA,  
 22 GISTEMP & Cowtan-Way. Note that differences between averages may not coincide with average  
 23 differences because of rounding.  
 24 9) No peer-reviewed publication available for these global combined land-sea datasets.  
 25 10) CMIP5 changes estimated relative to 1861–80 plus 0.02°C for the offset in HadCRUT4.6 from 1850–1900.  
 26 CMIP5 values are the mean of the RCP8.5 ensemble, with 5–95% ensemble range. They are included to  
 27 illustrate the difference between a complete global surface air temperature record (SAT) and a blended  
 28 surface air and sea surface temperature (SST) record accounting for incomplete coverage (masked),  
 29 following Richardson et al. (2016). Note that 1986–2005 temperatures in CMIP5 appear to have been  
 30 depressed more than observed temperatures by the eruption of Mount Pinatubo.  
 31  
 32

### 33 1.2.1.3 Total versus human-induced warming and warming rates

34  
 35 Total warming refers to the actual temperature change, irrespective of cause, while human-induced  
 36 warming refers to the component of that warming that is attributable to human activities. Mitigation  
 37 studies focus on human-induced warming (that is not subject to internal climate variability), while

1 studies of climate change impacts typically refer to total warming (often with the impact of internal  
2 variability minimised through the use of multi-decade averages).

3  
4 In the absence of strong natural forcing due to changes in solar or volcanic activity, the difference  
5 between total and human-induced warming is small: assessing empirical studies quantifying solar and  
6 volcanic contributions to GMST from 1890 to 2010, AR5 (Fig. 10.6 of Bindoff et al., 2013) found  
7 their net impact on warming over the full period to be less than  $\pm 0.1^\circ\text{C}$ . Figure 1.2 shows that the  
8 level of human-induced warming has been indistinguishable from total observed warming since 2000,  
9 including over the decade 2006–2015. Bindoff et al. (2013) assessed the magnitude of human-induced  
10 warming over the period 1951–2010 to be  $0.7^\circ\text{C} \pm 0.1^\circ\text{C}$ , slightly greater than the  $0.65^\circ\text{C}$  observed  
11 warming over this period (Figures 10.4 & 10.5) and a *likely* range of  $\pm 14\%$ . The key surface  
12 temperature attribution studies underlying this finding (Gillett et al., 2013; Jones et al., 2013;  
13 Ribes and Terray, 2013) used temperatures since the 19th century to constrain human-induced  
14 warming, and so their results are equally applicable to the attribution of causes of warming over  
15 longer periods. Jones et al. (2016) show (Figure 10) human-induced warming trends over the period  
16 1905–2005 to be indistinguishable from the corresponding total observed warming trend accounting  
17 for natural variability using spatio-temporal detection patterns from 12 out of 15 CMIP5 models and  
18 from the multi-model average. Figures from Ribes and Terray (2013), show the anthropogenic  
19 contribution to the observed linear warming trend 1880–2012 in the HadCRUT4 dataset ( $0.83^\circ\text{C}$  in  
20 Table 1.1) to be  $0.86^\circ\text{C}$  using a multi-model average global diagnostic, with a 5–95% confidence  
21 interval of  $0.72\text{--}1.00^\circ\text{C}$ . In all cases, since 2000 the estimated combined contribution of solar and  
22 volcanic activity to warming relative to 1850–1900 is found to be less than  $\pm 0.1^\circ\text{C}$  (Gillett et al.,  
23 2013), while anthropogenic warming is indistinguishable from, and if anything slightly greater than,  
24 the total observed warming, with 5–95% confidence intervals typically around  $\pm 20\%$ .

25  
26 Haustein et al. (2017) give a 5–95% confidence interval for human-induced warming in 2017 of  $0.87\text{--}$   
27  $1.22^\circ\text{C}$ , with a best estimate of  $1.02^\circ\text{C}$ , based on the HadCRUT4 dataset accounting for observational  
28 and forcing uncertainty and internal variability. Applying their method to the average of the 4 datasets  
29 shown in figure 1.2 gives an average level of human-induced warming in 2017 of  $1.04^\circ\text{C}$ . They also  
30 estimate a human-induced warming trend over the past 20 years of  $0.17^\circ\text{C}$  ( $0.13\text{--}0.33^\circ\text{C}$ ) per decade,  
31 consistent with estimates of the total observed trend of Foster and Rahmstorf (2011)  
32 ( $0.17 \pm 0.03^\circ\text{C}/\text{decade}$  uncertainty in linear trend only) and Kirtman et al. (2013) ( $0.3\text{--}0.7^\circ\text{C}$  over 30  
33 years, or  $0.1\text{--}0.23^\circ\text{C}/\text{decade}$ , *likely* range), and a best-estimate warming rate over the past five years  
34 of  $0.215^\circ\text{C}/\text{decade}$  (Leach et al., 2018). Drawing on these multiple lines of evidence, human-induced  
35 warming is assessed to have reached  $1.0^\circ\text{C}$  in 2017, having increased by  $0.13^\circ\text{C}$  from the mid-point of  
36 2006–2015, with a *likely* range of  $\pm 0.2^\circ\text{C}$  (reduced from 5–95% to account for additional forcing and  
37 model uncertainty), increasing at  $0.2^\circ\text{C}$  ( $\pm 0.1^\circ\text{C}$ ) per decade (estimates of human-induced warming  
38 given to  $0.1^\circ\text{C}$  precision only).

39  
40 Since warming is here defined in terms of a 30-year average, corrected for short-term natural  
41 fluctuations, when warming is considered to be at  $1.5^\circ\text{C}$ , global temperatures would fluctuate equally  
42 on either side of  $1.5^\circ\text{C}$  in the absence of a large cooling volcanic eruption (Bethke et al, 2017). Figure  
43 1.2 indicates there is a substantial chance of GMST in a single month fluctuating over  $1.5^\circ\text{C}$  between  
44 now and 2020, but this would not constitute temperatures ‘reaching  $1.5^\circ\text{C}$ ’ on our working definition.  
45 Rogelj et al. (2017) show limiting the probability of annual GMST exceeding  $1.5^\circ\text{C}$  to less than one-  
46 year-in-20 would require limiting warming, on the definition used here, to  $1.31^\circ\text{C}$  or lower.

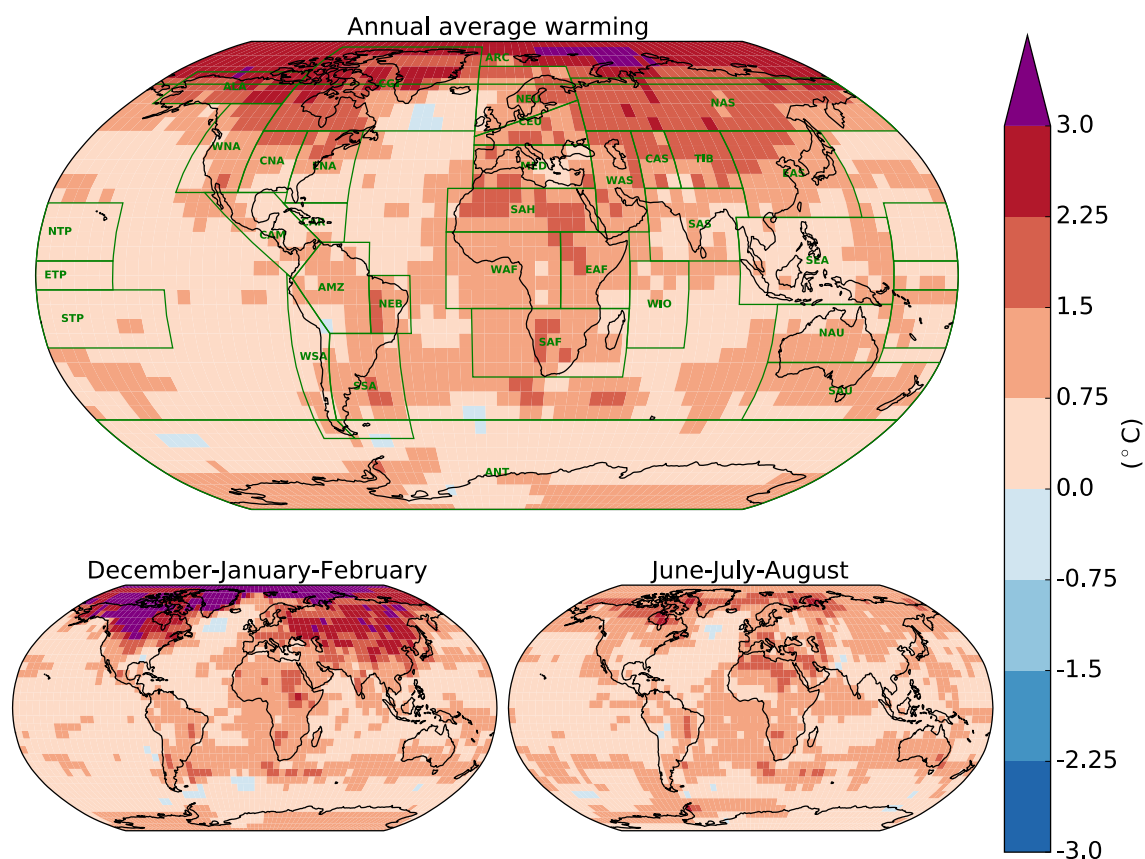
## 47 48 49 **1.2.2 Global versus regional and seasonal warming**

50  
51 Warming is not observed or expected to be spatially or seasonally uniform (IPCC, 2013b). A  $1.5^\circ\text{C}$   
52 increase in GMST will be associated with warming substantially greater than  $1.5^\circ\text{C}$  in many land  
53 regions, and less than  $1.5^\circ\text{C}$  in most ocean regions. This is illustrated by Figure 1.3, which shows an



1 estimate of the observed change in annual and seasonal average temperatures between the 1850-1900  
 2 pre-industrial reference period and the decade 2006–2015 in the Cowtan-Way dataset. These regional  
 3 changes are associated with an observed GMST increase of 0.91°C in the dataset shown here, or  
 4 0.87°C in the 4-dataset average (Table 1.1). This observed pattern reflects an on-going transient  
 5 warming: features such as enhanced warming over land may be less pronounced, but still present, in  
 6 equilibrium (IPCC, 2013b). This figure illustrates the magnitude of these differences, with many  
 7 locations, particularly in Northern-Hemisphere mid-latitude winter (December–February), already  
 8 experiencing regional warming more than double the global average. Individual seasons may be  
 9 substantially warmer, or cooler, than these expected long-term average changes.  
 10

### Regional warming in the decade 2006-2015 relative to preindustrial



11  
 12 **Figure 1.3: Spatial and seasonal pattern of present-day warming:** Regional warming for the 2006–2015  
 13 decade relative to 1850–1900 for the annual mean (top), the average of December, January and  
 14 February (bottom left) and for June, July and August (bottom right). Warming is evaluated by  
 15 regressing regional changes in the (Cowtan and Way, 2014) dataset onto the total (combined  
 16 human and natural) externally-forced warming (yellow line in Figure 1.2). See Supplementary  
 17 Material 1.SM for further details and versions using alternative datasets. The definition of regions  
 18 (green boxes and labels in top panel) is adopted from the AR5 (Christensen et al., 2013).  
 19  
 20

#### 21 **1.2.3 Definition of 1.5°C-consistent pathways: probability, transience, stabilization and** 22 **overshoot**

23  
 24 Pathways considered in this report, consistent with available literature on 1.5°C, primarily focus on  
 25 the timescale up to 2100, recognising that the evolution of GMST after 2100 is also important. Two  
 26 broad categories of 1.5°C-consistent pathways can be used to characterise mitigation options and

1 impacts: pathways in which warming (defined as 30-year averaged GMST relative to pre-industrial  
2 levels, see section 1.2.1) remains below 1.5°C throughout the 21st century, and pathways in which  
3 warming temporarily exceeds (‘overshoots’) 1.5°C and returns to 1.5°C either before or soon after  
4 2100. Pathways in which warming exceeds 1.5°C before 2100, but might return to that level in some  
5 future century, are not considered 1.5°C-consistent.

6  
7 Because of uncertainty in the climate response, a ‘prospective’ mitigation pathway (see Cross-Chapter  
8 Box 1 in this Chapter), in which emissions are prescribed, can only provide a level of probability of  
9 warming remaining below a temperature threshold. This probability cannot be quantified precisely  
10 since estimates depend on the method used (Rogelj et al., 2016b; Millar et al., 2017b; Goodwin et al.,  
11 2018; Tokarska and Gillett, 2018). This report defines a ‘1.5°C-consistent pathway’ as a pathway of  
12 emissions and associated possible temperature responses in which the majority of approaches using  
13 presently-available information assign a probability in the range of approximately one-in-two to two-  
14 in-three to warming remaining below 1.5°C or, in the case of an overshoot pathway, returning to  
15 1.5°C by around 2100 or earlier. In Chapter 2, the classification of pathways is based on one  
16 modeling approach to avoid ambiguity, but probabilities of exceeding 1.5°C are checked against other  
17 approaches to verify that they lie within this approximate range. All these absolute probabilities are  
18 imprecise, depend on the information used to constrain them, and hence are expected to evolve in the  
19 future. Imprecise probabilities can nevertheless be useful for decision-making, provided the  
20 imprecision is acknowledged (Hall et al., 2007; Kriegler et al., 2009; Simpson et al., 2016). Relative  
21 and rank probabilities can be assessed much more consistently: approaches may differ on the absolute  
22 probability assigned to individual outcomes, but typically agree on which outcomes are more  
23 probable.

24  
25 Importantly, 1.5°C-consistent pathways allow a substantial (up to one-in-two) chance of warming still  
26 exceeding 1.5°C. An ‘adaptive’ mitigation pathway in which emissions are continuously adjusted to  
27 achieve a specific temperature outcome (e.g. Millar et al., 2017b) reduces uncertainty in the  
28 temperature outcome while increasing uncertainty in the emissions required to achieve it. It has been  
29 argued (Otto et al., 2015; Xu and Ramanathan, 2017) that achieving very ambitious temperature goals  
30 will require such an adaptive approach to mitigation, but very few studies have been performed taking  
31 this approach (e.g. Jarvis et al., 2012).

32  
33 Figure 1.4 illustrates these categories of (a) 1.5°C-consistent temperature pathways and associated (b)  
34 annual and (c) cumulative emissions of CO<sub>2</sub>. It also shows (d) a ‘time-integrated impact’ that  
35 continues to increase even after GMST has stabilised, such as sea-level rise. This schematic assumes  
36 for illustration that the fractional contribution of non-CO<sub>2</sub> climate forcers to total anthropogenic  
37 forcing (which is currently increasing, Myhre et al., 2017) is approximately constant from now on.  
38 Consequently, total human-induced warming is proportional to cumulative CO<sub>2</sub> emissions (solid line  
39 in c), and GMST stabilises when emissions reach zero. This is only the case in the most ambitious  
40 scenarios for non-CO<sub>2</sub> mitigation (Leach et al., 2018). A simple way of accounting for varying non-  
41 CO<sub>2</sub> forcing in Figure 1.4 would be to note that every 1 W/m<sup>2</sup> increase in non-CO<sub>2</sub> forcing between  
42 now and the decade or two immediately prior to the time of peak warming reduces cumulative CO<sub>2</sub>  
43 emissions consistent with the same peak warming by approximately 1200±300 GtCO<sub>2</sub> (using values  
44 from AR5: Myhre et al, 2013; Jenkins et al, 2018; Allen et al, 2018; Cross-Chapter Box 2 in this  
45 Chapter).

### 46 47 48 *1.2.3.1 Pathways remaining below 1.5°C*

49  
50 In this category of 1.5°C-consistent pathways, human-induced warming either rises monotonically to  
51 stabilise at 1.5°C (Figure 1.4, brown lines) or peaks at or below 1.5°C and then declines (yellow  
52 lines). Figure 1.4, panel b demonstrates that pathways remaining below 1.5°C require net annual CO<sub>2</sub>  
53 emissions to peak and decline to near zero or below, depending on the long-term adjustment of the

1 carbon cycle and non-CO<sub>2</sub> emissions (Bowerman et al., 2013; Wigley, 2018). Reducing emissions to  
2 zero corresponds to stabilizing cumulative CO<sub>2</sub> emissions (panel c, solid lines) and falling  
3 concentrations of CO<sub>2</sub> in the atmosphere (panel c dashed lines) (Matthews and Caldeira, 2008;  
4 Solomon et al., 2009), which is required to stabilize GMST if non-CO<sub>2</sub> climate forcings are constant  
5 and positive. Stabilizing atmospheric greenhouse gas concentrations would result in continued  
6 warming (see Section 1.2.4).

7  
8 If starting emission reductions is delayed until temperatures are close to the proposed limit, pathways  
9 remaining below 1.5°C necessarily involve much faster rates of net CO<sub>2</sub> emission reductions (Figure  
10 1.4, green lines), combined with rapid reductions in non-CO<sub>2</sub> forcing, and also reach 1.5°C earlier.  
11 Note that the emissions associated with these schematic temperature pathways may not correspond to  
12 feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does  
13 not in itself determine peak warming: what matters is total cumulative emissions up to that time.  
14 Hence every year's delay before initiating emission reductions reduces by approximately two years  
15 the remaining time available to reduce emissions to zero on a pathway remaining below 1.5°C (Allen  
16 and Stocker, 2013; Leach et al., 2018).

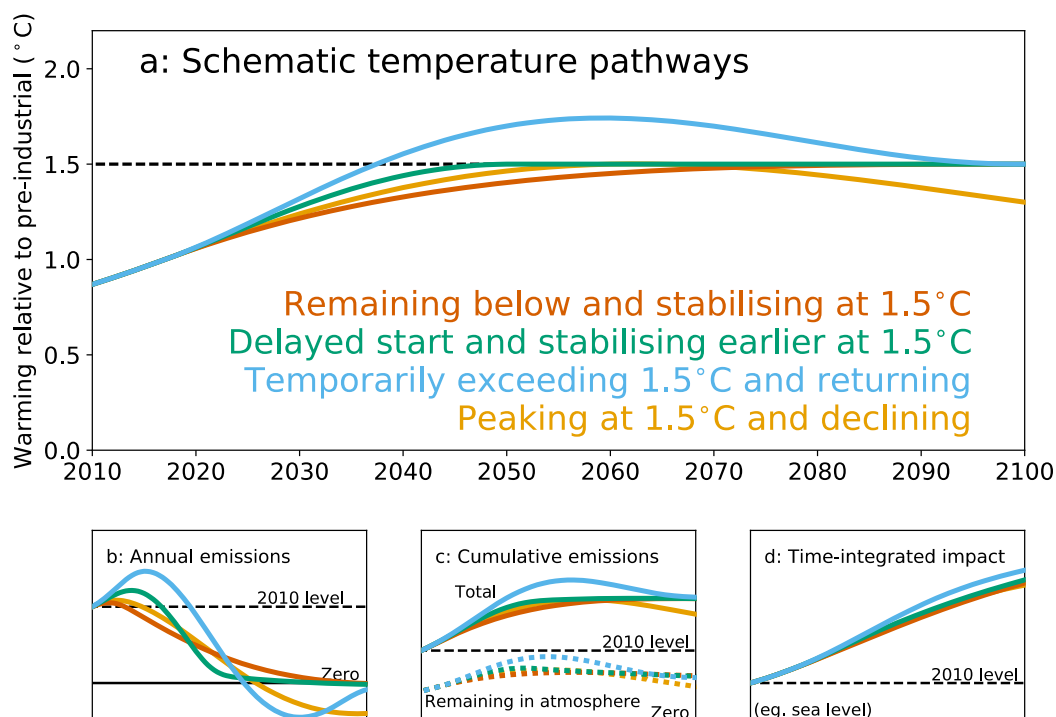
### 17 18 19 *1.2.3.2 Pathways temporarily exceeding 1.5°C*

20  
21 With the pathways in this category, also referred to as overshoot pathways, GMST rises above 1.5°C  
22 before peaking and returning to 1.5°C around or before 2100 (Figure 1.4, blue lines), subsequently  
23 either stabilising or continuing to fall. This allows initially slower or delayed emission reductions but  
24 lowering GMST requires net negative global CO<sub>2</sub> emissions (net anthropogenic removal of CO<sub>2</sub>;  
25 Figure 1.4, panel b). Cooling, or reduced warming, through sustained reductions of net non-CO<sub>2</sub>  
26 climate forcing (Cross-Chapter Box 2 in this Chapter) is also required, but their role is limited  
27 because emissions of most non-CO<sub>2</sub> forcings cannot be reduced to below zero. Hence the feasibility  
28 and availability of large-scale CO<sub>2</sub> removal limits the possible rate and magnitude of temperature  
29 decline. In this report, overshoot pathways are referred to as 1.5°C-consistent, but qualified by the  
30 amount of the temperature overshoot, which can have a substantial impact on irreversible climate  
31 change impacts (Mathesius et al., 2015; Tokarska and Zickfeld, 2015).

### 32 33 34 *1.2.3.3 Impacts at 1.5°C warming associated with different pathways: transience versus* 35 *stabilisation*

36  
37 Figure 1.4 also illustrates timescales associated with different impacts. While many impacts scale  
38 with the change in GMST itself, some (such as those associated with ocean acidification) scale with  
39 the change in atmospheric CO<sub>2</sub> concentration, indicated by the fraction of cumulative CO<sub>2</sub> emissions  
40 remaining in the atmosphere (dotted lines in panel c). Others may depend on the rate of change of  
41 GMST, while 'time-integrated impacts', such as sea-level rise, shown in panel (d) continue to  
42 increase even after GMST has stabilised.

43  
44 Hence impacts that occur when GMST reaches 1.5°C could be very different depending on the  
45 pathway to 1.5°C. CO<sub>2</sub> concentrations will be higher as GMST rises past 1.5°C (transient warming)  
46 than when GMST has stabilized at 1.5°C while sea level and, potentially, global mean precipitation  
47 (Pendergrass et al., 2015) would both be lower (see Figure 1.4). These differences could lead to very  
48 different impacts on agriculture, on some forms of extreme weather (e.g., Baker et al., 2018), and on  
49 marine and terrestrial ecosystems (e.g., Mitchell et al., 2017, )Box 3.1). Sea level would be higher still  
50 if GMST returns to 1.5°C after an overshoot (Figure 1.4, panel d), with potentially significantly  
51 different impacts in vulnerable regions. Temperature overshoot could also cause irreversible impacts  
52 (see Chapter 3).



1  
2  
3 **Figure 1.4: Different 1.5°C-consistent pathways<sup>1</sup>:** Schematic illustration of the relationship between (a)  
4 global mean surface temperature (GMST) change; (b) annual rates of CO<sub>2</sub> emissions, assuming  
5 constant fractional contribution of non-CO<sub>2</sub> forcing to total human-induced warming; (c) total  
6 cumulative CO<sub>2</sub> emissions (solid lines) and the fraction thereof remaining in the atmosphere  
7 (dashed lines; these also indicates changes in atmospheric CO<sub>2</sub> concentrations); and (d) a time-  
8 integrated impact, such as sea-level rise, that continues to increase even after GMST has  
9 stabilized. Colours indicate different 1.5°C-consistent pathways. Brown: GMST remaining below  
10 and stabilizing at 1.5°C in 2100; Green: a delayed start but faster implementation pathway with  
11 GMST remaining below and reaching 1.5°C earlier; Blue: a pathway temporarily exceeding  
12 1.5°C, with temperatures reduced to 1.5°C by net negative CO<sub>2</sub> emissions after temperatures  
13 peak; and Yellow: a pathway peaking at 1.5°C and subsequently declining. Temperatures are  
14 anchored to 0.87°C above pre-industrial in 2010; emissions-temperature relationships are  
15 computed using a simple climate model (Myhre et al., 2013; Millar et al., 2017a; Jenkins et al.,  
16 2018) with a lower value of the Transient Climate Response (TCR) than used in the quantitative  
17 pathway assessments in Chapter 2 to illustrate qualitative differences between pathways: this  
18 figure is not intended to provide quantitative information. The time-integrated impact is illustrated  
19 by the semi-empirical sea-level-rise model of Kopp et al. (2016).

<sup>1</sup> FOOTNOTE: An animated version of Figure 1.4 will be embedded in the web-based version of this Special Report

## Cross-Chapter Box 1: Scenarios and Pathways

**Contributing Authors:** Mikiko Kainuma (Japan), Kristie L. Ebi (US), Sabine Fuss (Germany), Elmar Kriegler (Germany), Keywan Riahi (Austria), Joeri Rogelj (Austria/Belgium), Petra Tschakert (Australia/Austria) and Rachel Warren (UK)

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. Subsequently, many policy scenarios have been developed based upon them (Morita et al., 2001). The SRES scenarios are superseded by a set of scenarios based on the Representative Concentration Pathways (RCPs) and Shared Socio-Economic Pathways (SSPs) (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<sup>-2</sup> (RCP2.6) to 8.5 W m<sup>-2</sup> (RCP8.5) by the end of the 21st century (van Vuuren et al., 2011). They were used to develop climate projections in the 5th Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) and were assessed in the IPCC 5th Assessment Report (AR5). Based on the CMIP5 ensemble, RCP2.6, provides a better than two in three chance 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. 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 levels (Rogelj et al., 2018). The SSP-based 1.5°C-consistent pathways are assessed in Chapter 2 of this report. These scenarios offer an integrated perspective on socio-economic, energy-system (Bauer et al., 2017), land use (Popp et al., 2017), air pollution (Rao et al., 2017) and GHG emissions developments (Riahi et al., 2017). 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 pathways that could limit the increase of global mean surface temperature (GMST) to 1.5°C above pre-industrial levels 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 benchmarks for comparison of mitigation, impacts, 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 nationally-determined contributions (NDCs); and scenarios holding warming below 2°C above pre-industrial levels. 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 GMST increase to 1.5°C and are thus indispensable when assessing implementation.

Different climate policies result in different temperature pathways, which result in different levels of climate risks and actual climate impacts with associated long-term implications. Temperature pathways are classified into continued warming pathways (in the cases of baseline and reference scenarios), pathways that keep the temperature below a specific limit (like 1.5°C or 2°C), and pathways that temporarily exceed and later fall to a specific limit (overshoot pathways). In the case of a temperature overshoot, net negative CO<sub>2</sub> emissions are required to remove excess CO<sub>2</sub> from the

1 atmosphere.

2  
3 In a ‘prospective’ mitigation pathway, emissions (or sometimes concentrations) are prescribed, giving  
4 a range of GMST outcomes because of uncertainty in the climate response. Prospective pathways are  
5 considered ‘1.5°C-consistent’ in this report if, based current knowledge, the majority of available  
6 approaches assign an approximate probability of one-in-two to two-in-three to temperatures either  
7 remaining below 1.5°C or returning to 1.5°C either before or around 2100. Most pathways assessed in  
8 Chapter 2 are prospective pathways, and therefore even ‘1.5°C-consistent pathways’ are also  
9 associated with risks of warming higher than 1.5°C, noting that many risks increase non-linearly with  
10 increasing GMST. In contrast, the ‘risks of warming of 1.5°C’ assessed in Chapter 3 refer to risks in a  
11 world in which GMST is either passing through (transient) or stabilized at 1.5°C, without considering  
12 probabilities of different GMST levels (unless otherwise qualified). To stay below any desired  
13 temperature limit, adjusting mitigation measures and strategies would be required as knowledge of the  
14 climate response is updated (Millar et al., 2017b; Emori et al., 2018). Such pathways can be called  
15 ‘adaptive’ mitigation pathways. Given there is always a possibility of a greater-than-expected climate  
16 response (Xu and Ramanathan, 2017), adaptive mitigation pathways are important to minimise  
17 climate risks, but need also to consider the risks and feasibility (see Cross-Chapter Box 3 in this  
18 Chapter) of faster-than-expected emission reductions. Aligning mitigation and adaptation pathways  
19 with sustainable development pathways and transformative visions for the future that would support  
20 avoiding negative impacts on the poorest and most disadvantaged populations and vulnerable sectors  
21 are assessed in Chapter 5.

### 22 **Definitions of Scenarios and Pathways**

23 Climate scenarios and pathways are terms that are sometimes used interchangeably, with a wide range  
24 of overlapping definitions (Rosenbloom, 2017).

25  
26  
27 A ‘**scenario**’ is an internally consistent, plausible, and integrated description of a possible future of  
28 the human–environment system, including a narrative with qualitative trends and quantitative  
29 projections (IPCC, 2000). Climate change scenarios provide a framework for developing and  
30 integrating emissions, climate change and climate impact projections, including an assessment of their  
31 inherent uncertainties. The long-term and multi-faceted nature of climate change requires climate  
32 scenarios to describe how assumptions about inherently uncertain socio-economic trends in the 21st  
33 century could influence future energy and land use, resulting in emissions, and climate change as well  
34 as human vulnerability and exposure to climate change. Such driving forces include population, GDP,  
35 technological innovation, governance, and lifestyles. Climate change scenarios are used for analysing  
36 and contrasting climate policy choices.

37  
38 The notion of a ‘**pathway**’ can have multiple meanings in the climate literature. It is often used to  
39 describe the temporal evolution of a set of scenario features, such as GHG emissions and  
40 socioeconomic development. As such, it can describe individual scenario components or sometimes  
41 be used interchangeably with the word ‘scenario’. For example, the RCPs describe GHG  
42 concentration trajectories (van Vuuren et al., 2011) and the SSPs are a set of narratives of societal  
43 futures augmented by quantitative projections of socio-economic determinants such as population,  
44 GDP, and urbanization (Kriegler et al., 2012; O’Neill et al., 2014). Socio-economic driving forces  
45 consistent with any of the SSPs can be combined with a set of climate policy assumptions (Kriegler et  
46 al., 2014) that together would lead to emissions and concentration outcomes consistent with the RCPs  
47 (Riahi et al., 2017). This is at the core of the scenario framework for climate change research that  
48 aims to facilitate creating scenarios integrating emissions and development pathways dimensions (Ebi  
49 et al., 2014; van Vuuren et al., 2014).

50  
51 In other parts of the literature, ‘pathway’ implies a solution-oriented trajectory describing a pathway  
52 from today’s world to achieving a set of future goals. **Sustainable Development Pathways** describe  
53 national and global pathways where climate policy becomes part of a larger sustainability

1 transformation (Shukla and Chaturvedi, 2013; Fleurbaey et al., 2014; van Vuuren et al., 2015). The  
2 AR5 presented **climate-resilient pathways** as sustainable development pathways that combine the  
3 goals of adaptation and mitigation (Denton et al., 2014), more broadly defined as iterative processes  
4 for managing change within complex systems in order to reduce disruptions and enhance  
5 opportunities associated with climate change (IPCC, 2014b). The AR5 also introduced the notion of  
6 **climate-resilient development pathways**, with a more explicit focus on dynamic livelihoods,  
7 multidimensional poverty, structural inequalities, and equity among poor and non-poor people  
8 (Olsson et al., 2014). **Adaptation pathways**, understood as a series of adaptation choices involving  
9 trade-offs between short-term and long-term goals and values (Reisinger et al., 2014). They are  
10 decision-making processes sequenced over time with the purpose of deliberating and identifying  
11 socially-salient solutions in specific places (Barnett et al., 2014; Wise et al., 2014; Fazey et al., 2016).  
12 There is a range of possible pathways for transformational change, often negotiated through iterative  
13 and inclusive processes (Harris et al., 2017; Fazey et al., 2018; Tàbara et al., 2018).

#### 16 *1.2.4 Geophysical warming commitment*

18 It is frequently asked whether limiting warming to 1.5°C is ‘feasible’ (Cross–Chapter Box 3 in this  
19 Chapter). There are many dimensions to this question, including the warming ‘commitment’ from  
20 past emissions of greenhouse gases and aerosol precursors. Quantifying commitment from past  
21 emissions is complicated by the very different behaviour of different climate forcers affected by  
22 human activity: emissions of long-lived greenhouse gases such as CO<sub>2</sub> and nitrous oxide (N<sub>2</sub>O) have a  
23 very persistent impact on radiative forcing (Myhre et al., 2013), lasting from over a century (in the  
24 case of N<sub>2</sub>O) to hundreds of thousands of years (for CO<sub>2</sub>). Short-lived climate forcers (SLCFs) such as  
25 methane (CH<sub>4</sub>) and aerosols, in contrast, persist for at most about a decade (in the case of methane)  
26 down to only a few days. These different behaviours must be taken into account in assessing the  
27 implications of any approach to calculating aggregate emissions (Cross-Chapter Box 2 in this  
28 Chapter).

30 Geophysical warming commitment is defined as the unavoidable future warming resulting from  
31 physical Earth system inertia. Different variants are discussed in the literature, including (i) the  
32 ‘constant composition commitment’ (CCC), defined by Meehl et al. (2007) as the further warming  
33 that would result if atmospheric concentrations of GHGs and other climate forcers were stabilised at  
34 the current level; and (ii) and the ‘zero emissions commitment’ (ZEC), defined as the further warming  
35 that would still occur if all future anthropogenic emissions of greenhouse gases and aerosol precursors  
36 were eliminated instantaneously (Meehl et al., 2007; Collins et al., 2013).

38 The CCC is primarily associated with thermal inertia of the ocean (Hansen et al., 2005), and has led to  
39 the misconception that substantial future warming is inevitable (Matthews and Solomon, 2013). The  
40 CCC takes into account the warming from past emissions, but also includes warming from future  
41 emissions (declining but still non-zero) that are required to maintain a constant atmospheric  
42 composition. It is therefore not relevant to the warming commitment from past emissions alone.

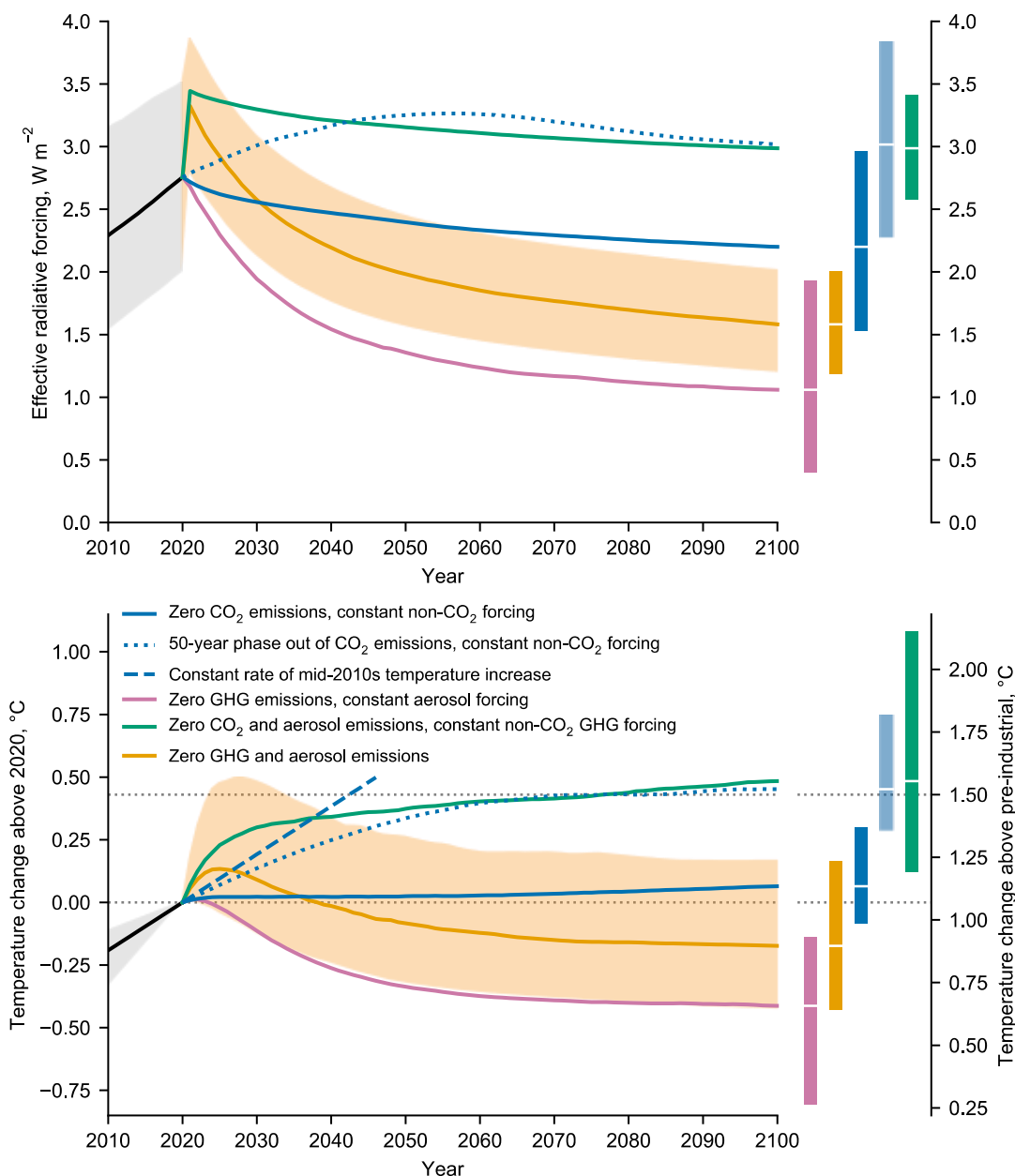
44 The ZEC, although based on equally idealised assumptions, allows for a clear separation of the  
45 response to past emissions from the effects of future emissions. The magnitude and sign of the ZEC  
46 depend on the mix of GHGs and aerosols considered. For CO<sub>2</sub>, which has an effective atmospheric  
47 residence time of centuries to millennia (Eby et al., 2009), the multi-century warming commitment  
48 from emissions to date is estimated to range from slightly negative (i.e., a slight cooling relative to  
49 present-day) to slightly positive (Matthews and Caldeira, 2008; Lowe et al., 2009; Gillett et al., 2011;  
50 Collins et al., 2013). Some studies estimate a larger ZEC from CO<sub>2</sub>, but for cumulative emissions  
51 much higher than those up to present day (Frölicher et al., 2014; Ehlert and Zickfeld, 2017). The ZEC  
52 from past CO<sub>2</sub> emissions is small because the continued warming effect from ocean thermal inertia is  
53 approximately balanced by declining radiative forcing due to CO<sub>2</sub> uptake by the ocean (Solomon et

1 al., 2009; Williams et al., 2017). Thus, although present-day CO<sub>2</sub>-induced warming is irreversible on  
2 millennial timescales (without human intervention such as active carbon dioxide removal or solar  
3 radiation modification (Section 1.4.1)), past CO<sub>2</sub> emissions do not commit to substantial further  
4 warming (Matthews and Solomon, 2013).

5  
6 For warming SLCFs, meaning those associated with positive radiative forcing such as methane, the  
7 ZEC is negative. Eliminating emissions of these substances (also sometimes referred to as short-lived  
8 climate pollutants, see Section 4.3.6) results in an immediate cooling relative to the present  
9 (Figure 1.5, magenta line) (Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Mauritsen and  
10 Pincus, 2017). Cooling SLCFs (those associated with negative radiative forcing) such as sulphate  
11 aerosols create a positive ZEC, as elimination of these forcers results in rapid warming (Matthews and  
12 Zickfeld, 2012; Mauritsen and Pincus, 2017; Samset et al., 2018). Estimates of the warming  
13 commitment from eliminating aerosol emissions are affected by large uncertainties in net aerosol  
14 radiative forcing (Myhre et al., 2013, 2017). If present-day emissions of all GHGs (short- and long-  
15 lived) and aerosols (including sulphate, nitrate and carbonaceous aerosols) are eliminated (Figure 1.5,  
16 yellow line) GMST rises over the following decade. This initial warming is followed by a gradual  
17 cooling driven by the decline in radiative forcing of short-lived greenhouse gases (Matthews and  
18 Zickfeld, 2012; Collins et al., 2013). Peak warming following elimination of all emissions was  
19 assessed at a few tenths of a degree in AR5, and century-scale warming was assessed to change only  
20 slightly relative to the time emissions are reduced to zero (Collins et al., 2013). New evidence since  
21 AR5 suggests a larger methane forcing (Etminan et al., 2016) but no revision in the range of aerosol  
22 forcing (although this remains an active field of research, e.g., Myhre et al., 2017). This revised  
23 methane forcing estimate results in a smaller peak warming and a faster temperature decline than  
24 assessed in AR5 (Figure 1.5, yellow line).

25  
26 Expert judgement based on the available evidence (including model simulations, radiative forcing and  
27 climate sensitivity) suggests that if all anthropogenic emissions were reduced to zero immediately,  
28 any further warming beyond the 1°C already experienced would *likely* be less than 0.5°C over the  
29 next two to three decades, and also *likely* less than 0.5°C on a century timescale.





1  
 2 **Figure 1.5: Different interpretations of warming commitment from past emissions:** Radiative forcing  
 3 (top) and global mean surface temperature change (bottom) for scenarios with different  
 4 combinations of greenhouse gas and aerosol precursor emissions reduced to zero in 2020.  
 5 Variables were calculated using a simple climate–carbon cycle model (Millar et al., 2017a) with a  
 6 simple representation of atmospheric chemistry (Smith et al., 2018). The bars on the right–hand  
 7 side indicate the median warming in 2100 and 5–95% uncertainty ranges (also indicated by the  
 8 plume around the yellow line) taking into account one estimate of uncertainty in climate response,  
 9 effective radiative forcing, and carbon cycle constraining simple model parameters with response  
 10 ranges from AR5 combined with historical climate observations (Smith et al., 2018).  
 11 Temperatures continue to increase slightly after elimination of CO<sub>2</sub> emissions (blue line) due to  
 12 adjusting to the recent increase in non-CO<sub>2</sub> forcing. The dashed blue line extrapolates one  
 13 estimate of the current rate of warming, while dotted blue lines show a case where CO<sub>2</sub> emissions  
 14 are reduced linearly to zero assuming constant non-CO<sub>2</sub> forcing after 2020. Under these highly  
 15 idealized assumptions, the time to stabilize temperatures at 1.5°C is approximately double the  
 16 time remaining to reach 1.5°C at the current warming rate.  
 17

1 Since most sources of emissions cannot, in reality, be brought to zero instantaneously due to techno-  
2 economic inertia, the current rate of emissions also constitutes a conditional commitment to future  
3 emissions and consequent warming depending on achievable rates of emission reductions. The current  
4 level and rate of human-induced warming determines both the time left before a temperature threshold  
5 is exceeded if warming continues (dashed blue line in Figure 1.5) and the time over which the  
6 warming rate must be reduced to avoid exceeding that threshold (approximately indicated by the  
7 dotted blue line in Figure 1.5). Leach et al. (2018) use a central estimate of human-induced warming  
8 of 1.02°C in 2017 increasing at 0.215°C per decade (Haustein et al., 2017), to argue that it will take  
9 13–32 years (one-standard-error range) to reach 1.5°C if the current warming rate continues, allowing  
10 25–64 years to stabilise temperatures at 1.5°C if the warming rate is reduced at a constant rate of  
11 deceleration starting immediately. Since the rate of human-induced warming is proportional to the  
12 rate of CO<sub>2</sub> emissions (Matthews et al., 2009; Zickfeld et al., 2009) plus a term approximately  
13 proportional to the rate of increase in non-CO<sub>2</sub> radiative forcing (Gregory and Forster, 2008; Allen et  
14 al., 2018; Cross-Chapter Box 2 in this Chapter), these timescales also provide an indication of  
15 minimum emission reduction rates required if a warming greater than 1.5°C is to be avoided (see  
16 Supplementary Material 1.SM and FAQ 1.2).

## 19 **Cross-Chapter Box 2: Measuring progress to net zero emissions combining long-lived and** 20 **short-lived climate forcers**

22 **Contributing Authors:** Piers Forster (UK), Myles Allen (UK), Elmar Kriegler (Germany), Joeri  
23 Rogelj (Austria/Belgium), Seth Schultz (US), Drew Shindell (US) and Kirsten Zickfeld  
24 (Canada/Germany)

26 Emissions of many different climate forcers will affect the rate and magnitude of climate change over  
27 the next few decades (Myhre et al., 2013). Since these decades will determine when 1.5°C is reached  
28 or whether a warming greater than 1.5°C is avoided, understanding the aggregate impact of different  
29 forcing agents is particularly important in the context of 1.5°C-consistent pathways. Paragraph 17 of  
30 Decision 1 of the 21st Conference of the Parties on the adoption of the Paris Agreement specifically  
31 states that this report is to identify aggregate greenhouse gas emission levels compatible with holding  
32 the increase in global average temperatures to 1.5°C above preindustrial levels (see Chapter 2). This  
33 request highlights the need to consider the implications of different methods of aggregating emissions  
34 of different gases, both for future temperatures and for other aspects of the climate system.

36 To date, reporting of GHG emissions under the UNFCCC has used Global Warming Potentials  
37 (GWPs) evaluated over a 100-year time horizon (GWP<sub>100</sub>) to combine multiple climate forcers. IPCC  
38 Working Group 3 reports have also used GWP<sub>100</sub> to represent multi-gas pathways (Clarke et al.,  
39 2014). For reasons of comparability and consistency with current practice, Chapter 2 in this Special  
40 Report continues to use this aggregation method. Numerous other methods of combining different  
41 climate forcers have been proposed, such as the Global Temperature-change Potential (GTP; Shine et  
42 al., 2005) and the Global Damage Potential (Tol et al., 2012; Deuber et al., 2013).

44 Climate forcers fall into two broad categories in terms of their impact on global temperature (Smith et  
45 al., 2012): long-lived GHGs, such as CO<sub>2</sub> and nitrous oxide (N<sub>2</sub>O), whose warming impact depends  
46 primarily on the total cumulative amount emitted over the past century or the entire industrial epoch;  
47 and short-lived climate forcers (SLCFs), such as methane and black carbon, whose warming impact  
48 depends primarily on current and recent annual emission rates (Reisinger et al., 2012; Myhre et al.,  
49 2013; Smith et al., 2013; Strefler et al., 2014). These different dependencies affect the emissions  
50 reductions required of individual forcers to limit warming to 1.5°C or any other level.

52 Natural processes that remove CO<sub>2</sub> permanently from the climate system are so slow that reducing the  
53 rate of CO<sub>2</sub>-induced warming to zero requires net zero global anthropogenic CO<sub>2</sub> emissions (Archer

1 and Brovkin, 2008; Matthews and Caldeira, 2008; Solomon et al., 2009), meaning almost all  
2 remaining anthropogenic CO<sub>2</sub> emissions must be compensated for by an equal rate of anthropogenic  
3 carbon dioxide removal (CDR). Cumulative CO<sub>2</sub> emissions are therefore an accurate indicator of  
4 CO<sub>2</sub>-induced warming, except in periods of high negative CO<sub>2</sub> emissions (Zickfeld et al., 2016), and  
5 potentially in century-long periods of near-stable temperatures (Bowerman et al., 2011; Wigley,  
6 2018). In contrast, sustained constant emissions of a SLCF such as methane, would (after a few  
7 decades) be consistent with constant methane concentrations and hence very little additional methane-  
8 induced warming (Allen et al., 2018; Fuglestedt et al., 2018). Both GWP and GTP would equate  
9 sustained SLCF emissions with sustained constant CO<sub>2</sub> emissions, which would continue to  
10 accumulate in the climate system, warming global temperatures indefinitely. Hence nominally  
11 ‘equivalent’ emissions of CO<sub>2</sub> and SLCFs, if equated conventionally using GWP or GTP, have very  
12 different temperature impacts, and these differences are particularly evident under ambitious  
13 mitigation characterising 1.5°C-consistent pathways.

14  
15 Since the AR5, a revised usage of GWP has been proposed (Lauder et al., 2013; Allen et al., 2016),  
16 denoted GWP\* (Allen et al., 2018), that addresses this issue by equating a permanently sustained  
17 change in the emission *rate* of an SLCF or SLCF-precursor (in tonnes-per-year), or other non-CO<sub>2</sub>  
18 forcing (in Watts per square metre), with a one-off *pulse* emission (in tonnes) of a fixed amount of  
19 CO<sub>2</sub>. Specifically, GWP\* equates a 1 tonne-per-year increase in emission rate of an SLCF with a  
20 pulse emission of  $GWP_H \times H$  tonnes of CO<sub>2</sub>, where  $GWP_H$  is the conventional GWP of that SLCF  
21 evaluated over time horizon  $H$ . While  $GWP_H$  for SLCFs decreases with increasing time horizon  $H$ ,  
22  $GWP_H \times H$  for SLCFs is less dependent on the choice of time horizon. Similarly, a permanent 1 W/m<sup>2</sup>  
23 increase in radiative forcing has a similar temperature impact as the cumulative emission of  
24  $H/AGWP_H$  tonnes of CO<sub>2</sub>, where  $AGWP_H$  is the Absolute Global Warming Potential of CO<sub>2</sub> (Shine et  
25 al., 2005; Myhre et al., 2013; Allen et al., 2018). This indicates approximately how future changes in  
26 non-CO<sub>2</sub> radiative forcing affect cumulative CO<sub>2</sub> emissions consistent with any given level of peak  
27 warming.

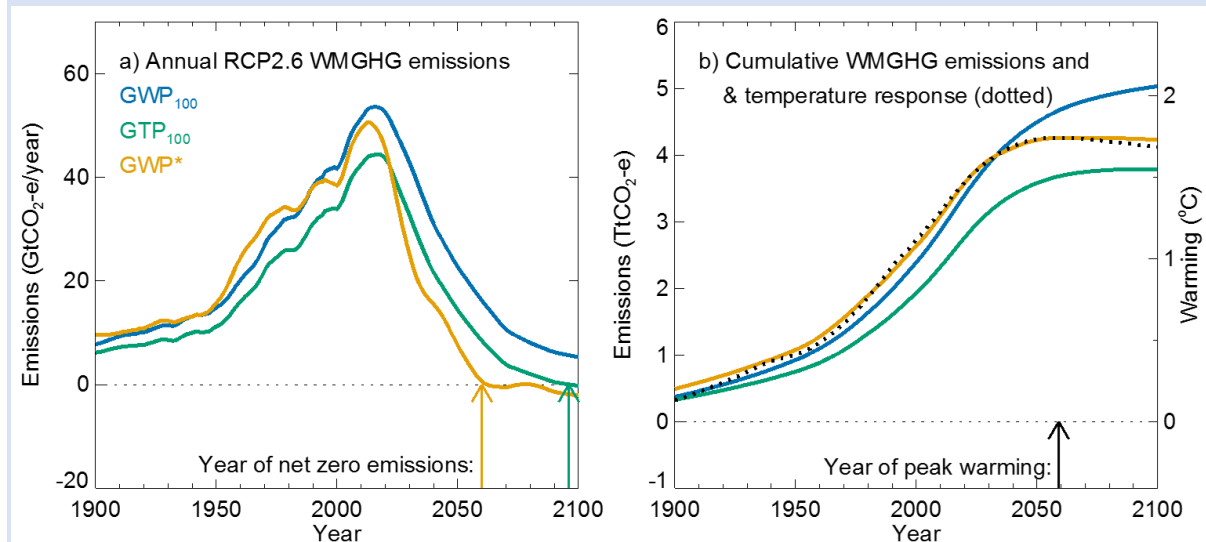
28  
29 When combined using GWP\*, cumulative aggregate GHG emissions are closely proportional to total  
30 GHG-induced warming, while the annual rate of GHG-induced warming is proportional to the annual  
31 rate of aggregate GHG emissions (see Cross-Chapter Box 2, Figure 1). This is not the case when  
32 emissions are aggregated using GWP or GTP, with discrepancies particularly pronounced when SLCF  
33 emissions are falling. Persistent net zero CO<sub>2</sub>-equivalent emissions containing a residual positive  
34 forcing contribution from SLCFs and aggregated using GWP<sub>100</sub> or GTP would result in a steady  
35 decline of GMST. Net zero global emissions aggregated using GWP\* (which corresponds to zero net  
36 emissions of CO<sub>2</sub> and other long-lived GHGs like nitrous oxide, combined with constant SLCF  
37 forcing – see Figure 1.5) results in approximately stable GMST (Fuglestedt et al., 2018; Allen et al.,  
38 2018 and Cross-Chapter Box 2, Figure 1, below).

39  
40 Whatever method is used to relate emissions of different greenhouse gases, scenarios achieving stable  
41 GMST well below 2°C require both near-zero net emissions of long-lived greenhouse gases and deep  
42 reductions in warming SLCFs (Chapter 2), in part to compensate for the reductions in cooling SLCFs  
43 that are expected to accompany reductions in CO<sub>2</sub> emissions (Rogelj et al., 2016b; Hienola et al.,  
44 2018). Understanding the implications of different methods of combining emissions of different  
45 climate forcers is, however, helpful in tracking progress towards temperature stabilisation and  
46 ‘balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases’ as  
47 stated in Article 4 of the Paris Agreement. Fuglestedt et al. (2018) and Tanaka and O’Neill  
48 (2018) show that when, and even whether, aggregate GHG emissions need to reach net zero before  
49 2100 to limit warming to 1.5°C depends on the scenario, aggregation method and mix of long-lived  
50 and short-lived climate forcers.

51  
52 The comparison of the impacts of different climate forcers can also consider more than their effects  
53 on GMST (Johansson, 2012; Tol et al., 2012; Deuber et al., 2013; Myhre et al., 2013). Climate

1 impacts arise from both magnitude and rate of climate change, and from other variables such as  
 2 precipitation (Shine et al., 2015). Even if GMST is stabilised, sea-level rise and associated impacts  
 3 will continue to increase (Sterner et al., 2014), while impacts that depend on CO<sub>2</sub> concentrations such  
 4 as ocean acidification may begin to reverse. From an economic perspective, comparison of different  
 5 climate forcers ideally reflects the ratio of marginal economic damages if used to determine the  
 6 exchange ratio of different GHGs under multi-gas regulation (Tol et al., 2012; Deuber et al., 2013;  
 7 Kolstad et al., 2014).

8  
 9 Emission reductions can interact with other dimensions of sustainable development (see Chapter 5).  
 10 In particular, early action on some SLCFs (including actions that may warm the climate such as  
 11 reducing SO<sub>2</sub> emissions) may have considerable societal co-benefits such as reduced air pollution and  
 12 improved public health with associated economic benefits (OECD, 2016; Shindell et al., 2016).  
 13 Valuation of broadly defined social costs attempts to account for many of these additional non-  
 14 climate factors along with climate-related impacts (Shindell, 2015; Sarofim et al., 2017; Shindell et  
 15 al., 2017). See Chapter 4, Section 4.3.6, for a discussions of mitigation options, noting that mitigation  
 16 priorities for different climate forcers depend on multiple economic and social criteria that vary  
 17 between sectors, regions and countries.



19  
 20  
 21 **Cross Chapter Box 2, Figure 1: Implications of different approaches to calculating aggregate greenhouse**  
 22 **gas emissions on a pathway to net zero** (a) Aggregate emissions of well-mixed greenhouse gases (WMGHGs)  
 23 under the RCP2.6 mitigation scenario expressed as CO<sub>2</sub>-equivalent using GWP<sub>100</sub> (blue); GTP<sub>100</sub> (green) and  
 24 GWP\* (yellow). Aggregate WMGHG emissions appear to fall more rapidly if calculated using GWP\* than  
 25 using either GWP or GTP, primarily because GWP\* equates falling methane emissions with negative CO<sub>2</sub>  
 26 emissions, as only active CO<sub>2</sub> removal would have the same impact on radiative forcing and GMST as a  
 27 reduction in methane emission rates. (b) Cumulative emissions of WMGHGs combined as in panel (a) (blue,  
 28 green & yellow lines & left hand axis) and warming response to combined emissions (black dotted line & right  
 29 hand axis, Millar et al. (2017a)). The temperature response under ambitious mitigation is closely correlated with  
 30 cumulative WMGHG emissions aggregated using GWP\*, but with neither emission rate nor cumulative  
 31 emissions if aggregated using GWP or GTP.

### 34 1.3 Impacts at 1.5°C and beyond

#### 36 1.3.1 Definitions

37  
 38 Consistent with the AR5 (IPCC, 2014e), 'impact' in this report refers to the effects of climate change  
 39 on human and natural systems. Impacts may include the effects of changing hazards, such as the

1 frequency and intensity of heat waves. ‘Risk’ refers to potential negative impacts of climate change  
2 where something of value is at stake, recognizing the diversity of values. Risks depend on hazards,  
3 exposure, vulnerability (including sensitivity and capacity to respond) and likelihood. Climate change  
4 risks can be managed through efforts to mitigate climate change forcings, adaptation of impacted  
5 systems and remedial measures (Section 1.4.1).

6  
7 In the context of this report, *regional* impacts of *global* warming at 1.5°C and 2°C are assessed in  
8 Chapter 3. The ‘*warming experience at 1.5°C*’ is that of regional climate change (temperature,  
9 rainfall, and other changes) at the time when global average temperatures, as defined in Section 1.2.1,  
10 reach 1.5°C above pre-industrial (the same principle applies to impacts at any other global mean  
11 temperature). Over the decade 2006-2015, many regions have experienced higher than average levels  
12 of warming and some are already now 1.5°C warmer with respect to the pre-industrial period (Figure  
13 1.3). At a global warming of 1.5°C, some seasons will be substantially warmer than 1.5°C above pre-  
14 industrial (Seneviratne et al., 2016). Therefore, most regional impacts of a global mean warming of  
15 1.5°C will be different from those of a regional warming by 1.5°C.

16  
17 The impacts of 1.5°C global warming will vary in both space and time (Ebi et al., 2016). For many  
18 regions, an increase in global mean temperature by 1.5°C or 2°C implies substantial increases in the  
19 occurrence and/or intensity of some extreme events (Fischer and Knutti, 2015; Karmalkar and  
20 Bradley, 2017; King et al., 2017), resulting in different impacts (see Chapter 3). By comparing  
21 impacts at 1.5°C vs. those at 2°C, this report discusses the ‘avoided impacts’ by maintaining global  
22 temperature increase at or below 1.5°C as compared to 2°C, noting that these also depend on the  
23 pathway taken to 1.5°C (see Section 1.2.3 and Cross-Chapter Box 8 in Chapter 3 on 1.5°C warmer  
24 worlds). Many impacts take time to observe, and because of the warming trend, impacts over the past  
25 20 years were associated with a level of human-induced warming that was, on average, 0.1–0.23°C  
26 colder than its present level, based on the AR5 estimate of the warming trend over this period (Section  
27 1.2.1 and Kirtman et al., 2013). Attribution studies (e.g., van Oldenborgh et al., 2017) can address this  
28 bias, but informal estimates of ‘recent impact experience’ in a rapidly warming world necessarily  
29 understate the temperature-related impacts of the current level of warming.

### 30 31 32 **1.3.2 Drivers of Impacts**

33  
34 Impacts of climate change are due to multiple environmental drivers besides rising temperatures, such  
35 as rising atmospheric CO<sub>2</sub>, shifting rainfall patterns, rising sea levels, increasing ocean acidification,  
36 and extreme events, such as floods, droughts, and heat waves (IPCC, 2014e). For example, changes in  
37 rainfall affect the hydrological cycle and water availability (Schewe et al., 2014). Several impacts  
38 depend on atmospheric composition, for example, increasing atmospheric carbon dioxide levels  
39 leading to changes in plant productivity (Forkel et al., 2016), but also to ocean acidification (Hoegh-  
40 Guldberg et al., 2007). Other impacts are driven by changes in ocean heat content, for example, the  
41 destabilization of coastal ice-sheets and sea-level rise (Bindoff et al., 2007; Chen et al., 2017),  
42 whereas impacts due to heat waves depend directly on ambient air or ocean temperature (Matthews et  
43 al., 2017). Impacts can be direct, for example, coral bleaching due to ocean warming, and indirect, for  
44 example, reduced tourism due to coral bleaching. Indirect impacts can also arise from mitigation  
45 efforts such as changed agricultural management (Section 3.6.2) or remedial measures such as solar  
46 radiation modification (Section 4.3.8, Cross-Chapter Box 10 in Chapter 4).

47  
48 Impacts may also be triggered by combinations of factors, including ‘impact cascades’ (Cramer et al.,  
49 2014) through secondary consequences of changed systems. Changes in agricultural water availability  
50 caused by upstream changes in glacier volume are a typical example. Recent studies also identify  
51 compound events (e.g., droughts and heat waves), that is, when impacts are induced by the  
52 combination of several climate events (AghaKouchak et al., 2014; Leonard et al., 2014; Martius et al.,  
53 2016; Zscheischler and Seneviratne, 2017).

1  
2 There are now techniques to attribute impacts formally to anthropogenic global warming and  
3 associated rainfall changes (Rosenzweig et al., 2008; Cramer et al., 2014; Hansen et al., 2016), taking  
4 into account other drivers such as land use change (Oliver and Morecroft, 2014) and pollution (e.g.,  
5 tropospheric ozone; Sitch et al., 2007). There are multiple lines of evidence that climate change has  
6 observable and often severely negative effects on people, especially where climate-sensitive  
7 biophysical conditions and socioeconomic / political constraints on adaptive capacities combine to  
8 create high vulnerabilities (IPCC, 2012c; World Bank, 2013; IPCC, 2014e). The character and  
9 severity of impacts depend not only on the hazards (e.g. changed climate averages and extremes) but  
10 also on the vulnerability (including sensitivities and adaptive capacities) of different communities and  
11 their exposure to climate threats. These impacts also affect a range of natural and human systems such  
12 as terrestrial, coastal and marine ecosystems and their services, agricultural production, infrastructure,  
13 the built environment, human health and other socio-economic systems (Rosenzweig et al., 2017).

14  
15 Sensitivity to changing drivers varies markedly across systems and regions. Impacts of climate change  
16 on natural and managed ecosystems can imply loss or increase in growth, biomass or diversity at the  
17 level of species populations, interspecific relationships such as pollination, landscapes or entire  
18 biomes. Impacts occur in addition to the natural variation in growth, ecosystem dynamics,  
19 disturbance, succession and other processes, rendering attribution of impacts at lower levels of  
20 warming difficult in certain situations. The same magnitude of warming can be lethal during one  
21 phase of the life of an organism and irrelevant during another. Many ecosystems (notably forests,  
22 coral reefs and others) undergo long-term successional processes characterised by varying levels of  
23 resilience to environmental change over time. Organisms and ecosystems may adapt to environmental  
24 change to a certain degree, for example, through changes in physiology, ecosystem structure, species  
25 composition or evolution. Large-scale shifts in ecosystems may cause important feedbacks, for  
26 example, in terms of changing water and carbon fluxes through impacted ecosystems – these can  
27 amplify or dampen atmospheric change at regional to continental scale. For example, of particular  
28 concern, is the response of most of the world's forests and seagrass ecosystems, which play key roles  
29 as carbon sinks (Settele et al., 2014; Marbà et al., 2015).

30  
31 Some ambitious efforts to constrain atmospheric greenhouse gas concentrations may themselves  
32 impact ecosystems. In particular, changes in land use, potentially required for massively enhanced  
33 production of biofuels (either as simple replacement of fossil fuels, or as part of Bioenergy with  
34 Carbon Capture and Storage, BECCS) impact all other land ecosystems through competition for land  
35 (e.g., Creutzig, 2016) (see Cross-Chapter Box 7 in Chapter 3, Section 3.6.2.1).

36  
37 Human adaptive capacity to a 1.5°C warmer world varies markedly for individual sectors and across  
38 sectors such as water supply, public health, infrastructure, ecosystems and food supply. For example,  
39 density and risk exposure, infrastructure vulnerability and resilience, governance and institutional  
40 capacity all drive different impacts across a range of human settlement types (Dasgupta et al., 2014;  
41 Revi et al., 2014; Rosenzweig et al., 2018). Additionally, the adaptive capacity of communities and  
42 human settlements in both rural and urban areas, especially in highly populated regions, raises equity,  
43 social justice and sustainable development issues. Vulnerabilities due to gender, age, level of  
44 education and culture act as compounding factors (Arora-Jonsson, 2011; Cardona et al., 2012;  
45 Resurrección, 2013; Olsson et al., 2014; Vincent et al., 2014).

### 46 47 48 *1.3.3 Uncertainty and non-linearity of impacts*

49  
50 Uncertainties in projections of future climate change and impacts come from a variety of different  
51 sources, including the assumptions made regarding future emission pathways (Moss et al., 2010), the  
52 inherent limitations and assumptions of the climate models used for the projections, including  
53 limitations in simulating regional climate variability (James et al., 2017), downscaling and bias-

1 correction methods (Ekström et al., 2015), and in impact models (e.g., Asseng et al., 2013). The  
2 evolution of climate change also affects uncertainty with respect to impacts. For example, the impacts  
3 of overshooting 1.5°C and stabilization at a later stage, compared to stabilization at 1.5°C without  
4 overshoot may differ in magnitude (Schleussner et al., 2016).

5  
6 AR5 IPCC (2013b) and World Bank (2013) underscored the non-linearity of risks and impacts as  
7 temperature rises from 2°C to 4°C of warming, particularly in relation to water availability, heat  
8 extremes, bleaching of coral reefs, and more. Recent studies (Schleussner et al., 2016; James et al.,  
9 2017; King et al., 2018) assess the impacts of 1.5°C versus 2°C warming, with the same message of  
10 non-linearity. The resilience of ecosystems, meaning their ability either to resist change or to recover  
11 after a disturbance, may change, and often decline, in a non-linear way. An example are reef  
12 ecosystems, with some studies suggesting that reefs will change, rather than disappear entirely, and  
13 particular species showing greater tolerance to coral bleaching than others (Pörtner et al., 2014). A  
14 key issue is therefore whether ecosystems such as coral reefs survive an overshoot scenario, and to  
15 what extent would they be able to recover after stabilization at 1.5°C or higher levels of warming (see  
16 Box 3.4).

## 17 18 19 **1.4 Strengthening the global response**

20  
21 This section frames the implementation options, enabling conditions (discussed further in Cross-  
22 Chapter Box 3 on feasibility in this Chapter), capacities and types of knowledge and their availability  
23 (Blicharska et al., 2017) that can allow institutions, communities and societies to respond to the 1.5°C  
24 challenge in the context of sustainable development and the Sustainable Development Goals (SDGs).  
25 It also addresses other relevant international agreements such as the Sendai Framework for Disaster  
26 Risk Reduction. Equity and ethics are recognised as issues of importance in reducing vulnerability  
27 and eradicating poverty.

28  
29 The connection between the enabling conditions for limiting global warming to 1.5°C and the  
30 ambitions of the SDGs are complex across scale and multifaceted (Chapter 5). Climate mitigation-  
31 adaptation linkages, including synergies and trade-offs, are important when considering opportunities  
32 and threats for sustainable development. The IPCC AR5 acknowledged that ‘adaptation and  
33 mitigation have the potential to both contribute to and impede sustainable development, and  
34 sustainable development strategies and choices have the potential to both contribute to and impede  
35 climate change responses’ (Denton et al., 2014). Climate mitigation and adaptation measures and  
36 actions can reflect and enforce specific patterns of development and governance that differ amongst  
37 the world’s regions (Gouldson et al., 2015; Termeer et al., 2017). The role of limited adaptation and  
38 mitigation capacity, limits to adaptation and mitigation, and conditions of mal-adaptation and mal-  
39 mitigation are assessed in this report (Chapters 4 and 5).

### 40 41 42 **1.4.1 Classifying Response Options**

43  
44 Key broad categories of responses to the climate change problem are framed here. **Mitigation** refers  
45 to efforts to reduce or prevent the emission of greenhouse gases, or to enhance the absorption of gases  
46 already emitted, thus limiting the magnitude of future warming (IPCC, 2014c). Mitigation requires the  
47 use of new technologies, clean energy sources, reduced deforestation, improved sustainable  
48 agricultural methods, and changes in individual and collective behaviour. Many of these may provide  
49 substantial co-benefits for air quality, biodiversity and sustainable development. Mal-mitigation  
50 includes changes that could reduce emissions in the short-term but could lock in technology choices  
51 or practices that include significant trade-offs for effectiveness of future adaptation and other forms of  
52 mitigation (Chapters 2 and 4).

1 **Carbon dioxide removal** (CDR) or ‘negative emissions’ activities are considered a distinct type of  
2 mitigation. While most types of mitigation focus on reducing the amount of carbon dioxide or  
3 greenhouse gases emitted, CDR aims to reduce concentrations already in the atmosphere.  
4 Technologies for CDR are mostly in their infancy despite their importance to ambitious climate  
5 change mitigation pathways (Minx et al., 2017). Although some CDR activities such as reforestation  
6 and ecosystem restoration are well understood, the feasibility of massive-scale deployment of many  
7 CDR technologies remains an open question (IPCC, 2014d; Leung et al., 2014) (Chapters 2 and 4).  
8 Technologies for the active removal of other greenhouse gases, such as methane, are even less  
9 developed, and are briefly discussed in Chapter 4.

10  
11 Climate change **adaptation** refers to the actions taken to manage the impacts of climate change  
12 (IPCC, 2014e). The aim is to reduce vulnerability and exposure to the harmful effects of climate  
13 change (e.g. sea-level rise, more intense extreme weather events or food insecurity). It also includes  
14 exploring the potential beneficial opportunities associated with climate change (for example, longer  
15 growing seasons or increased yields in some regions). Different adaptation-pathways can be  
16 undertaken. Adaptation can be incremental, or transformational, meaning fundamental attributes of  
17 the system are changed (Chapter 3 and 4). There can be limits to ecosystem-based adaptation or the  
18 ability of humans to adapt (Chapter 4). If there is no possibility for adaptive actions that can be  
19 applied to avoid an intolerable risk, these are referred to as hard adaptation limits, while soft  
20 adaptation limits are identified when there are currently no options to avoid intolerable risks, but they  
21 are theoretically possible (Chapter 3 and 4). While climate change is a global issue, impacts are  
22 experienced locally. Cities and municipalities are at the frontline of adaptation (Rosenzweig et al.,  
23 2018), focusing on reducing and managing disaster risks due to extreme and slow-onset weather and  
24 climate events, installing flood and drought early warning systems, and improving water storage and  
25 use (Chapters 3 and 4 and Cross-Chapter Box 12 in Chapter 5). Agricultural and rural areas, including  
26 often highly vulnerable remote and indigenous communities, also need to address climate-related  
27 risks by strengthening and making more resilient agricultural and other natural resource extraction  
28 systems.

29  
30 **Remedial measures** are distinct from mitigation or adaptation, as the aim is to temporarily reduce or  
31 offset warming (IPCC, 2012b). One such measure is Solar Radiation Modification (SRM), also  
32 referred to as Solar Radiation Management in the literature, which involves deliberate changes to the  
33 albedo of the Earth system, with the net effect of increasing the amount of solar radiation reflected  
34 from the Earth to reduce the peak temperature from climate change (The Royal Society, 2009; Smith  
35 and Rasch, 2013; Schäfer et al., 2015). It should be noted that while some radiation modification  
36 measures, such as cirrus cloud thinning (Kristjánsson et al., 2016), aim at enhancing outgoing long-  
37 wave radiation, SRM is used in this report to refer to all direct interventions on the planetary radiation  
38 budget. This report does not use the term ‘geo-engineering’ because of inconsistencies in the  
39 literature, which uses this term to cover SRM, CDR or both, whereas this report explicitly  
40 differentiates between CDR and SRM. Large-scale SRM could potentially be used to supplement  
41 mitigation in overshoot scenarios to keep the global mean temperature below 1.5°C and temporarily  
42 reduce the severity of near-term impacts (e.g., MacMartin et al., 2018). The impacts of SRM (both  
43 biophysical and societal), costs, technical feasibility, governance and ethical issues associated need to  
44 be carefully considered (Schäfer et al., 2015; Section 4.3.8 and Cross-Chapter Box 10 in Chapter 4).

#### 45 46 47 **1.4.2 Governance, implementation and policies**

48  
49 A challenge in meeting the enabling conditions of 1.5°C warmer world is the governance capacity of  
50 institutions to develop, implement and evaluate the changes needed within diverse and highly  
51 interlinked global social-ecological systems (Busby, 2016) (Chapter 4). Policy arenas, governance  
52 structures and robust institutions are key enabling conditions for transformative climate action



1 (Chapter 4). It is through governance that justice, ethics and equity within the adaptation-mitigation-  
2 sustainable development nexus can be addressed (Stechow et al., 2016) (Chapter 5).

3  
4 Governance capacity includes a wide range of activities and efforts needed by different actors to  
5 develop coordinated climate mitigation and adaptation strategies in the context of sustainable  
6 development taking into account equity, justice and poverty eradication. Significant governance  
7 challenges include the ability to incorporate multiple stakeholder perspectives in the decision-making  
8 process to reach meaningful and equitable decisions, interactions and coordination between different  
9 levels of government, and the capacity to raise financing and support for both technological and  
10 human resource development. For example, Lövbrand et al. (2017), argue that the voluntary pledges  
11 submitted by states and non-state actors to meet the conditions of the Paris Agreement will need to be  
12 more firmly coordinated, evaluated and upscaled.

13  
14 Barriers for transitioning from climate change mitigation and adaptation planning to practical policy  
15 implementation include finance, information, technology, public attitudes, social values and practices  
16 (Whitmarsh et al., 2011; Corner and Clarke, 2017) and human resource constraints. Institutional  
17 capacity to deploy available knowledge and resources is also needed (Mimura et al., 2014).  
18 Incorporating strong linkages across sectors, devolution of power and resources to sub-national and  
19 local governments with the support of national government and facilitating partnerships among  
20 public, civic, private sectors and higher education institutions (Leal Filho et al., 2018) can help in the  
21 implementation of identified response options (Chapter 4). Implementation challenges of 1.5°C  
22 pathways are larger than for those that are consistent with limiting warming to well below 2°C,  
23 particularly concerning scale and speed of the transition and the distributional impacts on ecosystems  
24 and socio-economic actors. Uncertainties in climate change at different scales and different capacities  
25 to respond combined with the complexities of coupled social and ecological systems point to a need  
26 for diverse and adaptive implementation options within and among different regions involving  
27 different actors. The large regional diversity between highly carbon-invested economies and emerging  
28 economies are important considerations for sustainable development and equity in pursuing efforts to  
29 limit warming to 1.5°C. Key sectors, including energy, food systems, health, and water supply, also  
30 are critical to understanding these connections.

### 33 **Cross-Chapter Box 3: Framing feasibility: Key concepts and conditions for limiting global** 34 **temperature increases to 1.5°C**

35  
36 **Contributing Authors:** William Solecki (US), Anton Cartwright (South Africa), Wolfgang Cramer  
37 (France/Germany), James Ford (UK/Canada), Kejun Jiang (China), Joana Portugal Pereira  
38 (Portugal/UK), Joeri Rogelj (Austria/Belgium), Linda Steg (Netherlands), Henri Waisman (France)

39  
40 This Cross-Chapter Box describes the concept of feasibility in relation to efforts to limit global  
41 warming to 1.5°C in the context of sustainable development and efforts to eradicate poverty and  
42 draws from the understanding of feasibility emerging within the IPCC (IPCC, 2017). Feasibility can  
43 be assessed in different ways, and no single answer exists as to the question of whether it is feasible to  
44 limit warming to 1.5°C. This implies that an assessment of feasibility would go beyond a 'yes' or a  
45 'no'. Rather, feasibility provides a frame to understand the different conditions and potential  
46 responses for implementing adaptation and mitigation pathways, and options compatible with a 1.5°C  
47 warmer world. This report assesses the overall feasibility of a 1.5°C world, and the feasibility of  
48 adaptation and mitigation options compatible with a 1.5°C warmer world in six dimensions:

49  
50 **Geophysical:** What global emission pathways could be consistent with conditions of a 1.5°C warmer  
51 world? What are the physical potentials for adaptation?

1 **Environmental-ecological:** What are the ecosystem services and resources, including geological  
2 storage capacity and related rate of needed land use change, available to promote transformations, and  
3 to what extent are they compatible with enhanced resilience?

4 **Technological:** What technologies are available to support transformation?

5 **Economic:** What economic conditions could support transformation?

6 **Socio-cultural:** What conditions could support transformations in behaviour and lifestyles? To what  
7 extent are the transformations socially acceptable and consistent with equity?

8 **Institutional:** What institutional conditions are in place to support transformations, including multi-  
9 level governance, institutional capacity, and political support?

10  
11 The report starts by assessing which mitigation pathways would lead to a 1.5°C world, which  
12 indicates that rapid and deep deviations from current emission pathways are necessary (Chapter 2). In  
13 the case of adaptation, an assessment of feasibility starts from an evaluation of the risks and impacts  
14 of climate change (Chapter 3). To mitigate and adapt to climate risks, system-wide technical,  
15 institutional and socio-economic transitions would be required, as well as the implementation of a  
16 range of specific mitigation and adaptation options. Chapter 4 applies various indicators categorised  
17 in these six dimensions to assess the feasibility of illustrative examples of relevant mitigation and  
18 adaptation options (Section 4.5.1). Such options and pathways have different effects on sustainable  
19 development, poverty eradication and adaptation capacity (Chapter 5).

20  
21 The six feasibility dimensions interact in complex, and place-specific ways. Synergies and trade-offs  
22 may occur between the feasibility dimensions, and between specific mitigation and adaptation options  
23 (Section 4.5.4). The presence or absence of enabling conditions would affect the options that  
24 comprise feasibility pathways (Section 4.4), and can reduce trade-offs and amplify synergies between  
25 options.

26  
27 Sustainable development, eradicating poverty and reducing inequalities are not only preconditions for  
28 feasible transformations, but the interplay between climate action (both mitigation and adaptation  
29 options) and the development patterns on which they apply may actually enhance the feasibility of  
30 particular options (see Chapter 5).

31  
32 The connections between the feasibility dimensions can be specified across three types of effects  
33 (discussed below). Each of these dimensions presents challenges and opportunities in realizing  
34 conditions consistent with a 1.5°C warmer world.

35  
36 **Systemic effects:** Conditions that have embedded within them system level functions that could  
37 include linear and non-linear connections and feedbacks. For example, the deployment of technology  
38 and large installations (e.g., renewable or low carbon energy mega-projects) depends upon economic  
39 conditions (costs, capacity to mobilize investments for R&D), social or cultural conditions  
40 (acceptability), and institutional conditions (political support; e.g., Sovacool et al., 2015). Case studies  
41 can demonstrate system level interactions and positive or negative feedback effects between the  
42 different conditions (Jacobson et al., 2015; Loftus et al., 2015). This suggests that each set of  
43 conditions and their interactions need to be considered to understand synergies, inequities and  
44 unintended consequences.

45  
46 **Dynamic effects:** Conditions that are highly dynamic and vary over time, especially under potential  
47 conditions of overshoot or no overshoot. Some dimensions might be more time sensitive or sequential  
48 than others (i.e., if conditions are such that it is no longer geophysically feasible to avoid overshooting  
49 1.5°C, the social and institutional feasibility of avoiding overshoot will be no longer relevant). Path  
50 dependencies, risks of legacy locks-ins related to existing infrastructures, and possibilities of  
51 acceleration permitted by cumulative effects like learning-by-doing driving dramatic costs decreases  
52 are all key features to be captured. The effects can play out over various time scales and thus require  
53 understanding the connections between near-term (meaning within the next several years to two

1 decades) and their long-term implications (meaning over the next several decades) when assessing  
2 feasibility conditions.

3  
4 **Spatial effects:** Conditions that are spatially variable and scale dependent, according to context-  
5 specific factors such as regional-scale environmental resource limits and endowment; economic  
6 wealth of local populations; social organisation, cultural beliefs, values and worldviews; spatial  
7 organisation, including conditions of urbanisation; and financial and institutional and governance  
8 capacity. This means that the conditions for achieving the global transformation required for a 1.5°C  
9 world will be heterogeneous and vary according to the specific context. On the other hand, the  
10 satisfaction of these conditions may depend upon global-scale drivers, such as international flows of  
11 finance, technologies or capacities. This points to the need for understanding feasibility to capture the  
12 interplay between the conditions at different scales.

13  
14 With each effect, the interplay between different conditions influences the feasibility of both  
15 pathways (Chapter 2) and options (Chapter 4), which in turn affect the likelihood of limiting warming  
16 to 1.5°C. The complexity of these interplays triggers unavoidable uncertainties, requiring  
17 transformations that remain robust under a range of possible futures that limit warming to 1.5°C.

### 18 19 20 **1.4.3 Transformation, transformation pathways, and transition: evaluating trade-offs and** 21 **synergies between mitigation, adaptation and sustainable development goals**

22  
23 Embedded in the goal of limiting warming to 1.5°C is the opportunity for intentional societal  
24 transformation (see Box 1.1 on the Anthropocene). The form and process of transformation are varied  
25 and multifaceted (Pelling, 2011; O'Brien et al., 2012; O'Brien and Selboe, 2015; Pelling et al., 2015).  
26 Fundamental elements of 1.5°C-related transformation include a decoupling of economic growth from  
27 energy demand and CO<sub>2</sub> emissions, leap-frogging development to new and emerging low-carbon,  
28 zero-carbon and carbon-negative technologies, and synergistically linking climate mitigation and  
29 adaptation to global scale trends (e.g., global trade and urbanization) that will enhance the prospects  
30 for effective climate action, as well as enhanced poverty reduction and greater equity (Tschakert et al.,  
31 2013; Rogelj et al., 2015; Patterson et al., 2017) (Chapters 4 and 5). The connection between  
32 transformative climate action and sustainable development illustrates a complex coupling of systems  
33 that have important spatial and time scale lag effects and implications for process and procedural  
34 equity including intergenerational equity and for non-human species (Cross-Chapter Box 4 in this  
35 Chapter, Chapter 5). Adaptation and mitigation transition pathways highlight the importance of  
36 cultural norms and values, sector specific context, and proximate (i.e. occurrence of an extreme event)  
37 drivers that when acting together enhance the conditions for societal transformation (Solecki et al.,  
38 2017; Rosenzweig et al., 2018) (Chapters 4 and 5).

39  
40 Diversity and flexibility in implementation choices exist for adaptation, mitigation (including carbon  
41 dioxide removal, CDR) and remedial measures (such as solar radiation modification, SRM), and a  
42 potential for trade-offs and synergies between these choices and sustainable development (IPCC,  
43 2014f; Olsson et al., 2014). The responses chosen could act to synergistically enhance mitigation,  
44 adaptation and sustainable development or they may result in trade-offs which positively impact some  
45 aspects and negatively impact others. Climate change is expected to increase the likelihood of not  
46 achieving the Sustainable Development Goals (SDGs), while some strategies limiting warming  
47 towards 1.5°C are expected to significantly lower that risk and provide synergies for climate  
48 adaptation and mitigation (Chapter 5).

49  
50 Dramatic transformations required to achieve the enabling conditions for a 1.5°C warmer world could  
51 impose trade-offs on dimensions of development (IPCC, 2014f; Olsson et al., 2014). Some choices of  
52 adaptation methods also could adversely impact development (Olsson et al., 2014). This report  
53 recognizes the potential for adverse impacts and focuses on finding the synergies between limiting

1 warming, sustainable development, and eradicating poverty, thus highlighting pathways that do not  
2 constrain other goals, such as sustainable development and eradicating poverty.

3  
4 The report is framed to address these multiple goals simultaneously and assesses the conditions to  
5 achieve a cost-effective and socially acceptable solution, rather than addressing these goals piecemeal  
6 (Stechow et al., 2016) (Section 4.5.4 and Chapter 5), although there may be different synergies and  
7 trade-offs between a 2°C (Stechow et al., 2016) and 1.5°C warmer world (Kainuma et al., 2017).  
8 Climate-resilient development pathways (see Cross-Chapter Box 12 in Chapter 5 and Glossary) are  
9 trajectories that strengthen sustainable development, including mitigating and adapting to climate  
10 change and efforts to eradicate poverty while promoting fair and cross-scalar resilience in a changing  
11 climate. They take into account dynamic livelihoods, the multiple dimensions of poverty, structural  
12 inequalities, and equity between and among poor and non-poor people (Olsson et al., 2014). Climate-  
13 resilient development pathways can be considered at different scales, including cities, rural areas,  
14 regions or at global level (Denton et al., 2014; Chapter 5).

#### 17 **Cross-Chapter Box 4: Sustainable Development and the Sustainable Development Goals**

18  
19 **Contributing Authors:** Diana Liverman (US), Mustafa Babiker (Sudan), Purnamita Dasgupta  
20 (India), Riyanti Djanlante (Indonesia), Stephen Humphreys (UK/Ireland), Natalie Mahowald (US),  
21 Yacob Mulugetta (UK/Ethiopia), Virginia Villariño (Argentina), Henri Waisman (France)

22  
23 Sustainable development is most often defined as ‘development that meets the needs of the present  
24 without compromising the ability of future generations to meet their own needs’ (WCED, 1987) and  
25 includes balancing social wellbeing, economic prosperity and environmental protection. The AR5  
26 used this definition and linked it to climate change (Denton et al., 2014). The most significant step  
27 since AR5 is the adoption of the UN Sustainable Development Goals, and the emergence of literature  
28 that links them to climate (von Stechow et al., 2015; Wright et al., 2015; Epstein et al., 2017; Hammill  
29 and Price-Kelly, 2017; Kelman, 2017; Lofts et al., 2017; Maupin, 2017; Gomez-Echeverri, 2018).

30  
31 In September 2015, the UN endorsed a universal agenda – ‘Transforming our World: the 2030  
32 Agenda for Sustainable Development’ – which aims ‘to take the bold and transformative steps which  
33 are urgently needed to shift the world onto a sustainable and resilient path’. Based on a participatory  
34 process, the resolution in support of the 2030 agenda adopted 17 non-legally-binding Sustainable  
35 Development Goals (SDGs) and 169 targets to support people, prosperity, peace, partnerships and the  
36 planet (Kanie and Biermann, 2017).

37  
38 The SDGs expanded efforts to reduce poverty and other deprivations under the UN Millennium  
39 Development Goals (MDGs). There were improvements under the MDGs between 1990 and 2015,  
40 including reducing overall poverty and hunger, reducing infant mortality, and improving access to  
41 drinking water (United Nations, 2015). However, greenhouse gas emissions increased by more than  
42 50% from 1990 to 2015, and 1.6 billion people were still living in multidimensional poverty with  
43 persistent inequalities in 2015 (Alkire et al., 2015).

44  
45 The SDGs raise the ambition for eliminating poverty, hunger, inequality and other societal problems  
46 while protecting the environment. They have been criticised: as too many and too complex, needing  
47 more realistic targets, overly focused on 2030 at the expense of longer term objectives, not embracing  
48 all aspects of sustainable development, and even contradicting each other (Horton, 2014; Death and  
49 Gabay, 2015; Biermann et al., 2017; Weber, 2017; Winkler and Satterthwaite, 2017).

50  
51 Climate change is an integral influence on sustainable development, closely related to the economic,  
52 social and environmental dimensions of the SDGs. The IPCC has woven the concept of sustainable  
53 development into recent assessments, showing how climate change might undermine sustainable

1 development, and the synergies between sustainable development and responses to climate change  
2 (Denton et al., 2014). Climate change is also explicit in the SDGs. SDG13 specifically requires  
3 ‘urgent action to address climate change and its impacts’. The targets include strengthening resilience  
4 and adaptive capacity to climate-related hazards and natural disasters; integrating climate change  
5 measures into national policies, strategies and planning; and improving education, awareness-raising  
6 and human and institutional capacity.

7  
8 Targets also include implementing the commitment undertaken by developed-country parties to the  
9 UNFCCC to the goal of mobilizing jointly \$100 billion annually by 2020 and operationalizing the  
10 Green Climate Fund, as well as promoting mechanisms for raising capacity for effective climate  
11 change-related planning and management in least developed countries and Small Island Developing  
12 States, including focusing on women, youth and local and marginalised communities. SDG13 also  
13 acknowledges that the United Nations Framework Convention on Climate Change (UNFCCC) is the  
14 primary international, intergovernmental forum for negotiating the global response to climate change.

15  
16 Climate change is also mentioned in SDGs beyond SDG13, for example in goal targets 1.5, 2.4, 11.B,  
17 12.8.1 related to poverty, hunger, cities and education respectively. The UNFCCC addresses other  
18 SDGs in commitments to ‘control, reduce or prevent anthropogenic emissions of greenhouse gases  
19 [...] in all relevant sectors, including the energy, transport, industry, agriculture, forestry and waste  
20 management sectors’ (Art4, 1(c)) and to work towards ‘the conservation and enhancement, as  
21 appropriate, of [...] biomass, forests and oceans as well as other terrestrial, coastal and marine  
22 ecosystems’ (Art4, 1(d)). This corresponds to SDGs that seek clean energy for all (Goal 7),  
23 sustainable industry (Goal 9) and cities (Goal 11) and the protection of life on land and below water  
24 (14 and 15).

25  
26 The SDGs and UNFCCC also differ in their time horizons. The SDGs focus primarily on 2030  
27 whereas the Paris Agreement sets out that ‘Parties aim [...] to achieve a balance between  
28 anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of  
29 this century’.

30  
31 The IPCC decision to prepare this report of the impacts of 1.5°C and associated emission pathways  
32 explicitly asked for the assessment to be in the context of sustainable development and efforts to  
33 eradicate poverty. Chapter 1 frames the interaction between sustainable development, poverty  
34 eradication and ethics and equity. Chapter 2 assesses how risks and synergies of individual mitigation  
35 measures interact with 1.5°C pathways within the context of the SDGs, and how these vary according  
36 to the mix of measures in alternative mitigation portfolios (Section 2.5). Chapter 3 examines the  
37 impacts of 1.5°C global warming on natural and human systems with comparison to 2°C and provides  
38 the basis for considering the interactions of climate change with sustainable development in  
39 Chapter 5. Chapter 4 analyses strategies for strengthening the response to climate change, many of  
40 which interact with sustainable development. Chapter 5 takes sustainable development, eradicating  
41 poverty and reducing inequalities as its focal point for the analysis of pathways to 1.5°C, and  
42 discusses explicitly the linkages between achieving SDGs while eradicating poverty and reducing  
43 inequality.



1  
2 **Cross-Chapter Box 4, Figure 1: Climate action is number 13 of the UN Sustainable Development Goals.**  
3  
4

## 5 **1.5 Assessment frameworks and emerging methodologies that integrate climate change** 6 **mitigation and adaptation with sustainable development** 7

8 This report employs information and data that are global in scope and include region-scale analysis. It  
9 also includes syntheses of municipal, sub-national, and national case studies. Global level statistics  
10 including physical and social science data are used, as well as detailed and illustrative case study  
11 material of particular conditions and contexts. The assessment provides the state of knowledge,  
12 including an assessment of confidence and uncertainty. The main timescale of the assessment is the  
13 21st century and the time is separated into the near-, medium-, and long-term. Spatial and temporal  
14 contexts are illustrated throughout including: assessment tools that include dynamic projections of  
15 emission trajectories and the underlying energy and land transformation (Chapter 2); methods for  
16 assessing observed impacts and projected risks in natural and managed ecosystems and at 1.5°C and  
17 higher levels of warming in natural and managed ecosystems and human systems (Chapter 3); assess  
18 the feasibility of mitigation and adaptation options (Chapter 4); and linkages of the Shared  
19 Socioeconomic Pathways (SSPs) and Sustainable Development Goals (SDGs) (Cross-Chapter  
20 Boxes 1 and 4 in this Chapter, Chapter 2 and Chapter 5).  
21  
22

### 23 **1.5.1 Knowledge sources and evidence used in the report** 24

25 This report is based on a comprehensive assessment of documented evidence of the enabling  
26 conditions to pursuing efforts to limit the global average temperature to 1.5°C and adapt to this level  
27 of warming in the overarching context of the Anthropocene (Delanty and Mota, 2017). Two sources  
28 of evidence are used; peer-reviewed scientific literature and ‘grey’ literature in accordance with  
29 procedure on the use of literature in IPCC reports (IPCC, 2013a, Annex 2 to Appendix A), with the  
30 former being the dominant source. Grey literature is largely used on key issues not covered in peer-  
31 reviewed literature.  
32

33 The peer-reviewed literature includes the following sources: 1) knowledge regarding the physical  
34 climate system and human-induced changes, associated impacts, vulnerabilities and adaptation  
35 options, established from work based on empirical evidence, simulations, modelling and scenarios,  
36 with emphasis on new information since the publication of the IPCC AR5 to the cut-off date for this

1 report (15th of May 2018); 2) Humanities and social science theory and knowledge from actual  
2 human experiences of climate change risks and vulnerability in the context of the social-ecological  
3 systems, development, equity, justice, and the role of governance, and from indigenous knowledge  
4 systems; and 3) Mitigation pathways based on climate projections into the future.

5  
6 The grey literature category extends to empirical observations, interviews, and reports from  
7 government, industry, research institutes, conference proceedings and international or other  
8 organisations. Incorporating knowledge from different sources, settings and information channels  
9 while building awareness at various levels will advance decision making and motivate  
10 implementation of context specific responses to 1.5°C warming (Somanathan et al., 2014). The  
11 assessment does not assess non-written evidence and does not use oral evidence, media reports, or  
12 newspaper publications. With important exceptions, such as China, published knowledge from the  
13 most vulnerable parts of the world to climate change is limited (Czerniewicz et al., 2017).

## 16 *1.5.2 Assessment frameworks and methodologies*

### 18 *Climate models and associated simulations*

19  
20 The multiple sources of climate model information used in this assessment are provided in Chapter 2  
21 (Section 2.2) and Chapter 3 (Section 3.2). Results from global simulations, which have also been  
22 assessed in previous IPCC reports and that are conducted as part of the World Climate Research  
23 Programme (WCRP) Coupled Models Inter-comparison Project (CMIP) are used. The IPCC AR4 and  
24 Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation  
25 (SREX) reports were mostly based on simulations from the CMIP3 experiment, while the AR5 was  
26 mostly based on simulations from the CMIP5 experiment. The simulations of the CMIP3 and CMIP5  
27 experiments were found to be very similar (e.g.; Knutti and Sedláček, 2012; Mueller and Seneviratne,  
28 2014). In addition to the CMIP3 and CMIP5 experiments, results from coordinated regional climate  
29 model experiments (e.g.; the Coordinated Regional Climate Downscaling Experiment, CORDEX)  
30 have been assessed, which are available for different regions (Giorgi and Gutowski, 2015). For  
31 instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et  
32 al., 2014; Jacob and Solman, 2017) are newly available for 1.5°C projections. Recently, simulations  
33 from the ‘Half a degree Additional warming, Prognosis and Projected Impacts’ (HAPPI) multi-model  
34 experiment have been performed to specifically assess climate changes at 1.5°C vs 2°C global  
35 warming (Mitchell et al., 2016). The HAPPI protocol consists of coupled land-atmosphere initial  
36 condition ensemble simulations with prescribed sea surface temperatures (SSTs), sea-ice, GHG and  
37 aerosol concentrations, solar and volcanic activity that coincide with three forced climate states:  
38 present-day (2006–2015) (see section 1.2.1), and future (2091–2100) either with 1.5°C or 2°C global  
39 warming (prescribed by modified SSTs).

### 41 *Detection and attribution of change in climate and impacted systems*

42  
43 Formalized scientific methods are available to detect and attribute impacts of greenhouse gas forcing  
44 on observed changes in climate (e.g. Hegerl et al., 2007; Seneviratne et al., 2012; Bindoff et al., 2013)  
45 and impacts of climate change on natural and human systems (e.g. Stone et al., 2013; Hansen and  
46 Cramer, 2015; Hansen et al., 2016). The reader is referred to these sources, as well as to the AR5 for  
47 more background on these methods.

48  
49 Global climate warming has already reached approximately 1°C (see Section 1.2.1) relative to pre-  
50 industrial conditions, and thus ‘climate at 1.5°C global warming’ corresponds to approximately the  
51 addition of only half a degree of warming compared to the present day, comparable to the warming  
52 that has occurred since the 1970s (Bindoff et al., 2013). Methods used in the attribution of observed  
53 changes associate with this recent warming are therefore also applicable to assessments of future

1 changes in climate at 1.5°C warming, especially in cases where no climate model simulations or  
2 analyses are available.

3  
4 Impacts of 1.5°C global warming can be assessed in part from regional and global climate changes  
5 that have already been detected and attributed to human influence (e.g., Schleussner et al., 2017) and  
6 are components of the climate system that are most responsive to current and projected future forcing.  
7 For this reason, when specific projections are missing for 1.5°C global warming, some of the  
8 assessments of climate change provided in Chapter 3 (Section 3.3) build upon joint assessments of a)  
9 changes that were observed and attributed to human influence up to the present, i.e. for 1°C global  
10 warming and b) projections for higher levels of warming (e.g., 2°C, 3°C or 4°C) to assess the changes  
11 at 1.5°C. Such assessments are for transient changes only (see Chapter 3, Section 3.3).

12  
13 Besides quantitative detection and attribution methods, assessments can also be based on indigenous  
14 and local knowledge (see Chapter 4, Box 4.3). While climate observations may not be available to  
15 assess impacts from a scientific perspective, local community knowledge can also indicate actual  
16 impacts (Brinkman et al., 2016; Kabir et al., 2016). The challenge is that a community's perception of  
17 loss due to the impacts of climate change is an area that requires further research (Tschakert et al.,  
18 2017).

### 19 *Costs and benefits analysis*

20  
21  
22 Cost-benefit analyses are common tools used for decision-making, whereby the costs of impacts are  
23 compared to the benefits from different response actions (IPCC, 2014d, e). However, for the case of  
24 climate change, recognising the complex inter-linkages of the Anthropocene, cost-benefit analyses  
25 tools can be difficult to use because of disparate impacts versus costs and complex interconnectivity  
26 within the global social-ecological system (see Box 1.1 and Cross-Chapter Box 5 in Chapter 2). Some  
27 costs are relatively easily quantifiable in monetary terms but not all. Climate change impacts humans'  
28 lives and livelihoods, culture and values and whole ecosystem. It has unpredictable feedback loops  
29 and impacts on other regions, (IPCC, 2014e) giving rise to indirect, secondary, tertiary and  
30 opportunity costs that are typically extremely difficult to quantify. Monetary quantification is further  
31 complicated by the fact that costs and benefits can occur in different regions at very different times,  
32 possibly spanning centuries, while it is extremely difficult if not impossible to meaningfully estimate  
33 discount rates for future costs and benefits. Thus standard cost-benefit analyses become difficult to  
34 justify (IPCC, 2014e; Dietz et al., 2016) and are not used as an assessment tool in this report.

## 35 36 37 **1.6 Confidence, uncertainty and risk**

38  
39 This report relies on the IPCC's uncertainty guidance provided in Mastrandrea et al. (2011), and  
40 sources given therein. Two metrics for qualifying key findings are used:

41  
42 **Confidence:** Five qualifiers are used to express levels of confidence in key findings, ranging from  
43 *very low*, through *low*, *medium*, *high*, to *very high*. The assessment of confidence involves at least two  
44 dimensions, one being the type, quality, amount or internal consistency of individual lines of  
45 evidence, and the second being the level of agreement between different lines of evidence. Very high  
46 confidence findings must either be supported by a high level of agreement across multiple lines of  
47 mutually independent and individually robust lines of evidence or, if only a single line of evidence is  
48 available, by a very high level of understanding underlying that evidence. Findings of low or very low  
49 confidence are presented only if they address a topic of major concern.

50  
51 **Likelihood:** A calibrated language scale is used to communicate assessed probabilities of outcomes,  
52 ranging from *exceptionally unlikely* (<1%), *extremely unlikely* (<5%), *very unlikely* (<10%), *unlikely*  
53 (<33%), *about as likely as not* (33–66%), *likely* (>66%), *very likely* (>90%), *extremely likely* (>95%)



1 to *virtually certain* (>99%). These terms are normally only applied to findings associated with high or  
2 very high confidence. Frequency of occurrence within a model ensemble does not correspond to  
3 actual assessed probability of outcome unless the ensemble is judged to capture and represent the full  
4 range of relevant uncertainties.

5  
6 Three specific challenges arise in the treatment of uncertainty and risk in this report. First, the current  
7 state of the scientific literature on 1.5°C means that findings based on multiple lines of robust  
8 evidence for which quantitative probabilistic results can be expressed may be few, and not the most  
9 policy-relevant. Hence many key findings are expressed using confidence qualifiers alone.

10  
11 Second, many of the most important findings of this report are conditional because they refer to  
12 ambitious mitigation scenarios. Conditional probabilities often depend strongly on how conditions are  
13 specified, such as whether temperature goals are met through early emission reductions, reliance on  
14 negative emissions, or through a low climate response. Whether a certain risk is deemed likely at  
15 1.5°C may therefore depend strongly on how 1.5°C is specified, whereas a statement that a certain  
16 risk may be substantially higher at 2°C relative to 1.5°C may be much more robust.

17  
18 Third, achieving ambitious mitigation goals will require active, goal-directed efforts aiming explicitly  
19 for specific outcomes and incorporating new information as it becomes available (Otto et al., 2015).  
20 This shifts the focus of uncertainty from the climate outcome itself to the level of mitigation effort  
21 that may be required to achieve it. Probabilistic statements about human decisions are always  
22 problematic, but in the context of robust decision-making, many near-term policies that are needed to  
23 keep open the option of achieving 1.5°C may be the same, regardless of the actual probability that the  
24 goal will be met (Knutti et al., 2015).

## 25 26 27 **1.7 Storyline of the report**

28  
29 The storyline of this report (Figure 1.6) includes a set of interconnected components. The report  
30 consists of five chapters, a Technical Summary and a Summary for Policymakers. It also includes a  
31 set of boxes to elucidate specific or cross-cutting themes, as well as Frequently Asked Questions for  
32 each chapter and a Glossary.

33  
34 At a time of unequivocal and rapid global warming, this report emerges from the long-term  
35 temperature goal of the Paris Agreement; strengthening the global response to the threat of climate  
36 change by pursuing efforts to limit warming to 1.5°C through reducing emissions to achieve a balance  
37 between anthropogenic emissions by sources and removals by sinks of greenhouse gases. The  
38 assessment focuses first, in Chapter 1, on how 1.5°C is defined and understood, what is the current  
39 level of warming to date, and the present trajectory of change. The framing presented in Chapter 1  
40 provides the basis through which to understand the enabling conditions of a 1.5°C warmer world and  
41 connections to the SDGs, poverty eradication, and equity and ethics.

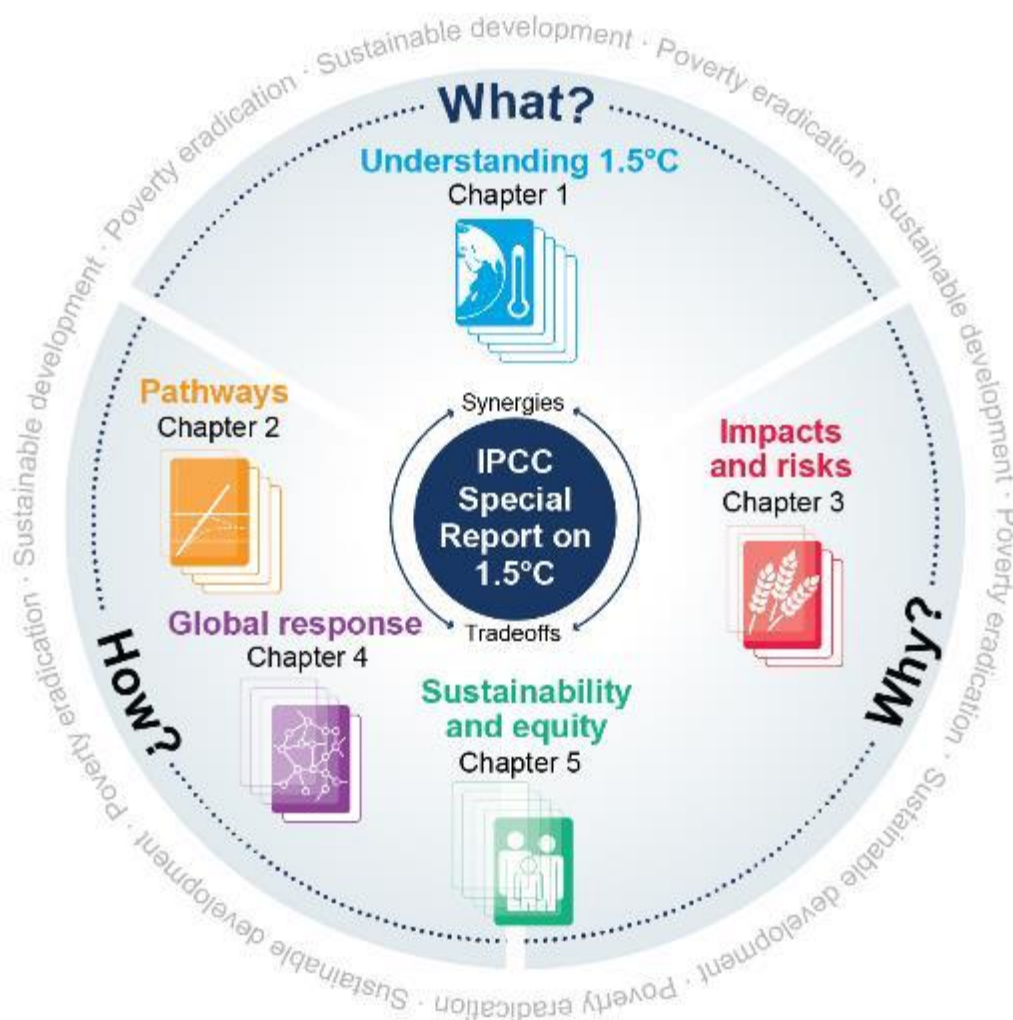
42  
43 In Chapter 2, scenarios of a 1.5°C warmer world and the associated pathways are assessed. The  
44 pathways assessment builds upon the AR5 with a greater emphasis on sustainable development in  
45 mitigation pathways. All pathways begin now, and involve rapid and unprecedented societal  
46 transformation. An important framing device for this report is the recognition that choices that  
47 determine emissions pathways, whether ambitious mitigation or ‘no policy’ scenarios, do not occur  
48 independently of these other changes and are, in fact, highly interdependent.

49  
50 Projected impacts that emerge in a 1.5°C warmer world and beyond are dominant narrative threads of  
51 the report and are assessed in Chapter 3. The chapter focuses on observed and attributable global and  
52 regional climate changes and impacts and vulnerabilities. The projected impacts have diverse and  
53 uneven spatial, temporal, and human, economic, and ecological system-level manifestations. Central

1 to the assessment is the reporting of impacts at 1.5°C and 2°C, potential impacts avoided through  
 2 limiting warming to 1.5°C, and, where possible, adaptation potential and limits to adaptive capacity.

3  
 4 Response options and associated enabling conditions emerge next, in Chapter 4. Attention is directed  
 5 to exploring questions of adaptation and mitigation implementation and integration and  
 6 transformation in a highly interdependent world, with consideration of synergies and trade-offs.  
 7 Emission pathways, in particular, are broken down into policy options and instruments. The role of  
 8 technological choices, institutional capacity and large-scale global scale trends like urbanization and  
 9 changes in ecosystems are assessed.

10  
 11 Chapter 5 covers linkages between achieving the SDGs and a 1.5°C warmer world and turns toward  
 12 identifying opportunities and challenges of transformation. This is assessed within a transition to  
 13 climate-resilient development pathways, and connection between the evolution towards 1.5°C,  
 14 associated impacts, and emission pathways. Positive and negative effects of adaptation and mitigation  
 15 response measures and pathways for a 1.5°C warmer world are examined. Progress along these  
 16 pathways involves inclusive processes, institutional integration, adequate finance and technology, and  
 17 attention to issues of power, values, and inequalities to maximize the benefits of pursuing climate  
 18 stabilisation at 1.5°C and the goals of sustainable development at multiple scales of human and  
 19 natural systems from global, regional, national to local and community levels.



20  
 21  
 22 **Figure 1.6: Schematic of report storyline.**

## 1 Frequently Asked Questions

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

5 *Summary: Climate change represents an urgent and potentially irreversible threat to human societies*  
6 *and the planet. In recognition of this, the overwhelming majority of countries around the world*  
7 *adopted the Paris Agreement in December 2015, the central aim of which includes pursuing efforts to*  
8 *limit global temperature rise to 1.5°C. In doing so, these countries, through the United Nations*  
9 *Framework Convention on Climate Change (UNFCCC) also invited the IPCC to provide a Special*  
10 *Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global*  
11 *greenhouse gas emissions pathways.*

13 At the 21st Conference of the Parties (COP21) in December 2015, 195 nations adopted the Paris  
14 Agreement<sup>2</sup>. The first instrument of its kind, the landmark agreement includes the aim to strengthen  
15 the global response to the threat of climate change by ‘holding the increase in the global average  
16 temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the  
17 temperature increase to 1.5°C above pre-industrial levels’.

19 The first UNFCCC document to mention a limit to global warming of 1.5°C was the Cancun  
20 Agreement, adopted at the sixteenth COP (COP16) in 2010. The Cancun Agreement established a  
21 process to periodically review the ‘adequacy of the long-term global goal (LTGG) in the light of the  
22 ultimate objective of the Convention and the overall progress made towards achieving the LTGG,  
23 including a consideration of the implementation of the commitments under the Convention’. The  
24 definition of LTGG in the Cancun Agreement was ‘to hold the increase in global average temperature  
25 below 2°C above pre-industrial levels’. The agreement also recognised the need to consider  
26 ‘strengthening the long term global goal on the basis of the best available scientific knowledge... to a  
27 global average temperature rise of 1.5°C’.

29 Beginning in 2013 and ending at the COP21 in Paris in 2015, the first review period of the long term  
30 global goal largely consisted of the Structured Expert Dialogue (SED). This was a fact-finding, face-  
31 to-face exchange of views between invited experts and UNFCCC delegates. The final report of the  
32 SED<sup>3</sup> concluded that ‘in some regions and vulnerable ecosystems, high risks are projected even for  
33 warming above 1.5°C’. The SED report also suggested that Parties would profit from restating the  
34 temperature limit of the long-term global goal as a ‘defence line’ or ‘buffer zone’, instead of a  
35 ‘guardrail’ up to which all would be safe, adding that this new understanding would ‘probably also  
36 favour emission pathways that will limit warming to a range of temperatures below 2°C’. Specifically  
37 on strengthening the temperature limit of 2°C, the SED’s key message was: ‘While science on the  
38 1.5°C warming limit is less robust, efforts should be made to push the defence line as low as  
39 possible’. The findings of the SED, in turn, fed into the draft decision adopted at COP21.

41 With the adoption of the Paris Agreement, the UNFCCC invited the IPCC to provide a Special Report  
42 in 2018 on ‘the impacts of global warming of 1.5°C above pre-industrial levels and related global  
43 greenhouse gas emissions pathways’. The request was that the report, known as SR1.5, should not  
44 only assess what a 1.5°C warmer world would look like but also the different pathways by which  
45 global temperature rise could be limited to 1.5°C. In 2016, the IPCC accepted the invitation, adding  
46 that the Special Report would also look at these issues in the context of strengthening the global  
47 response to the threat of climate change, sustainable development and efforts to eradicate poverty.

---

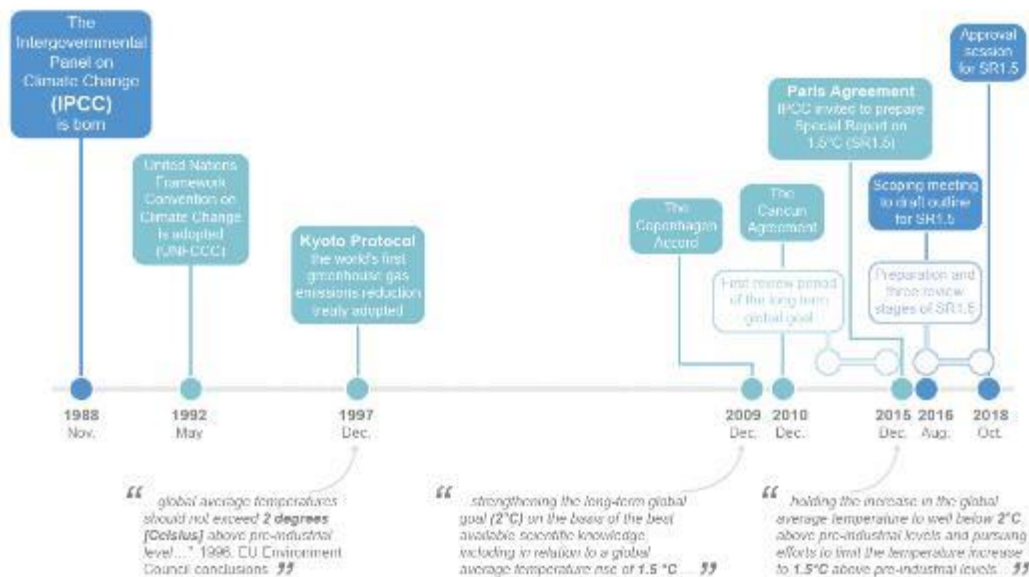
<sup>2</sup> FOOTNOTE: Paris Agreement FCCC/CP/2015/10/Add.1 <https://unfccc.int/documents/9097>

<sup>3</sup> FOOTNOTE: Structured Expert Dialogue (SED) final report FCCC/SB/2015/INF.1  
<https://unfccc.int/documents/8707>

1 The combination of rising exposure to climate change and the fact that there is a limited capacity to  
 2 adapt to its impacts amplifies the risks posed by warming of 1.5°C and 2°C. This is particularly true  
 3 for developing and island countries in the tropics and other vulnerable countries and areas. The risks  
 4 posed by global warming of 1.5°C are greater than for present day conditions but lower than at 2°C.  
 5  
 6

**FAQ1.1: Timeline of 1.5°C**

Milestones in the IPCC's preparation of the Special Report on Global Warming of 1.5°C and some relevant events in the history of international climate negotiations



7  
 8 **FAQ1.1, Figure 1:** A timeline of notable dates in preparing the IPCC Special Report on Global Warming of  
 9 1.5°C (blue) embedded within processes and milestones of the United Nations Framework Convention on  
 10 Climate Change (UNFCCC; grey), including events that may be relevant for discussion of temperature limits.  
 11

**FAQ 1.2: How close are we to 1.5°C?**

***Summary:** Human-induced warming has already reached about 1°C above pre-industrial levels at the time of writing of this Special Report. By the decade 2006–2015, human activity had warmed the world by 0.87°C (±0.12°C) compared pre-industrial times (1850–1900). If the current warming rate continues, the world would reach human-induced global warming of 1.5°C around 2040.*

Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions with a view to ‘holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels’. While the overall intention of strengthening the global response to climate change 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, we need to first be clear about how both terms are defined in this Special Report.

The choice of pre-industrial reference period, along with the method used to calculate global average temperature, can alter scientists’ estimates of historical warming by a couple of tenths of a degree Celsius. Such differences become important in the context of a global temperature limit just half a degree above where we are now. But provided consistent definitions are used, they do not affect our understanding of how human activity is influencing the climate.

In principle, ‘pre-industrial levels’ could refer to any period of time before the start of the industrial revolution. But the number of direct temperature measurements decreases as we go back in time. Defining a ‘pre-industrial’ reference period is, therefore, a compromise between the reliability of the temperature information and how representative it is of truly pre-industrial conditions. Some pre-industrial periods are cooler than others for purely natural reasons. This could be because of spontaneous climate variability or the response of the climate to natural perturbations, such as volcanic eruptions and variations in the sun’s activity. This IPCC Special Report on Global Warming of 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 is the reference period used as an approximation of pre-industrial temperatures in the IPCC Fifth Assessment Report.

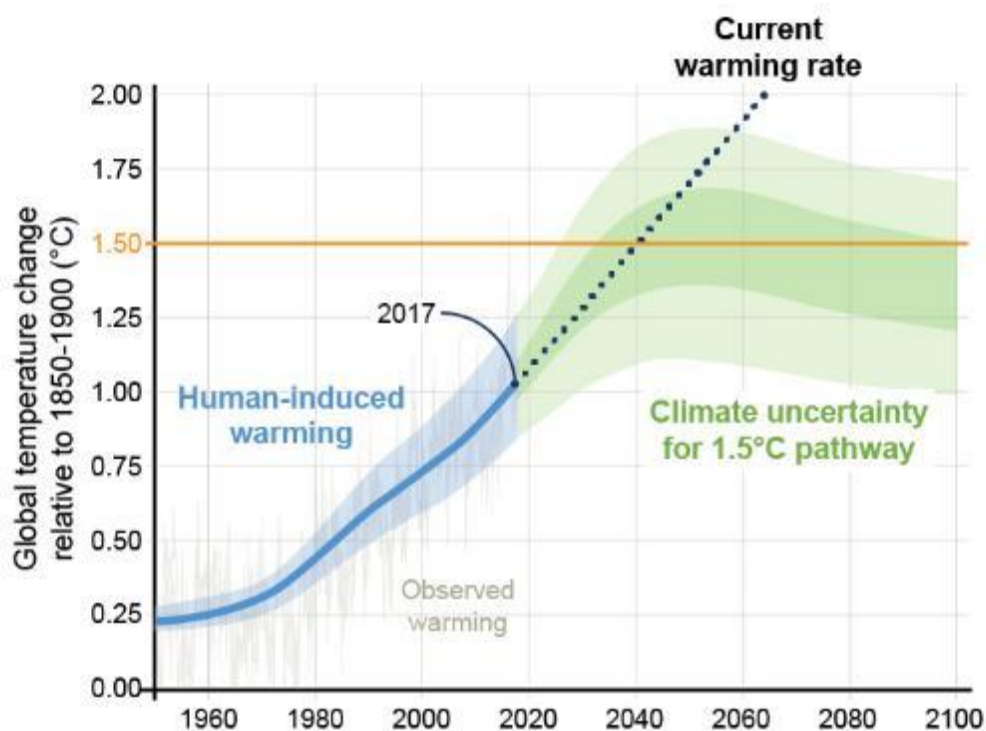
Once scientists have defined ‘pre-industrial’, the next step is to calculate the amount of warming at any given time relative to that reference period. In this report, warming is defined as the increase in the 30-year global average of combined temperature over land and at the ocean surface. The 30-year timespan accounts for the effect of natural variability, which can cause global temperatures to fluctuate from one year to the next. For example, 2015 and 2016 were both affected by a strong El Niño event, which amplified the underlying human-caused warming.

In the decade 2006–2015, warming reached 0.87°C (±0.12°C) relative to 1850–1900, predominantly due to human activity increasing the amount of greenhouse gases in the atmosphere. Given that global temperature is currently rising by 0.2°C (±0.1°C) per decade, human-induced warming reached 1°C above pre-industrial levels around 2017 and, if this pace of warming continues, would reach 1.5°C around 2040.

While the change in global average temperature tells researchers about how the planet as a whole is changing, looking more closely at specific regions, countries and seasons reveals important details. Since the 1970s, most land regions have been warming faster than the global average, for example. This means that warming in many regions has already exceeded 1.5°C above pre-industrial levels. Over a fifth of the global population live in regions that have already experienced warming in at least one season that is greater than 1.5°C above pre-industrial levels.

## FAQ1.2: How close are we to 1.5°C?

Human-induced warming reached approximately 1°C above pre-industrial levels in 2017



1  
2 **FAQ1.2, Figure 1:** Human-induced warming reached approximately 1°C above pre-industrial levels in 2017.  
3 At the present rate, global temperatures would reach 1.5°C around 2040.  
4  
5

1 **References**

- 2  
3 Aaheim, A., T. Wei, and B. Romstad, 2017: Conflicts of economic interests by limiting global warming to +3  
4 °C. *Mitigation and Adaptation Strategies for Global Change*, **22(8)**, 1131-1148, doi:10.1007/s11027-  
5 016-9718-8.
- 6 Adger, W.N. et al., 2014: Human Security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability.*  
7 *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report*  
8 *of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach,  
9 M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S.  
10 Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University  
11 Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.
- 12 AghaKouchak, A., L. Cheng, O. Mazdiyasi, and A. Farahmand, 2014: Global warming and changes in risk of  
13 concurrent climate extremes: Insights from the 2014 California drought. *Geophysical Research Letters*,  
14 **41(24)**, 8847-8852, doi:10.1002/2014GL062308.
- 15 Ajibade, I., 2016: Distributive justice and human rights in climate policy: the long road to Paris. *Journal of*  
16 *Sustainable Development Law and Policy (The)*, **7(2)**, 65, doi:10.4314/j.sdlp.v7i2.4.
- 17 Albert, S. et al., 2017: Heading for the hills: climate-driven community relocations in the Solomon Islands and  
18 Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, 1-12, doi:10.1007/s10113-  
19 017-1256-8.
- 20 Alkire, S., C. Jindra, G. Robles Aguilar, S. Seth, and A. Vaz, 2015: Multidimensional poverty index. *OPHI*  
21 *Briefing 42*.
- 22 Allen, M.R. and T.F. Stocker, 2013: Impact of delay in reducing carbon dioxide emissions. *Nature Climate*  
23 *Change*, **4(1)**, 23-26, doi:10.1038/nclimate2077.
- 24 Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate  
25 pollutants. *Nature Climate Change*, **6(May)**, 1-5, doi:10.1038/nclimate2998.
- 26 Allen, M.R. et al., 2018: A solution to the misrepresentations of CO<sub>2</sub>-equivalent emissions of short-lived climate  
27 pollutants under ambitious mitigation. *npj Climate and Atmospheric Science* (in press).
- 28 Archer, D. and V. Brovkin, 2008: The millennial atmospheric lifetime of anthropogenic CO<sub>2</sub>. *Climatic Change*,  
29 **90(3)**, 283-297, doi:10.1007/s10584-008-9413-1.
- 30 Arora-Jonsson, S., 2011: Virtue and vulnerability: Discourses on women, gender and climate change. *Global*  
31 *Environmental Change*, **21(2)**, 744-751, doi:10.1016/j.gloenvcha.2011.01.005.
- 32 Asseng, S. et al., 2013: Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*,  
33 **3(9)**, 827-832, doi:10.1038/nclimate1916.
- 34 Bäckstrand, K., J.W. Kuyper, B.O. Linnér, and E. Lövbrand, 2017: Non-state actors in global climate  
35 governance: from Copenhagen to Paris and beyond. *Environmental Politics*, **26(4)**, 561-579,  
36 doi:10.1080/09644016.2017.1327485.
- 37 Baker, H.S. et al., 2018: Higher CO<sub>2</sub> concentrations increase extreme event risk in a 1.5°C world. *Nature*  
38 *Climate Change* (in press).
- 39 Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4(12)**, 1103-1108,  
40 doi:10.1038/nclimate2383.
- 41 Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives.  
42 *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.
- 43 Bereiter, B. et al., 2015: Revision of the EPICA Dome C CO<sub>2</sub> record from 800 to 600-kyr before present.  
44 *Geophysical Research Letters*, **42(2)**, 542-549, doi:10.1002/2014GL061957.
- 45 Bethke, I. et al., 2017: Potential volcanic impacts on future climate variability. *Nature Climate Change*, **7(11)**,  
46 799-805, doi:10.1038/nclimate3394.
- 47 Biermann, F., N. Kanie, and R.E. Kim, 2017: Global governance by goal-setting: the novel approach of the UN  
48 Sustainable Development Goals. *Current Opinion in Environmental Sustainability*, **26-27**, 26-31,  
49 doi:10.1016/j.cosust.2017.01.010.
- 50 Biermann, F. et al., 2016: Down to Earth: Contextualizing the Anthropocene. *Global Environmental Change*,  
51 **39**, 341-350, doi:10.1016/j.gloenvcha.2015.11.004.
- 52 Bindoff, N.L. et al., 2007: Observations: Oceanic Climate Change and Sea Level. *Climate Change 2007: The*  
53 *Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the*  
54 *Intergovernmental Panel on Climate Change*.
- 55 Bindoff, N.L. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate*  
56 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment*  
57 *Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M.  
58 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge

- 1 University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 426-488.
- 2 Birkmann, J., T. Welle, W. Solecki, S. Lwasa, and M. Garschagen, 2016: Boost resilience of small and mid-  
3 sized cities. *Nature*, **537(7622)**, 605-608, doi:10.1038/537605a.
- 4 Blicharska, M. et al., 2017: Steps to overcome the North-South divide in research relevant to climate change  
5 policy and practice. *Nature Climate Change*, **7(1)**, 21-27, doi:10.1038/nclimate3163.
- 6 Bodansky, D., J. Brunnée, and L. Rajamani, 2017: *International Climate Change Law*. Oxford University Press,  
7 416 pp.
- 8 Bowerman, N.H.A., D.J. Frame, C. Huntingford, J.A. Lowe, and M.R. Allen, 2011: Cumulative carbon  
9 emissions, emissions floors and short-term rates of warming: implications for policy. *Philosophical  
10 Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369(1934)**,  
11 45-66, doi:10.1098/rsta.2010.0288.
- 12 Bowerman, N.H.A. et al., 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nature  
13 Climate Change*, **3(12)**, 1021-1024, doi:10.1038/nclimate2034.
- 14 Brinkman, T.J. et al., 2016: Arctic communities perceive climate impacts on access as a critical challenge to  
15 availability of subsistence resources. *Climatic Change*, **139(3-4)**, 413-427, doi:10.1007/s10584-016-  
16 1819-6.
- 17 Brondizio, E.S. et al., 2016: Re-conceptualizing the Anthropocene: A call for collaboration. *Global  
18 Environmental Change*, **39**, 318-327, doi:10.1016/j.gloenvcha.2016.02.006.
- 19 Busby, J., 2016: After Paris: Good enough climate governance. *Current History*, **15(777)**, 3-9.
- 20 Caney, S., 2005: Cosmopolitan Justice, Responsibility, and Global Climate Change. *Leiden Journal of  
21 International Law*, **18(04)**, 747-75, doi:10.1017/S0922156505002992.
- 22 Caney, S., 2010: Climate change and the duties of the advantaged. *Critical Review of International Social and  
23 Political Philosophy*, **13(1)**, 203-228, doi:10.1080/13698230903326331.
- 24 Cardona, O.D. et al., 2012: Determinants of Risk: Exposure and Vulnerability. In: *Managing the Risks of  
25 Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working  
26 Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C.B., V.R. Barros,  
27 T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen,  
28 M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and  
29 New York, NY, USA, pp. 65-108.
- 30 Chen, X. et al., 2017: The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate  
31 Change*, **7(7)**, 492-495, doi:10.1038/nclimate3325.
- 32 Christensen, J.H. et al., 2013: Climate Phenomena and their Relevance for Future Regional Climate Change  
33 Supplementary Material. In: *Climate Change 2013: The Physical Science Basis. Contribution of  
34 Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*  
35 [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex,  
36 and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York,  
37 NY, USA, pp. 62.
- 38 Clarke, L.E. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate  
39 Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental  
40 Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K.  
41 Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C.  
42 von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United  
43 Kingdom and New York, NY, USA, pp. 413-510.
- 44 Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate  
45 Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment  
46 Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M.  
47 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. pp. 1029-1136.
- 48 Corner, A. and J. Clarke, 2017: *Talking Climate - From Research to Practice in Public Engagement*. Palgrave  
49 Macmillan, Oxford, UK, 146 pp.
- 50 Cowtan, K. and R.G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent  
51 temperature trends. *Quarterly Journal of the Royal Meteorological Society*, **140(683)**, 1935-1944,  
52 doi:10.1002/qj.2297.
- 53 Cowtan, K. et al., 2015: Robust comparison of climate models with observations using blended land air and  
54 ocean sea surface temperatures. *Geophysical Research Letters*, **42(15)**, 6526-6534,  
55 doi:10.1002/2015GL064888.
- 56 Cramer, W. et al., 2014: Detection and attribution of observed impacts. In: *Climate Change 2014: Impacts,  
57 Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II  
58 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R.  
59 Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada,



- 1 R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White  
2 (eds.]. Cambridge University Press, pp. 979-1037.
- 3 Creutzig, F., 2016: Economic and ecological views on climate change mitigation with bioenergy and negative  
4 emissions. *GCB Bioenergy*, **8(1)**, 4-10, doi:10.1111/gcbb.12235.
- 5 Crutzen, P.J., 2002: Geology of mankind. *Nature*, **415(6867)**, 23, doi:10.1038/415023a.
- 6 Crutzen, P.J. and E.F. Stoermer, 2000: The Anthropocene. *Global Change Newsletter*, **41**, 17-18.
- 7 Czerniewicz, L., S. Goodier, and R. Morrell, 2017: Southern knowledge online? Climate change research  
8 discoverability and communication practices.. *Information, Communication & Society*, **20(3)**, 386-405,  
9 doi:10.1080/1369118X.2016.1168473.
- 10 Dasgupta, P. et al., 2014: Rural areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part*  
11 *A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of*  
12 *the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach,  
13 M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S.  
14 Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.]. Cambridge University  
15 Press, Cambridge, United Kingdom and New York, NY, USA, pp. 613-657.
- 16 Death, C. and C. Gabay, 2015: Doing biopolitics differently? Radical potential in the post-2015 MDG and SDG  
17 debates. *Globalizations*, **12(4)**, 597-612, doi:10.1080/14747731.2015.1033172.
- 18 Delanty, G. and A. Mota, 2017: Governing the Anthropocene. *European Journal of Social Theory*, **20(1)**, 9-38,  
19 doi:10.1177/1368431016668535.
- 20 Denton, F. et al., 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. In:  
21 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.*  
22 *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on*  
23 *Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M.  
24 Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken,  
25 P.R. Mastrandrea, and L.L. White (eds.]. Cambridge University Press, Cambridge, United Kingdom  
26 and New York, NY, USA, pp. 1101-1131.
- 27 Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012: Communication of the Role of Natural Variability in  
28 Future North American Climate. *Nature Climate Change*, **2(11)**, 775-779, doi:10.1038/nclimate1562.
- 29 Deuber, O., G. Luderer, and O. Edenhofer, 2013: Physico-economic evaluation of climate metrics: A conceptual  
30 framework. *Environmental Science & Policy*, **29**, 37-45, doi:10.1016/j.envsci.2013.01.018.
- 31 Dietz, S., B. Groom, and W.A. Pizer, 2016: Weighing the Costs and Benefits of Climate Change to Our  
32 Children. *The Future of Children*, **26(1)**, 133-155.
- 33 Dinah, S., 2008: Equity. In: *The Oxford Handbook of International Environmental Law* [Bodansky, D., J.  
34 Brunnée, and E. Hey (eds.]. Oxford University Press, Oxford, UK.
- 35 Dooley, K., J. Gupta, and A. Patwardhan, 2018: INEA editorial: Achieving 1.5 °C and climate justice.  
36 *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 1-9,  
37 doi:10.1007/s10784-018-9389-x.
- 38 Dryzek, J.S., 2016: Institutions for the Anthropocene: Governance in a Changing Earth System. *British Journal*  
39 *of Political Science*, **46(04)**, 937-956, doi:10.1017/S0007123414000453.
- 40 Duyck, S., S. Jodoin, and A. Johl (eds.), 2018: *Routledge Handbook of Human Rights and Climate Governance*.  
41 Routledge, Abingdon, Oxon, 430 pp.
- 42 Ebi, K.L., L.H. Ziska, and G.W. Yohe, 2016: The shape of impacts to come: lessons and opportunities for  
43 adaptation from uneven increases in global and regional temperatures. *Climatic Change*, **139(3)**, 341-  
44 349, doi:10.1007/s10584-016-1816-9.
- 45 Ebi, K.L. et al., 2014: A new scenario framework for climate change research: Background, process, and future  
46 directions. *Climatic Change*, **122(3)**, 363-372, doi:10.1007/s10584-013-0912-3.
- 47 Eby, M. et al., 2009: Lifetime of anthropogenic climate change: Millennial time scales of potential CO<sub>2</sub> and  
48 surface temperature perturbations. *Journal of Climate*, **22(10)**, 2501-2511,  
49 doi:10.1175/2008JCLI2554.1.
- 50 Ehlert, D. and K. Zickfeld, 2017: What determines the warming commitment after take back cessation of CO<sub>2</sub>  
51 emissions? *Environmental Research Letters*, **12(1)**, doi:10.1088/1748-9326/aa564a.
- 52 Ekström, M., M.R. Grose, and P.H. Whetton, 2015: An appraisal of downscaling methods used in climate  
53 change research. *Wiley Interdisciplinary Reviews: Climate Change*, **6(3)**, 301-319,  
54 doi:10.1002/wcc.339.
- 55 Emori, S. et al., 2018: Risk implications of long-term global climate goals: overall conclusions of the ICA-RUS  
56 project. *Sustainability Science*, **13(2)**, 279-289.
- 57 England, M.H. et al., 2014: Recent intensification of wind-driven circulation in the Pacific and the ongoing  
58 warming hiatus. *Nature Climate Change*, **4(3)**, 222-227, doi:10.1038/nclimate2106.
- 59 Epstein, A.H., and S.L.H. Theuer, 2017: *Sustainable development and climate action: thoughts on an integrated*

- 1 *approach to SDG and climate policy implementation*, 50 pp.
- 2 Etmnan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane,  
3 and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research*  
4 *Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.
- 5 Fazez, I. et al., 2016: Past and future adaptation pathways. *Climate and Development*, **8(1)**, 26-44,  
6 doi:10.1080/17565529.2014.989192.
- 7 Fazez, I. et al., 2018: Community resilience for a 1.5°C world. *Current Opinion in Environmental*  
8 *Sustainability*, **31**, 30-40, doi:10.1016/j.cosust.2017.12.006.
- 9 Field, C.B. et al., 2014: Technical Summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability.*  
10 *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report*  
11 *of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach,  
12 M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S.  
13 Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University  
14 Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.
- 15 Fischer, E.M. and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and  
16 high-temperature extremes. *Nature Climate Change*, **5(6)**, 560-564, doi:10.1038/nclimate2617.
- 17 Fleurbaey, M. et al., 2014: Sustainable Development and Equity. In: *Climate Change 2014: Mitigation of*  
18 *climate change. Contribution of Working Group III to the Fifth Assessment Report of the*  
19 *Intergovernmental Panel on Climate Change* [Edenhofer, O., Pichs-Madruga, Y. Sokona, E. Farahani,  
20 S. Kadner, P.E. K. Seyboth, A. Adler, I. Baum, S. Brunner, and T.Z.J.C.M. B. Kriemann, J.  
21 Savolainen, S. Schlömer, C. von Stechow (eds.)]. Cambridge University Press, Cambridge, Cambridge,  
22 United Kingdom and New York, NY, USA, pp. 283-350.
- 23 Forkel, M. et al., 2016: Enhanced seasonal CO<sub>2</sub> exchange caused by amplified plant productivity in northern  
24 ecosystems. *Science*, **351(6274)**, 696 LP - 699.
- 25 Foster, G. and S. Rahmstorf, 2011: Global temperature evolution 1979-2010. *Environmental Research Letters*,  
26 **6(4)**, 044022, doi:10.1088/1748-9326/6/4/044022.
- 27 Frölicher, T.L. and F. Joos, 2010: Reversible and irreversible impacts of greenhouse gas emissions in multi-  
28 century projections with the NCAR global coupled carbon cycle-climate model. *Climate Dynamics*,  
29 **35(7)**, 1439-1459, doi:10.1007/s00382-009-0727-0.
- 30 Frölicher, T.L., M. Winton, and J.L. Sarmiento, 2014: Continued global warming after CO<sub>2</sub> emissions stoppage.  
31 *Nature Climate Change*, **4(1)**, 40-44, doi:10.1038/nclimate2060.
- 32 Fuglestedt, J. et al., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris  
33 Agreement. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and*  
34 *Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0445.
- 35 Gillett, N.P., V.K. Arora, D. Matthews, and M.R. Allen, 2013: Constraining the ratio of global warming to  
36 cumulative CO<sub>2</sub> emissions using CMIP5 simulations. *Journal of Climate*, **26(18)**, 6844-6858,  
37 doi:10.1175/JCLI-D-12-00476.1.
- 38 Gillett, N.P., V.K. Arora, K. Zickfeld, S.J. Marshall, and W.J. Merryfield, 2011: Ongoing climate change  
39 following a complete cessation of carbon dioxide emissions. *Nature Geoscience*, **4**, 83-87,  
40 doi:10.1038/ngeo1047.
- 41 Giorgi, F. and W.J. Gutowski, 2015: Regional Dynamical Downscaling and the CORDEX Initiative. *Annual*  
42 *Review of Environment and Resources*, **40(1)**, 467-490, doi:10.1146/annurev-environ-102014-021217.
- 43 Gomez-Echeverri, L., 2018: Climate and development: enhancing impact through stronger linkages in the  
44 implementation of the Paris Agreement and the Sustainable Development Goals (SDGs).  
45 *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, **376(2119)**,  
46 20160444, doi:10.1098/rsta.2016.0444.
- 47 Goodwin, P. et al., 2018: Pathways to 1.5 °c and 2 °c warming based on observational and geological  
48 constraints. *Nature Geoscience*, **11(2)**, 102-107, doi:10.1038/s41561-017-0054-8.
- 49 Gouldson, A. et al., 2015: Exploring the economic case for climate action in cities. *Global Environmental*  
50 *Change*, **35**, 93-105, doi:10.1016/j.gloenvcha.2015.07.009.
- 51 Gradstein, F.M., J.G. Ogg, M.D. Schmitz, and G.M. Ogg (eds.), 2012: *The Geologic Time Scale*. Elsevier BV,  
52 Boston, MA, USA, 1144 pp.
- 53 Gregory, J.M. and P.M. Forster, 2008: Transient climate response estimated from radiative forcing and observed  
54 temperature change. *Journal of Geophysical Research Atmospheres*, **113(23)**,  
55 doi:10.1029/2008JD010405.
- 56 Hall, J., G. Fu, and J. Lawry, 2007: Imprecise probabilities of climate change: Aggregation of fuzzy scenarios  
57 and model uncertainties. *Climatic Change*, **81(3-4)**, 265-281, doi:10.1007/s10584-006-9175-6.
- 58 Hammill, B.A. and H. Price-Kelly, 2017: *Using NDCs, NAPs and the SDGs to Advance Climate-Resilient*  
59 *Development*. Cambridge University Press, Cambridge, United Kingdom, 1-10 pp.

- 1 Hansen, G. and W. Cramer, 2015: Global distribution of observed climate change impacts. *Nature Climate*  
2 *Change*, **5(3)**, 182-185, doi:10.1038/nclimate2529.
- 3 Hansen, G., D. Stone, M. Auffhammer, C. Huggel, and W. Cramer, 2016: Linking local impacts to changes in  
4 climate: a guide to attribution. *Regional Environmental Change*, **16(2)**, 527-541, doi:10.1007/s10113-  
5 015-0760-y.
- 6 Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Reviews of Geophysics*,  
7 **48(4)**, RG4004, doi:10.1029/2010RG000345.
- 8 Hansen, J. et al., 2005: Earth's energy imbalance: confirmation and implications.. *Science*, **308(November)**,  
9 1431-1435, doi:10.1126/science.1110252.
- 10 Harlan, S.L. et al., 2015: Climate Justice and Inequality: Insights from Sociology. In: *Climate Change and*  
11 *Society: Sociological Perspectives* [Dunlap, R.E. and R.J. Brulle (eds.)]. Oxford University Press, New  
12 York, NY, USA, pp. 127-163.
- 13 Harrington, C., 2016: The Ends of the World: International Relations and the Anthropocene. *Millennium:*  
14 *Journal of International Studies*, **44(3)**, 478-498, doi:10.1177/0305829816638745.
- 15 Harris, L.M., E.K. Chu, and G. Ziervogel, 2017: Negotiated resilience. *Resilience*, **3293**, 1-19,  
16 doi:10.1080/21693293.2017.1353196.
- 17 Hartmann, D.J. et al., 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical*  
18 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*  
19 *Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K.  
20 Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press,  
21 Cambridge, United Kingdom and New York, NY, USA, pp. 159-254.
- 22 Haustein, K. et al., 2017: A real-time Global Warming Index. *Scientific Reports*, **7(1)**, 15417,  
23 doi:10.1038/s41598-017-14828-5.
- 24 Hawkins, E. et al., 2017: Estimating changes in global temperature since the pre-industrial period. *Bulletin of*  
25 *the American Meteorological Society*, BAMS-D-16-0007.1, doi:10.1175/BAMS-D-16-0007.1.
- 26 Hegerl, G.C. et al., 2007: Understanding and Attributing Climate Change. In: *Climate Change 2007: The*  
27 *Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the*  
28 *Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis,  
29 K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United  
30 Kingdom and New York, NY, USA, pp. 663-745.
- 31 Hienola, A. et al., 2018: The impact of aerosol emissions on the 1.5 °C pathways. *Environmental Research*  
32 *Letters*, **13(4)**, 44011.
- 33 Hoegh-Guldberg, O. et al., 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science*,  
34 **318(5857)**, 1737 LP - 1742, doi:10.1126/science.1152509.
- 35 Holz, C., S. Kartha, and T. Athanasiou, 2017: Fairly sharing 1.5: national fair shares of a 1.5 °C-compliant  
36 global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**,  
37 1-18, doi:10.1007/s10784-017-9371-z.
- 38 Horton, R., 2014: Why the sustainable development goals will fail. *The Lancet*, **383(9936)**, 2196,  
39 doi:10.1016/S0140-6736(14)61046-1.
- 40 Humphreys, S., 2017: Climate, Technology, Justice. In: *Protecting the Environment for Future Generations:*  
41 *Principles and Actors in International Environmental Law*. Erich Schmidt Verlag, Berlin.
- 42 IBA, 2014: *Achieving Justice and Human Rights in an Era of Climate Disruption*. 240 pp.
- 43 IPCC, 2000: Special Report on Emissions Scenarios: A Special Report of Working Group III of the  
44 Intergovernmental Panel on Climate Change. [Nakićenović, N. and R. Swart (eds.)]. 570 pp.
- 45 IPCC, 2012a: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A  
46 Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC).  
47 [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach,  
48 G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press,  
49 Cambridge, United Kingdom and New York, NY, USA, 582 pp.
- 50 IPCC, 2012b: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on  
51 Geoengineering. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, C. Field, V. Barros, T.F. Stocker, Q.  
52 Dahe, J. Minx, K. Mach, G.K. Plattner, S. Schlömer, G. Hansen, and M. Mastrandrea (eds.)]. IPCC  
53 Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam,  
54 Germany, 99 pp.
- 55 IPCC, 2012c: Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance*  
56 *Climate Change Adaptation* [Field, C.B., V.R. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi,  
57 M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)].  
58 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3-21.
- 59 IPCC, 2013a: *Principles Governing IPCC Work*. Intergovernmental Panel on Climate Change (IPCC), Geneva,

- 1 Switzerland, 2 pp.
- 2 IPCC, 2013b: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution*  
3 *of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*  
4 [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex,  
5 and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York,  
6 NY, USA, pp. 33.
- 7 IPCC, 2014a: Climate Change 2014 Synthesis Report. [Core Writing Team, R.K. Pachauri, and L.A. Meyer  
8 (eds.)]. IPCC, Geneva, Switzerland, 1-112 pp.
- 9 IPCC, 2014b: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral  
10 Aspects. , 1132.
- 11 IPCC, 2014c: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the  
12 Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-  
13 Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P.  
14 Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx  
15 (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1454 pp.
- 16 IPCC, 2014d: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change.*  
17 *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on*  
18 *Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A.  
19 Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow,  
20 T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New  
21 York, NY, USA, pp. 1-30.
- 22 IPCC, 2014e: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability.*  
23 *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report*  
24 *of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach,  
25 M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S.  
26 Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University  
27 Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.
- 28 IPCC, 2014f: Summary for Policymakers. In: *Climate Change 2014 Synthesis Report. Contribution of Working*  
29 *Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*  
30 [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. pp. 2-34.
- 31 IPCC, 2017: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Mitigation,  
32 Sustainability and Climate Stabilization Scenarios. [Shukla, P.R., J. Skea, R. Diemen, E. Huntley, M.  
33 Pathak, J. Portugal-Pereira, J. Scull, and R. Slade (eds.)]. IPCC Working Group III Technical Support  
34 Unit, Imperial College London, London, UK, 44 pp.
- 35 Jacob, D. and S. Solman, 2017: IMPACT2C - An introduction. *Climate Services*, **7**, 1-2,  
36 doi:10.1016/j.cliser.2017.07.006.
- 37 Jacobson, M.Z. et al., 2015: 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy  
38 roadmaps for the 50 United States. *Energy Environ. Sci.*, **8(7)**, 2093-2117, doi:10.1039/C5EE01283J.
- 39 James, R., R. Washington, C.F. Schleussner, J. Rogelj, and D. Conway, 2017: Characterizing half-a-degree  
40 difference: a review of methods for identifying regional climate responses to global warming targets.  
41 *Wiley Interdisciplinary Reviews: Climate Change*, **8(2)**, e457--n/a, doi:10.1002/wcc.457.
- 42 Jarvis, A.J., D.T. Leedal, and C.N. Hewitt, 2012: Climate-society feedbacks and the avoidance of dangerous  
43 climate change. *Nature Climate Change*, **2(9)**, 668-671, doi:10.1038/nclimate1586.
- 44 Jenkins, S., R.J. Millar, N. Leach, and M.R. Allen, 2018: Framing Climate Goals in Terms of Cumulative CO<sub>2</sub>-  
45 Forcing-Equivalent Emissions. *Geophysical Research Letters*, **45(6)**, 2795-2804,  
46 doi:10.1002/2017GL076173.
- 47 Johansson, D.J.A., 2012: Economics- and physical-based metrics for comparing greenhouse gases. *Climatic*  
48 *Change*, **110(1-2)**, 123-141, doi:10.1007/s10584-011-0072-2.
- 49 Jones, G.S., P.A. Stott, and N. Christidis, 2013: Attribution of observed historical near-surface temperature  
50 variations to anthropogenic and natural causes using CMIP5 simulations. *Journal of Geophysical*  
51 *Research: Atmospheres*, **118(10)**, 4001-4024, doi:10.1002/jgrd.50239.
- 52 Jones, G.S., P.A. Stott, and J.F.B. Mitchell, 2016: Uncertainties in the attribution of greenhouse gas warming  
53 and implications for climate prediction. *Journal of Geophysical Research: Atmospheres*, **121(12)**,  
54 6969-6992, doi:10.1002/2015JD024337.
- 55 Jones, P., 2016: The reliability of global and hemispheric surface temperature records. *Advances in Atmospheric*  
56 *Sciences*, **33(3)**, 269-282, doi:10.1007/s00376-015-5194-4.
- 57 Kabir, M.I. et al., 2016: Knowledge and perception about climate change and human health: findings from a  
58 baseline survey among vulnerable communities in Bangladesh. *BMC Public Health*, **16(1)**, 266,  
59 doi:10.1186/s12889-016-2930-3.

- 1 Kainuma, M., R. Pandey, T. Masui, and S. Nishioka, 2017: Methodologies for leapfrogging to low carbon and  
2 sustainable development in Asia. *Journal of Renewable and Sustainable Energy*, **9(2)**,  
3 doi:10.1063/1.4978469.
- 4 Kanie, N. and F. Biermann, 2017: Governing through goals: Sustainable development goals as governance  
5 innovation.
- 6 Karl, T.R. et al., 2015: Possible artifacts of data biases in the recent global surface warming hiatus. *Science*,  
7 **348(6242)**, 1469-1472, doi:10.1126/science.aaa5632.
- 8 Karmalkar, A. and R.S. Bradley, 2017: Consequences of Global Warming of 1.5°C and 2°C for Regional  
9 Temperature and Precipitation Changes in the Contiguous United States. *PLOS ONE*, **12(1)**, e0168697,  
10 doi:10.1371/journal.pone.0168697.
- 11 Kelman, I., 2017: Linking disaster risk reduction, climate change, and the sustainable development goals.  
12 *Disaster Prevention and Management: An International Journal*, **26(3)**, 254-258, doi:10.1108/DPM-  
13 02-2017-0043.
- 14 King, A.D., D.J. Karoly, and B.J. Henley, 2017: Australian climate extremes at 1.5°C and 2°C of global  
15 warming. *Nature Climate Change*, **7(6)**, 412-416, doi:10.1038/nclimate3296.
- 16 King, A.D. et al., 2018: Reduced Heat Exposure by Limiting Global Warming to 1.5°C. *Nature Climate Change*  
17 (in press).
- 18 Kirtman, B., A. Adedoyin, and N. Bindoff, 2013: Near-term Climate Change: Projections and Predictability. In:  
19 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*  
20 *Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K.  
21 Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)].  
22 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 953-1028.
- 23 Klein, R.J.T. et al., 2014: Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts,*  
24 *Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II*  
25 *to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R.  
26 Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada,  
27 R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White  
28 (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-  
29 943.
- 30 Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C  
31 world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering*  
32 *Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0461.
- 33 Knox, J.H., 2015: Human Rights Principles and Climate Change. In: *Oxford Handbook of International Climate*  
34 *Change Law* [Carlarne, C., K.R. Gray, and R. Tarasofsky (eds.)]. Oxford University Press, Oxford.
- 35 Knutti, R. and J. Sedláček, 2012: Robustness and uncertainties in the new CMIP5 climate model projections.  
36 *Nature Climate Change*, **3(4)**, 369-373, doi:10.1038/nclimate1716.
- 37 Knutti, R., J. Rogelj, J. Sedláček, and E.M. Fischer, 2015: A scientific critique of the two-degree climate change  
38 target. *Nature Geoscience*, **9(1)**, 13-18, doi:10.1038/ngeo2595.
- 39 Kolstad, C. et al., 2014: Social, Economic, and Ethical Concepts and Methods. In: *Climate Change 2014:*  
40 *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the*  
41 *Inter- governmental Panel on Climate Change* [Edenhofer, O.,  
42 R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P.  
43 Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx  
44 (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207-  
45 282.
- 46 Kopp, R.E. et al., 2016: Temperature-driven global sea-level variability in the Common Era. *Proceedings of the*  
47 *National Academy of Sciences*, **113(11)**, 1-8, doi:10.1073/pnas.1517056113.
- 48 Kosaka, Y. and S.P. Xie, 2013: Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*,  
49 **501(7467)**, 403-407, doi:10.1038/nature12534.
- 50 Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of  
51 tipping points in the climate system. *Proceedings of the National Academy of Sciences*, **106(13)**, 5041-  
52 5046, doi:10.1073/pnas.0809117106.
- 53 Kriegler, E. et al., 2012: The need for and use of socio-economic scenarios for climate change analysis: A new  
54 approach based on shared socio-economic pathways. *Global Environmental Change*, **22(4)**, 807-822,  
55 doi:10.1016/j.gloenvcha.2012.05.005.
- 56 Kriegler, E. et al., 2014: A new scenario framework for climate change research: The concept of shared climate  
57 policy assumptions. *Climatic Change*, **122(3)**, 401-414, doi:10.1007/s10584-013-0971-5.
- 58 Kristjánsson, J.E., M. Helene, and S. Hauke, 2016: The hydrological cycle response to cirrus cloud thinning.  
59 *Geophysical Research Letters*, **42(24)**, 10,807-810,815, doi:10.1002/2015GL066795.

- 1 Lauder, A.R. et al., 2013: Offsetting methane emissions - An alternative to emission equivalence metrics.  
2 *International Journal of Greenhouse Gas Control*, **12**, 419-429, doi:10.1016/j.ijggc.2012.11.028.
- 3 Leach, N.J. et al., 2018: Current level and rate of warming determine emissions budgets under ambitious  
4 mitigation. *Nature Geoscience* (in press).
- 5 Leal Filho, W. et al., 2018: Implementing climate change research at universities: Barriers, potential and  
6 actions. *Journal of Cleaner Production*, **170**, 269-277, doi:10.1016/j.jclepro.2017.09.105.
- 7 Leggett, J. et al., 1992: Emissions scenarios for the IPCC: an update. In: *Climate change 1992: The  
8 Supplementary Report to the IPCC Scientific Assessment* [Houghton, J.T., B.A. Callander, and S.K.  
9 Varney (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,  
10 pp. 69-95.
- 11 Leichenko, R. and J.A. Silva, 2014: Climate change and poverty: Vulnerability, impacts, and alleviation  
12 strategies. *Wiley Interdisciplinary Reviews: Climate Change*, **5(4)**, 539-556, doi:10.1002/wcc.287.
- 13 Leonard, M. et al., 2014: A compound event framework for understanding extreme impacts. *Wiley  
14 Interdisciplinary Reviews: Climate Change*, **5(1)**, 113-128, doi:10.1002/wcc.252.
- 15 Leung, D.Y.C., G. Caramanna, and M.M. Maroto-Valer, 2014: An overview of current status of carbon dioxide  
16 capture and storage technologies. *Renewable and Sustainable Energy Reviews*, **39**, 426-443,  
17 doi:10.1016/j.rser.2014.07.093.
- 18 Lofts, K., S. Shamin, T.S. Zaman, and R. Kibugi, 2017: Brief on Sustainable Development Goal 13 on Taking  
19 Action on Climate Change and Its Impacts: Contributions of International Law, Policy and  
20 Governance., *McGill Journal of Sustainable Development Law*, **11(1)**, 183-192, doi:10.3868/s050-004-  
21 015-0003-8.
- 22 Loftus, P.J., A.M. Cohen, J.C.S. Long, and J.D. Jenkins, 2015: A critical review of global decarbonization  
23 scenarios: What do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change*,  
24 **6(1)**, 93-112, doi:10.1002/wcc.324.
- 25 Lövbrand, E., M. Hjerpe, and B.O. Linnér, 2017: Making climate governance global: how UN climate summitry  
26 comes to matter in a complex climate regime. *Environmental Politics*, **26(4)**, 580-599,  
27 doi:10.1080/09644016.2017.1319019.
- 28 Lowe, J.A. et al., 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental  
29 Research Letters*, **4(1)**, 014012, doi:10.1088/1748-9326/4/1/014012.
- 30 Lüthi, D. et al., 2008: High-resolution carbon dioxide concentration record 650,000-800,000 years before  
31 present. *Nature*, **453(7193)**, 379-382, doi:10.1038/nature06949.
- 32 MacMartin, D.G., K.L. Ricke, and D.W. Keith, 2018: Solar geoengineering as part of an overall strategy for  
33 meeting the 1.5C Paris target. *Philosophical Transactions of the Royal Society of London A:  
34 Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0454.
- 35 Marbà, N. et al., 2015: Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks.  
36 *Journal of Ecology*, **103(2)**, 296-302, doi:10.1111/1365-2745.12370.
- 37 Marcott, S.A., J.D. Shakun, P.U. Clark, and A.C. Mix, 2013: A reconstruction of regional and global  
38 temperature for the past 11,300 years. *Science*, **339(6124)**, 1198-201, doi:10.1126/science.1228026.
- 39 Marsicek, J., B.N. Shuman, P.J. Bartlein, S.L. Shafer, and S. Brewer, 2018: Reconciling divergent trends and  
40 millennial variations in Holocene temperatures. *Nature*, **554**, 92.
- 41 Martius, O., S. Pfahl, and C. Chevalier, 2016: A global quantification of compound precipitation and wind  
42 extremes. *Geophysical Research Letters*, **43(14)**, 7709-7717, doi:10.1002/2016GL070017.
- 43 Masson-Delmotte, V. et al., 2013: Information from Paleoclimate Archives. In: *Climate Change 2013: The  
44 Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the  
45 Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K.  
46 Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press,  
47 Cambridge, UK and New York, NY, USA.
- 48 Mastrandrea, M.D. et al., 2011: The IPCC AR5 guidance note on consistent treatment of uncertainties: a  
49 common approach across the working groups. *Climatic Change*, **108(4)**, 675-691, doi:10.1007/s10584-  
50 011-0178-6.
- 51 Mathesius, S., M. Hofmann, K. Caldeira, and H.J. Schellnhuber, 2015: Long-term response of oceans to CO<sub>2</sub>  
52 removal from the atmosphere. *Nature Climate Change*, **5(12)**, 1107-1113, doi:10.1038/nclimate2729.
- 53 Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.*,  
54 **35(4)**, L04705, doi:10.1029/2007GL032388.
- 55 Matthews, H.D. and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols.  
56 *Nature Climate Change*, **2(5)**, 338-341, doi:10.1038/nclimate1424.
- 57 Matthews, H.D. and S. Solomon, 2013: Irreversible Does Not Mean Unavoidable. *Science*, **340(6131)**, 438-439,  
58 doi:10.1126/science.1236372.
- 59 Matthews, H.D., N.P. Gillett, P. Stott, and K. Zickfeld, 2009: The proportionality of global warming to

- 1 cumulative carbon emissions. *Nature*, **459(7248)**, 829-32, doi:10.1038/nature08047.
- 2 Matthews, T.K.R., R.L. Wilby, and C. Murphy, 2017: Communicating the deadly consequences of global  
3 warming for human heat stress. *Proceedings of the National Academy of Sciences*, **114(15)**, 3861-3866,  
4 doi:10.1073/pnas.1617526114.
- 5 Maupin, A., 2017: The SDG13 to combat climate change: an opportunity for Africa to become a trailblazer?  
6 *African Geographical Review*, **36(2)**, 131-145, doi:10.1080/19376812.2016.1171156.
- 7 Mauritsen, T. and R. Pincus, 2017: Committed warming inferred from observations. *Nature Climate Change*,  
8 **2(July)**, 1-5, doi:10.1038/nclimate3357.
- 9 Medhaug, I., M.B. Stolpe, E.M. Fischer, and R. Knutti, 2017: Reconciling controversies about the 'global  
10 warming hiatus'. *Nature*, **545(7652)**, 41-47, doi:10.1038/nature22315.
- 11 Meehl, G.A. et al., 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis.*  
12 *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on*  
13 *Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor,  
14 and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp.  
15 747-845.
- 16 Millar, R.J., Z.R. Nicholls, P. Friedlingstein, and M.R. Allen, 2017a: A modified impulse-response  
17 representation of the global near-surface air temperature and atmospheric concentration response to  
18 carbon dioxide emissions. *Atmospheric Chemistry and Physics*, **17(11)**, 7213-7228, doi:10.5194/acp-  
19 17-7213-2017.
- 20 Millar, R.J. et al., 2017b: Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature*  
21 *Geoscience*, **10(10)**, 741-747, doi:10.1038/NNGEO3031.
- 22 Mimura, N. et al., 2014: Adaptation planning and implementation. In: *Climate Change 2014: Impacts,*  
23 *Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II*  
24 *to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R.  
25 Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada,  
26 R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White  
27 (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 869-898.
- 28 Minx, J.C., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative  
29 emissions. *Environmental Research Letters*, **12(3)**, doi:10.1088/1748-9326/aa5ee5.
- 30 Mitchell, D. et al., 2016: Realizing the impacts of a 1.5°C warmer world. *Nature Climate Change*, **6(8)**, 735-  
31 737, doi:10.1038/nclimate3055.
- 32 Mitchell, D. et al., 2017: Half a degree Additional warming, Projections, Prognosis and Impacts (HAPPI):  
33 Background and Experimental Design. *Geoscientific Model Development*, **10**, 571-583,  
34 doi:10.5194/gmd-10-571-2017.
- 35 Miyan, M.A., 2015: Droughts in Asian Least Developed Countries: Vulnerability and sustainability. *Weather*  
36 *and Climate Extremes*, **7**, 8-23, doi:10.1016/J.WACE.2014.06.003.
- 37 Morice, C.P., J.J. Kennedy, N.A. Rayner, and P.D. Jones, 2012: Quantifying uncertainties in global and regional  
38 temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of*  
39 *Geophysical Research Atmospheres*, **117(8)**, doi:10.1029/2011JD017187.
- 40 Morita, T. et al., 2001: Greenhouse Gas Emission Mitigation Scenarios and Implications. In: *Climate Change*  
41 *2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the*  
42 *Intergovernmental Panel on Climate Change* [Metz, B., O. Davidson, R. Swart, and J. Pan (eds.)].  
43 Cambridge University Press, Cambridge, pp. 115-164.
- 44 Moss, R.H. et al., 2010: The next generation of scenarios for climate change research and assessment. *Nature*,  
45 **463(7282)**, 747-756, doi:10.1038/nature08823.
- 46 Mueller, B. and S.I. Seneviratne, 2014: Systematic land climate and evapotranspiration biases in CMIP5  
47 simulations. *Geophysical Research Letters*, **41(1)**, 128-134, doi:10.1002/2013GL058055.
- 48 Myhre, G. et al., 2013: Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical*  
49 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*  
50 *Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K.  
51 Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press,  
52 Cambridge, United Kingdom and New York, NY, USA, pp. 658-740.
- 53 Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic  
54 emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709-2720,  
55 doi:10.5194/acp-17-2709-2017.
- 56 Mysiak, J., S. Surminski, A. Thieken, R. Mechler, and J. Aerts, 2016: Brief communication: Sendai framework  
57 for disaster risk reduction - Success or warning sign for Paris? *Natural Hazards and Earth System*  
58 *Sciences*, **16(10)**, 2189-2193, doi:10.5194/nhess-16-2189-2016.
- 59 O'Brien, K. and E. Selboe, 2015: Social transformation. In: *The Adaptive Challenge of Climate Change*

- 1 [O'Brien, K. and E. Selboe (eds.)]. Cambridge University Press, Cambridge, UK, pp. 311-324.
- 2 O'Brien, K. et al., 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events*  
3 *and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of*  
4 *the Intergovernmental Panel on Climate Change (IPCC)* [Field, C.B., V. Barros, T.F. Stocker, D. Qin,  
5 D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M.  
6 Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,  
7 pp. 437-486.
- 8 OECD, 2016: *The OECD supporting action on climate change*. Organisation for Economic Co-operation and  
9 Development (OECD), Paris, France, 18 pp.
- 10 OHCHR, 2009: *Report of the Office of the United Nations High Commissioner for Human Rights on the*  
11 *relationship between climate change and human rights*. A/HRC/10/61, 32 pp.
- 12 OHCHR, 2015: *Understanding Human Rights and Climate Change*. Office of the United Nations High  
13 Commissioner for Human Rights (OHCHR), 28 pp.
- 14 OHCHR, 2017: *Analytical study on the relationship between climate change and the full and effective*  
15 *enjoyment of the rights of the child*. UN Doc. A/HRC/35/13, 18 pp.
- 16 Okereke, C., 2010: Climate justice and the international regime. *Wiley Interdisciplinary Reviews: Climate*  
17 *Change*, **1(3)**, 462-474, doi:10.1002/wcc.52.
- 18 Oliver, T.H. and M.D. Morecroft, 2014: Interactions between climate change and land use change on  
19 biodiversity: attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate*  
20 *Change*, **5(3)**, 317-335, doi:10.1002/wcc.271.
- 21 Olsson, L. et al., 2014: Livelihoods and poverty. In: *Climate Change 2014: Impacts, Adaptation, and*  
22 *Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth*  
23 *Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J.  
24 Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C.  
25 Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)].  
26 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 798-832.
- 27 O'Neill, B.C. et al., 2014: A new scenario framework for climate change research: The concept of shared  
28 socioeconomic pathways. *Climatic Change*, **122(3)**, 387-400, doi:10.1007/s10584-013-0905-2.
- 29 Otto, F.E.L., D.J. Frame, A. Otto, and M.R. Allen, 2015: Embracing uncertainty in climate change policy.  
30 *Nature Climate Change*, **5(August)**, 1-5, doi:10.1038/nclimate2716.
- 31 Otto, F.E.L., R.B. Skeie, J.S. Fuglestedt, T. Berntsen, and M.R. Allen, 2017: Assigning historic responsibility  
32 for extreme weather events. *Nature Climate Change*, **7(11)**, 757-759, doi:10.1038/nclimate3419.
- 33 Pattberg, P. and F. Zelli (eds.), 2016: *Environmental politics and governance in the anthropocene: Institutions*  
34 *and legitimacy in a complex world*. Routledge, 268 pp.
- 35 Patterson, J. et al., 2017: Exploring the governance and politics of transformations towards sustainability.  
36 *Environmental Innovation and Societal Transitions*, **24**, 1-16, doi:10.1016/j.eist.2016.09.001.
- 37 Pelling, M., 2011: *Adaptation to Climate Change: From Resilience to Transformation*. Routledge, Abingdon,  
38 Oxon, UK and New York, NY, USA, 274 pp.
- 39 Pelling, M., K. O'Brien, and D. Matyas, 2015: Adaptation and transformation. *Climatic Change*, **133(1)**, 113-  
40 127, doi:10.1007/s10584-014-1303-0.
- 41 Pendergrass, A.G., F. Lehner, B.M. Sanderson, and Y. Xu, 2015: Does extreme precipitation intensity depend  
42 on the emissions scenario? *Geophysical Research Letters*, **42(20)**, 8767-8774,  
43 doi:10.1002/2015GL065854.
- 44 Pfleiderer, P., C.F. Schleussner, M. Mengel, and J. Rogelj, 2018: Global mean temperature indicators linked to  
45 warming levels avoiding climate risk. *Environmental Research Letters*.
- 46 Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*,  
47 **42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.
- 48 Porter, J.R. et al., 2014: Food security and food production systems. *Climate Change 2014: Impacts,*  
49 *Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II*  
50 *to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R.  
51 Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada,  
52 R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White  
53 (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-  
54 533.
- 55 Pörtner, H.O. et al., 2014: Ocean systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability.*  
56 *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report*  
57 *of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach,  
58 M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S.  
59 Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University



- 1 Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.
- 2 Rao, S. et al., 2017: Future Air Pollution in the Shared Socio-Economic Pathways. *Global Environmental*  
3 *Change*, **42(January)**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.
- 4 Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective.  
5 *Environment & Urbanization*, **29(1)**, 159-182, doi:10.1177/0956247816677778.
- 6 Reisinger, A. et al., 2012: Implications of alternative metrics for global mitigation costs and greenhouse gas  
7 emissions from agriculture. *Climatic Change*, 1-14, doi:10.1007/s10584-012-0593-3.
- 8 Reisinger, A. et al., 2014: Australasia. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part*  
9 *B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the*  
10 *Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D.  
11 Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma,  
12 E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge  
13 University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.
- 14 Resurrección, B.P., 2013: Persistent women and environment linkages in climate change and sustainable  
15 development agendas. *Women's Studies International Forum*, **40(Supplement C)**, 33-43,  
16 doi:10.1016/j.wsif.2013.03.011.
- 17 Revi, A. et al., 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A:*  
18 *Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the*  
19 *Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D.  
20 Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel,  
21 A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press,  
22 Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.
- 23 Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas  
24 emissions implications: An overview. *Global Environmental Change*, **42**, 153-168,  
25 doi:10.1016/j.gloenvcha.2016.05.009.
- 26 Ribes, A. and L. Terray, 2013: Application of regularised optimal fingerprinting to attribution. Part II:  
27 application to global near-surface temperature. *Climate Dynamics*, **41(11)**, 2837-2853,  
28 doi:10.1007/s00382-013-1736-6.
- 29 Ribes, A., F.W. Zwiers, J.M. Azaïs, and P. Naveau, 2017: A new statistical approach to climate change  
30 detection and attribution. *Climate Dynamics*, **48(1)**, 367-386, doi:10.1007/s00382-016-3079-6.
- 31 Richardson, M., K. Cowtan, and R.J. Millar, 2018: Global temperature definition affects achievement of long-  
32 term climate goals. *Environmental Research Letters*, **13(5)**, 054004.
- 33 Richardson, M., K. Cowtan, E. Hawkins, and M.B. Stolpe, 2016: Reconciled climate response estimates from  
34 climate models and the energy budget of Earth. *Nature Climate Change*, **6**, 931-935.
- 35 Robinson, M. and T. Shine, 2018: Achieving a climate justice pathway to 1.5°C. *Nature Clim. Change* (in  
36 press).
- 37 Rogelj, J., C.F. Schleussner, and W. Hare, 2017: Getting It Right Matters: Temperature Goal Interpretations in  
38 Geoscience Research. *Geophysical Research Letters*, **44(20)**, 10,662-10,665,  
39 doi:10.1002/2017GL075612.
- 40 Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C.  
41 *Nature Climate Change*, **5(6)**, 519-527, doi:10.1038/nclimate2572.
- 42 Rogelj, J. et al., 2016a: Paris Agreement climate proposals need boost to keep warming well below 2°C. *Nature*  
43 *Climate Change*, **534(June)**, 631-639, doi:10.1038/nature18307.
- 44 Rogelj, J. et al., 2016b: Differences between carbon budget estimates unravelled. *Nature Climate Change*, **6(3)**,  
45 245-252, doi:10.1038/nclimate2868.
- 46 Rogelj, J. et al., 2018: Transition pathways towards limiting climate change below 1.5°C. *Nature Climate*  
47 *Change*, **8(4)**, 325-332.
- 48 Rohde, R. et al., 2013: Berkeley Earth Temperature Averaging Process. *Geoinformatics & Geostatistics: An*  
49 *Overview*, **1(2)**, 1-13, doi:10.4172/2327-4581.1000103.
- 50 Rosenbloom, D., 2017: Pathways: An emerging concept for the theory and governance of low-carbon  
51 transitions. *Global Environmental Change*, **43**, 37-50, doi:10.1016/j.gloenvcha.2016.12.011.
- 52 Rosenzweig, C. et al., 2008: Attributing physical and biological impacts to anthropogenic climate change.  
53 *Nature*, **453(7193)**, 353-357, doi:10.1038/nature06937.
- 54 Rosenzweig, C. et al., 2017: Assessing inter-sectoral climate change risks: the role of ISIMIP. *Environmental*  
55 *Research Letters*, **12(1)**, 10301.
- 56 Rosenzweig, C., W. Solecki, P. Romeo-Lankao, M. Shagun, S. Dhakal, and S. Ali Ibrahim (eds.), 2018: *Climate*  
57 *Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*.  
58 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 59 Samset, B.H. et al., 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical*

- 1           *Research Letters*, **45(2)**, 1020-1029, doi:10.1002/2017GL076079.
- 2 Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of  
3 Methane Emission Controls. *Environmental and Resource Economics*, **66(1)**, 45-63,  
4 doi:10.1007/s10640-015-9937-6.
- 5 Savaresi, A., 2016: The Paris Agreement: a new beginning? *Journal of Energy & Natural Resources Law*,  
6 **34(1)**, 16-26, doi:10.1080/02646811.2016.1133983.
- 7 Schäfer, S., M. Lawrence, H. Stelzer, W. Born, and S. Low (eds.), 2015: *The European Transdisciplinary*  
8 *Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere*  
9 *and Reflecting Sunlight away from Earth*. 170 pp.
- 10 Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proceedings of the*  
11 *National Academy of Sciences*, **111(9)**, 3245-3250.
- 12 Schleussner, C.F., P. Pfleiderer, and E.M. Fischer, 2017: In the observational record half a degree matters.  
13 *Nature Climate Change*, **7(7)**, 460-462, doi:10.1038/nclimate3320.
- 14 Schleussner, C.F. et al., 2016: Differential climate impacts for policy relevant limits to global warming: the case  
15 of 1.5°C and 2°C. *Earth System Dynamics*, **7(2)**, 327-351, doi:10.5194/esd-7-327-2016.
- 16 Schroeder, H., M.T. Boykoff, and L. Spiers, 2012: Equity and state representations in climate negotiations.  
17 *Nature Climate Change*, **2**, 834-836, doi:10.1038/nclimate1742.
- 18 Schurer, A.P., M.E. Mann, E. Hawkins, S.F.B. Tett, and G.C. Hegerl, 2017: Importance of the pre-industrial  
19 baseline for likelihood of exceeding Paris goals. *Nature Climate Change*, doi:10.1038/nclimate3345.
- 20 Seneviratne, S.I., M.G. Donat, A.J. Pitman, R. Knutti, and R.L. Wilby, 2016: Allowable CO<sub>2</sub> emissions based  
21 on regional and impact-related climate targets. *Nature*, **529(7587)**, 477-483, doi:10.1038/nature16542.
- 22 Seneviratne, S.I. et al., 2012: Changes in climate extremes and their impacts on the natural physical  
23 environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change*  
24 *Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate*  
25 *Change (IPCC)* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D.  
26 Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge  
27 University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 109-230.
- 28 Settele, J. et al., 2014: Terrestrial and inland water systems. In: *Part A: Global and Sectoral Aspects.*  
29 *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on*  
30 *Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M.  
31 Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken,  
32 P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom  
33 and New York, NY, USA, pp. 271-359.
- 34 Shiferaw, B. et al., 2014: Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan  
35 Africa: Technological, institutional and policy options. *Weather and Climate Extremes*, **3**, 67-79,  
36 doi:10.1016/J.WACE.2014.04.004.
- 37 Shindell, D.T., 2015: The social cost of atmospheric release. *Climatic Change*, **130(2)**, 313-326,  
38 doi:10.1007/s10584-015-1343-0.
- 39 Shindell, D.T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions  
40 consistent with 2C. *Nature Climate Change*, **6**, 503-509.
- 41 Shindell, D.T., J.S. Fuglestedt, and W.J. Collins, 2017: The social cost of methane: theory and applications.  
42 *Faraday Discussions*, **6**, 773, doi:10.1039/C7FD00009J.
- 43 Shine, K.P., J.S. Fuglestedt, K. Hailemariam, and N. Stuber, 2005: Alternatives to the Global Warming  
44 Potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*, **68(3)**,  
45 281-302, doi:10.1007/s10584-005-1146-9.
- 46 Shine, K.P., R.P. Allan, W.J. Collins, and J.S. Fuglestedt, 2015: Metrics for linking emissions of gases and  
47 aerosols to global precipitation changes. *Earth System Dynamics*, **6(2)**, 525-540, doi:10.5194/esd-6-  
48 525-2015.
- 49 Shue, H., 2013: Climate Hope: Implementing the Exit Strategy. *Chicago Journal of International Law*, **13(2)**,  
50 381.
- 51 Shue, H., 2014: *Climate Justice: Vulnerability and Protection*. Oxford University Press, Oxford, UK, 366 pp.
- 52 Shue, H., 2018: Mitigation gambles: uncertainty, urgency and the last gamble possible. *Philosophical*  
53 *Transactions of the Royal Society*, doi:10.1098/rsta.2017.0105.
- 54 Shukla, P.R. and V. Chaturvedi, 2013: Sustainable energy transformations in India under climate policy.  
55 *Sustainable Development*, **21(1)**, 48-59, doi:10.1002/sd.516.
- 56 Simmons, A.J. et al., 2017: A reassessment of temperature variations and trends from global reanalyses and  
57 monthly surface climatological datasets. *Quarterly Journal of the Royal Meteorological Society*,  
58 **143(702)**, 101-119, doi:10.1002/qj.2949.
- 59 Simpson, M. et al., 2016: Decision Analysis for Management of Natural Hazards. *Annual Review of*

- 1 *Environment and Resources*, **41(1)**, 489-516, doi:10.1146/annurev-environ-110615-090011.
- 2 Sitch, S., P.M. Cox, W.J. Collins, and C. Huntingford, 2007: Indirect radiative forcing of climate change  
3 through ozone effects on the land-carbon sink. *Nature*, **448**, 791.
- 4 Skeie, R.B. et al., 2017: Perspective has a strong effect on the calculation of historical contributions to global  
5 warming. *Environmental Research Letters*, **12(2)**, doi:10.1088/1748-9326/aa5b0a.
- 6 Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model.  
7 *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.
- 8 Smith, S.J. and P.J. Rasch, 2013: The long-term policy context for solar radiation management. *Climatic  
9 Change*, **121(3)**, 487-497, doi:10.1007/s10584-012-0577-3.
- 10 Smith, S.J., J. Karas, J. Edmonds, J. Eom, and A. Mizrahi, 2013: Sensitivity of multi-gas climate policy to  
11 emission metrics. *Climatic Change*, **117(4)**, 663-675, doi:10.1007/s10584-012-0565-7.
- 12 Smith, S.M. et al., 2012: Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Climate  
13 Change*, **2(7)**, 535-538, doi:10.1038/nclimate1496.
- 14 Solecki, W., M. Pelling, and M. Garschagen, 2017: Transitions between risk management regimes in cities.  
15 *Ecology and Society*, **22(2)**, art38, doi:10.5751/ES-09102-220238.
- 16 Solomon, S., G.K.G. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon  
17 dioxide emissions.. *Proceedings of the National Academy of Sciences of the United States of America*,  
18 **106(6)**, 1704-9, doi:10.1073/pnas.0812721106.
- 19 Somanathan, E. et al., 2014: National and Sub-national Policies and Institutions. In: *Climate Change 2014:  
20 Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the  
21 Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E.  
22 Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J.  
23 Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University  
24 Press, Cambridge, United Kingdom and New York, NY, USA.
- 25 Sovacool, B.K., B.O. Linnér, and M.E. Goodsite, 2015: The political economy of climate adaptation. *Nature  
26 Climate Change*, **5(7)**, 616-618, doi:10.1038/nclimate2665.
- 27 Stavins, R. et al., 2014: International Cooperation: Agreements and Instruments. In: *Climate Change 2014:  
28 Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the  
29 Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E.  
30 Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J.  
31 Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University  
32 Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1001-1082.
- 33 Stechow, C. et al., 2016: 2°C and the SDGs: United they stand, divided they fall? *Environmental Research  
34 Letters*, **11(3)**, 34022, doi:10.1088/1748-9326/11/3/034022.
- 35 Steffen, W. et al., 2016: Stratigraphic and Earth System approaches to defining the Anthropocene. *Earth's  
36 Future*, **4(8)**, 324-345, doi:10.1002/2016EF000379.
- 37 Sterner, E., D.J.A. Johansson, and C. Azar, 2014: Emission metrics and sea level rise. *Climatic Change*, **127(2)**,  
38 335-351, doi:10.1007/s10584-014-1258-1.
- 39 Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis.  
40 Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on  
41 Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels,  
42 Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom  
43 and New York, NY, USA, pp. 33-115.
- 44 Stone, D. et al., 2013: The challenge to detect and attribute effects of climate change on human and natural  
45 systems. *Climatic Change*, **121(2)**, 381-395, doi:10.1007/s10584-013-0873-6.
- 46 Strefler, J., G. Luderer, T. Aboumahboub, and E. Kriegler, 2014: Economic impacts of alternative greenhouse  
47 gas emission metrics: a model-based assessment. *Climatic Change*, **125(3-4)**, 319-331,  
48 doi:10.1007/s10584-014-1188-y.
- 49 Tàbara, J.D. et al., 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental  
50 Sustainability*, **31**, 120-129, doi:10.1016/j.cosust.2018.01.012.
- 51 Tanaka, K. and B.C. O'Neill, 2018: The Paris Agreement zero-emissions goal is not always consistent with the  
52 1.5°C and 2°C temperature targets. *Nature Climate Change*, **8(4)**, 319-324, doi:10.1038/s41558-018-  
53 0097-x.
- 54 Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bulletin  
55 of the American Meteorological Society*, **93(4)**, 485-498, doi:10.1175/BAMS-D-11-00094.1.
- 56 Termeer, C.J.A.M., A. Dewulf, and G.R. Biesbroek, 2017: Transformational change: governance interventions  
57 for climate change adaptation from a continuous change perspective. *Journal of Environmental  
58 Planning and Management*, **60(4)**, 558-576, doi:10.1080/09640568.2016.1168288.
- 59 The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*. 1-5 pp.

- 1 Tokarska, K.B. and K. Zickfeld, 2015: The effectiveness of net negative carbon dioxide emissions in reversing  
2 anthropogenic climate change. *Env. Res. Lett.*, **10**, 94013, doi:doi:10.1088/1748-9326/10/9/094013.
- 3 Tokarska, K.B. and N.P. Gillett, 2018: Cumulative carbon emissions budgets consistent with 1.5 °C global  
4 warming. *Nature Climate Change*, **8(4)**, 296-299, doi:10.1038/s41558-018-0118-9.
- 5 Tol, R.S.J., T.K. Berntsen, B.C. O'Neill, Fuglestvedt, and P.S. Keith, 2012: A unifying framework for metrics  
6 for aggregating the climate effect of different emissions. *Environmental Research Letters*, **7(4)**, 44006.
- 7 Tschakert, P., B. van Oort, A.L. St. Clair, and A. LaMadrid, 2013: Inequality and transformation analyses: a  
8 complementary lens for addressing vulnerability to climate change. *Climate and Development*, **5(4)**,  
9 340-350, doi:10.1080/17565529.2013.828583.
- 10 Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley*  
11 *Interdisciplinary Reviews: Climate Change*, **8(5)**, e476--n/a, doi:10.1002/wcc.476.
- 12 UNDP, 2016: *Human Development Report 2016: Human Development for Everyone*. 286 pp.
- 13 UNFCCC, 2016: *Aggregate effect of the intended nationally determined contributions: an update*.  
14 FCCC/CP/2016/2, United Nations Framework Convention on Climate Change (UNFCCC), 75 pp.
- 15 UNGA, 2015: *Transforming our world: The 2030 agenda for sustainable development*. A/RES/70/1, United  
16 Nations General Assembly (UNGA), 35 pp.
- 17 United Nations, 2015: *The Millennium Development Goals Report 2015*. 75 pp.
- 18 van Oldenborgh, G.J. et al., 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017.  
19 *Environmental Research Letters*, **12(12)**, 124009.
- 20 van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Climatic Change*,  
21 **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.
- 22 van Vuuren, D.P. et al., 2014: A new scenario framework for Climate Change Research: Scenario matrix  
23 architecture. *Climatic Change*, **122(3)**, 373-386, doi:10.1007/s10584-013-0906-1.
- 24 van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050:  
25 Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social*  
26 *Change*, **98**, 303-323, doi:10.1016/j.techfore.2015.03.005.
- 27 Vautard, R. et al., 2014: The European climate under a 2°C global warming. *Environmental Research Letters*,  
28 **9(3)**, doi:10.1088/1748-9326/9/3/034006.
- 29 Vincent, K.E., P. Tschakert, J. Barnett, M.G. Rivera-Ferre, and A. Woodward, 2014: Cross-chapter box on  
30 gender and climate change. In: *Part A: Global and Sectoral Aspects. Contribution of Working Group II*  
31 *to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R.  
32 Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada,  
33 R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White  
34 (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 105-  
35 107.
- 36 von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability  
37 Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363-394,  
38 doi:10.1146/annurev-environ-021113-095626.
- 39 Vose, R.S. et al., 2012: NOAA's merged land-ocean surface temperature analysis. *Bulletin of the American*  
40 *Meteorological Society*, **93(11)**, 1677-1685, doi:10.1175/BAMS-D-11-00241.1.
- 41 Waters, C.N. et al., 2016: The Anthropocene is functionally and stratigraphically distinct from the Holocene.  
42 *Science*, **351(6269)**, aad2622-aad2622, doi:10.1126/science.aad2622.
- 43 WCED, 1987: *Our Common Future*. World Commission on Environment and Development (WCED), Geneva,  
44 Switzerland, 383 pp.
- 45 Weber, H., 2017: Politics of 'Leaving no one behind': contesting the 2030 Sustainable development goals.  
46 *Globalizations*, **14(3)**, 399-414.
- 47 Whitmarsh, L., S. O'Neill, and I. Lorenzoni (eds.), 2011: *Engaging the Public with Climate Change: Behaviour*  
48 *Change and Communication*. Earthscan, London, UK and Washington, DC, USA, 289 pp.
- 49 Wigley, T.M.L., 2018: The Paris warming targets: emissions requirements and sea level consequences. *Climatic*  
50 *Change*, **147(1-2)**, 31-45, doi:10.1007/s10584-017-2119-5.
- 51 Williams, R.G., V. Roussenov, T.L. Frölicher, and P. Goodwin, 2017: Drivers of Continued Surface Warming  
52 After Cessation of Carbon Emissions. *Geophysical Research Letters*, **44(20)**, 10,633-10,642,  
53 doi:10.1002/2017GL075080.
- 54 Winkler, I.T. and M.L. Satterthwaite, 2017: Leaving no one behind? Persistent inequalities in the SDGs. *The*  
55 *International Journal of Human Rights*, **21(8)**, 1073-1097, doi:10.1080/13642987.2017.1348702.
- 56 Wise, R.M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and  
57 response. *Global Environmental Change*, **28**, 325-336, doi:10.1016/j.gloenvcha.2013.12.002.
- 58 World Bank, 2013: *Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience*. 254  
59 pp.

- 1 Wright, H., S. Huq, and J. Reeves, 2015: Impact of climate change on least developed countries: are the SDGs  
2 possible? IIED Briefing May 2015, 4 pp.
- 3 Xu, Y. and V. Ramanathan, 2017: Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic  
4 climate changes. *Proc. Natl. Acad. Sci.* 1-9, doi:10.1073/pnas.1618481114.
- 5 Zalasiewicz, J. et al., 2017: Making the case for a formal Anthropocene Epoch: an analysis of ongoing critiques.  
6 *Newsletters on Stratigraphy*, **50(2)**, 205-226, doi:10.1127/nos/2017/0385.
- 7 Zickfeld, K., A.H. MacDougall, and H. Damon Matthews, 2016: On the proportionality between global  
8 temperature change and cumulative CO<sub>2</sub> emissions during periods of net negative CO<sub>2</sub> emissions.  
9 *Environmental Research Letters*, **11(5)**, doi:10.1088/1748-9326/11/5/055006.
- 10 Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009: Setting cumulative emissions targets to reduce  
11 the risk of dangerous climate change.. *Proceedings of the National Academy of Sciences of the United*  
12 *States of America*, **106(38)**, 16129-16134, doi:10.1073/pnas.0805800106.
- 13 Zscheischler, J. and S.I. Seneviratne, 2017: Dependence of drivers affects risks associated with compound  
14 events. *Science Advances*, **3(6)**, doi:10.1126/sciadv.1700263.
- 15  
16