

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

Coordinating Lead Authors: Ove Hoegh-Guldberg (Australia), Daniela Jacob (Germany), Michael Taylor (Jamaica)

Lead Authors: Marco Bindi (Italy), Ines Camilloni (Argentina), Arona Diedhiou (Senegal), Riyanti Djalante (Indonesia), Kristie Ebi (United States of America), Francois Engelbrecht (South Africa), Joel Guiot (France), Yasuaki Hijioka (Japan), Shagun Mehrotra (United States of America /India), Antony Payne (United Kingdom), Sonia Seneviratne (Switzerland), Rachel Warren (United Kingdom), Guangsheng Zhou (China)

Contributing Authors: Myles Allen (United Kingdom), Peter Berry (Canada), Kathryn Bowen (Australia), Christopher Boyer (United States of America), Lorenzo Brillì (Italy), Sally Brown (United Kingdom), William Cheung (Canada), Jason Evans (Australia), Hubertus Fisher (Switzerland), Klaus Fraedrich (Germany), Sabine Fuss (Germany), Jean Pierre Gattuso (France), Peter Greve (Germany/Austria), Naota Hanasaki (Japan), Tomoko Hasegawa (Japan), Katie Hayes (Canada), Annette Hirsch (Australia/Switzerland), Chris Jones (United Kingdom), Thomas Jung (Germany), Makku Kanninen (Finland), Gerhard Krinner (France), David Lawrence (United States of America), Tim Lenton (United Kingdom), Natalie Mahowald (United States of America), Kathleen McInnes (Australia), Katrin J. Meissner (Australia), Dann Mitchell (United Kingdom), Alan C. Mix (United States), Dirk Notz (Germany), Leonard Nurse (Barbados), Lennart Olsson (Sweden), Michael Oppenheimer (United States of America), Shlomit Paz (Israel), Mohammad Feisal Rahman (Bangladesh), Carl-Friedrich Schleussner (Germany), Roland Séférian (France), Daniel Scott (Canada), Jana Sillmann (Germany/Norway), Tannecia Stephenson (Jamaica), Mouhamadou B. Sylla (Senegal), Mark Tebboth (United Kingdom), Adelle Thomas (Bahamas), Petra Tschakert (Australia/Austria), Robert Vautard (France), Richard Wartenburger (Germany/Switzerland), Gary Yohe (United States of America), Robert B. Zougmore (Burkina Faso/Mali)

Review Editors: Jose Antonio Marengo (Brazil), Joy Pereira (Malaysia), Boris Sherstyukov (Russian Federation)

Chapter Scientist: Tania Guillén Bolaños (Germany/Nicaragua)

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4

1 **Executive Summary**

3 *Interpreting 1.5°C*

5 **Understanding how the 1.5°C warmer world unfolds is of great importance to physical, chemical,**
6 **biological and human systems upon which humanity depends.** Here we explore the impacts and the
7 associated responses and adaptation options for future warming in the case that the average surface
8 temperature of Earth warms to 1.5°C relative to the Preindustrial Period. Overall, impacts depend on the
9 system affected, with broad differences and confidence between across systems.

11 **There are multiple pathways to a 1.5°C warmer world.** Each involves different patterns of warming and
12 related impacts {3.2.1; 3.3; cross-chapter Box 3.12 on “1.5°C warmer worlds”}. Different pathways may
13 involve a transition through 1.5°C, both short and long-term stabilization (without overshoot), or a temporary
14 rise and fall over decades and centuries (overshoot) {3.2.1, 3.3}. The influence of these different “1.5°C
15 climate” pathways is small for some climate variables (e.g., regional temperature and precipitation
16 extremes), but can be very large for others (e.g., sea level rise) {3.2.1, 3.3, cross-chapter Box 3.12 on “1.5°C
17 warmer worlds”}.

19 **Assessments of impacts of 1.5°C warming are generally based on climate simulations for different**
20 **pathways to 1.5°C.** More data and analyses are available for transient impacts. A more limited number of
21 dedicated climate model simulations are available to assess other pathways. There is very limited data basis
22 to assess changes at climate equilibrium. In some cases, inferences regarding impacts of changes in global
23 warming of 0.5°C can also be drawn from observations based on observed changes. However, impacts can
24 only be partly inferred based on observations because of the presence of non-linear and lag effects for some
25 climate variables (e.g., sea level rise, snow and ice melt) and the fact that the observed record only represents
26 one possible realization of the climate system

28 **A climate characterized by mean global warming of 1.5°C is determined over a climatological period**
29 **that is typically 20–30 years on average.** By definition, a 1.5°C warmer world includes temperatures that
30 are warmer and cooler than 1.5°C across different regions, years and seasons. {3.3.1, 3.3.2, cross-chapter
31 Box 3.12 on “1.5°C warmer worlds”}. Distinguishing between 1.5°C and 2°C is difficult in the short run and
32 the impacts of 1.5°C global warming cannot be determined without some associated degree of uncertainty.

34 *The climate characteristics of a 1.5°C world*

36 **There are systematic differences across regions and timescales.** In particular, terrestrial regions will
37 warm more than oceanic regions over the coming decades (transient climate conditions). Extreme hot days
38 warm faster than mean temperatures across mid-latitude continental regions (e.g., Central Europe, Central
39 North America, Southern Africa) and the coldest days of the year warm more than mean temperature in snow
40 and/or ice-covered regions (e.g., in Arctic land regions, snow-cover mountainous regions). {3.3.1, 3.3.2,
41 cross-chapter Box 3.12 on “1.5°C warmer worlds”}

43 **In some regions and for some models, the rise in extreme temperatures can be more than three times**
44 **larger than the change in global mean surface temperature (GMST).** For instance, climate model
45 projections show, on average, that a 4.5°C warming of the coldest nights over Arctic land with 1.5°C of
46 global warming {3.3.1, 3.3.2}. Single models also project a mean 4.5°C warming of the hottest days in
47 Central Europe and Central North America with a global mean temperature rise of 1.5°C. {3.3.1, 3.3.2,
48 cross-chapter Box 3.12 on “1.5°C warmer worlds”}

1 **Land use is an important driver of regional climate.** Decisions on changes in land use can strongly affect
2 regional climate change through biophysical feedbacks (e.g., changes in land evaporation or surface albedo),
3 potentially affecting regional temperature and precipitation. However, these effects are not considered in the
4 development of the socio-economic pathways in Chapter 2. {3.2.1}

5
6 **We are two thirds of the way to a 1.5°C world,** given that the average global surface temperature in 2017
7 was approximately 1°C warmer than the pre-industrial Period {Chapter 1, 3.3.1}. Consequently, achieving a
8 global mean temperature of 1.5°C requires an additional warming of 0.5°C compared to present. Impacts,
9 however, can only be partly inferred based on observations because of the presence of non-linear and lag
10 effects for some climate variables (e.g., sea level rise, snow and ice melt) and the fact that the observed
11 record only represents one possible realisation of the climate system. {3.2.1, 3.3.3, cross-chapter Box 3.12 on
12 “1.5° warmer worlds”}

13
14 **The impact of 0.5°C of global warming on temperature and precipitation extremes is already**
15 **detectable in the observational record, with the reservations of the preceding paragraph** {3.3.1}.
16 Similarly, analyses of transient climate projections reveal observable differences between 1.5°C and 2°C
17 global warming in terms of mean temperature and extremes, on a global scale and for most land regions
18 {3.3.1, 3.3.2, 3.3.13}. Such studies also reveal detectable differences between 1.5°C and 2°C global warming
19 precipitation extremes in many land regions {3.3.1, 3.3.3, 3.3.13}. For mean precipitation and various
20 drought measures there is substantially lower risk in the Mediterranean region at 1.5°C compared to 2°C.
21 {3.3.4}

22
23 **Projected risks of water availability and extreme hydrological events (flood and drought) at 1.5°C**
24 **global warming would be reduced compared to the risks at 2°C.** Socioeconomic drivers, however, could
25 have greater influence on risks than those associated with the difference between 1.5°C and 2°C global
26 warming (*limited evidence, medium agreement*). Regional projected changes in flood risk are consistent
27 with projected patterns in mean precipitation under a warming scenario of 1.5°C with the largest increases in
28 Asia, the U.S., and Europe.

29
30 **Large storm systems are expected to change with the relatively small amounts of further warming.**
31 Very few studies to date have directly explored the changing attributes of tropical cyclone attributes under
32 1.5°C vs. 2°C of global warming. The differences in of the characteristics tropical cyclones under 1.5°C vs
33 2°C may be small. The most intense (category 4 and 5) cyclones are projected to occur more frequently, with
34 higher peak wind speeds and lower central pressures under 2°C vs 1.5°C of global warming. The
35 accumulated cyclonic energy is projected to increase globally and consistently for the North Atlantic,
36 northwestern Pacific and northeastern Pacific Oceans, but with slight decreases projected for the South
37 Pacific, northern Indian and southern Indian Oceans, under both 1.5°C and 2°C of global warming {3.3.7}.

38
39 **Sea level will continue to rise in both 1.5°C and 2.0°C worlds well beyond the end of the current**
40 **century.** As a result, the difference between these worlds will manifest as a delay as to when a 1.5°C world
41 reaches a particular height above present-day sea-level. Current literature is insufficient to quantify the
42 current difference in sea level between 1.5°C and 2.0°C worlds. Given the in-depth mechanistic
43 understanding sea level rise (thermal expansion, and ice-sheet and glacier melt) sea level rise will be lower in
44 a 1.5°C world (*high confidence*). Paleorecords show that that once melting is triggered such high sea level
45 rise rates (two times larger than the recent rates) will be sustained over many millennia and are likely
46 unstoppable even within a 2°C warming guardrail.

47
48 **The world’s icesheets are melting at high rates with significant millennial scale thresholds in both**
49 **Greenland and Antarctica around 1.5 and 2.0C.** Consequently, a 1.5°C world may also have a

1 significantly reduced probability of a long-term commitment to multi-metre-scale sea level rise.

2
3 **Ocean chemistry is undergoing fundamental changes which may take many millennia to recover from.**

4 Changes in pH, oxygen, and carbonate are creating areas of the ocean where conditions kill oxygenic life
5 (dead zones). Dead zones are increasing exponentially as a result of both climate change and non-climate
6 change drivers (e.g., eutrophication).

7
8 **Sea ice may persist in a 1.5°C world but not at global temperatures of 2°C or higher.** Significant
9 advances have been made in understanding the wide spreads in projections of future Arctic **sea-ice** extent
10 and the inability of models to capture the sensitivity of sea ice to climate forcing apparent from recent
11 observations, nonetheless uncertainty remains substantial. There is a very real possibility that year-round sea
12 ice in the Arctic will persist in a 1.5°C world (such it likely persisted during the previous interglacial
13 periods) and appreciably probability that late-summer ice cover will disappear in warmer worlds.

14
15 *Impacts on natural and human systems of a 1.5°C world*

16
17 **Impacts on natural and human systems are lower at 1.5°C than at 2.0°C.** Impacts are likely to be less
18 1.5°C than at 2.0°C from our understanding of past impacts and the fact that a 1.5°C climate is significantly
19 different from a 2°C climate in terms of temperature extremes on global scale and in many regions {Sections
20 3.3.1 and 3.3.2}. However, global warming of 1.5°C involves a substantial risk to natural and human
21 systems as compared to the present day warming of 1°C. Hence, warming of 1.5°C cannot be considered a
22 ‘safe’ option and requires organisms to adapt (*no evidence*) or shift their biogeographic ranges or biomes
23 (*moderate confidence*) if impacts of climate change are to be reduced or avoided.

24
25 **Natural systems will experience fewer impacts when warming is limited to 1.5°C as opposed to 2.0°C.**
26 Limiting warming to 1.5°C will carry significant benefits (*very likely*) for terrestrial, wetland, coastal, and
27 ocean ecosystems including coral reefs, freshwater systems, and food production systems (i.e., fisheries and
28 aquaculture). Constraining warming to 1.5°C versus 2°C is projected {section 3.4.1} to limit biome shifts by
29 10% rather than 25% towards high latitude and/or altitude on average. Paleorecords show that during the
30 previous interglacial periods (129–11 kyr BP, 10–5 kyr BP, equivalent to a 1.5°C warming), main shifts
31 were higher Arctic and Alpine treeline and reduction of rainforest. Constraining to 1.5°C will bring seasonal
32 events a few days earlier in the spring phenology of plants and animals, decreasing the risk of maladaptation
33 (*likely*) by spring frost in temperate and boreal regions and more generally by climate variability.

34
35 **Local species extirpation risks are much less in a 1.5°C versus a 2°C world.** Climatic range losses in
36 plants, vertebrates and insects are reduced by 50% in a 1.5°C versus 2°C warmer world (*medium confidence*)
37 leading to a higher level of ecosystem service provision, and will be accompanied by reduced risks of other
38 biodiversity related factors such as forest fires, storm damage and the geographic spread of invasive species,
39 pests and diseases. The number of species at risk of commitment to eventual extinction due to climate
40 change would also be *reduced (low confidence)*.

41
42 **Ocean acidification is driving large-scale changes and is amplifying the effects of temperature.** Recent
43 studies have revealed risks to the survival, calcification, growth, development, and abundance of a broad
44 range of taxonomic groups (i.e. from algae to fish) with considerable evidence of predictable trait-based
45 sensitivities. While studies are limited but growing in number, is clear that ocean acidification that is
46 equivalent to 1.5°C will be much less damaging than that at 2°C or more.

47
48 **Soil respiration and then soil carbon storage are reduced with temperatures increase.** This reduction
49 will occur at lower rates a 1.5°C global warming, but is likely to be balanced by enhanced gross primary

1 production due to fertilization effect and higher temperature under higher CO₂ concentration, especially in
2 medium and high latitudes. Nevertheless, historical records show that the soil respiration reduction is higher
3 than the fertilization effect.
4

5 **High latitude regions will see amplified differences in impacts due to warming rates being above the**
6 **global average.** Habitats at high latitudes will see reduced establishment of woody species in tundra areas,
7 faunal hibernation and migration (high confidence) in a 1.5°C versus 2°C world. Restraining global
8 temperatures to 1.5°C will prevent the melting of an estimated 2 million km² of permafrost (high
9 confidence), although the timescale for the release of this thawed carbon is likely to be many centuries.
10

11 **Risks described for natural and managed ecosystems are amplified on drylands as compared to humid**
12 **lands.** A possible tipping point exists in the Mediterranean between 1.5°C and 2°C warming, above which
13 biome experiences changes that are unprecedented in the last 10,000 years (high confidence).
14

15 **Oceans are experiencing unprecedented changes with critical thresholds being reached at 1.5°C and**
16 **above.** In the transition to 1.5°C, changes to water temperatures will drive some species to relocate and
17 novel ecosystems to appear. Other ecosystems are relatively less able to move, however, and will experience
18 high rates of mortality and loss. A large portion of the coral reefs that exist today will disappear as average
19 global surface temperature reaches 1.5°C above pre-industrial levels, for example.
20

21 **Fisheries and aquaculture are already experiencing pressure from ocean warming and acidification,**
22 **and these impacts are projected to get progressively worse under 1.5°C, 2.0°C and higher global**
23 **temperatures.** Marine food sources provide 20% of the nutrition of 3 billion people globally. Fisheries and
24 aquaculture will be negatively affected by relocating stocks, and the increased risk of invasive species and
25 disease. Coastal human communities will experience changes to food, income and livelihoods, affecting food
26 security. Nevertheless, there are clear advantages to restraining ocean warming and acidification to levels
27 consistent with a 1.5°C warmer world, compared to 2°C.
28

29 **The ecosystem services from the ocean are diminished under 1.5°C and greater warming.** The risks of
30 declining ocean productivity, distributional shifts and loss of fisheries, and changing ocean chemistry (e.g.,
31 acidification, hypoxia), however, are lower when warming (and corresponding atmospheric greenhouse gas
32 concentrations) are restrained to 1.5°C above pre-industrial levels.
33

34 **Constraining global warming to 1.5°C compared to 2°C, reduces global water resources stress by an**
35 **estimated 50% (relative to 1980–2009), with particularly large benefits in the Mediterranean.** In food
36 production systems, limiting warming to 1.5°C above preindustrial levels significantly reduces risks to crop
37 production in Sub-Saharan Africa, West Africa, SE Asia, and Central and South America, as compared to
38 2°C of warming. In region with unsustainable agriculture, such as in Middle East, the risk for food
39 production and extreme poverty is already important at 1.5°C global warming.
40

41 **Impacts associated with sea level rise and salinity changes to groundwater or estuaries are critically**
42 **important in sensitive environments such as small islands.** Sea-levels will not stop rising with
43 temperature stabilisation at 1.5°C or 2°C which predicts that salinization, flooding, permanent inundation,
44 storm damage, erosion and impacts on ecosystems will continue to get worse well beyond the end of the
45 century. Over multi-centennial timescales, adaptation remains essential.
46

47 **Natural coastal ecosystems may be cost effective solutions to rising sea levels and intensifying storms**
48 **by protecting coastal regions.** Whilst some coasts will be overwhelmed with sea-level rise or adversely

1 react to warmer temperatures, other natural coasts may be able to respond positively by vertical accretion of
2 sediment or by landward migration of wetlands. Small islands are projected to experience multiple inter-
3 related impacts, but there are considerable knowledge gaps and understanding future impacts and possible
4 responses, especially in the context of aligning wider development needs.

5
6 *Key economic sectors, human health, food production, safety and conflict in a 1.5°C world*

7 **In most cases, warming of 2°C poses greater risks to urban areas than warming of 1.5°C, often**
8 **varying by vulnerability of location (coastal and non-coastal), infrastructure sectors (energy, water,**
9 **transport), and by levels of poverty.** Linear associations between temperature and adverse impacts,
10 including those due to heat waves, floods, droughts, and storms, mean that additional 0.5°C warming
11 enhances risks to cities. Scale and distribution of future impacts depend on the scope and effectiveness of
12 additional adaptation by cities of its vulnerable assets, and people, and on mitigation for risks from further
13 warming.

14
15 **Climate is an important ‘push and pull’ factor influencing the geography and seasonality of tourism**
16 **demand and spending globally** (*very high confidence*). Increasing temperatures will directly impact climate
17 dependant tourism markets, including sun and beach and snow sports tourism, with lesser impact on other
18 tourism markets that are less climate sensitive (*high confidence*). The translation of changes in climate
19 resources for tourism, together with other major drivers of tourism, into projections of tourism demand and
20 spending remains geographically limited.

21
22 **Substantial benefits exist for marine fisheries if the 1.5°C global warming target is achieved.** Similarly,
23 the risks for dependent coastal communities (which number in the hundreds of millions of people) from
24 reduced income, livelihoods, cultural identity, coastal protection, protection from erosion, and health are
25 much lower with 1.5°C of global warming compared to 2°C.

26
27 **Warming of 2°C poses greater risks to human health than warming of 1.5°C, often with complex**
28 **regional patterns, with a few exceptions.** Each additional unit of warming will *very likely* increase heat-
29 related mortality, will *very likely* increase ozone-related mortality if precursor emissions remain the same,
30 and *likely* increase undernutrition.

31
32 **Warmer temperatures are likely to affect the transmission of infectious diseases,** with increases and
33 decreases projected depending on disease (e.g., malaria, dengue, West Nile virus, and Lyme disease), region,
34 and degree of temperature change. The magnitude and pattern of future impacts will *very likely* depend on
35 the extent and effectiveness of additional adaptation and vulnerability reduction, and on mitigation for risks
36 past mid-century.

37
38 **Average global temperatures that extend beyond 1.5°C are likely to increase poverty and disadvantage**
39 **in many populations globally.** By the mid to late of 21st century, climate change is projected to be a
40 **poverty multiplier** that makes poor people poorer and increases poverty head count, and the association of
41 temperature and economic productivity is not linear (*high confidence*). Temperature has a positive and
42 statistically significant effect on outmigration for agricultural-dependent communities (*medium confidence*).

43
44 **Keeping global temperature to 1.5°C will still prove challenging for small island developing states**
45 **(SIDS) which are already facing significant threat from climate change and other stressors at 1°C of**
46 **warming.** At 1.5°C, the compounding impacts from projected climatic changes will be evident across
47 multiple natural and human systems important to SIDS. This will likely contribute to loss of or change in
48 critical ecosystems, freshwater resources and associated livelihoods, economic stability, coastal settlements

1 and infrastructure. There are potential benefits to SIDS from avoided risks at 1.5°C versus 2.0°C, especially
2 when coupled with adaptation efforts. Adaptation, however, needs to be considered in light of sustainable
3 development.

4
5 **Keeping average global warming to 1.5°C is likely to reduce the factors that can contribute to human**
6 **conflict such as extreme events and eroding food and water supplies.** Disaster related displacement is
7 projected to increase over the 21st century, with over 90% of displacement between 2001 to 2015 was related
8 to climate and weather disasters (medium confidence). There is stronger evidence for indirect results in
9 agricultural and over vulnerable settings and for exacerbating ongoing violence, with conflicting results
10 during the relationships between climatic variables and a range of forms of human conflict and violence (low
11 confidence).

12
13 **Globally, the projected impacts on economic growth of 1.5°C of global warming are very similar to**
14 **current impacts under about 1°C of global warming. Under 2°C of global warming, however, lower**
15 **economic growth is projected for many countries, with low-income countries projected to experience**
16 **the greatest losses.** Globally, the impact of agriculture, coastal storms, energy, human mortality, labour and
17 crime on gross domestic product is estimated to increase by about 1.6% across 1°C of global warming.
18 However, reducing climate costs through limiting the degree of global warming are in certain key sectors
19 projected to be offset by the impacts of increasing mitigation costs.

20
21 **In mitigating costs associated with climate change impacts on many nations, food production is a key**
22 **factor for consideration.** That is, although restraining the global temperature increase to 2°C is projected to
23 reduce crop losses under climate change, the associated mitigation costs may imply an increased risk of
24 hunger in low-income countries. It is plausible that the even more stringent mitigation measures required to
25 restrict global warming to 1.5°C will further increase this risk. Food trade may thus be a key response
26 measure to alleviate hunger in developing countries under 1.5 and 2°C stabilization scenarios.

3.1 About the Chapter

This chapter uses peer-reviewed scientific evidence published since the AR5 to assess changes in the climate system and their impacts on natural and human systems. The chapter specifically focuses on global warming at 1.5°C above the pre-industrial period. While impacts are also assessed for higher levels of global warming levels (in particular 2°C), this is generally done for comparison to 1.5°C, and to assess the implications of constraining warming to 1.5°C.

The structure of the chapter (Figure 3.1) reflects the emphasis on 1.5°C and outlines the scope of the chapter. Where it is felt that more detailed results would be of benefit to the reader, these are provided in the supplementary material that accompanies this chapter.

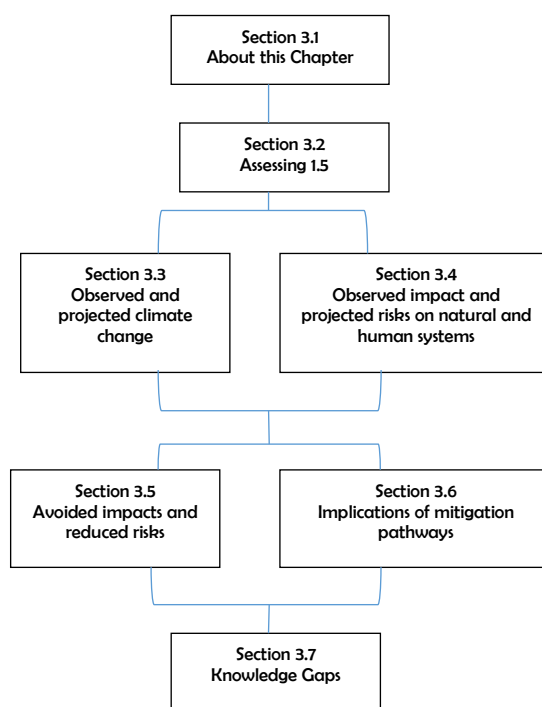


Figure 3.1: Chapter 3 structure

Chapter 3 is extensive in the material that it covers, spanning the climate system, natural and managed ecosystems, and human systems and responses. For efficiency in presentation and to eliminate overlap and repetition, the assessment is initially presented along traditional lines of division used in similar reports (e.g., AR5) of extensive scope (e.g., climatic changes in Section 3.3 and impacts in Section 3.4). A deliberate attempt is made, however, in the later sections of the chapter, to emphasize that climate is an integrated part of the lived experience in the natural world and for humans (see again Figure 3.1 for the flow and linkages between the chapter sections).

The chapter necessarily crosses disciplines, presenting a challenge with respect to the terminology used. For example, the important terms ‘impact’ and ‘risk’ are used differently, interchangeably, and inconsistently within and across disciplines, with different explicit or implicit definitions. To promote clarity and

1 consistency, this report uses the definitions presented in Box 3.1. Other definitions of key terms are found in
2 the glossary of this report.

3
4 The chapter also includes boxes in order to integrate information across chapter sections. In this regard,
5 boxes focus on regions, hotspots and themes that are relevant to the 1.5°C focus. These include boxes that
6 focus on geographic regions or climatic zones: Box 3.2 focuses on Sub-Saharan Africa, Box 3.3 on the
7 Mediterranean Basin, and Box 3.7 on Small Island Developing States, SIDS). The boxes also cover topical
8 issues: Box 3.3 on using paleoclimate data for understanding 1.5°C vs 2°C, Box 3.5 on tipping points
9 achieved or avoided, Box 3.6 on coral reefs in a 1.5°C warmer world, Box 3.8 on cascading and interacting
10 impacts, Box 3.9 on economic pros and cons of the USA limiting, or not, global warming to 1.5°C or 2°C).
11 Two cross chapter boxes also synthesize information across chapters (Cross-Chapter Box 3.1 on Land use,
12 Cross-Chapter Box 3.2 on 1.5°C Warmer worlds).

13
14 Other things to note about the chapter are:

- 15
16 • The chapter builds directly on Chapters 1 and 2 and their assessment of gradual versus overshooting
17 scenarios and relevant definitions of a potential 1.5°C warmer world. Other interactions with
18 information presented in Chapter 2 are via the provision of specifics related to the mitigation
19 pathways (e.g., land use changes) and their implications for impacts.
- 20 • It provides information for the assessment and implementation of adaptation options in Chapter 4,
21 and the context for considering the interactions of climate change with sustainable development in
22 Chapter 5.
- 23 • Sections and subsections begin with a concise summary of relevant knowledge from AR5, as a
24 starting point and context for considering the subsequent assessments.
- 25 • While climate change is acknowledged as a centrally important driver, it is not the only driver of
26 risks to human and natural systems (see Box 3.1).
- 27 • The IPCC calibrated language is applied throughout the chapter. (See Chapter 1 for guidance on
28 interpreting its usage).

29 **[START BOX 3.1 HERE]**

30
31 **Box 3.1:** How *impact* and *risk* are used throughout this chapter.

- 32
33 • Consistent with the definition used in the AR5, *impact* refers to observed consequences or outcomes
34 (positive or negative) of weather, climate variability and climate change on human and natural
35 systems;
- 36 • *Projected impact* refers to the future consequences of climate change for physical (e.g., air, water,
37 wind) and biogeochemical (e.g., carbon cycle, ecosystems) systems where there is high confidence in
38 the change and that other drivers would not alter the projection (e.g., projected impact of climate
39 change on the frequency and intensity of heat waves); and
- 40 • Consistent with the definition used in the AR5, *risk or projected risk* refers to the potential
41 consequence(s) of climate change for human-influenced systems where drivers of vulnerability and
42 exposure (e.g., demographic change, urbanization pathways, changes in income, research and
43 development) can influence the magnitude and pattern of the projection (e.g., heat-related mortality in
44 future decades, or changes in crop yields).
- 45 • Consistent with AR5, *risk* is also determined by the extent to which these systems are exposed to
46 changing weather patterns and sea level rise; by the degree to which systems are vulnerable; and by
47 the capacity to prepare for and manage risks. The risks of climate change will interact with

development pathways. Increasing resilience by following a sustainable development pathway will decrease exposure and vulnerability to many climate change hazards, thus reducing the magnitude and pattern of *projected risks*. Further, timing of when projected hazards are likely to occur will partially determine the extent of impacts experienced; warming of 2°C later in the century in a world on a sustainable development pathway (SSP1) will present different risks than warming of 2°C in mid-century under SSP3.

[END BOX 3.1 HERE]

Finally, Figure 3.2 provides a quick guide for reading particular sections of the chapter for a particular focus or interest. It is presented for convenience, recognizing both the breadth of topics covered in the chapter and the diversity of interests of the potential reader. Notwithstanding, readership of the entire chapter is strongly encouraged for the comprehensive assessment, which offers about the changes in the climate system and the impacts on natural and human system for global warming of 1.5°C, from presently available scientific literature.

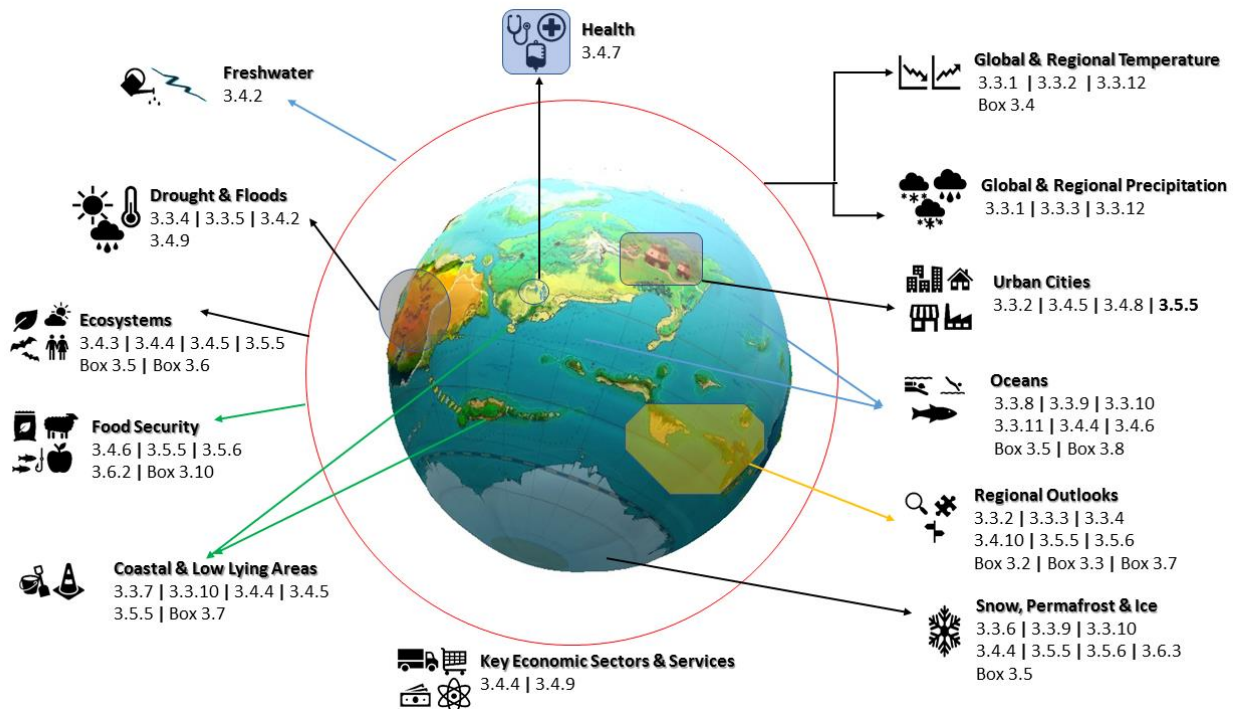


Figure 3.2: A reader’s guide to Chapter 3

3.2 How are risks at 1.5°C and higher levels of global warming assessed in this chapter?

The underlying literature assessed in this chapter is broad, involving information covered in at least two chapters of the IPCC SREX report (i.e. physical changes in extremes and associated impacts) (Seneviratne et al., 2012; Handmer et al., 2012); at least 5 chapters of the IPCC WG1 AR5 report on the physical basis of climate change (Bindoff et al., 2013b; Christensen et al., 2013; Church et al., 2013; Collins et al., 2013; Hartmann et al., 2013); and a large number of chapters which assess impacts on natural and managed

1 ecosystems and humans and adaptation options from the IPCC WG2 AR5 report (Cramer et al., 2014a;
2 Dasgupta et al., 2014; Hoegh-Guldberg et al., 2014; Jiménez Cisneros et al., 2014b; Oppenheimer et al.,
3 2014; Porter et al., 2014; Pörtner et al., 2014a; Revi et al., 2014; Settele et al., 2014; Wong et al., 2014). For
4 this reason, this chapter provides information based on a broad range of assessment methods.
5

6 The methods that are applied for assessing observed and projected changes in climate and weather are
7 presented in Section 3.2.1 and methods used to assess observed impacts and projected risks to natural and
8 managed systems, and human settlements, are described in Section 3.2.2. In some cases, methods that were
9 applied in the IPCC WG1 and WG2 reports presented differences and needed to be harmonized for the
10 present report. Additionally, given that changes in climate at 1.5°C of global warming were not the focus of
11 past IPCC reports, dedicated approaches based in part on recent literature were applied here by the chapter
12 authors and are specific to the present report.
13

14 3.2.1 *How are changes in observed and projected changes in climate and weather at 1.5°C vs higher* 15 *levels of warming assessed?* 16

17
18 Climate models are necessary for the investigation of the response of the climate system to various forcings.
19 In this regard, they are used to perform climate predictions on seasonal to decadal time scales and to
20 compute projections of future climate over the coming century. Using these various time frames, global
21 climate models or downscaled output from global climate models (see Supplementary Information) are also
22 used as input for impact models to evaluate the risk related to climate change for natural and human systems.
23

24 Climate model simulations were generally used in the context of particular “climate scenarios” in previous
25 IPCC reports (e.g., IPCC 2007, 2013). This means that emission scenarios (IPCC, 2000) were used to drive
26 climate models, providing different projections for given emissions pathways. The results were consequently
27 used in a “storyline” framework, which presents the development of climate in the course of the 21st century
28 and beyond, if a given emissions’ pathway were to be followed. Results were assessed for different time
29 slices within the model projections, e.g., for 2016–2035 (“near term”, which is slightly below a 1.5°C global
30 warming in most scenarios, Kirtman et al., 2013), 2046–65 (mid 21st century; Collins et al., 2013), and
31 2081–2100 (end of 21st century; Collins et al. 2013). Given that this report focuses on climate change for a
32 given mean global temperature response (1.5°C or 2°C), methods of analysis had to be developed and/or
33 adapted from previous studies in order to provide existing climate model simulations for the specific
34 purposes here.
35

36 A major challenge in assessing climate change under 1.5°C (or 2°C and higher-level) global warming
37 pertains to the **definition of a “1.5°C or 2°C climate projection”** (see also Cross-Chapter Box 3.2 on “1.5°C
38 warmer worlds”). Resolving this challenge includes the following considerations:
39

- 40 A. The need for distinguishing between (a) *transient climate responses* (i.e. those that “pass through” 1.5°C or
41 2°C global warming), (b) *short-term stabilization responses* (i.e. late 21st century scenarios that result in
42 stabilization at a mean global warming of 1.5°C or 2°C by 2100), and (c) *long-term equilibrium*
43 *stabilization responses* (i.e. once climate equilibrium at 1.5°C or 2°C is reached, after several millenia).
44 These responses can be very different in terms of climate variables and the inertia associated with a given
45 climate forcing. A striking example is sea level rise. In this case, projected increases within the 21st
46 century are minimally dependent on the considered scenario, yet stabilize at very different levels for a
47 long-term warming of 1.5°C vs 2°C (see Section 3.3.12).
48

- 1 B. That “1.5°C or 2°C emissions scenarios” presented in Chapter 2 are targeted to hold warming below
2 1.5°C or 2°C with a *certain probability* (generally 2/3) over the course, or end, of the 21st century. They
3 should be seen as operationalisations of a 1.5°C or 2°C world. However, when these emissions scenarios
4 are used to drive climate models, the resulting simulations include some that lead to warming above these
5 respective thresholds (typically with a probability of 1/3, see Chapter 2 and Cross-Chapter Box 3.2 on
6 “1.5°C warmer worlds”). This is due both to discrepancies between models and internal climate
7 variability. For this reason, the climate model outcome for any of these scenarios, even those excluding
8 an overshoot (see next point, C.), include some probability of reaching a global climate warming higher
9 than 1.5°C or 2.0°C. Hence, a comprehensive assessment of climate risks associated with “1.5°C or 2°C
10 climate scenarios” needs to include consideration of higher levels of warming (e.g., up to 2.5–3.0°C at
11 most, see Chapter 2).
- 12
- 13 C. Most of the “1.5°C scenarios”, and some of the “2°C emissions scenarios” of Chapter 2, include a
14 temperature overshoot during the course of the 21st century. This means that median temperature
15 projections under these scenarios exceed the target warming levels over the course of the century
16 (typically up to 0.5–1.0°C higher than the respective target levels at most), before warming returns to
17 below 1.5°C or 2.0°C achieved by 2100. During the overshoot phase, impacts would therefore correspond
18 to higher transient temperature levels than 1.5°C or 2.0°C. For this reason, impacts for transient responses
19 at these higher levels are also briefly addressed in Section 3.3. Most importantly, different overshoot
20 scenarios may have very distinct impacts depending on (a) the peak temperature of the overshoot, (b) the
21 length of the overshoot period, and (c) the associated rate of change in global temperature over the time
22 period of the overshoot. While some of these issues are briefly addressed in Sections 3.3 and 3.6, and the
23 Cross-Chapter Box 3.2 on “1.5° warmer worlds”, the definition and questions surrounding overshoot will
24 need to be addressed more comprehensively in the IPCC AR6 report.
- 25
- 26 D. The meaning of “1.5°C or 2°C” climate was not defined prior to this report, although it is defined as
27 relative to the climate associated with the pre-industrial climate conditions. This requires an agreement on
28 the exact reference time period (for 0°C warming) and the time frame over which the global warming is
29 assessed (e.g., typically a climatic time period, such as one that is 20 or 30 years in length). As discussed
30 in Chapter 1, a 1.5°C climate is one in which temperature differences averaged over a multi-decade
31 timescale are 1.5°C above the pre-industrial reference period. In this case, given the absence of a
32 substantial secular trend emerging in natural forcing, this is a world in which human-induced warming
33 has reached 1.5°C relative to the pre-industrial reference period (1850–1879). This definition is used in
34 all assessments of this chapter. Inherent to this is the observation that the mean temperature of a “1.5°C
35 global climate” can be regionally and temporally much higher (e.g., regional annual temperature extremes
36 can display a warming of more than 6°C, see Section 3.3 and cross-chapter box on “1.5°C warmer
37 worlds”).
- 38
- 39 E. Non-greenhouse-gas related interference with mitigation pathways can strongly affect regional climate.
40 For example, biophysical feedbacks from changes in land use and irrigation (e.g., Hirsch et al., 2017;
41 Thiery et al., 2017), or projected changes in short-lived pollutants (e.g., Wang et al., 2017), can have large
42 influences on local temperatures and climate conditions. While these effects are not explicitly integrated
43 into the scenarios developed in Chapter 2, they may affect projected changes in climate for 1.5°C of
44 global warming. These issues are addressed in more detail in Section 3.6.2.

45

46 There is a lack of climate model simulations for the low-emission scenarios described in Chapter 2 at
47 present. Therefore, with a few exceptions, the present assessment needed to focus on analyses of transient
48 responses at 1.5°C and 2°C (see point A. above), while simulations of short-term stabilization scenarios
49 could be assessed in some cases. In general, long-term equilibrium stabilization responses could not be

1 assessed due to lack of data availability. More details on the approaches followed for the respective
2 assessments are provided below. This shortfall needs to be addressed as part of the IPCC AR6 in order to
3 provide a comprehensive assessment of changes in climate at 1.5° global climate warming. We also note that
4 possible interventions in the climate system through such avenues as sulphate aerosols injections or other
5 radiation modification measures, are not tied to reductions of greenhouse gas emissions or concentrations are
6 not assessed. However, a short assessment on this topic is provided in Section 3.6.3 and a more detailed
7 assessment is provided in the Cross-Chapter Box 4.2.

8
9 The assessment of **transient responses in climate at 1.5°C vs 2°C** and higher levels of warming (Section
10 3.3) generally use the “time sampling” approach (James et al., 2017) which consists of sampling the response
11 at 1.5°C global warming from all available global climate model scenarios for the 21st century (e.g.,
12 Schleussner et al., 2016; Seneviratne et al. 2016; Wartenburger et al. 2017). A similar approach in the case of
13 regional climate model (RCM) simulations consists of sampling the RCM model output corresponding to the
14 time frame at which the driving global climate model (GCM) reaches the considered temperature level (e.g.,
15 as done within the IMPACT2°C project (Jacob and Solman, 2017), see description in Vautard et al. (2014)).
16 As an alternative to the “time sampling” approach, pattern scaling may be used. Pattern scaling is a statistical
17 approach that describes relationships of specific climate responses as a function of global temperature
18 change. Some assessments of this chapter are also based on this method. The disadvantage of pattern scaling,
19 however, is that the relationship may not perfectly emulate the models’ responses at each location and for
20 each global temperature level (James et al., 2017). Expert judgement is a third methodology that can be used
21 to assess probable changes at 1.5°C or 2°C by combining changes that have been attributed for the observed
22 time period (corresponding already to a warming of 1°C, Chapter 1) and known projected changes at 3°C or
23 4°C above the pre-industrial (see Supplementary Information). In order to compare effects induced by a
24 0.5°C difference in global warming, it is also possible to use, in a first approximation, the historical record as
25 a proxy in which two periods are compared in cases where they approximate this difference in warming,
26 (e.g., such as 1991–2010 and 1960–1979, e.g., Schleussner et al., 2017). Using observations, however, does
27 not allow an accounting for possible non-linear changes that would occur above 1°C or as 1.5°C of global
28 warming is achieved.

29
30 In some cases, assessments for **short-term stabilization responses** could also be provided, derived from
31 using a subset of model simulations that reach a given temperature limit by 2100, or were driven with sea
32 surface temperature (SST) consistent with such scenarios. This includes new results from the “Half a degree
33 additional warming, prognosis and projected impacts” (HAPPI) project (Mitchell et al., 2017a). It should be
34 noted that there is evidence that for some variables (temperature and precipitation extremes) responses after
35 short-term stabilization (i.e. approximately equivalent to the RCP2.6 scenario) that are very similar to the
36 transient response of higher-emission scenarios (Seneviratne et al., 2016; Seneviratne et al.). This is,
37 however, less the case for mean precipitation (e.g., Pendergrass et al., 2015) for which other aspects of the
38 emissions scenarios appear relevant.

39
40 For the assessment of **long-term equilibrium stabilization responses**, this chapter uses results from existing
41 simulations where available (e.g., for sea level rise), although the available data for this type of approach is
42 limited for many variables and scenarios.

43
44 The Supplementary Information of this chapter includes greater detail of the climate models and associated
45 simulations that were used to support the present assessment, as well as a background on detection and
46 attribution approaches of relevance to assessing changes in climate at 1.5°C global warming.

3.2.2 *How are potential impacts at 1.5°C vs higher levels of warming assessed?*

Considering that most of the known impacts are of lower amplitude than those projected for a global warming of 1.5°C, there are no observed time series available for providing direct information on the causal effect of a global warming of 1.5°C. The global distribution of observed impacts shown in the AR5 (Cramer et al. 2014), however, demonstrates that methodologies now exist which are capable of detecting impacts in systems strongly influenced by confounding factors (e.g., urbanization or more generally human pressure) or where climate may play only a secondary role.

One approach for assessing impacts on natural and managed systems at 1.5°C consists of roughly multiplying observed impacts (under +1°C global warming) by a 1.5 factor. This provides a first approximation of trends and relies on the assumption of linear dynamics. While this may be a too strong approximation, the observational record can help identify aspects of the climate system that are sensitive to half a degree warming (e.g., Schleussner et al. 2017). A second approach, which is complementary to the first one, is to use conclusions from paleontological data combined with the modeling of the relationships between climate drivers and natural systems (it is impossible to consider human systems for a remote past) [see Box 3.4]. A third approach relies on lab or field experiments (Bonal et al., 2016; Dove et al., 2013), which provide useful information on the causal effect of a few factors (which can be as diverse as climate, GHG, management practices, biological and ecological) on natural systems. The latter can be important in helping develop and ‘tune’ impact mechanisms and models.

Risks for natural and human systems are often assessed with impact models where inputs are provided by RCP-based climate projections. Studies projecting impacts at 1.5 or 2°C global warming have increased in recent times (see Section 3.4) even if the four RCP scenarios used in the AR5 are not strictly associated to these levels of global warming levels. Several approaches have been used to extract the required climate scenarios, as described by James et al. (2017) (see also Section 3.2.2). As an example of a methodology applied, Schleussner et al. (2016) estimated the differential effect of 1.5°C and 2°C global warming on water availability and impacts on agriculture using an ensemble of simulations under the RCP8.5 scenario, using time slices centered around these specific levels of warming (i.e. the “time sampling” approach, see Section 3.2.2). Lizumi et al. (2017) interpolated the 1.5°C scenario within an agrosystem model as being mid way between the no-change (approximately 2010) conditions and the RCP2.6 scenario (with a global warming of +1.8°C in 2100) and the 2°C scenario from RCP2.6 and RCP4.5 in 2100. Guiot & Cramer (2016) used a similar approach to Schleussner et al. (2016) to define the +1.5°C, 2°C and 3°C global warming simulations, and in addition compared the future vegetation changes to the paleovegetation changes (up to 10,000 years ago) and drew conclusions regarding adaptability.

Alternatively, projections of regional changes in climate means or extremes at 1.5°C vs 2°C (e.g., Section 3.2.2) can be combined with assessments of the sensitivity of impacts to these changes derived from observations or models. This combination of information requires expert judgement and underlies several assessments of impacts provided in this chapter.

Global warming (e.g., of 1.5°C or 2°C) is based on a global average of the daily temperature. At a regional scale, the signal to noise ratio decreases and the temporal variability increases. The amplitude of the signal may be larger but not necessarily more significant. Seneviratne et al. (2016) have shown that the spatial variations may be much larger (e.g., 6°C for the nighttime in the Arctic, 3.5°C for the daytime in the Mediterranean or Brazil), so the effects on ecosystems and human systems can be considerably amplified in these areas. For example, some phenological processes in the forest (leaf onset) are triggered by daytime maximum temperature (and not the daily mean; Piao et al., 2015).

1 Assessment of local impacts of climate change necessarily involves a change in scale (i.e from the global
2 scale to that of natural or human systems). An appropriate method of downscaling (see Supplementary
3 Information) is crucially important in translating perspectives on 1.5°C and 2.0°C to scales and impacts
4 relevant to humans and ecosystems. A major challenge that is associated with this requirement is to
5 reproduce correctly the variance of local to regional changes, as well as the frequency and amplitude of the
6 extreme events (see Section 3.2.3). Another major challenge relates to the propagation of the uncertainties at
7 each step of the methodology, from the global forcings to the global climate, and regional climate to the
8 impacts at the ecosystem level, taking into account local disturbances and local policy effects. The risks for
9 natural and human systems are the result of intricate global and local drivers, which makes quantitative
10 uncertainty analysis difficult. Such analyses are partly done by multi-model approaches, such as multi-
11 climate and multi-impact models (Warszawski et al., 2013, 2014). In some cases, the greater proportion of
12 the uncertainty (e.g., crop projections) is due to variation among crop models rather than that of the
13 downscaled climate models being used (Asseng et al., 2013). The study of the error propagation is an
14 important issue for which some more holistic approaches such as Bayesian frameworks being adopted
15 (Holden et al., 2015). Dealing correctly with the uncertainties in a robust probabilistic model is particularly
16 important when considering the potential for relatively small changes to affect the already small signal
17 associated with 0.5°C (see Supplementary Information). It is already an issue for the physical systems
18 (Rougier and Goldstein, 2014; Tran et al., 2016; Williamson and Goldstein, 2012), but not yet for biological
19 systems.

22 3.2.3 Summary

24 In order to assess impacts at 1.5°C, several considerations need to be taken into account. Projected climates
25 under 1.5°C of global warming can be different depending on temporal aspects and pathways of emissions.
26 Considerations include whether global temperature is a) temporarily at this level (i.e. is a transient phase on
27 its way to higher levels of warming), b) arrives at 1.5°C after stabilization of greenhouse gas concentrations
28 without overshoot, c) arrives at 1.5°C warming after the stabilization of greenhouse gas concentrations but
29 including a phase with overshoot, d) is at this level as part of long-term climate equilibrium (after several
30 millennia). Assessments of impacts of 1.5°C warming are generally based on climate simulations for these
31 different possible pathways. More data and analyses are available for transient impacts (a). Data are less for
32 dedicated climate model simulations that are able to assess pathways consistent with (b) or (c) above. There
33 are very limited data available for the assessment of changes at climate equilibrium (d). In some cases,
34 inferences regarding the impacts of further warming of 0.5°C above today (i.e. 1.5°C global warming) can
35 also be drawn from observations of similar sized changes (0.5°C) that have occurred in the past (e.g., last 50
36 years). However, impacts can only be partly inferred from these types of observations given the strong
37 possibility of non-linear changes as well as lag effects for some climate variables (e.g., sea level rise, snow
38 and ice melt).

41 3.3 Global and regional climate changes and associated hazards

43 This section provides the assessment of changes in climate at 1.5°C relative to other levels of global
44 warming. Section 3.3.1 provides an overview on changes in global climate, with a focus on global patterns of
45 temperature and precipitation. Sections 3.3.2–3.3.11 provide assessments for specific aspects of the climate
46 system, including regional assessments for temperature (3.3.2) and precipitation (3.3.3) means and extremes.
47 A synthesis of the main conclusions is provided in Section 3.3.12

48 The section builds upon assessments from the IPCC AR5 WG1 report (Bindoff et al., 2013b; Christensen et

1 al., 2013; Collins et al., 2013; Hartmann et al., 2013; Stocker et al., 2013) and Chapter 3 of the IPCC SREX
2 report (Seneviratne et al., 2012), and as on more recent literature related to projections of climate at 1.5°C
3 and 2°C of warming above the pre-industrial period (e.g., Déqué et al., 2017; Jacob et al.; Maule et al., 2017;
4 Schleussner et al., 2016d; Seneviratne et al., 2016; Vautard et al., 2014; Wartenburger et al., 2017a; Zaman
5 et al., 2017). Background on the applied methods of assessment is provided in Section 3.2. The main
6 assessment on projections build on the transient evaluation of climate at 1.5°C vs 2°C global warming based
7 on global climate model simulations driven with the RCP8.5 scenario (see Section 3.2.), and supplemented
8 when available with results of simulations more specifically targeted as evaluating climate at 1.5°C and 2°C
9 warming (e.g., simulations from the HAPPI experiment; Mitchell et al., 2017). As discussed in Section 3.2.,
10 for temperature and precipitation extremes, these evaluations are approximately consistent for scenarios
11 stabilizing close to 1.5°C or 2.0°C global warming (RCP 2.6), however they may differ for other quantities
12 (e.g., mean precipitation). Analyses based on observed changes in hazards for differences of 0.5°C in global
13 warming are also available in some cases (e.g., Schleussner et al. 2017).
14
15

16 3.3.1 *Global changes in climate*

17 3.3.1.1 *Observed and attributed changes*

18 The reader is referred to Chapter 1 as well as the supplementary material of this chapter (see Annex 3.1) for
19 general background on observed and projected mean changes in global temperature. Aspects of most
20 relevance to changes in hazards at 1.5°C and higher levels of warming are addressed hereafter.
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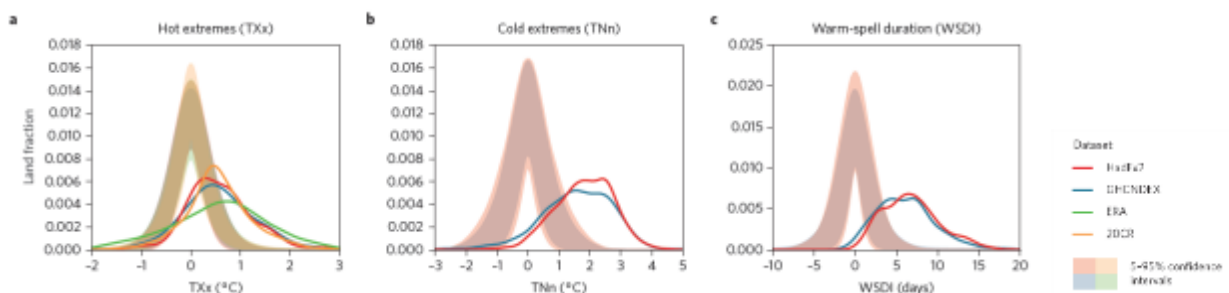
23 The Global Mean Surface Temperature (GMST) warming has reached 1°C above pre-industrial levels at the
24 time of writing (2017, see Chapter 1). Hartmann et al. (2013) assessed that the globally averaged combined
25 land and ocean surface temperature data (i.e. for time frames up to 2012; Stocker et al. 2013) using a linear
26 trend revealed warming of 0.85 [0.65 to 1.06]°C above the period 1880–2012 (see also Annex 3.1 to this
27 section for more details). As discussed in Chapter 1, recent analyses suggest that these estimates may need
28 to be revised in view of new observational datasets, in particular when accounting for biases in observational
29 sampling (Cowtan and Way, 2014; Richardson et al., 2016). Sampling biases and different approaches to
30 estimate GMST (e.g., using water vs air temperature over oceans) can sensibly impact estimates of GMST
31 warming as well as differences between model simulations and observations-based estimates (Richardson et
32 al., 2016).
33

34 As highlighted in Chapter 1, an area in which substantial new literature has become available since AR5 is
35 the global mean surface temperature trend over the period 1998-2012, which has been referred to by some as
36 the ‘global warming hiatus’ (Karl et al., 2015; Lewandowsky et al., 2016; Medhaug et al., 2017; Stocker et
37 al., 2013). This term was used to refer to an apparent slowdown of GMST warming over that time period
38 (although other climate variables continued to display unabated changes during that period, including a
39 particular intense warming of hot extremes over land; Seneviratne et al., 2014). Medhaug et al. (2017) note
40 that from a climate point of view, with 2015 and 2016 being the two warmest years on record (based on
41 GMST), the question of whether ‘global warming has stopped’ is no longer present in the public debate.
42 Nonetheless, the related literature is relevant for the assessment of changes in climate at 1.5°C global
43 warming, since this event illustrates the possibility that the global temperature response may be decoupled
44 from the radiative forcing over short time periods. While this may be associated with cooler global
45 temperatures as experienced during the incorrectly labeled “hiatus” period, this implies that there could also
46 be time periods with global warming higher than 1.5°C even if the radiative forcing would be consistent with
47 a global warming of 1.5°C in long-term average. Recent publications have highlighted that the ‘slow-down’
48 in global temperature warming that occurred in the time frame of the “hiatus” episode was possibly
49 overestimated at the time of the AR5 due to issues with data corrections, in particular related to data

1 coverage (Cowtan and Way 2014; Karl et al. 2015; Annex 3.1, see Figure S3.3). This has some relevance for
 2 the definition of a “1.5°C climate” (see Chapter 1 and Cross-chapter Box 3.2 on “1.5°C warmer worlds”).
 3 Overall, the issue of internal climate variability is the reason why a 1.5°C warming level needs to be
 4 determined in terms of “human-induced warming” (see Chapter 1 for additional background on this issue).
 5

6 A large fraction of the detected global warming has been attributed to anthropogenic forcing in the AR5
 7 (Bindoff et al., 2013b). It is assessed that it is *virtually certain* that human influence has warmed the global
 8 climate system and that it is *extremely likely* that human activities caused more than half of the observed
 9 increase in GMST from 1951 to 2010 (Bindoff et al., 2013b; see Annex 3.1, Supplementary Information to
 10 Section 3.3 for more details). Regarding observed global changes in temperature extremes, the IPCC SREX
 11 report assessed that since 1950 it is *very likely* that there has been an overall decrease in the number of cold
 12 days and nights and an overall increase in the number of warm days and nights at the global scale, that is, for
 13 land areas with sufficient data (Seneviratne et al., 2012).
 14

15 As highlighted in Section 3.2, the observational record can be used to assess past changes associated with a
 16 global warming of 0.5°C, with this type of assessment being considered as an analogue for the difference
 17 between a scenario at 1.5°C and at 2°C global warming. This approach has its limitations. For example, the
 18 methodology does not account for non-linearity in responses, including possible regional or global tipping
 19 points (see Box 3.5 on tipping points). Nonetheless, it can provide a first assessment of aspects of the climate
 20 system that have been identified as being sensitive to a global warming change of this magnitude.
 21 Schleussner et al. (2017) using this approach, assessed observed changes in extreme indices for the 1991–
 22 2010 versus the 1960–1979 period, which corresponds to just about 0.5°C GMST difference in the observed
 23 record (based on the GISTEMP dataset; Hansen et al., 2010). They found that substantial changes due to
 24 0.5°C warming are apparent for indices related to hot and cold extremes, as well as for the Warm Spell
 25 Duration Indicator (WSDI). Some results are displayed in Figure 3.3. Using two well established
 26 observational datasets (HadEX2 and GHCNDEX; Donat et al., 2013a,b) they show that one quarter of the
 27 land has experienced an intensification of hot extremes (TXx) by more than 1°C and a reduction of the
 28 intensity of cold extremes by at least 2.5°C (TNn). Half of the global land mass has experienced changes in
 29 WSDI of more than 6 days and the emergence of extremes outside the range of natural variability is
 30 particularly pronounced for this duration-based indicator (Figure 3.3). Results for TXx based on reanalysis
 31 products are similar for the 20CR product, but even more pronounced for the ERA reanalysis. As noted by
 32 Schleussner et al. (2017), however, results based on reanalysis products need to be considered with caution.
 33 The observational record does, however, suggest that a 0.5°C change in global warming has noticeable
 34 global impacts on temperature extremes.
 35



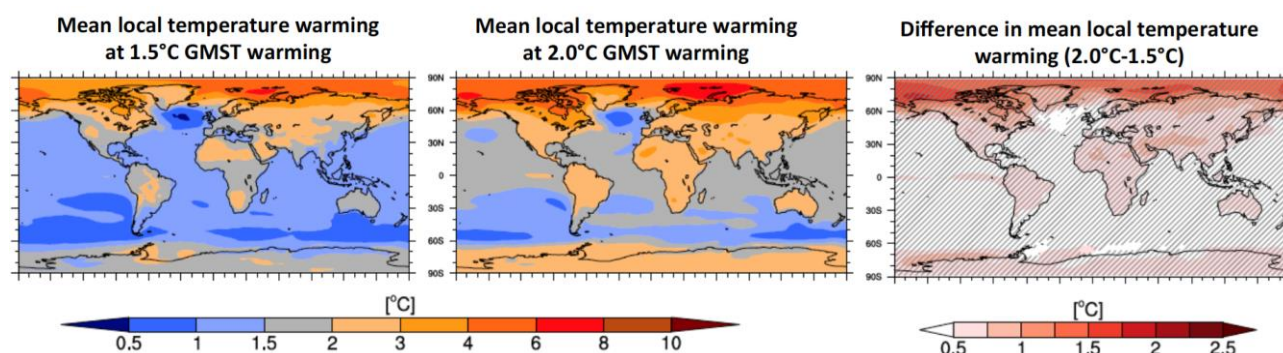
36
 37 **Figure 3.3:** Differences in extreme temperature event indices for 0.5°C warming over the observational record.
 38 Probability density functions show the globally aggregated land fraction that experienced a certain
 39 change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. For
 40 TXx, the analysis includes also reanalysis data from ERA and 20CR over the global land area. Light-
 41 coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically
 42 resampling individual years. Based on Schleussner et al. (2017).

1 Observed global changes in the water cycle, including precipitation, are more uncertain than observed
 2 changes in temperature (Hartmann et al., 2013; Stocker et al., 2013; see also Annex 3.1 Supplementary
 3 Information to Section 3.3 for more details). Some regional precipitation trends appear to be robust with
 4 respect to precipitation (Stocker et al., 2013). When virtually all the land area is filled in using a
 5 reconstruction method, however, the resulting time series of global mean land precipitation shows little
 6 change since 1900. For heavy precipitation, the AR5 concluded that for land regions, where observational
 7 coverage was sufficient for assessment, there is *medium confidence* that anthropogenic forcing has
 8 contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century
 9 (Bindoff et al., 2013b).

11 Specific analyses of observed global changes in precipitation, which are indicative of responses to a global
 12 warming of 0.5°C (Schleussner et al., 2017), have also provided support for changes in precipitation
 13 extremes (Annex 3.1 Supplementary Figure S3.4) that are similar to those previously discussed for
 14 temperature extremes (Figure 3.3). While the changes are more moderate than for temperature extremes
 15 (Figure 3.3), robust increases in observed precipitation extremes can also be identified for annual maximum
 16 one day precipitation (RX1day) and consecutive five day precipitation (RX5day). The analysis also reveals
 17 that a quarter of the land mass has experienced an increase of at least 9% for extreme precipitation
 18 (RX5day).

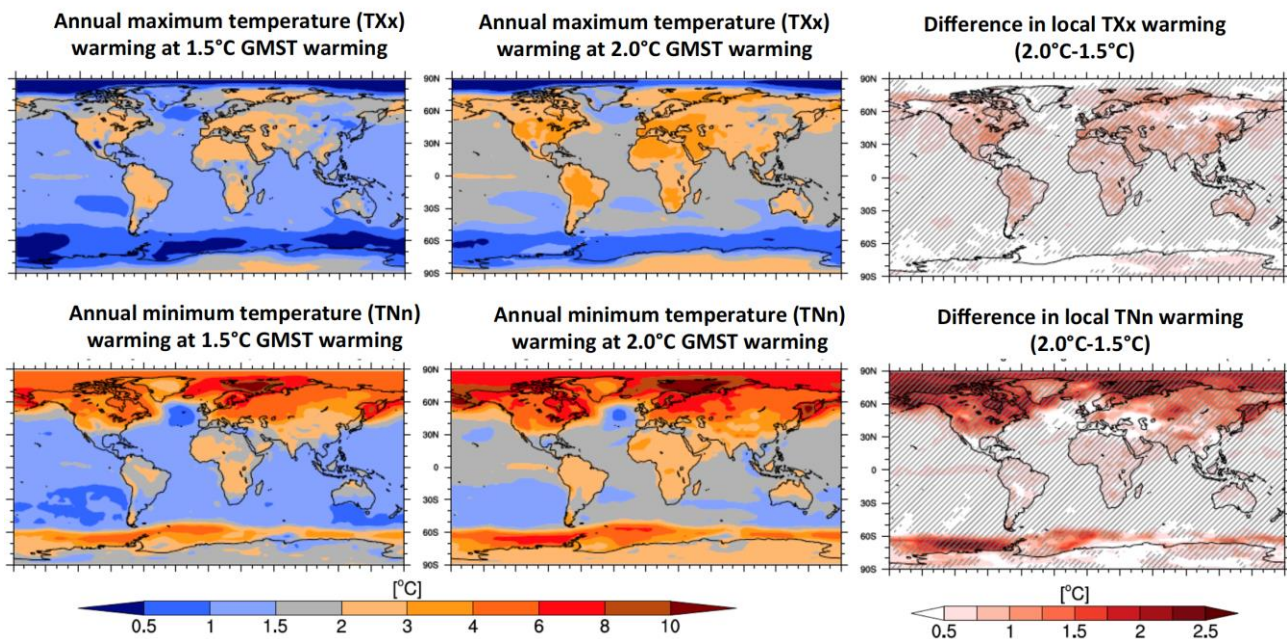
3.3.1.2 Projected changes at 1.5°C vs 2°C

22 Figure 3.4 depicts maps of projected changes in local mean temperature warming at 1.5°C vs 2°C global
 23 warming. Similar analyses are provided for temperature extremes (changes in the maximum temperature of
 24 the local hottest day of the year, TXx, and in the minimum temperature of the local coldest day of the year,
 25 TNn) in Figure 3.5. The responses for both analyses are derived from transient simulations of the 5th phase of
 26 the Coupled Model Intercomparison Project (CMIP5) for the RCP8.5 scenario, using empirical scaling
 27 relationships (ESR; Seneviratne et al.) similar to Seneviratne et al. (2016) and Wartenburger et al. (2017). As
 28 highlighted in Section 3.2, the results are similar for other emissions scenarios, in particular with respect to
 29 the responses of simulations for the RCP2.6 scenario, which stabilize at around 2°C until the end of the 21st
 30 century (Seneviratne et al., 2016; Wartenburger et al., 2017b; see also Supplementary Figure S3.5). In
 31 addition, more recent analyses comparing results from CMIP5-based ESR analyses with simulations from
 32 the HAPPI experiment (Mitchell et al., 2017b) show also an overall good consistency (Seneviratne et al.; see
 33 Sections 3.3.2, 3.3.3 and 3.3.4).



35 **Figure 3.4:** Projected local mean temperature warming at 1.5°C global warming (left), 2.0°C global warming
 36 (middle), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of
 37 change). Assessed from transient response over 20-year time period at given warming, based on RCP8.5
 38 CMIP5 model simulations (adapted from Seneviratne et al. (2016) and Wartenburger et al. (2017)). Note
 39

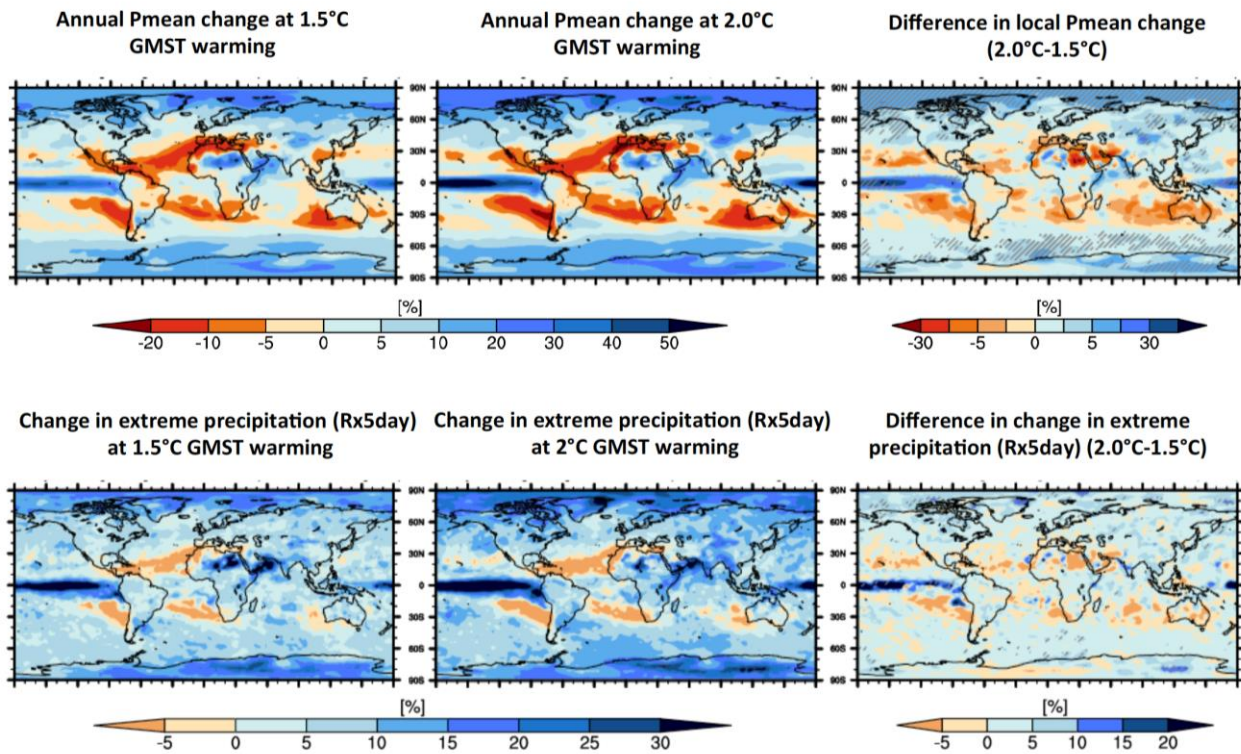
1 that the warming at 1.5°C GMST warming is similar for RCP2.6 simulations (see Annex 3.1 Figure S3.5).
 2 Figures 3.4 and 3.5 highlight some important features. First, because of the land-sea warming contrast (e.g.,
 3 Collins et al., 2013; Christensen et al., 2013; Seneviratne et al., 2016), the warming on land is much stronger
 4 than on the oceans, which implies that warming of several land regions display a higher level of mean
 5 warming at 1.5°C (Figure 3.4). As highlighted in Seneviratne et al. (2016), this feature is even stronger for
 6 temperature extremes (Figure 3.5; see also Section 3.3.2 for a more detailed discussion). Second, even for a
 7 change of 0.5°C in global warming between the two considered global temperature limits (e.g., 1.5°C and
 8 2°C) substantial differences in mean temperature, and in particular in extreme temperature warming can be
 9 identified on land, as well as over sea in the Arctic. These differences are larger than 2–2.5°C in some
 10 locations (Figure 3.5) and thus four or five times larger than the differences in global mean temperature.
 11 These regional differences are addressed in more detail in Section 3.3.2.
 12



13 **Figure 3.5:** Projected local warming of extreme temperatures (top: Annual maximum daytime temperature, TXx;
 14 bottom: Annual minimum nighttime temperature, TNn) warming at 1.5°C global warming (left), 2.0°C
 15 global warming (middle), and difference (right; hatching highlights areas in which 2/3 of the models agree
 16 on the sign of change). Assessed from transient response over 20-year time period at given warming,
 17 based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. 2016 and Wartenburger et al.
 18 2017). Note that the warming at 1.5°C GMST warming is similar for RCP2.6 simulations (see
 19 Supplementary Figure S3.6).
 20
 21

22 Figure 3.6 displays the projected changes in mean precipitation and heavy precipitation (five day maximum
 23 precipitation, Rx5day) at 1.5°C, 2°C and their difference, using the same approach as for Figures 3.4 and 3.5
 24 (see also Section 3.2.). Compared to changes in temperature, changes in precipitation are not globally
 25 uniform and projections are more uncertain. Some regions display substantial changes in mean precipitation
 26 between 1.5°C vs. 2°C global warming, in particular decreases in the Mediterranean area, including Southern
 27 Europe, the Arabian Peninsula and Egypt. There are also changes towards increased heavy precipitation in
 28 some regions, as highlighted in Section 3.3.3. The differences are generally small between 1.5°C and 2°C
 29 global warming (Figure 3.6). Some regions display substantial increases, for instance in Southern Asia, but
 30 generally in less than 2/3 of the models (Figure 3.6).

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Figure 3.6: Projected changes of mean (top) and extreme (5-day maximum precipitation) precipitation at 1.5°C global warming (left), 2.0°C global warming (middle), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al., 2016 and Wartenburger et al., 2017). Note that the response at 1.5°C GMST warming is similar for the RCP2.6 simulations (see Annex 3.1 Figure S3.7).

Analyses were done to assess changes in the risks of exceeding pre-industrial thresholds for temperature and precipitation extremes. Results suggest substantial differences in risks for very hot extremes already between 1.5°C and 2°C, both on global and regional scales (Fischer and Knutti, 2015; see also Figure 3.7, left). The differences are more moderate for heavy precipitation (Figure 3.7, right), also consistent with the analyses summarized in Figure 3.6. It should be noted that the approximately exponential increase in the number of occurrence of extreme days when defined with respect to a given threshold as illustrated in Figure 3.7 is directly tied to the use of a threshold in the definition of extreme indices. When assessing absolute changes in temperature or precipitation extremes (i.e. changes in °C or mm/day, rather than the frequency of exceedance of a given threshold) the changes as a function of global temperature are often close to linear (Sections 3.3.2 and 3.3.3; see also Seneviratne et al., 2016; Wartenburger et al., 2017; Seneviratne et al.)

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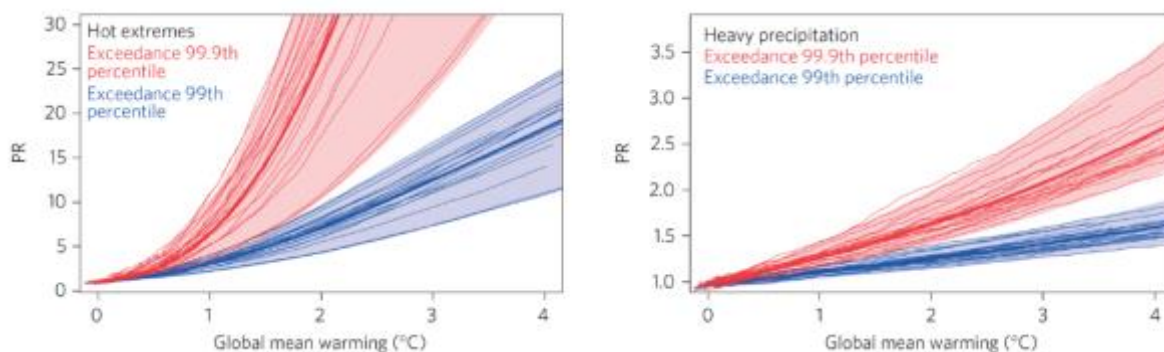


Figure 3.7: Probability ratio of exceeding the (blue) 99th and (red) 99.9th percentile of pre-industrial daily temperature (left) and precipitation (right) at a given warming level relative to pre-industrial conditions averaged across land [From Fischer and Knutti (2015)].

3.3.2 Regional temperature on land, including extremes and urban climate

This section addresses regional changes in temperature on land, with a focus on extreme temperatures.

3.3.2.1 Observed and attributed changes in regional temperature means and extremes

While the quality of temperature measurements obtained through ground observational networks tend to be high compared to that of measurements for other climate variables (Seneviratne et al., 2012), it should be noted that some regions are undersampled. Cowtan and Way (2014) highlighted issues regarding undersampling being concentrated at the Poles and over Africa, which may lead to biases in estimated changes in global mean surface temperature (see also Section 3.3.1.2 and Chapter 1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature.

Despite this partly limited coverage, the attribution chapter of the AR5 (Bindoff et al., 2013b) and recent papers (e.g., Sylla et al., 2016; Abatzoglou and Williams, 2016; Guo et al., 2017) assessed that over every continental region and in many sub-continental regions, anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century. For Antarctica, while changes are occurring, statistical assessment (presumably to 95% confidence) has not been achieved due primarily to the large natural variability in the weather that occurs there and the comparatively short observational record.

Regarding observed regional changes in temperature extremes, the IPCC SREX report assessed that since 1950 it is *likely* that an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights have occurred at the continental scale in North America, Europe, and Australia (Seneviratne et al., 2012), consistent with detected global changes (Section 3.3.1). It also concluded from its assessment that there is *medium confidence* in a warming trend in daily temperature extremes in much of Asia, and that there is *low to medium confidence* in historical trends in daily temperature extremes in Africa and South America depending on the region. Further the IPCC SREX assessed (Seneviratne et al., 2012) that globally, in many (but not all) regions with sufficient data there is *medium confidence* that the length and the number of warm spells or heat waves has increased since the middle of the 20th century, and that it is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale. Hence, observed and attributed changes in both mean and extreme temperature consistently point to a widespread influence of human-induced warming in most land regions. Specific attribution statements for changes associated with a global warming of 0.5°C

1 are currently not available on a regional scale from the literature, unlike global assessments (Schleussner et
2 al., 2017), although preliminary results suggest that a 0.5°C global warming can also be identified for
3 temperature extremes in a few large regions (Europe, Asia, Russia, North America; see supplementary
4 material of Schleussner et al., 2017).

5
6 An area of particular concern is related to possible changes in extreme heat events in cities (e.g., Section
7 3.5.2. and Cross-chapter Box 5.1 on cities). The climate in cities differs from surrounding regions due to the
8 structures present and intensive human activity that occurs there. The surface geometry transformation and
9 the alteration of energy and water exchanges between the atmosphere and the artificial soil is reflected in the
10 urban space by a change in the wind regime, in moisture and in rainfall, and above all by an increase in
11 temperature compared to what is observed in the surrounding rural area. This phenomenon is often referred
12 to as the urban heat island (UHI) effect (Tzavali et al., 2015). The UHI shows cycles in time and space. At
13 mid-latitudes, it is characterized by a daily cycle having its maximum intensity at night, a minimum of
14 intensity generally before dawn (which may reach negative values e.g., the town centre being colder than the
15 surrounding environs) during the day, and a slow increase from sunrise onwards. Seasonal cycles also affect
16 the frequency and intensity of the UHI (Arnfield, 2003). There is growing evidence supporting the existence
17 of phase and amplitude deviations in the UHI of tropical cities in comparison with the corresponding
18 description in mid-latitude cities (Flores Rojas et al., 2017). Multiple other mechanisms have been cited for
19 causing and influencing the UHI such as the density of buildings in built-up areas, geographical setting of
20 city, time of day and season, energy consumption, vegetation index, transportation issues, and waste heat
21 input from building Heating, Ventilation and Air-Conditioning (HVAC; Rizwan et al., 2008; Quah and Roth,
22 2012; Chow et al., 2014; Zhao et al., 2014; Tzavali et al., 2015; Hong and Hong, 2016).

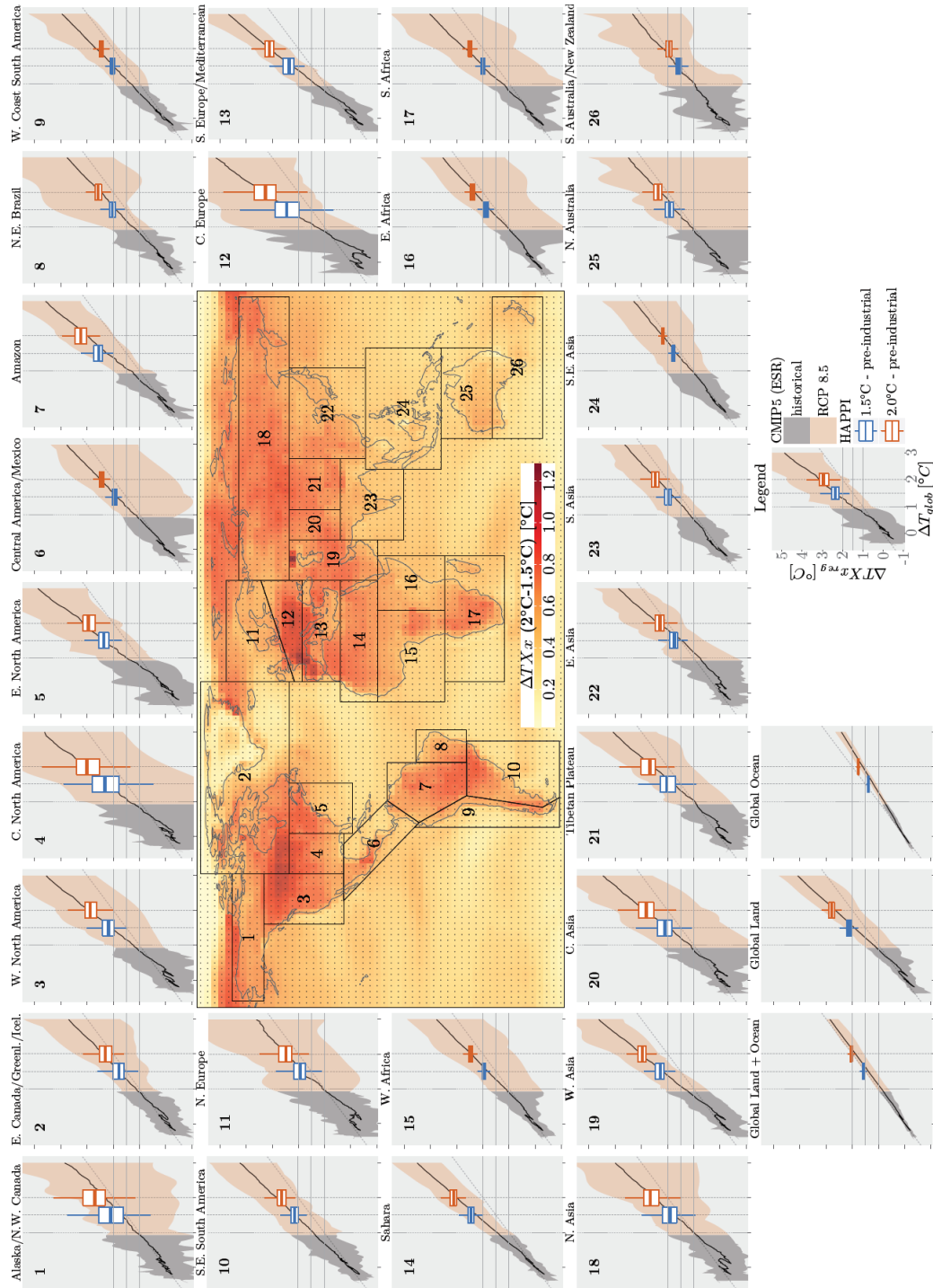
23
24 Studies have been conducted to estimate the UHI intensity in many cities and metropolitan areas (Mirzaei
25 and Haghighat 2010; Stewart, 2011; Tzavali et al., 2015). Using satellite data to examine the annual average
26 surface UHI intensity in the 32 largest cities in China, Zhou et al. (2014) found considerable variability, with
27 values of UHI ranging from 0.01 to 1.87°C in daytime. In the USA, Imhoff et al. (2010) found an average
28 annual surface UHI intensity across the 38 largest cities of 2.9°C, except for cities in arid and semi-arid
29 climates where the cities were found to be cooler than their surrounding rural areas. Peng et al. (2012) used
30 similar satellite data to examine the surface UHI across 419 global big cities. They estimate an annual
31 average UHI intensity of 1.3°C, with some cities reaching as high as 7°C during daytime in summer, and a
32 few cities surrounded by desert having negative surface UHI intensity. Tropical cities generally have UHI
33 intensities that are lower than comparable temperate cities (Roth, 2007). It should be noted that while the
34 annual mean UHI intensity is a few degrees, the urban environment can enhance heat waves by more than
35 the average UHI intensity (Li and Bou-Zeid, 2013; Hamdi et al., 2016).

38 3.3.2.2 *Projected changes at 1.5°C vs. 2°C in regional temperature means and extremes, including urban* 39 *climate*

40 A further increase of 0.5°C or 1°C is likely to have detectable effects on mean temperature and/or extremes
41 in some regions given that changes in mean and extreme temperatures have already been detected for several
42 years (e.g., IPCC SREX, Seneviratne et al., 2012) at global and also continental scale (Sections 3.3.1. and
43 3.3.2.1) for a global warming of less than 1°C (Chapter 1). More detailed regional assessments can also be
44 performed based on climate projections as presented hereafter.

45
46 This section provides a regional assessment of differences in temperature extremes projections at 1.5°C vs.
47 2°C global warming using two underlying data bases: (1) empirical scaling relationship presented in Section
48 3.2 and (2) output from simulations from the HAPPI (Section 3.2) experiment. Figure 3.8 shows for the
49 IPCC SREX regions changes in temperature hot extremes (annual maximum daytime temperature, TXx) as a

1 function of global mean temperature warming. The plot insets display the full range of CMIP5 simulations
2 (orange range for RCP8.5 simulations, blue range for RCP2.6 simulations) as well as the mean response for
3 both simulation ensembles (orange and blue lines, respectively). The mean response of climate models to
4 changes in the absolute temperature of extremes is approximately linear and independent of the considered
5 emission scenario (Seneviratne et al., 2016; Wartenburger et al., 2017a). This implies that the transient
6 response (inferred from the RCP8.5 simulations) is close to the equilibrium response (corresponding to the
7 RCP2.6 simulations).



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Figure 3.8: Projected changes in annual maximum daytime temperature (TXx) as function of global temperature warming for IPCC SREX regions, based on empirical scaling relationship applied to CMIP5 data (adapted from Seneviratne et al., 2016 and Wartenburger et al., 2017) together with projected changes from the HAPPI multi-model experiment (Mitchell et al., 2017b) (bar plots on regional analyses and central plot). After Seneviratne et al.

1 There is a stronger warming of the regional land-based hot extremes compared to the mean global
2 temperature warming in most land regions (also discussed in Seneviratne et al., 2016). The regions
3 displaying the stronger contrast are Central North America, Eastern North America, Central Europe,
4 Southern Europe/Mediterranean, Western Asia, Central Asia, and Southern Africa. As highlighted in Vogel
5 et al. (2017), these regions are characterized by transitional climate regimes between dry and wet climates,
6 which are associated with strong soil moisture-temperature coupling (related to a transitional soil moisture
7 regime; Koster et al., 2004; Seneviratne et al., 2010). Several of these regions display enhanced drying under
8 enhanced greenhouse forcing (see Section 3.3.4), which leads to a decrease of evaporative cooling and an
9 additional regional warming compared to the global temperature response. In a recent study, Karmalkar and
10 Bradley (2017) also found consistent results for the contiguous United States, with all subregions being
11 projected to reach 2°C about 10–20 years before the global mean temperature.

12
13 In general, these transitional climate regions also show the largest spread in temperature extremes response,
14 likely related to the impact of the soil moisture-temperature coupling for the overall response. This spread is
15 due to both intermodel variations in the representation of drying trends (Greve and Seneviratne, 2015;
16 Orłowsky and Seneviratne, 2013)(see also Section 3.3.4) and to differences in soil moisture-temperature
17 coupling in climate models (Seneviratne et al., 2013; Sippel et al., 2016; Stegehuis et al., 2013), whereby
18 feedbacks with clouds and surface radiation are also relevant (Cheruy et al., 2014). Furthermore, in some
19 regions internal climate variability can also explain the spread in projections (Deser et al., 2012). Regions
20 with the most striking spread in projections of hot extremes include Central Europe, with projected regional
21 TXx warming at 1.5°C ranging from 1°C to 5°C warming, and Central North America, which displays
22 projected changes at 1.5°C global warming ranging from no warming to 4°C warming (Figure 3.8).

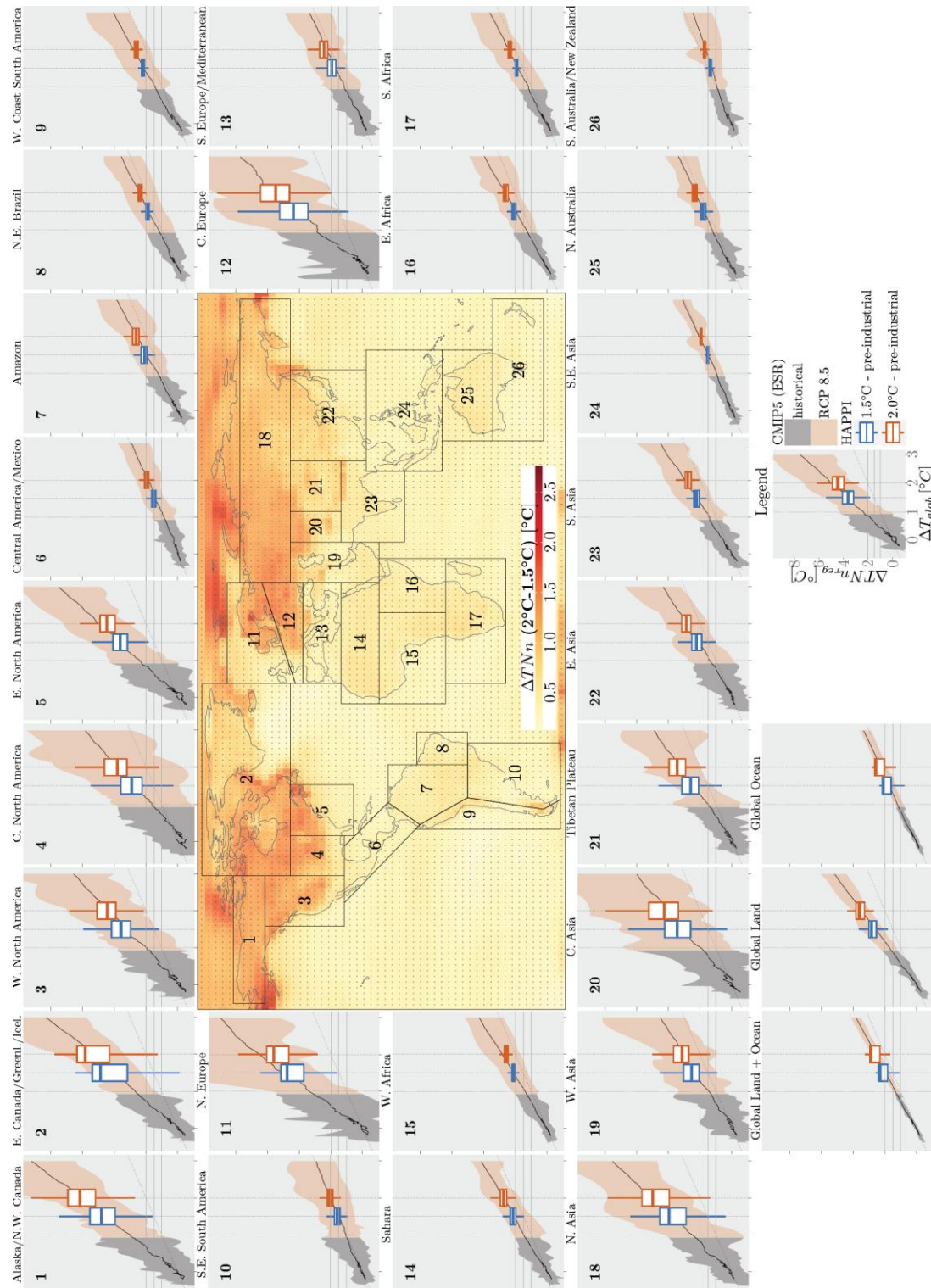
23
24 Regarding results from regional studies, Vautard et al. (2014) report that most of Europe will experience
25 higher warming than the global average with strong distributional patterns across Europe for global warming
26 of 2°C, which is consistent with the present assessment for 1.5°C warming (Jacob et al, in review). For
27 instance, a North–South (West–East) warming gradient is found for summer (winter) along with a general
28 increase and summer extreme temperatures.

29
30 It should be noted that recent evidence suggests that climate models overestimate the strength of soil
31 moisture-temperature coupling in transitional climate regions, although it is not clear if this behavior would
32 lead to an overestimation of projected changes in hot temperatures (Sippel et al., 2016). In addition, there are
33 discrepancies in projections from regional vs. global climate models in Europe, possibly due to differences in
34 prescribed aerosol concentrations (Bartók et al., 2017).

35
36 While the above-mentioned hot spots of changes in temperature extremes are located in transitional climate
37 regimes between dry and wet climates, a recent study has also performed a separate analysis of changes in
38 temperature extremes between ‘drylands’ and ‘humid’ lands, defining the first category based on mean
39 precipitation lower than 600 mm and the ratio of mean precipitation to potential evaporation (P/PET) being
40 lower than 0.65 (Huang et al., 2017). This study identifies that warming is much larger in drylands compared
41 to humid lands (by 44%), although the latter are mostly responsible for greenhouse gas emissions that
42 underlie this change.

43
44 Figure 3.9 displays similar analyses as Figure 3.8 but for the annual minimum nighttime temperatures, TNn.
45 The mean response of these cold extremes displays less discrepancy with the global levels of warming (often
46 close to the 1:1 line in many regions), however, there is a clear amplified warming in regions with snow and
47 ice cover. This is expected given the Arctic warming amplification (Serreze and Barry, 2011), which is to a
48 large extent due to snow-albedo-temperature feedbacks (Hall and Qu, 2006). In some regions and for some
49 model simulations, the warming of TNn at 1.5°C global warming can reach up to 8°C regionally (e.g.,

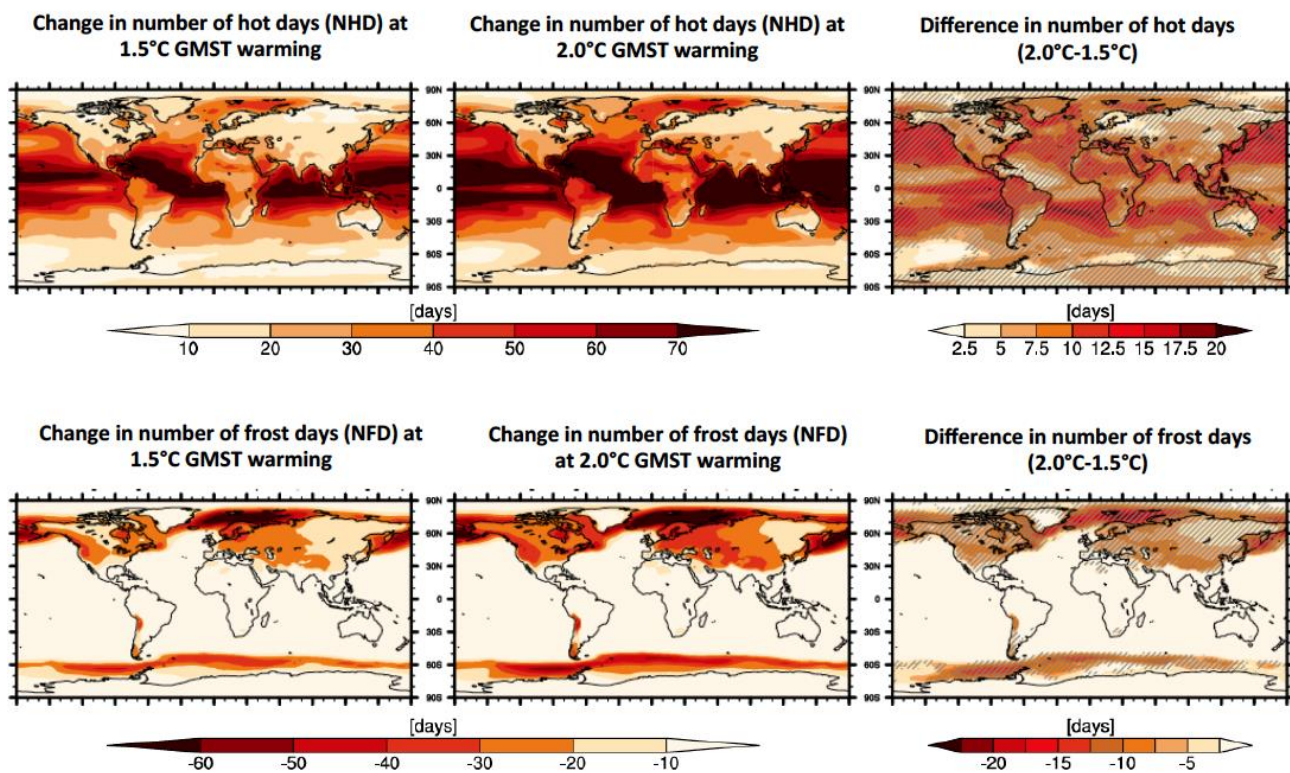
1 Northern Europe, Figure 3.9) and thus be much larger than the global temperature warming.
2



3 **Figure 3.9:** Projected changes in annual minimum nighttime temperature (TNn) as function of global temperature
4 warming for IPCC SREX regions, based on empirical scaling relationship applied to CMIP5 data (adapted
5

1 from Seneviratne et al., 2016 and Wartenburger et al., 2017) together with projected changes from the
 2 HAPPI multi-model experiment (Mitchell et al., 2017b) (bar plots on regional analyses and central plot).
 3 After Seneviratne et al.

4
 5 Figure 3.10 displays maps of changes in the number of hot days (NHD) and number of frost days (NFD) at
 6 1.5°C and 2°C global mean surface temperature warming. These analyses reveal clear patterns of changes
 7 between the two warming levels. For the number of hot days, the largest differences are found in the tropics
 8 due to the lower interannual temperature variability (Mahlstein et al., 2011), and despite the tendency for
 9 higher absolute changes in temperature extremes in mid-latitudes (Figures 3.5, 3.8 and 3.9). These analyses
 10 are consistent with other recent assessments. Coumou and Robinson (2013) find that under a 1.5°C warming,
 11 already 20% of the global land area, centered in low latitude regions, is projected to experience highly
 12 unusual monthly temperatures during boreal summers (which nearly double for 2°C of global warming) are
 13 projected to occur on a regular basis.
 14



15 **Figure 3.10:** Projected changes in number of hot days (10% warmest days, top) and in number of frost days (days with
 16 $T < 0^\circ\text{C}$, bottom) at 1.5°C (left) and 2°C (right) GMST warming, and their difference (right; hatching
 17 highlights areas in which 2/3 of the models agree on the sign of change). Adapted from Wartenburger et
 18 al. (2017a).
 19
 20

21 Figure 3.11 includes an objective identification of “hot spots” / key risks in temperature indices subdivided
 22 by regions, based on the ESR approach applied to CMIP5 simulations (Wartenburger et al., 2017a). It is
 23 noted that results based on the HAPPI multi-model experiment (Mitchell et al., 2017b) display similar results
 24 (Seneviratne et al.). The considered regions follow the classification of the IPCC SREX report (IPCC, 2012a;
 25 Seneviratne et al., 2012) and also include the global land. The figure displays red shading for all instances in
 26 which a significant difference is found between regional responses at 1.5°C vs. 2°C.
 27

1 Based on these analyses, the following can be stated. Significant changes in responses are found in all
 2 regions, for most temperature indices, with the exception of i) the diurnal temperature range (DTR) in most
 3 regions, of ii) ice days (ID), frost days (FD), and growing season length (GSL) in mostly warm regions, and
 4 of iii) the minimum yearly value of the maximum daily temperature (TXn) in very few regions. In terms of
 5 the sign of the changes, it can be seen that warm extremes display an increase in intensity, frequency and
 6 spell length (e.g., increase of the temperature of the hottest day of the year (TXx) in all regions, increase of
 7 proportion of days above 90th percentile of Tmax (TX90p) in all regions, increase of the length of the warm
 8 spell duration index (WSDI) in all regions), while cold extremes display a decrease in intensity, frequency
 9 and spell length (e.g., increase of the temperature of the coldest night of the year (TNn) in all regions,
 10 decrease in the proportion of days below the 10th percentile of Tmin (TN10p), decrease in the length of the
 11 cold spell duration index (CSDI) in all regions). Hence, while warm extremes are intensified, it should also
 12 be noted that cold extremes become less intense in affected regions.
 13

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

14
 15
 16 **Figure 3.11:** Significance of differences of regional mean temperature and range of temperature indices between the
 17 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: T: mean temperature; CSDI:
 18 Cold Spell Duration Index; DTR: Diurnal Temperature Range; FD: Frost Days; GSL: Growing Season
 19 Length; ID: Ice Days; SU: Summer Days; TN10P: Proportion of days with minimum temperature (TN)
 20 below 10th percentile of TN; TN90p: Proportion of days with TN higher than 90th percentile TN; TNn:
 21 minimum yearly value of TN; TNx: maximum yearly value of TN; TR: Tropical Nights; TX10p:

1 Proportion of days with maximum Temperature (TX) lower than 10th percentile of TX; TX90p: Proportion
2 of days with TX higher than 90th percentile of TX; TXn: minimum yearly value of TX; TXx: maximum
3 yearly value of TX; WSDI: Warm Spell Duration Index. Columns indicate analysed regions and global
4 land (see Annex 3.1 Figure 3.8 for definition). Significant differences are shown in red shading (increases
5 indicated with + sign, decreases indicated with – sign), insignificant differences are shown in grey
6 shading. Significance is tested using a two-sided paired Wilcoxon test ($p=0.01$, after controlling the false
7 discovery rate according to Benjamini and Hochberg (1995)) (adapted from Wartenburger et al., 2017).
8

9 Regarding projections of changes in temperature in cities, few studies have been conducted on the combined
10 effect of UHI and global warming. A small number of studies have used km-scale regional climate models
11 to investigate this for selected cities (Argüeso et al., 2014; Conlon et al., 2016; Georgescu et al., 2012;
12 Grossman-Clarke et al., 2017; Kusaka et al., 2016). In general, these studies find that the UHI remains in a
13 future warmer climate with increases in UHI intensity occurring due to increases in population and city size.
14 The impact on humans depends on humidity as well as temperature changes. The first studies to look
15 explicitly at these effects (Argüeso et al., 2015; Suzuki-Parker et al., 2015) suggest the possibility that future
16 global warming and urban expansion could lead to greater heat stress extremes.
17

18 Matthews et al. (2017) assessed projected changes in the occurrence of deadly heatwaves in cities at 1.5°C,
19 2°C and higher levels of global warming in megacities. The study used global climate model simulations,
20 and integrated the effects of UHI as well as of relative humidity on human heat stress. Matthews et al. (2017)
21 conclude that even if global warming was held below 2°C, there would already be a substantial increase in
22 the occurrence of deadly heatwaves in cities, and that the impacts would be similar at 1.5°C and 2°C for
23 considered megacities, but substantially larger than under the present climate. They assess in particular that
24 twice as many megacities (such as Lagos, Nigeria, and Shanghai, China) could become heat stressed
25 compared to present, exposing more than 350 million more people to deadly heat stress by 2050 under a
26 midrange population growth scenario, with only 1.5°C of global warming. Matthews et al. (2017) also
27 conclude that Karachi (Pakistan) and Kolkata (India) could have conditions equivalent to their deadly 2015
28 heatwaves every year at 2°C global warming. While the study already highlights substantial risks of deadly
29 heat in megacities at 1.5°C global warming, it also suggests that the changes at 1.5°C and 2°C global
30 warming would still be substantially less than the outcomes of higher levels of global warming (e.g., global
31 warming of 2.7°C or 4°C).
32

33 Another study for key European cities shows that stabilising climate at 1.5°C would decrease extreme
34 temperature-related mortality by 15-22% per summer compared with stabilisation at 2°C, assuming
35 no adaptation and constant vulnerability (Mitchell et al.). Jacob et al. show an increase of heat waves across
36 Europe with 1.5°C and 2°C of global warming. The likelihood of a one-in-20-year-event in selected cities is
37 increasing by a factor of 5 to 10 (depending on the city and assumed global warming), with small differences
38 between 1.5°C and 2°C global warming, but with a substantial increase compared to 1971 to 2000. As a
39 caveat on both studies (Matthews et al., 2017; Mitchell et al.), it should be noted, nonetheless, that such
40 projections do not integrate adaptation to projected warming, for instance cooling that could be achieved
41 with more reflective roofs and urban surfaces overall (Akbari et al., 2009; Oleson et al., 2010). Pfeifer et al.,
42 also find an increasing the number of people at risk in Europe under global warming of 1.5°, 2° and 3°C by
43 combining projected increase in tropical nights and summer intense precipitation days with population
44 density. Downscaling results of the HAPPI multi-model experiment (Mitchell et al., 2017b) for Europe reveal
45 a distinct difference in near surface atmospheric temperature above 28°C with 0.5°C more warming (Sieck).
46
47
48

3.3.2.3 Summary

In summary, there are statistically significant differences in temperature means and extremes at 1.5°C vs 2°C global warming, both in the global average (Schleussner et al., 2016e) as well as in most land regions (Seneviratne et al.; Wartenburger et al., 2017a). Increases of this magnitude in global mean temperature will have an exaggerated effect on regional land-based heat extremes (Seneviratne et al., 2016), in particular in Central and Eastern North America, Central and Southern Europe, the Mediterranean, Western and Central Asia, and Southern Africa. These regions have a strong soil-moisture-temperature coupling in common (Vogel et al., 2017) leading to increased dryness and, consequently, a reduction in evaporative cooling. Some of these regions also show a wide range of responses to temperature extremes, in particular Central Europe and Central North America. The number of hot days is another index of temperature extremes, and shows the largest differences between 1.5 and 2.0°C in the tropics because of their low interannual temperature variability (Mahlstein et al., 2011). A warming of 2°C vs 1.5°C leads to more frequent and more intense hot extremes in most land regions, as well as to longer warm spells. On the other hand, cold extremes would become less intense and less frequent, and cold spells would be less extended. Published literature shows that impacts of global warming to 1.5°C and 2.0 C on cities would include a substantial increase in the occurrence of deadly heatwaves compared to the present-day (Matthews et al., 2017; Mitchell et al.). A study for megacities suggests that this effect would be similar for warming of 1.5 and 2.0 C (Matthews et al., 2017), and increase substantially above 2°C global warming. However, in some other urban regions, there would be significant changes between 1.5°C and 2°C global warming as well (Jacob et al.; Mitchell et al.; Pfeifer et al.)

3.3.3 Regional precipitation, including heavy precipitation and monsoons

This section addresses regional changes in precipitation on land, with a focus on heavy precipitation and consideration of changes in the key features of monsoons. As discussed in Section 3.3.1, observed and projected changes in precipitation are more uncertain than for temperature.

3.3.3.1 Observed and attributed changes in regional precipitation

Bindoff et al. (2013) concluded in AR5 (for land regions with sufficient observations) that the largest differences in mean precipitation, between models with and without anthropogenic forcings, was at the high latitudes of the Northern Hemisphere. In these regions, increases in precipitation are a robust feature of climate model simulations forced by elevated greenhouse gas levels. There was *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al., 2013b) in land regions where observational coverage is sufficient for assessment. The IPCC SREX (Seneviratne et al., 2012) assessed that it is *likely* that there have been statistically significant increases in the number of heavy precipitation events (e.g., 95th percentile) in more regions than there have been statistically significant decreases. Their consensus also highlighted that there are strong regional and subregional variations in the trends (Seneviratne et al., 2012). Further, it highlighted that many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The SREX assessed that the overall most consistent trends toward heavier precipitation events are found in North America (*likely* increase over the continent). It provided further detailed regional assessments of observed trends in heavy precipitation (Seneviratne et al., 2012).

SREX assessed that there is *low confidence* in trends for monsoons because of insufficient evidence (Seneviratne et al., 2012). There are a few new assessments available (Singh et al., 2014) which use precipitation observations (1951–2011) of the South Asian summer monsoon and show that there have been

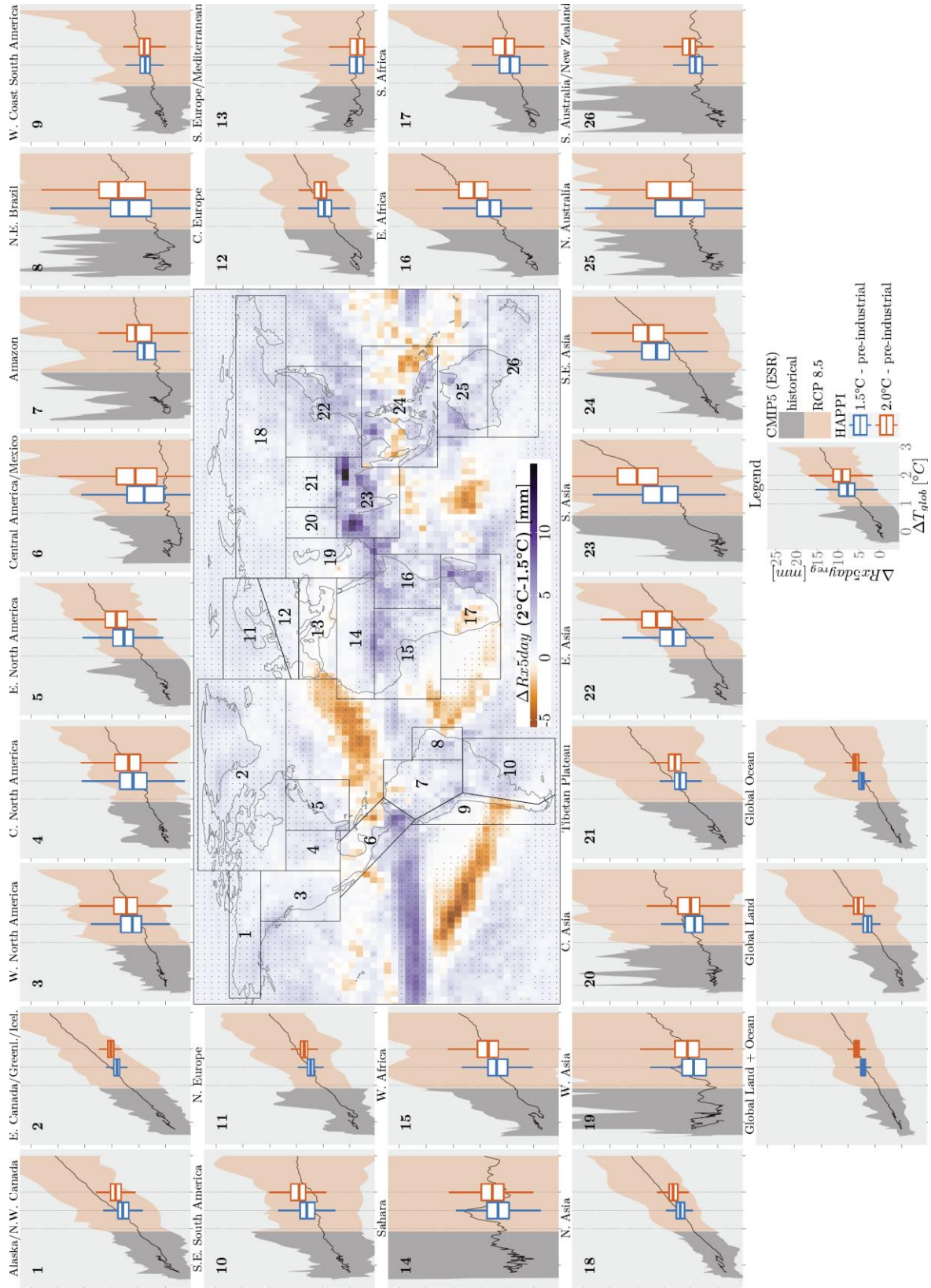
1 significant decreases in peak-season precipitation over the core-monsoon region and significant increases in
2 daily-scale precipitation variability. However, there is not sufficient evidence to revise the SREX assessment
3 of *low confidence* in overall observed trends in monsoons.

4 5 3.3.3.2 Projected changes at 1.5°C vs. 2°C in regional precipitation

6 Section 3.3.1.2 summarizes the projected changes in mean precipitation displayed in Figure 3.6. Some other
7 evaluations are also available for regions across the world. For instance, Déqué et al. (2016) investigates the
8 impact of a 2°C global warming on precipitation over tropical Africa and found that average precipitation
9 does not show a significant response due to two compensating phenomena: (a) the number of rain days
10 decreases whereas the precipitation intensity increases, and (b) the rainy season occurs later during the year
11 with less precipitation in early summer and more precipitation in late summer. The assessment of
12 insignificant differences between 1.5°C and 2°C scenarios for tropical Africa is consistent with the results of
13 Figure 3.6. For Europe, for 2°C global warming, a robust increase of precipitation over Central and Northern
14 Europe in winter and only over Northern Europe in summer, and decreases of precipitation in
15 Central/Southern Europe in summer, with changes reaching 20% have been reported by Vautard et al. (2014)
16 and is more pronounced than with +1.5°C global warming (Jacob et al.).

17
18 Regarding changes in heavy precipitation, Figure 3.12 displays projected changes in the five-day maximum
19 precipitation (Rx5day) as a function of global temperature increase, using a similar approach as in Figures
20 3.8 and 3.9. This analysis shows that projected changes in heavy precipitation are more uncertain than for
21 temperature extremes. However, the mean response of model simulations is generally robust and linear (see
22 also Fischer et al., 2014; Seneviratne et al., 2016). As highlighted in Seneviratne et al. (2016), this response
23 is also found to be mostly independent of the considered emissions scenario (e.g., RCP2.6 vs. RCP8.5). This
24 appears to be a specific feature of heavy precipitation, possibly due to a stronger coupling with temperature,
25 as the scaling of projections of mean precipitation changes with global warming shows some scenario
26 dependency (Pendergrass et al., 2015). Wartenburger et al. (2017a) suggests that for Eastern Asia, there are
27 substantial differences in heavy precipitation at 1.5°C vs. 2°C. Vautard et al. (2014) found a robust increase
28 in heavy precipitation everywhere in Europe and in all seasons, except Southern Europe in summer,
29 consistent with the analysis of Jacob et al. (2014) which used more recent scenarios (EURO-CORDEX) and
30 a higher resolution (12km) for +2°C global warming. There is a consistent agreement in the direction of
31 change for +1.5°C global warming over much of Europe (Jacob et al.; Pfeifer et al.). Downscaling results of
32 the HAPPI multi-model experiment (Mitchell et al., 2017b) for Europe show an increase in the yearly
33 maximum five-day sum of precipitation with 0.5°C more warming (Sieck). It should be noted that heavy
34 rainfall associated with tropical cyclones has been assessed to be likely to increase under increasing global
35 warming and effects of global warming have been for instance attributed to the heavy rainfall associated with
36 the Hurricane Harvey, i.e. already for 1°C of warming (Section 3.3.7). This is particularly important in
37 coastal areas.

1



1 **Figure 3.12:** Projected changes in annual five-day maximum precipitation (Rx5day) as function of global temperature
2 warming for IPCC SREX regions, based on empirical scaling relationship applied to CMIP5 data (adapted
3 from Seneviratne et al. 2016 and Wartenburger et al. 2017) together with projected changes from the
4 HAPPI multi-model experiment (Mitchell et al., 2017b) (bar plots on regional analyses and central plot).
5 After Seneviratne et al.
6

7 At the time of the IPCC SREX report, the assessment was that there was *low confidence* in overall projected
8 changes in monsoons (for high-emissions scenarios) because of insufficient agreement between climate
9 models (Seneviratne et al., 2012). There are a few publications that provide more recent evaluations on
10 projections of changes in monsoons for high-emissions scenarios. Jiang and Tian (2013), who compared the
11 results of 31 and 29 reliable climate models under the SRES A1B scenario or the RCP4.5 scenario,
12 respectively, found weak projected changes in the East Asian winter monsoon as a whole relative to the
13 reference period (1980–1999). Regionally, they found a weakening north of about 25°N in East Asia and a
14 strengthening south of this latitude, which resulted from atmospheric circulation changes over the western
15 North Pacific and Northeast Asia. This is linked to the weakening and northward shift of the Aleutian Low,
16 and from decreased northwest-southeast thermal and sea level pressure differences across Northeast Asia. In
17 summer, Jiang and Tian (2013) found a projected strengthening (albeit, slight) of monsoon in East China
18 over the 21st century as a consequence of an increased land-sea thermal contrast between the East Asian
19 continent and the adjacent western North Pacific and South China Sea. Using six CMIP5 model simulations
20 of the RCP8.5 high-emission scenario, Jones and Carvalho (2013) found a 30% increase in the amplitude of
21 the South American Monsoon System (SAMS) from the current level by 2045–50. They also found an
22 ensemble mean onset date of the SAMS which was 17 days earlier, and a demise date 17 days later, by
23 2045–2050. The most consistent CMIP5 projections analysed confirmed the increase in the total
24 precipitation over southern Brazil, Uruguay, and northern Argentina. Given that scenarios at 1.5°C or 2°C
25 would include a substantially smaller radiative forcing than those assessed in the studies of Jiang and Tian
26 (2013) and Jones and Carvalho (2013), there is *low confidence* regarding changes in monsoons at these low
27 global warming levels, as well as regarding differences in responses at 1.5°C vs. 2°C.
28

29 Several analyses of GCM-RCM simulations in the framework of the COordinated Downscaling EXperiment
30 for Africa (CORDEX-AFRICA) were performed to capture changes in the African climate system in a
31 warmer climate. Sylla et al. (2015, 2016) analyzed the response of the annual cycle of high-intensity daily
32 precipitation events over West Africa to anthropogenic greenhouse gas for the late twenty-first century. The
33 late-twenty-first-century projected changes in mean precipitation exhibit a delay of the monsoon season and
34 a decrease in frequency but increase in intensity of very wet events, particularly in the premonsoon and early
35 mature monsoon stages, more pronounced in RCP8.5 over the Sahel and in RCP4.5 over the Gulf of Guinea.
36 The premonsoon season also experiences the largest changes in daily precipitation statistics, with increased
37 risk of drought associated with a decrease in mean precipitation and frequency of wet days and an increased
38 risk of flood associated with very wet events. Weber et al. assessed the changes in temperature and rainfall
39 related climate change indices in a 1.5°C, 2°C and 3°C global warming world for the Africa continent. The
40 results showed that even if the global temperature will be kept below 2°C, there is an increase in hot nights
41 and longer and more frequent heat waves, particularly for regions between 15°S and 15°N. These effects
42 intensify if the global mean temperature exceeds the 2°C threshold. The daily rainfall intensity is also
43 expected to increase for higher global warming scenarios especially for the African Sub-Saharan coastal
44 regions.
45

46 Similarly, as for Figure 3.11, Figure 3.13 includes an objective identification of “hot spots” / key risks in
47 heavy precipitation indices subdivided by regions, based on Wartenburger et al. (2017a). The considered
48 regions follow the classification of the IPCC SREX report (IPCC, 2012a; Seneviratne et al., 2012) and also
49 include global land areas. The figure displays red shading for all instances in which a significant difference is

1 found between regional responses at 1.5°C vs 2°C.

2

3 Hot spots displaying statistically significant changes in heavy precipitation between 1.5°C and 2°C global
 4 warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern
 5 Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including
 6 China and Japan) and in Eastern North America. Results are less consistent for other regions. Note that
 7 analyses for meteorological drought (lack of precipitation) are provided in Section 3.3.4.
 8

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

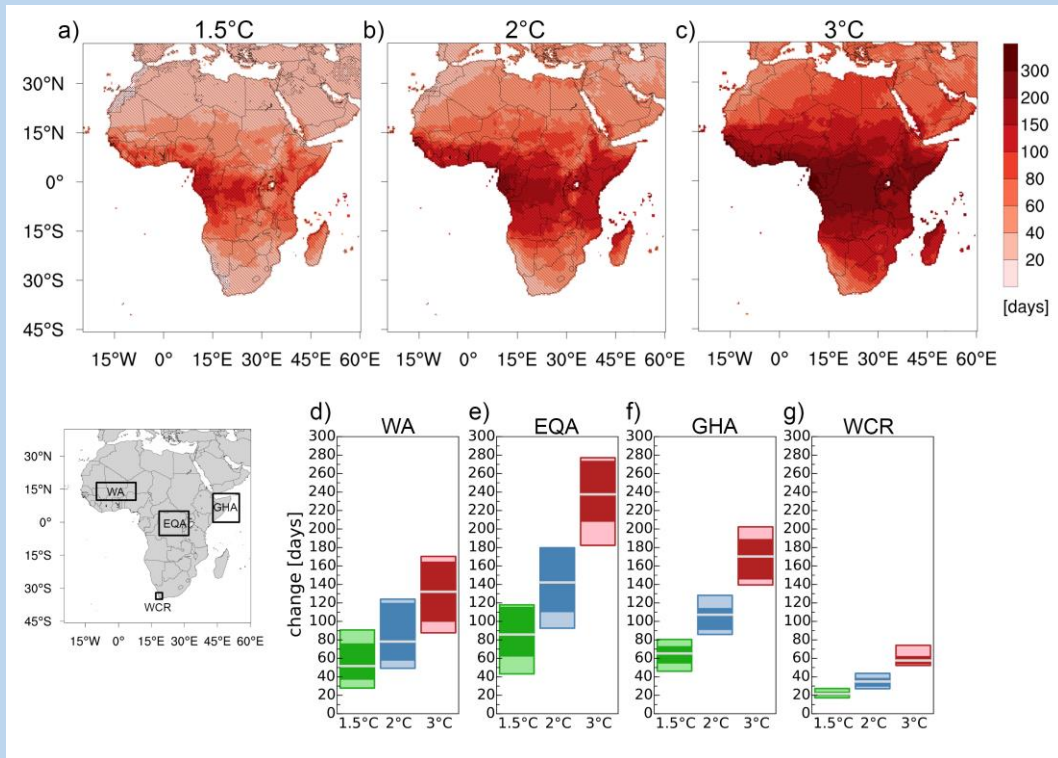
9 **Figure 3.13:** Significance of differences of regional mean precipitation and range of precipitation indices between the
 10 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: PRCPTOT: mean
 11 precipitation; CWD: Consecutive Wet Days; R10mm: Number of days with precipitation > 10mm;
 12 R1mm: Number of days with precipitation > 1mm; R20mm: Number of days with precipitation > 20mm;
 13 R95ptot: Proportion of rain falling as 95th percentile or higher; R99ptot: Proportion of rain falling as 99th
 14 percentile or higher; RX1day: Intensity of maximum yearly 1-day precipitation; RX5day: Intensity of
 15 maximum yearly 5-day precipitation; SDII: Simple Daily Intensity Index. Columns indicate analysed
 16 regions and global land (see Fig. 3.3.13.XXXd for definition). Significant differences are shown in red
 17 shading (increases indicated with + sign, decreases indicated with – sign), insignificant differences are
 18 shown in grey shading. Significance is tested using a two-sided paired Wilcoxon test (p=0.01, after
 19 controlling the false discovery rate according to Benjamini and Hochberg (1995)). Adapted from
 20 Wartenburger et al. (2017).
 21
 22
 23

24 **3.3.3.3 Summary**

25 Projections for heavy precipitation are less robust than for temperature means and extremes. However,
 26 several regions display statistically significant differences in heavy precipitation at 1.5°C vs. 2°C warming
 27 (with stronger increase at 2°C ; (Wartenburger et al. 2017; Seneviratne et al.), and there is a global tendency
 28 towards increases in heavy precipitation on land between these two temperature levels (Fischer and Knutti,
 29 2015; Schleussner et al., 2016e). Southern Asia is a hot spot for increases in heavy precipitation between
 30 these two global temperature levels (Schleussner et al., 2016e; Seneviratne et al., 2016). Overall, regions that
 31 display statistically significant changes in heavy precipitation between 1.5°C and 2°C global warming are
 32 found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe,
 33 Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including China and
 34 Japan) and in Eastern North America. Results are less consistent for other regions.

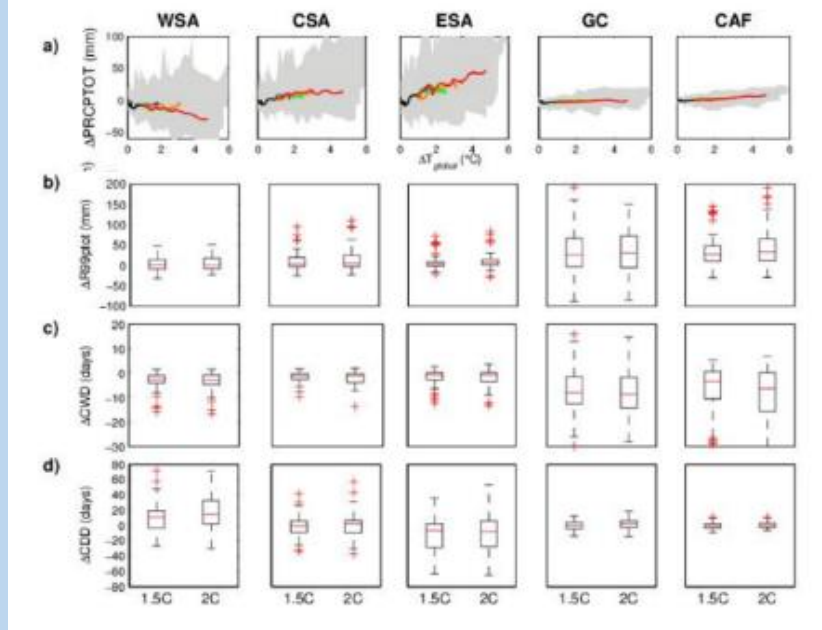
[START BOX 3.2 HERE]

Box 3.2: Sub Saharan Africa



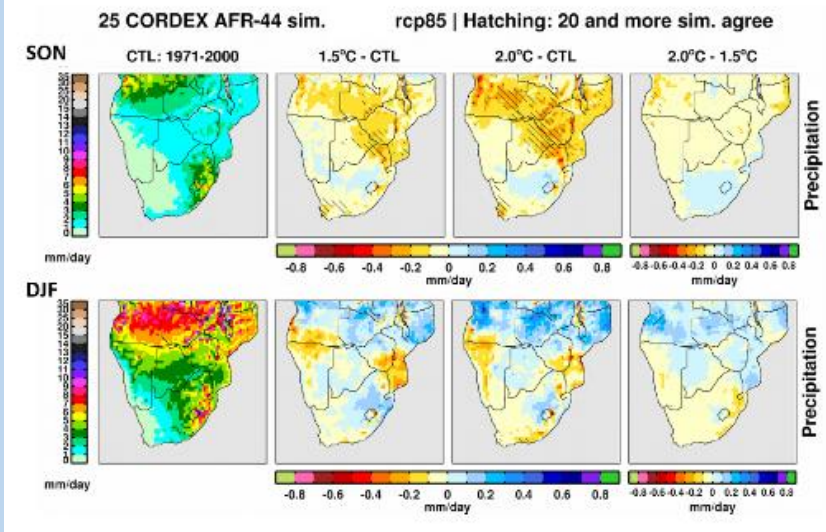
Box 3.2, Figure 1: Projected changes of mean annual hot nights [days] by the regional model ensemble: Spatial distribution of median for a) 1.5°C, b) 2°C and c) 3°C global warming scenario. Dotted areas indicate the exceedance of the single standard deviation; hatched areas indicate the exceedance of the double standard deviation. Ensemble minimum/maximum (light color), 17th and 83th percentile (dark color) and median (grey) as field means for the focus regions d) West Africa, e) Equatorial Africa, f) Greater Horn of Africa and g) Western Cape Region. The colors of the boxes indicate the 1.5°C (green), 2°C (blue) and 3°C (red) global warming scenario. Source: Weber et al.

At regional scales, temperature increases in the Africa Continent are projected to be higher than the global mean temperature increase (at global warming of 1.5°C and at 2°C). The African continent, in particular the regions between 15°S and 15°N, will see an increase in hot nights as well as longer and more frequent heat waves, even if the global temperature are kept below 2°C. These effects intensify if the global mean temperature exceeds 2°C of global warming.



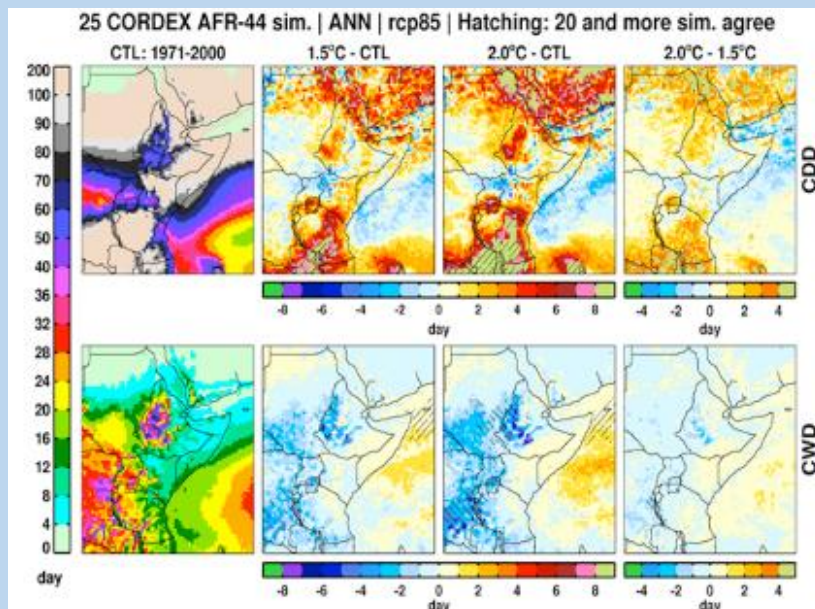
Box 3.2, Figure 2: Scaling plots and box plots for 1.5°C and 2°C global mean temperature warming. Top: Scaling plots of ΔT_g against regional temperature ΔT (in y axis labels) averaged across the WAF domain (top) and all of its subregions: Western Sahel (WSA), Central Sahel (CSA), Eastern Sahel (ESA), Guinea Coast (GC), and Central Africa (CAF). Bottom rows: Regional responses to a global temperature increase of 1.5°C and 2°C of R99ptot (contribution of very wet days ie 99eme percentile), consecutive wet days (ΔCWD) et consecutive dry days (ΔCDD). The upper and lower hinges of the box plots represent the first and third quartile. The whiskers extend to the highest (lowest) value that is within 1.5 times the interquartile range of the upper (lower) hinge. Source: Diedhiou et al.

Over West and Central Africa, there are several uncertainties and a large ensemble spread in the projections of precipitation indices, mainly in the Central and Eastern Sahel. Most models, however, show weak change in the total precipitation and a decrease of the length of wet spells with an increase of heavy rainfall over the Guinea Coast and Central Africa. Western Sahel is projected by most models to experience the strongest drying with a significant increase in the length of dry spells. This is coherent with (Klutse et al.).



1
2 **Box 3.2, Figure 3:** September-October-November (SON, top) and December-January-February (DJF, bottom)
3 historical (first column) and projected changes in temperature (top row) and precipitation (bottom
4 row) over land in southern Africa under RCP8.5 for 1.5 and 2 degrees global warming. Source
5 Maúre et al.
6

7 Over southern Africa, models agree in a positive sign of change for temperature, with temperature rising
8 faster at 2°C (1.5–2.5°C) compared to 1.5°C (0.5–1.5°C). Areas of the south-western region, especially in
9 South Africa and parts of Namibia and Botswana are expected to experience the highest increases in
10 temperature. On the other hand, models based on 1.5°C exhibit a robust signal of precipitation reduction over
11 the Limpopo basin and smaller areas of the Zambezi basin, in Zambia, as well as in parts of Western Cape, in
12 South Africa, while an increase is projected over central and western South Africa as well as in southern
13 Namibia. The region is projected to face robust precipitation decreases of around 10–20% accompanied by
14 increases in length of consecutive dry days at 2°C of global warming.
15



16
17 **Box 3.2, Figure 4:** Annual changes in CDD (first row) and CWD (second row) under 1.5°C and 2.0°C global warming

1 relative to 1971–2000 historical period based on 25 CORDEX rcp85 simulations. First column
2 indicates the number of CCD and CWD for control climate (CTL). Second and third columns show
3 projected changes in CDD and CWD between future and present under 1.5°C and 2°C global
4 warming periods, respectively. Fourth column shows differences in CDD and CWD between 2°C
5 and 1.5°C. Hatching denotes areas where 20 and more simulations agree on changes. Source: Osima
6 et al.

7
8 Annual, rainfall projections show a robust wetting signal over Somalia and a less robust decrease over
9 central and northern Ethiopia in the Greater Horn of Africa. Within rainy seasons the length of Consecutive
10 Dry Days (CDD) and Consecutive Wet Days (CWD) spells are projected to increase and decrease
11 respectively.

12
13 **[END BOX 3.2 HERE]**

14 15 16 **3.3.4 Drought and dryness**

17 18 **3.3.4.1 Observed and attributed changes**

19 The IPCC SREX assessed that there is *medium confidence* that some regions of the world have experienced
20 more intense and longer droughts, in particular in southern Europe and West Africa, but that opposite trends
21 also exist in other regions (Seneviratne et al., 2012). Assessment of the literature indicates that there is
22 *medium confidence* that anthropogenic influence has contributed to some changes in the drought patterns
23 observed in the second half of the 20th century and based on its attributed impact on precipitation and
24 temperature changes. It is important to note, however, that temperature can only be indirectly related to
25 drought trends (e.g., Sheffield et al. 2012). However, there was *low confidence* in SREX in the attribution of
26 changes in droughts at the level of single regions due to inconsistent or insufficient evidence (Seneviratne et
27 al., 2012). Recent analyses have not provided support for the detection of increasing drying in dry regions
28 and increasing wetting in wet regions, except in high latitudes (Greve et al., 2014), thus revising the AR5
29 assessment (Hartmann et al., 2013) on this point.

30
31 Because of the uncertainty in the detection of observed changes in droughts over the whole historical record
32 (i.e. for close to 1°C warming, see above), the level of confidence in the attribution of changes in regional
33 drought is generally expected to be *low*, and at most *medium* for global assessments. For this reason,
34 observed trends can generally not be used to infer possible changes in dryness associated with a further
35 0.5°C or 1°C warming. However, it should be noted that recent publications based on observational and
36 modeling evidence assessed that human emissions have substantially increased the probability of drought
37 years in the Mediterranean region (Gudmundsson et al., 2017; Gudmundsson and Seneviratne, 2016).

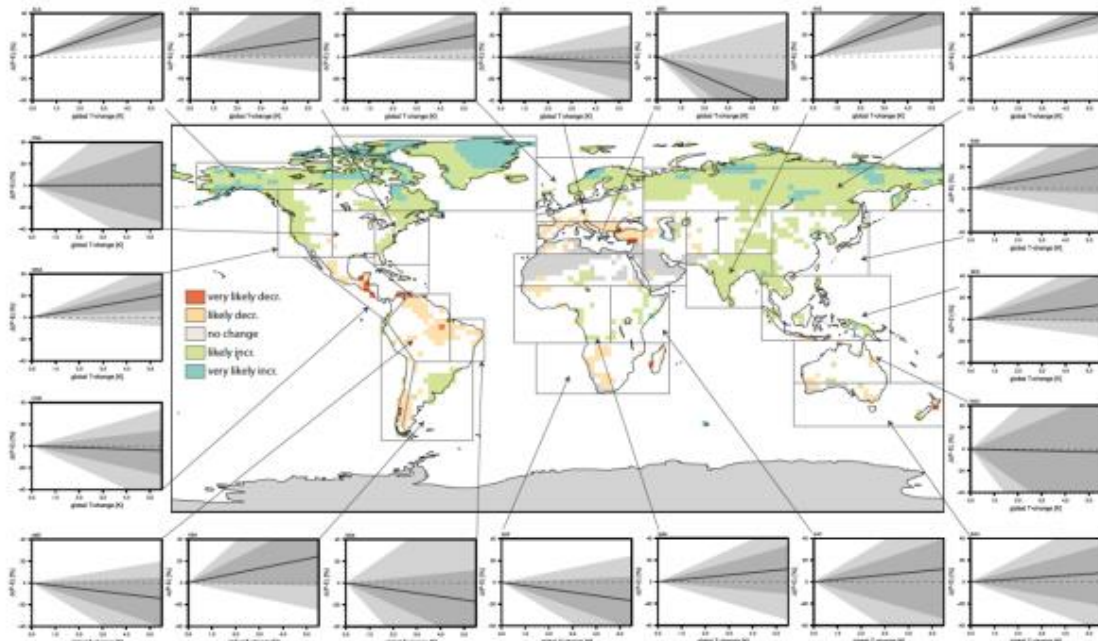
38 39 40 **3.3.4.2 Projected changes in drought and dryness at 1.5°C vs. 2°C**

41 Projections of changes in drought and dryness for high-emissions scenarios (e.g., RCP8.5 corresponding to
42 ca. 4°C global warming) are uncertain in many regions, and also dependent on the drought indices
43 considered (e.g., Seneviratne et al. 2012; Orłowsky and Seneviratne 2013). Uncertainty is thus expected to
44 be even larger for conditions of smaller signal-to-noise ratio such as for global warming levels of 1.5°C and
45 2°C.

46
47 Some submitted and published literature is now available on the evaluation differences in drought and
48 dryness occurrence at 1.5°C and 2°C global warming for a) precipitation-evapotranspiration (P-E, i.e. as a
49 general measure of water availability; Greve et al. 2017; Wartenburger et al. 2017), b) soil moisture

1 anomalies (Lehner et al., 2017; Wartenburger et al., 2017a) c) consecutive dry days (Schleussner et al.,
 2 2016d; Wartenburger et al., 2017a) d) the 12-month Standardized Precipitation Index (Wartenburger et al.,
 3 2017a), e) the Palmer-Drought Severity Index (Lehner et al., 2017), f) annual mean runoff (Schleussner et
 4 al., 2016d), see also next section). These analyses are overall consistent, despite the known sensitivity of
 5 drought assessment to chosen drought indices (see above).

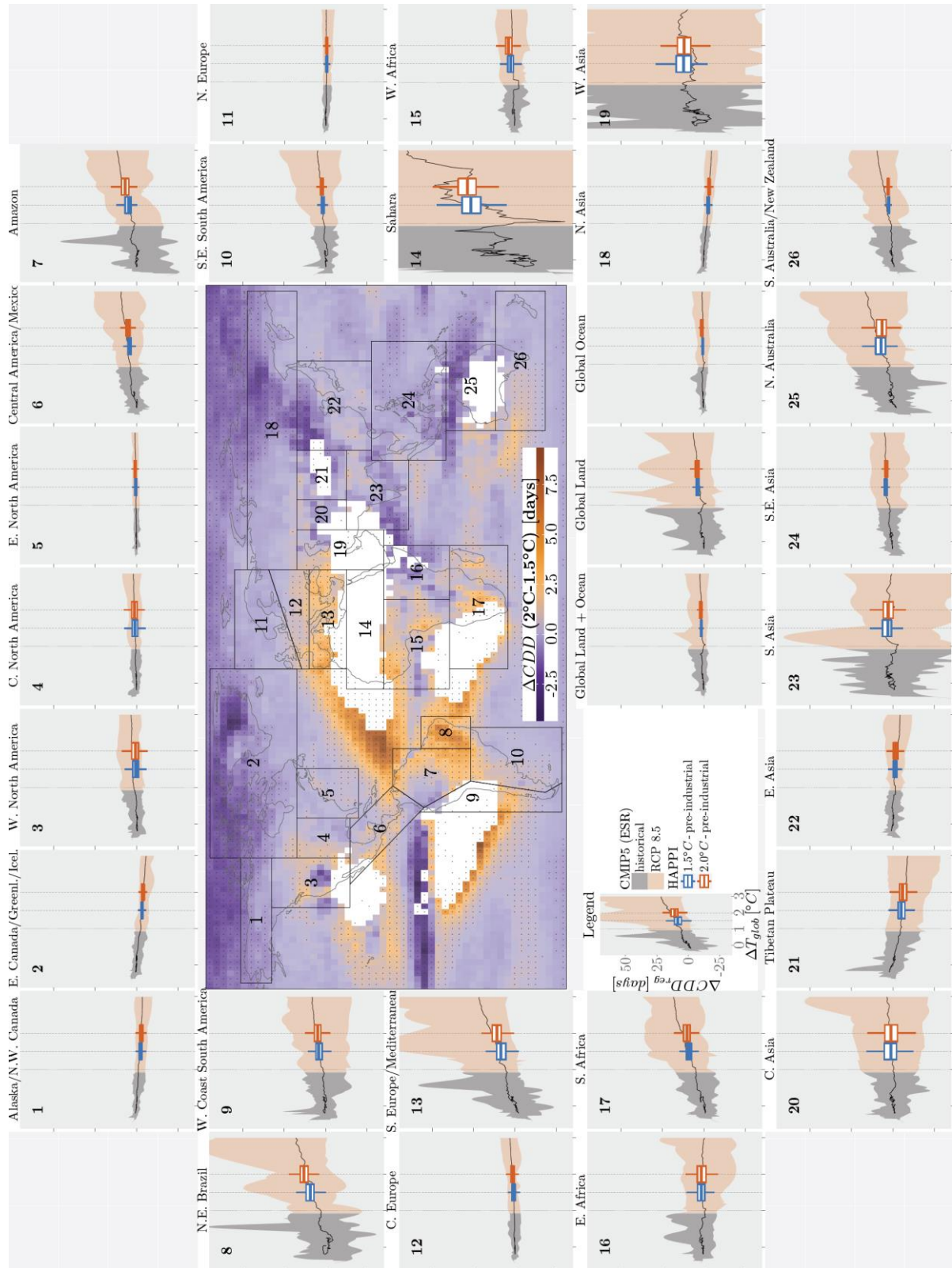
6
 7 Figure 3.14 from Greve et al. (2017), derives the sensitivity of regional changes in precipitation minus
 8 evapotranspiration to global temperature changes. The analysed simulations span the full range of available
 9 emissions scenarios and the sensitivities are derived using a modified pattern scaling approach. The applied
 10 approach assumes linear dependencies on global temperature changes while thoroughly addressing
 11 associated uncertainties via resampling methods. Northern high latitude regions display robust responses
 12 towards increased wetness, while subtropical regions display a tendency towards drying but with a large
 13 range of responses. Even though both internal variability and the scenario choice play an important role in
 14 the overall spread of the simulations, the uncertainty stemming from the climate model choice usually
 15 accounts for about half of the total uncertainty in most regions Greve et al. (2017). An assessment of the
 16 implications of limiting global mean temperature warming to values below (i) 1.5°C or (ii) 2°C show that
 17 opting for the 1.5°C-target might just slightly influence the mean response, but could substantially reduce the
 18 risk of experiencing extreme changes in regional water availability (Greve et al., 2017).



20
 21 **Figure 3.14:** Summary of the likelihood of increases/decreases in P-E considering all climate models and all scenarios.
 22 Panel plots show the uncertainty distribution of the sensitivity of P-E to global temperature change as a
 23 function of global mean temperature change averaged for each SREX regions outlined in the map (from
 24 Greve et al., 2017).

25
 26 The analysis for the mean response is also qualitatively consistent with results from Wartenburger et al.
 27 (2017a), which uses an empirical scaling relationship (ESR) rather than pattern scaling for a range of drought
 28 and dryness indices, as well as with a recent assessment of Lehner et al. (2017) which considers changes in
 29 droughts assessed from the soil moisture changes and from the Palmer-Drought Severity Index. We note that
 30 these two further publications do not provide a specific assessment for changes in tails of the drought and

1 dryness distribution. The conclusions of Lehner et al. (2017) are that a) risks of consecutive drought years
2 shows little change in the US Southwest and Central Plains, but robust increases in Europe and the
3 Mediterranean, and that b) limiting warming to 1.5°C may have benefits for future drought risk, but such
4 benefits are regional, and in some cases highly uncertain.
5
6 Figure 3.15 displays projected changes in consecutive dry days (CDD) as a function of global temperature
7 increase, using a similar approach as in Figures 3.8, 3.9 and 3.12 (based on Wartenburger et al., 2017a). The
8 analyses also include results from the HAPPI experiment (Mitchell et al., 2017b). Again, the CMIP5-based
9 ESR estimates and the results of the HAPPI experiment are found to agree well. We note the large disparity
10 of responses depending on the considered regions.



1
2
3

Figure 3.15: Projected changes in consecutive dry days (CDD) as function of global temperature warming for IPCC

SREX regions, based on empirical scaling relationship applied to CMIP5 data (adapted from Seneviratne et al., 2016 and Wartenburger et al., 2017a) together with projected changes from the HAPPI multi-model experiment (Mitchell et al., 2017b) (bar plots on regional analyses and central plot). After Seneviratne et al.

Similarly as for Figure 3.11, Figure 3.16 includes an objective identification of “hot spots” / key risks in dryness indices subdivided by regions, based on Wartenburger et al. (2017a). The considered regions follow the classification of the IPCC SREX report (IPCC, 2012a; Seneviratne et al., 2012) and also include the global land. The figure displays red shading for all instances in which a significant difference is found between regional responses at 1.5°C vs 2°C. This analysis reveals the following hot spots of drying, i.e. with increases in CDD, and decreases in P-E, SMA, and SPI2, with at least one of the indices displaying statistically significant drying : The Mediterranean region (MED ; including Southern Europe, northern Africa, and the near-East), Northeastern Brazil (NEB), and Southern Africa.

Overall the available literature, consistent with this analysis, report particularly strong increases in dryness and decreases in water availability in Southern Europe and the Mediterranean when shifting from a 1.5°C to a 2°C global warming (Schleussner et al. 2016; Lehner et al. 2017; Greve et al. 2017; Wartenburger et al.; Fig. 3.13). The fact that this is a region that is also already displaying substantial drying in the observational record (Greve et al., 2014; Gudmundsson et al., 2017; Gudmundsson and Seneviratne, 2016; Seneviratne et al., 2012; Sheffield et al., 2012) provides additional evidence supporting this tendency, suggesting that it is a hot spot of dryness change above 1.5°C (see also Box 3.3).

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

Figure 3.16: Similar as Figure 3.11 but for changes in dryness indices. Significance of differences of regional drought and dryness indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: CDD: Consecutive Dry Days; P-E: Precipitation minus Evaporation; SMA: Soil Moisture Anomalies; SPI12: 12-month SPI. Columns indicate regions and global land (see Figure 3.3.15 for definitions). Significant differences are shown in red shading (increases indicated with + sign, decreases indicated with - sign), insignificant differences are shown in grey shading. Significance is tested using a two-sided paired Wilcoxon test (p=0.01, after controlling the false discovery rate according to Benjamini and Hochberg (1995)) (adapted from Wartenburger et al., 2017a).

3.3.4.3 Summary

In terms of drought, limiting global warming to 1.5°C may substantially reduce the probability of extremes changes in water vailability in several regions (Greve et al., 2017). When shifting from 1.5 to 2.0°C, available studies and analyses suggest strong increases in dryness and reduced water availability in the Mediterranean region (including Southern Europe, northern Africa, and the near-East), in Northeastern Brazil, and in Southern Africa (Schleussner et al. 2015; Lehner et al. 2017; Greve et al. 2017; Wartenburger et al. 2017a, Figs. 3.15 and 3.16). Based on observations and model experiments, a drying trend is already detectable in the Mediterranean region (Gudmundsson et al., 2017; Gudmundsson and Seneviratne, 2016), i.e. for a global warming of 1°C.

1 **[START BOX 3.3 HERE]**2
3 **Box 3.3: Mediterranean Basin and the Middle East droughts**

4
5 Human society and the natural environment have developed together in the Mediterranean Basin over several
6 millennia, laying the ground for very diverse and culturally rich communities with global ramifications. Even
7 if the technology level may protect them in some way from climatic hazards, the consequences of climatic
8 changes for inhabitants of the Mediterranean continue to depend on the interplay between an array of societal
9 and environmental factors (Holmgren et al., 2016). Previous IPCC assessments and recent publications have
10 shown that the Mediterranean region (including both the northern and southern part of the Mediterranean
11 Basin) is projected to be particularly affected by regional changes in climate under increased warming,
12 including consistent climate model projections of increased drying and strong regional warming (Seneviratne
13 et al. 2012; Collins et al. 2013; Christensen et al. 2013; Greve and Seneviratne 2015; see also Section 3.3).
14 These changes are also expected at 1.5°C global warming (Section 3.3.4; Jacob et al.; Pfeifer et al.) and they
15 are consistent with currently observed changes (Greve et al., 2014; Section 3.3.4). Risks of drying in the
16 Mediterranean region can be substantially reduced if global warming is limited to 1.5°C compared to 2°C or
17 higher levels of warming (Guiot and Cramer 2016; see also Section 3.3.4).

18
19 Consistent with the highlighted projected regional climate changes in the Mediterranean region, the
20 AR5WGII Chapter 23 has shown that Southern Europe is particularly vulnerable to climate change (*high*
21 *confidence*) as multiple sectors are projected to be adversely affected under higher levels of global warming
22 (tourism, agriculture, forestry, infrastructure, energy, population health) (*high confidence*). The risk (with
23 current adaptation) related to water deficit is high for a global warming of 2°C and very high for a global
24 warming of +4°C (AR5 WGII Table 23.5). In regions affected by seasonal or chronic water scarcity,
25 agricultural yields are strongly dependent on irrigation. In North African and Middle East countries (e.g.,
26 Algeria, Morocco, Syria, Tunisia, and Yemen), the total volume of water required for yield gap closure
27 would exceed sustainable levels of freshwater consumption (i.e., 40% of total renewable surface and
28 groundwater resources; Davis et al., 2017).

29
30 This may be illustrated by the long-term history of the region of Middle East, which was recently subjected
31 to an intense and prolonged drought episode between 2007 and 2010, partly related to La Niña events
32 (Barlow et al., 2016). Very low precipitation generated a steep decline in agricultural productivity in the
33 Euphrates and Tigris drainage basins, and displaced hundreds of thousands of people, mainly in Syria. Dried
34 soils and diminished vegetation cover in the historically called ‘Fertile Crescent’ region, as evident through
35 remotely sensed enhanced vegetation indices, supported greater dust generation and transport to the Arabian
36 Peninsula in 2007–2013 (Notaro et al., 2015). Impacts have also been noticed on the water resource
37 (Yazdanpanah et al., 2016b) and the crop performance in Iran (Saeidi et al., 2017).

38
39 The Syrian up-rising of March 2011 is the outcome of complex but interrelated factors (Gleick and
40 Heberger, 2014; Kelley et al., 2015). While the main target of the multi-sided armed conflict has been a
41 political regime change, the up-rising was also triggered by a set of social, economic, religious and political
42 factors leading to a disintegration of the country, with a growing rural-urban divide, rising unemployment,
43 and growing poverty (De Châtel, 2014). For instance, population growth, poor agricultural policies,
44 aggressive liberalization policies and the influx of Iraqi refugees had all placed an unsustainable burden on
45 water resources, including rainfall and groundwater resources increasing Syria’s vulnerability in 2006–2007
46 (Kelley et al., 2015). The climate hypothesis has been contested and although causality cannot be found in
47 such a simple direct relationship (Hendrix, 2017; Selby et al., 2016), drought may have played an important
48 role in triggering the crisis, as this drought was the longest and the most intense in the last 900 years (Cook
49 et al., 2016; Mathbout et al., 2017). Recent evidence shows that the severe drought triggered agricultural

1 collapse and internal displacement of rural farm families in Syria (Kelley et al., 2017). Approximately
2 300,000 families were driven to Damascus, Aleppo and other cities by the drought causing one of the largest
3 internal displacement in the Middle East in recent years (Kelley et al., 2017).

4
5 The example of Syriacan be seen as part of a long history of societal decline and/or collapse of civilizations
6 in the Middle East. Many of these coincided with severe droughts, such as that which occurred at the end of
7 the Bronze Age, approximately 3200 years ago (Kaniewski et al., 2015). In this case, a number of flourishing
8 Eastern Mediterranean civilizations collapsed. Most of the coastal cities of Eastern Mediterranean were
9 destroyed and often left unoccupied thereafter. The rural settlements that afterwards re-emerged with agro-
10 pastoral activities and limited long-distance trade (Kaniewski et al., 2015). Even if vulnerabilities of modern
11 societies differ from those of the late Bronze Age, declines such as these illustrate the fact that drought may
12 hastenthe fall of a civilization by triggering famine, invasions and conflicts, leading to the political,
13 economic and cultural chaos.

14
15 The droughts of the 21st century and those in the Holocene are also climatically different. Trigo et al. (2010)
16 revealed that the two-fold precipitation deficit in 1998–2002 and in 2007–2009 period lead to two long
17 periods with a 10m-decrease on the water level of Lake Tharthar, the largest lake in Iraq located between the
18 Tigris and Euphrates. Impact on wheat and barley production was the highest in Iraq and Syria. Kelley et al.
19 (2015) showed that the precipitation deficit was strongly amplified by the high evapotranspiration due to
20 high temperatures, while the Holocene droughts were only due to precipitation deficits during a long period
21 (several centuries). This suggests that future precipitation reduction amplified by high temperature are of
22 high risk for the Mediterranean natural and managed ecosystems.

23
24 The evolution of the drought under 1.5°C and 2°C warming can be extrapolated by comparing of the 2008
25 drought (high temperature, low precipitation) with the 1960 drought (low precipitation, normal temperature).
26 The Palmer drought severity index (PDSI) in 2008 was –3 against –2 in 1960. With comparable precipitation
27 deficits, an index of –4 under a global warming of 1.5°C and –5 with 2°C may be expected. Even if this
28 index reflects local conditions, it is accepted that indices of about –3 reflect severe droughts and below –4
29 extreme droughts (in comparison with local normal conditions). The risk of extreme drought conditions for
30 the Fertile Crescent is, consequently, important under 1.5°C global warming, and this risk is clearly higher
31 than what has been known during the last 900 years (Cook et al., 2016) and perhaps even the last 10,000
32 years (Guiot and Cramer, 2016). Consequently, in the context of the sustainable development goals, it is
33 crucial to limit global warming to 1.5°C. As shown in Syria, drought has already affected food security and
34 has pushed two to three million people into extreme poverty.

35
36 **[END BOX 3.3 HERE]**

37 38 39 **3.3.5 *Runoff and river flooding***

40
41 AR5 concluded that there is *low confidence* of an increasing trend in global river discharge during the 20th
42 century (Hartmann et al., 2013). In regions with seasonal snow storage, warming since the 1970s has led to
43 earlier spring discharge maxima (*robust evidence, high agreement*) and has increased winter flows because
44 more winter precipitation falls as rain instead of snow. In these cases, streamflow is lower in summer due to
45 the decrease in snow storage exacerbating summer dryness (Jiménez Cisneros et al., 2014a). Additionally,
46 AR5 also concluded that there is also *limited evidence* and thus *low confidence* regarding the sign of trend in
47 the magnitude and/or frequency of floods on a global scale (Hartmann et al., 2013) and on the anthropogenic
48 climate change influence on modifications in the frequency and magnitudes of floods (Jiménez Cisneros et al.,
49 2014a). Finally, AR5 reached the consensus that increasing trends in extreme precipitation and discharge in

1 some catchments implies greater risks of flooding at regional scale (*medium confidence*; IPCC 2014).
2 Among the human activities that influence the hydrological cycle are land-use/land-cover change,
3 modifications in river morphology and water depth, construction and operation of hydropower plants, dikes
4 and weirs, wetland drainage and agricultural practices as water withdrawal for irrigation, all of which can have
5 a big impact on runoff at river basin scales although there is less agreement over its influence on global mean
6 runoff (Betts et al., 2015; Gerten et al., 2008; Hall et al., 2014; Sterling et al., 2012). Some studies suggest
7 that increases in global runoff resulting from changes in land-cover or land-use (predominantly
8 deforestation) are counterbalanced by decreases from irrigation (Gerten et al., 2008; Sterling et al., 2012).
9 Likewise, forest and grassland fires can also modify the hydrological response at a watershed scale when the
10 burned area is significant (Springer et al., 2015; Versini et al., 2013; Wine and Cadol, 2016).

11
12 There has been progress since the AR5 in identifying historical changes in streamflow and continental runoff.
13 Dai (2016) using available streamflow data shows that long-term (1948–2012) flow trends are statistically
14 significant only for 27.5% of the 200 world’s major rivers with negative trends outnumbering the positive ones.
15 However, although streamflow trends are mostly statistically insignificant, they are consistent with observed
16 regional precipitation changes. From 1950 to 2012 precipitation and runoff have increased over southeastern
17 South America, central and northern Australia, the central and northeast United States, central and northern
18 Europe, and most of Russia and decreased over most of Africa, East and South Asia, eastern coastal Australia,
19 southeastern and northwestern United States, western and eastern Canada, and in some regions of Brazil (Dai,
20 2016). A large part of these regional trends could have resulted from internal multidecadal and multiyear climate
21 variations, especially the Pacific decadal variability (PDV), the Atlantic multidecadal oscillation (AMO) and
22 the El Niño-Southern Oscillation (ENSO) although the effect of anthropogenic GHG and aerosols are likely
23 also important (Gu and Adler, 2013, 2015; Hidalgo et al., 2009; Luo et al., 2016). However, a decreasing trend
24 of runoff in the Mediterranean region was recently attributed to anthropogenic warming (Gudmundsson et al.,
25 2017; see also Section 3.3.4).

26
27 Projected changes in runoff reveal that differences are most prominent in the Mediterranean region where
28 the median reduction in annual runoff almost double from about 9% (likely range: 4.5–15.5%) at 1.5°C to 17%
29 (8–25%) at 2°C (Schleussner et al., 2016e). There are also projected increases in much of the high
30 northern latitudes in parts of India, East Africa and parts of the Sahel (Schleussner et al., 2016e). Similar results
31 are found by Doell et al. with decreases of 10–30% in the mean annual streamflow around the Mediterranean
32 region that become significant with an increase in global warming from 1.5°C to 2°C. Donnelly et al. (2017)
33 also found that constraining global warming to 1.5°C reduces the extent and severity of runoff in southern
34 Europe. Substantial increases in runoff affect the Scandinavian mountains and are associated with decreases
35 in mean annual runoff in Portugal at 1.5°C warming (Donnelly et al., 2017a). Marx et al. (2017) analyzed how
36 hydrological low flows in Europe are affected under different future global warming levels, finding that low
37 flows decrease in the Mediterranean due to the projected decreases in annual precipitation while they increase
38 in the Alpine and Northern regions because of the snow melt contribution under global warming of 1.5°C. Under
39 this scenario, the mountainous regions in Europe show the strongest low flow increase (Marx et al., 2017). Zhai
40 et al. (2017) assessed the spatial-temporal changes in river runoff under 1.5°C and 2°C warming scenarios
41 across China. Their results indicate that annual river runoff is projected to increase in most areas in China
42 although the variations of river runoff would enlarge under the 2°C scenario compared with the 1.5°C one.

43
44 Gosling et al. (2017) analyzed the impact of global warming of 1°C, 2°C and 3°C above pre-industrial level on
45 river runoff at catchment scale, focusing on eight major rivers covering all continents and several global hydro-
46 regions: Upper Amazon, Darling, Ganges, Lena, Upper Mississippi, Upper Niger, Rhine and Tagus. Their
47 results show that the sign and magnitude of change with global warming for the Upper Amazon, Darling,
48 Ganges, Upper Niger and Upper Mississippi is unclear. There is considerable evidence, however, that

1 significant hydrological hazards are avoided for the Rhine, Tagus and Lena if global-mean temperature rise is
2 kept below 2°C. The Rhine and Tagus may experience decreases in the magnitude of low and high flows, and
3 the mean annual runoff, with increasing warming due to large reduction in precipitation (Tagus) or little change
4 (Rhine) combined with increases in evapotranspiration associated to warmer temperatures. In the case of the
5 Lena, the analysis shows increases in the mean annual runoff and high flows. Projected mean annual runoff of
6 the Yiluo River catchment in northern China will decrease by 22% compared with that of the baseline period
7 for the 1.5°C global warming scenario and by 21% for the 2°C scenario while in the case of the Beiji River
8 in southern China, the mean annual runoff is projected to increase by less than 1% and 3% compared with that
9 during the baseline period for the 1.5°C and 2°C global scenarios, respectively (Liu et al., 2017). Chen et al.
10 (2017) assessed the future changes of water resources in the Upper Yangtze River Basin for the same warming
11 levels and found a slight decrease in the annual discharge for the 1.5°C scenario that reverses in sign for the
12 2°C one. Montroull et al.) studied the hydrological impacts in La Plata basin in South America under 1.5°C
13 and 2°C global warming. Their results show that the sign of variations in mean streamflow of the largest rivers
14 highly depends on the RCP and GCM used.

15
16 Recent analysis of trends and projections in flooding and extreme runoff are available both at basin or country
17 scales (Aich et al., 2016; Alfieri et al., 2015a; Camilloni et al., 2013; Dankers et al., 2014; Huang et al., 2015;
18 Liu et al., 2017; Mallakpour and Villarini, 2015; Marx et al., 2017; Stevens et al., 2016; Zaman et al., 2017)
19 and at global or continental scales (Hirabayashi et al., 2013; Dankers et al., 2014; Asadieh et al., 2016; Dai
20 2016; Alfieri et al., 2015a; Alfieri et al., 2015b; Kundzewicz et al., 2016; Alfieri et al., 2017; Alfieri et al.).
21 Under a high greenhouse gas concentration scenario, large increases in flood frequency are expected in
22 Southeast Asia, Peninsular India, eastern Africa and the northern half of the Andes (Hirabayashi et al., 2013). In
23 some regions such as the La Plata basin in South America (Camilloni et al., 2013), the Elbe basin and rivers
24 flowing from the Alps in Germany (Huang et al., 2015) and the Niger basin in West Africa (Aich et al., 2016)
25 projected flood changes are associated to increases in magnitude and/or in frequency consistent with the
26 projected patterns in precipitation. The Ganges-Brahmaputra-Meghna basin in south Asia shows a significant
27 increase in the area flooded at both 1.5°C or 2.0°C compared with present day (Uhe et al.). Floods will be more
28 frequent and flood magnitudes greater at 2.0°C warming level than at 1.5°C in the Brahmaputra River in
29 Bangladesh (Mohammed et al., 2017). In coastal regions, increases in heavy precipitation associated with
30 tropical cyclones (Section 3.3.7) combined with increased sea levels (Section 3.3.10) may lead to increased
31 flooding. Thober et al. identifies the Mediterranean region as a hotspot of change with significant decreases in
32 high flows and floods for 1.5°C global warming mainly resulting from reduced precipitation.

33
34 Under 1.5°C global warming Alfieri et al. (2017) project a global increase in extreme river flood events. Flood
35 magnitudes are expected to increase significantly in Europe south of 60°N, except for some regions (Bulgaria,
36 Poland, south of Spain) while they are projected to decrease in most of Finland, NW Russia and North of
37 Sweden, with the exception of southern Sweden and some coastal areas in Norway where floods may increase
38 (Roudier et al., 2016).

41 3.3.6 Snow and permafrost

42
43 Collins et al. (2013) assessed a weak decrease in the seasonal snow cover (SCE, in the Northern Hemisphere
44 spring, March-April mean) for RCP2.6 of $7 \pm 4\%$ (one standard deviation range) in the last two decades of
45 the century compared to the 1986–2005 reference period (AR5). They were only able to attach *medium*
46 *confidence* to this conclusion because of the considerable variability between CMIP5 model projections and
47 the strong simplifications inherent in incorporating snow processes within global climate models. For
48 comparison, the equivalent decrease for RCP8.5 was $25 \pm 8\%$. These reductions are related to both
49 precipitation and temperature changes, which also lead to a shortening of the duration of seasonal snow

1 cover. This interaction is complex in a warming world with more precipitation falling as rain as opposed to
2 snow and more snowmelt countered by projected increases in snowfall in winter months. Using the CESM
3 climate model (Sanderson et al. 2017; Wang et al.), a difference of $0.67 \times 10^6 \text{ km}^2$ between 1.5°C and 2°C
4 worlds exists as far as the anomaly in snow area extent (decline in Northern Hemisphere snow area extent
5 relative to pre-industrial) averaged over the period 2071–2100, which suggests that loss of snow cover in a
6 1.5°C world is roughly 75% that of a 2°C world.

7
8 It is *virtually certain* (Collins et al., 2013) that projected warming in the northern high latitudes combined
9 with changes in snow cover will lead to the extent of near-surface permafrost shrinking. For RCP2.6, Collins
10 et al. (2013) assigned *medium confidence* to their assessment because of the simplified representation of soil
11 physics in climate models. For RCP2.6, they quote Slater and Lawrence's (2013) finding of a reduction in the
12 area of near-surface permafrost of $37 \pm 11\%$ for the last two decades of the century compared to the 1986–
13 2005 reference period (compared to $81 \pm 12\%$ for RCP8.5). Chadburn et al. (2017) use an empirical relation
14 between fractional cover of permafrost and mean annual air temperature to estimate differences in
15 permafrost extent between stabilized 1.5°C and 2°C worlds. In their projections, the area of permafrost
16 declines by 21–37% (1 σ confidence interval) and 35–47% from 1960–1990 levels respectively, so that a
17 1.5°C world would have roughly $4 \times 10^6 \text{ km}^2$ of permafrost more than a 2°C world.

18 19 20 **3.3.7 Tropical cyclones, extratropical storms and winds**

21
22 There is increasing evidence of an increase in the number of very intense tropical cyclones (category 4 and 5
23 hurricanes on the Saffir-Simpson scale) over recent decades across most ocean basins, with a decrease in the
24 overall number of tropical cyclones (Elsner et al., 2008; Emanuel, 2005; Holland and Bruyère, 2014; Knutson
25 et al., 2010). This trend holds in particular for the North Atlantic, North Indian and South Indian Ocean basins
26 (e.g., Singh et al., 2000; Singh, 2010; Kossin et al., 2013; Holland and Bruyère, 2014), and is largely based on
27 the observational record of the satellite era (the last three decades), with the tropical cyclone observational
28 record being extremely heterogeneous before this period (e.g., Walsh et al. 2016).

29
30 Small islands are particularly exposed to the impacts of tropical cyclones (Hay, 2013; Woodruff et al., 2013).
31 The observational record of the last 30 years reveals a significant average poleward migration of tropical
32 cyclone activity at a rate of about one degree of latitude per decade (Kossin et al., 2014). A pronounced
33 poleward migration in the average latitude at which tropical cyclones have achieved their lifetime-maximum
34 intensity has similarly been recorded, with the displacements taking place at a rate of 53 (62) kilometres per
35 decade in the Northern (Southern) Hemisphere. The migration away from the tropics is linked to changes in
36 the mean meridional structure of vertical wind shear to the “tropical expansion”, which has been linked to
37 anthropogenic drivers (Lucas et al., 2014). Migration along these lines within the western North Pacific is
38 expected to decrease tropical cyclone exposure and risks in the region of the Philippine and South China Seas,
39 including the Marianas, the Philippines, Vietnam, and southern China, and to increase exposure in the region
40 of the East China Sea, including Japan and its Ryukyu Islands, the Korea Peninsula, and parts of eastern China
41 (Kossin et al., 2016; Li et al., 2017a; Zhan and Wang, 2017). Park et al. (2014, 2017) showed that tropical
42 cyclones frequency will decrease over the North Atlantic, particularly in the Gulf of Mexico, but will increase
43 over the western North Pacific, especially in terms of landfall over Korea and Japan, suggesting that North
44 America may experience less tropical cyclones landfalls, while northeast Asia may experience more tropical
45 cyclones than in the present-day climate. However, in terms of changes in landfalling cyclones recorded to
46 date, the analysis by Weinkle et al. (2012) does not indicate significant trends at global or basin scales. A
47 significant increase in the landfalling tropical cyclones frequency also not confirmed in the Philippines,
48 between 1945 and 2013, except for the latitude zone between 10°N and 12°N, which shows a linear increase
49 at 0.02 times per year (Takagi and Esteban, 2016).

1 Coupled global climate model (CGCM) projections of the changing attributes of tropical cyclones under
2 climate change are consistently indicating increases in the global number of very intense tropical cyclones.
3 For example, Christensen et al. (2013) indicate an increase in the frequency of categories 4 and 5 storms by
4 0–25% between 2081–2100 and 2000–2019, although with large inter-basin variations, under low mitigation
5 (e.g. A1B scenario). Model projections are also indicative of general decreases of tropical cyclone frequencies
6 under climate change, although more uncertainties are associated with such projections at the ocean basin scale
7 (e.g., Knutson et al., 2010; Sugi and Yoshimura, 2012; Christensen et al., 2013).

8
9 It should be noted that heavy rainfall associated with tropical cyclones has been assessed to be likely to
10 increase under increasing global warming (Seneviratne et al., 2012). Two recent articles suggest that global
11 warming for present conditions (i.e. 1°C, see Section 3.3.1) has likely increased the heavy precipitation
12 associated with the 2017 Hurricane Harvey by about 15% or more (Risser and Wehner; van Oldenborgh et
13 al., 2017). Hence, it can be inferred that further increases would occur under 1.5°C, 2°C and higher levels of
14 global warming.

15
16
17 Current climate models currently have difficulty projecting how cyclone attributes are likely to vary under
18 1.5°C vs. 2°C of global warming. Only two studies have to date directly explored the changing attributes of
19 tropical cyclone attributes under 1.5°C vs. 2°C of global warming. Using a high resolution global atmospheric
20 model, Wehner et al. (2017) concluded that the differences in tropical cyclone statistics under 1.5°C vs. 2°C
21 stabilization scenarios as defined by the HAPPI protocols (Half A degree additional warming, Prognosis and
22 Projected Impacts; Mitchell et al., 2017) are small. Consistent with earlier studies performed for higher degrees
23 of global warming, the total number of tropical cyclones is projected to decrease under global warming, whilst
24 the most intense (category 4 and 5) cyclones are projected to occur more frequently. These very intense storms
25 are projected to be associated with higher peak wind speeds and lower central pressures under 2°C vs 1°C of
26 global warming. The accumulated cyclonic energy is projected to increase globally and consistently so for the
27 North Atlantic, northwestern Pacific and northeastern Pacific Oceans, but with slight decreases projected for
28 the South Pacific, northern Indian and southern Indian Oceans (Wehner et al., 2017). Using a high resolution
29 regional climate model, (Mavhungu et al.) explored the effects of different degrees of global warming on
30 tropical cyclones over the southwest Indian Ocean, in transient simulations that downscaled a number of
31 RCP8.5 GCM projections. Decreases in tropical cyclone frequencies are projected, including decreases in the
32 most intense systems, under both 1.5°C and 2°C of global warming. The decreases in cyclone frequencies
33 under 2°C of global warming are somewhat larger than under 1.5°C of global warming, but with no further
34 decreases projected under 3°C of global warming. This suggests that 2°C of warming, at least in these
35 downscalings, represent a type of stabilization level in terms of tropical cyclone formation over the southwest
36 Indian Ocean and landfall over southern Africa (Mavhungu et al.).

37
38 Assessments in how winds will change are usually motivated by the need to understand changes in the context
39 of their relevance to sectors and issues such as agriculture (McVicar et al., 2012; McVicar et al., 2008; Vautard
40 et al., 2010), wind energy generation (Pryor and Barthelmie, 2010; Troccoli et al., 2012) and ocean waves
41 (Hemer et al., 2013; Hemer and Trenham, 2016; Young et al., 2011). Extreme wind hazards are most
42 meaningfully assessed in terms of the specific meteorological storms (e.g., Walsh et al., 2016a) whereby
43 factors such as changes in the region over which the storms occur (e.g., Kossin et al., 2014), changes in
44 frequency and intensity of the storms, and how they are influenced by modes of natural variability are relevant
45 considerations. Recent research show that, depending on the location along the European coastline, the impact
46 of change in winds on storm surge levels is significant and may exceed 30% of the relative sea level rise
47 (Vousdoukas et al., 2016).

48
49 Over the oceans, Zheng et al. (2016) confirmed that the global oceanic sea-surface wind speeds increased at

1 a significant overall rate of $3.35 \text{ cm s}^{-1} \text{ yr}^{-1}$ for the period 1988–2011 and that only a few regions exhibited
2 decreasing wind speeds without significant variation over this period. The increasing wind speeds were more
3 noticeable over the Pacific low-latitude region than over region of higher latitude. Wind speeds trends over
4 the western Atlantic were stronger than those over the eastern Atlantic, while the south Indian Ocean winds
5 were stronger than that those over the north Indian Ocean. This is confirmed by Ma et al. (2016) who showed
6 that the surface wind speed has not decreased in the averaged tropical oceans. Liu et al. (2016) used twenty
7 years (1996–2015) of satellite observations to study the climatology and trends of oceanic winds and waves in
8 the Arctic Ocean in the summer season (August–September). The Atlantic-side seas, exposed to the open
9 ocean, host more energetic waves than those on the Pacific side. Waves in the Chukchi Sea, Beaufort Sea (near
10 the northern Alaska), and Laptev Sea have been significantly increasing at a rate of $0.1\text{--}0.3 \text{ m decade}^{-1}$. The
11 trend of waves in the Greenland and Barents Seas, on the contrary, is weak and not statistically significant. In
12 the Barents and Kara Seas, winds and waves initially increased between 1996 and 2006 and later decreased.
13 Large-scale atmospheric circulations such as the Arctic Oscillation and Arctic dipole anomaly have a clear
14 impact on the variation of winds and waves in the Atlantic sector. Studies addressing the difference between
15 1.5°C and 2°C scenarios don't exist.

18 3.3.8 *Ocean circulation and temperature*

19
20 The temperature of the upper layers of the ocean (0–700 m) has been increasing at a rate just behind that of
21 the warming trend for the planet. The surface of three ocean basins have been warming over the period 1950–
22 2016 (by 0.11°C , 0.07°C , and 0.05°C per decade for the Indian, Atlantic and Pacific oceans respectively;
23 Hoegh-Guldberg et al. 2014, AR5 Ch30), with the greatest changes occurring at the highest latitudes.
24 Isotherms (i.e. lines of equal temperature) are traveling to higher latitudes at rates of up to 40km per year
25 (Burrows et al., 2014; García Molinos et al., 2015). Long-term patterns of variability make detecting signals
26 due to climate change complex, although the recent acceleration of changes to the temperature of the surface
27 layers of the ocean has made the climate signal more distinct (AR5 WGII Ch30). Increasing climate
28 extremes in the ocean are associated with the general rise in global average surface temperature as well as
29 more intense patterns of climate variability (e.g. climate change intensification of ENSO). Increased heat in
30 the upper layers of the ocean is also driving more intense storms and greater rates of inundation, which,
31 together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas.

32
33 Increasing land-sea temperature gradients, as induced by higher rates of continental warming compared to
34 the surrounding oceans under climate change, have the potential to strengthen upwelling systems associated
35 with the eastern boundary currents (Benguela, Canary, Humboldt and Californian Currents) (Bakun, 1990).
36 The most authoritative studies of observed trends are indicative of a general strengthening of longshore
37 winds (Sydeman et al., 2014), but are unclear in terms of trends detected in the upwelling currents
38 themselves (Lluch-Cota et al., 2014). However, the weight of evidence from CGCM projections of future
39 climate change indicates the general strengthening of the Benguela, Canary and Humboldt up-welling
40 systems under enhanced anthropogenic forcing (Wang et al., 2015a). This strengthening is projected to be
41 stronger at higher latitudes. In fact, evidence from regional climate modelling is supportive of an increase in
42 long-shore winds at higher latitudes, but at lower latitudes long-shore winds may decrease as a consequence
43 of the poleward displacement of the subtropical highs under climate change (Christensen et al., 2007;
44 Engelbrecht; Engelbrecht et al., 2009). Key to analysis of the relative impact of 1.5°C and 2°C of global
45 warming on upwelling systems, may be the analysis of changing land-temperature gradients for different
46 temperature goals. Such an analysis can be performed for the large ensembles of CMIP5 CGCMs, and can be
47 supplemented by more detailed parameterisations derived from high-resolution regional climate modelling
48 studies (Engelbrecht).

1 Evidence that thermohaline circulation is slowing has been building over the past years, including the
2 detection of the cooling of surface waters in the north Atlantic plus strong evidence that the Gulf Stream has
3 slowed by 30% since the late 1950s. These changes have serious implications for the reduced movement of
4 heat to many higher latitude countries (Cunningham et al., 2013; Kelly et al., 2016; Rahmstorf et al., 2015)
5

6 Increasing average surface temperature to 1.5°C will increase these risks although precise quantification of
7 the added risk due to an additional increase to 2°C is difficult to access. The surface layers of the ocean will
8 continue to warm and acidify but rates will continue to vary regionally. Ocean conditions will eventually
9 reach stability around mid-century under scenarios that represent stabilization at or below 1.5°C.
10

11 3.3.9 Sea ice

12 Summer sea ice in the Arctic has been retreating rapidly in recent decades. During the period 1997 to 2014,
13 for example, the monthly mean sea-ice extent during September decreased on average by 130,000km² per
14 year (Serreze and Stroeve, 2015). This is about four times as fast as the September sea-ice loss during the
15 period 1979–1996. Sea-ice cover also decreases in CMIP5-model simulations of the recent past, and is
16 simulated to decrease in the future. Collins et al. (2013) report that the CMIP5 multi-model average for
17 fractional Arctic sea ice loss under RCP2.6 is 8% for February and 43% for September (2081–2100
18 compared to a reference of 1986–2005). For comparison, the equivalent figures for RCP8.5 are 34 and 94%,
19 respectively. There is *medium confidence* in these scenarios given errors in the modelled present-day extent
20 and the large spread of model responses. In particular, the modeled sea-ice loss in most CMIP5 models is
21 much weaker than observed. Compared to observations, the simulations are weak in terms of their sensitivity
22 to both global mean temperature rise (Rosenblum and Eisenman, 2017) and to anthropogenic CO₂ emissions
23 (Notz and Stroeve, 2016a). This mismatch between the observed and modeled sensitivity of Arctic sea ice
24 implies that the multi-model-mean response of future sea-ice evolution probably underestimates the sea-ice
25 loss for a given amount of global warming. Three distinct approaches have been suggested to address this
26 concern.
27

28 One approach is to robustly identify the subset of CMIP5 models that describe the evolution of sea ice more
29 realistically than the multi-model ensemble mean. This approach is based on the fact that the simulated
30 timing of an ice-free Arctic is correlated with simulated metrics such as September sea-ice extent over recent
31 decades (e.g., Massonnet et al., 2012). Stroeve and Notz (2015), however, caution that care must be taken to
32 not use too few metrics for the model selection because this might distort the results. The approach of model
33 selection, which was for example adopted in Chapter 12 of AR5, predicts a faster ice loss than the full
34 CMIP5 ensemble would suggest. The subset of five CMIP5 models selected in AR5 averages a fractional
35 loss of September extent of 56% for RCP2.6 (compared to 43% noted above). This subset of models
36 simulates a nearly ice-free Arctic during summer for 1.6 to 2.1°C global warming relative to the present day
37 (or ~2.6 to 3.1°C relative to preindustrial) (Collins et al., 2013).
38

39 A second approach to improve model performance is re-calibrating model simulations. Such recalibration is
40 often based on the robust linear relationship found between global mean warming and Arctic sea-ice loss
41 both in the observational record and across model simulations. For example, Mahlstein and Knutti (2012) use
42 this linear relationship with CMIP3 models to estimate the threshold of an ice-free Arctic Ocean during
43 summer as ~2°C global warming relative to the present day (or ~3°C relative to preindustrial, consistent with
44 the estimate of Collins et al., (2013). Rosenblum and Eisenman (2016) explain why the sensitivity estimated
45 by Mahlstein and Knutti (2012) might be too low, estimating instead that September sea ice in the Arctic
46 disappears for ~1°C global warming relative to the present day (or 2°C relative to preindustrial). Also, other
47 recent studies based on recalibration conclude that there is a fairly high probability of sea ice in September
48
49

1 vanishing for 2°C global warming above pre-industrial, while the probability is fairly low for 1.5°C global
2 warming above pre-industrial (Niederdrenk and Notz; Screen and Williamson, 2017). During winter, little
3 ice is lost for either 1.5°C or 2.0°C global warming (Niederdrenk and Notz). Notz and Stroeve (2016) use the
4 observed correlation between September sea-ice extent and cumulative CO₂ emissions to estimate that
5 Septembers would become nearly ice-free with a further 1000Gt of emissions, which also implies a sea-ice
6 loss at around 2°C global warming. Some of the uncertainty in these numbers derives from the possible
7 impact of aerosols (Gagne et al., 2017) and of volcanic forcing (Rosenblum and Eisenman, 2016).
8

9 A third approach is to ensure that the observed evolution of Arctic sea ice is contained in the ensemble
10 spread. This then allows one to estimate the likelihood of an ice-free Arctic Ocean from the ensemble. Using
11 the large ensemble of the CESM model, (Jahn) agrees with recent recalibration studies that the probability is
12 still very high that the Arctic Ocean will become ice free during summer if global warming is limited to 2°C
13 above pre-industrial levels, while restraining global warming to 1.5°C global warming would lead to a
14 situation where Arctic summer sea ice will be retained. Using a large ensemble of the HadGEM2-ES model,
15 Ridley and Blockley (submitted) report that the Arctic will become ice free at 1.5°C global warming with
16 less than 1% probability, and ice free at 2°C global warming at a probability of slightly less than 50%.
17 Sanderson et al. (2017) also conclude that it is *as likely as not* that sea ice can be maintained in summer for a
18 warming of 2°C above pre-industrial levels. As explained by Jahn (submitted), they find a higher likelihood
19 for an ice free Arctic for a certain warming than Sanderson et al. (2017). because Sanderson et al. (2017)
20 examine the chance that a particular September is ice free, while Jahn (submitted) examines whether any
21 September becomes ice free for a given amount of global warming.
22

23 Using large ensembles of model simulations allows one to estimate the impact of internal variability on any
24 estimate of the most likely temperature at which the Arctic becomes ice free. Niederdrenk and Notz find
25 from their combination of modeled internal variability and observed sea-ice sensitivity that the Arctic most
26 likely becomes ice free at a warming of $1.7 \pm 0.2^\circ\text{C}$ global warming above preindustrial levels. This
27 uncertainty spread encapsulates much of the recent estimates for when the Arctic becomes ice free. In line
28 with Jahn (submitted), this estimate implies that even at 1.5°C global warming, there is a some (minor)
29 probability that Arctic summer sea ice will be lost in some years. In terms of time, the uncertainty of the first
30 year of an ice-free Arctic Ocean arising from internal variability in high-emission scenarios is about 20 years
31 (Jahn et al., 2016; Notz, 2015).
32

33 Collins et al. (2013) discuss the loss of Arctic sea ice in the context of potential tipping points. Observed rapid
34 declines in sea ice extent are not necessarily indicative of the existence of a tipping point, and could well be
35 a consequence of large inter-annual natural climate variability combining with anthropogenically-forced
36 change (Holland et al., 2006). Climate models have been used to assess whether a bifurcation exists that
37 would lead to the irreversible loss of Arctic sea ice (Armour et al., 2011; Boucher et al., 2012; Ridley et al.,
38 2012) and to test whether Summer sea ice extent can recover after it has been lost (Schroeder and Connolley,
39 2007; Sedláček et al., 2011; Tietsche et al., 2011). These studies do not find evidence of bifurcation and find
40 that sea ice returns within a few years of its loss, leading Collins et al. (2013) to conclude that there is little
41 evidence for a tipping point in the transition from perennial to seasonal ice cover.
42

43 Collins et al. (2013) have low confidence in Antarctic sea ice projections because of the wide range of model
44 projections and an inability of almost all models to reproduce observations such as the seasonal cycle,
45 interannual variability and a trend towards increased ice extents over recent decades.
46

3.3.10 Sea level

Sea level varies over a wide range of temporal and spatial scales, which can be divided into three broad topics. These are Global Mean Sea Level (GMSL), regional variation about this mean, and the occurrence of sea-level extremes associated with storm surges. Projected Global Mean Sea Level (GMSL) change is the sum of contributions from thermal expansion, glacier and ice-sheet mass loss, as well as anthropogenic intervention in water storage on land. Mass loss from glaciers and the ice sheets of Greenland and Antarctica, can be divided into Surface Mass Balance (SMB, the difference between mass gain at the ice surface, mostly snowfall, and mass loss at the surface, mostly melt and subsequent runoff) and outflow (mass loss directly to the ocean by either iceberg calving or submarine melt). This sub-section discusses the component contributors to GMSL to 2100 in the context of a 1.5°C world, before considering projections for total GMSL, including those made using Semi-Empirical Methods (SEMs). It then goes on to consider projections of regional and extreme sea level, before assessing projections of millennial GMSL and associated commitment and reversibility issues.

Church et al.'s (2013) projections of GMSL rise were given as *likely* ranges because changes in global mean surface air temperature, thought to be the principle driver of GMSL change, were given as *likely* ranges. Two contributors to these GMSL rise projections (ice sheet outflow and terrestrial water storage) were given without scenario dependence because, at that time, there was insufficient scientific basis to quantify these differences. The assessment also noted that the collapse of marine sectors of the Antarctic ice sheet could lead to GMSL rise above the *likely* range, and that there was *medium confidence* that this additional contribution “would not exceed several tenths of a metre during the 21st century” (Church et al., 2013). This process is known as Marine Ice Sheet Instability (MISI) and focusses on the continued, potentially-unstable retreat of an ice sheet resting on bedrock below sea level once triggered by external warming of the surrounding ocean and/or atmosphere.

Thermal expansion is the dominant component in the AR5 assessment of Church et al. (2013) and contributes 0.10–0.18 m of 0.26–0.55 m total GMSL rise in scenario RCP2.6 (*likely* ranges, 2081–2100 relative to 1986–2005). Schewe et al. (2011) use the CLIMBER-3 climate model with the RCP3-PD scenario to study thermal expansion in a 1.5°C world. Due to the inertia introduced by slow ocean heat uptake, in particular at high latitudes, thermal expansion continues for 200 years after a mid-21st-century air temperature peak and peaks at 0.3 m (above the 1980–1999 level) before slowly falling. Oceanic warming at 300–800m depth persists for centuries with potential consequences for ice-sheet stability, oceanic methane hydrates and marine ecosystems.

Mass loss from mountain glaciers and ice caps is projected to account for a *likely* range of 0.04–0.16 m GMSL rise at 2100 in the AR5 assessment for RCP2.6 (Church et al., 2013). The rate at which mass is lost is projected to be fairly constant through time despite increased global warming, which may represent a balance between increased warming towards the end of the century and the depletion of low-elevation ice. Marzeion et al. force a global glacier model with temperature-scaled scenarios based on RCP2.6 to investigate the difference between 1.5°C and 2°C worlds and find no significant difference between scenarios in the glacier contribution to GMSL at 2100 (0.05–10 mm relative to present day for 1.5°C, and 0.06–0.11 mm for 2°C using a 90% confidence interval). This arises because melt during the remainder of the century is dominated by the response to warming from preindustrial to present-day levels (in turn a reflection of the slow response times of glaciers). In fact, Marzeion et al. find that 28–44% of present-day glacier volume is unsustainable in the present-day climate, so that it would eventually melt even if there were no further climate change. Further warming to sustained levels of 1.5°C and 2°C, leads to an equilibrium GMSL rise of 0.12–0.18 m and 0.14–0.21 m (compared to a present-day volume of 0.29–0.33 m sea-level equivalent), respectively.

1 Fuerst et al. (2015) make projections Greenland ice sheet's contribution to GMSL based on emission
2 scenario using an ice-flow model forced by the regional climate model MAR (considered by Church et al.,
3 2013 to be the 'most realistic' such model). They obtain an RCP2.6 *likely* range of 0.02–0.06 m by the end of
4 the century (relative to 2000). This is somewhat smaller than the RCP2.6 projection made by Church et al.
5 (2013) (0.04–0.10 m) probably reflecting an over estimate of the scenario-independent contribution from
6 outflow ('rapid dynamics'). There is no available literature that allows the difference between 1.5°C and 2°C
7 worlds to be evaluated.

8
9 Published process-model projections are now available for the contribution of the Antarctic ice sheet to
10 GMSL change. They are based on models that could potentially allow MISI so that the separate assessment
11 of MISI used by Church et al. (2013) may no longer be necessary. Antarctica may become a source of future
12 GMSL fall if snow accumulation increases due to the increased moisture-bearing capacity of a warmer
13 atmosphere. In line with previous assessments, Frieler et al. (2015) suggest a range of 3.5–8.7% K⁻¹ for this
14 effect, which is consistent with the AR5 RCP2.6 assessment of 0.0–0.04 m GMSL fall (2081–2100 relative
15 to 1986–2005). Clearly, this compensatory effect will be more important at 2°C than 1.5°C.

16
17 Three scenarios-dependent projections of the contribution of Antarctica outflow to GMSL now exist.
18 Levermann et al. (2014) derive scenario-dependent estimates by developing response functions emulating
19 the results of the SeaRISE ice-sheet model intercomparison (Bindschadler et al., 2013). They obtain a range
20 of 0.02–0.14 m GMSL rise (66% confidence interval) for RCP2.6, however there are concerns about the
21 numerical treatment of grounding-line migration in the models participating in SeaRISE (Durand and Pattyn,
22 2015). Using an ice-sheet model tuned using estimates of palaeo-sea-level, DeConto and Pollard (2016) find
23 a contribution to GMSL rise of 0.0–0.22 m (1 σ) by the end of the century for RCP2.6. While Golledge et al.
24 (2015) obtain 0.0–0.10 m from two experiments with their ice-sheet model, in which melt at the grounding
25 line is parameterized differently. These estimates are broadly comparable to the scenario-independent
26 contribution for ice outflow used by Church et al. (2013) (–0.01–0.16 m *likely* range for Antarctica).

27
28 While there is a good level of agreement between these studies, there are concerns that they may not be
29 consistent with the contemporary understanding of the causes for recent increases in Antarctic outflow,
30 which emphasizes the role of changes in regional oceanography (Jenkins et al., 2016) and ice dynamics (Nias
31 et al., 2016). This is illustrated by Cornford et al. (2015) who find that SRES scenario E1 (emissions
32 stabilized at 500 ppm CO₂ by 2050) results in greater GMSL rise than A1B because ocean warming in both
33 A1B and E1 is similar and generates similar increases in outflow, however increases in snow fall caused by
34 atmospheric warming (e.g., Frieler et al. 2015) have a greater compensatory effect in A1B.

35
36 This assessment of process-based projections of GMSL to 2100 suggests that there is insufficient literature to
37 distinguish between emission scenarios associated with 1.5°C and 2°C worlds. In some cases (e.g., glaciers)
38 the literature suggests that there is no significant difference between the two (Marzeion et al.). Literature
39 since AR5 is consistent with Church et al.'s (2013) assessment of a *likely* range of 0.26–0.55 m GMSL rise in
40 scenario RCP2.6.

41
42 Church et al. (Church et al., 2013) assigned *low confidence* to the use of SEMs because of their assumption
43 that the relation between climate forcing and GMSL is the same the in past (calibration) and future
44 (projection). Probable future changes in the relative contributions of thermal expansion, glaciers and (in
45 particular) ice sheets invalidate this assumption. Recent advances in SEM and related modelling frameworks
46 attempt to overcome this issue by treating these contributors separately (Kopp et al., 2014; Mengel et al.,
47 2016; Nauels et al., 2017). Relative past and future contributions are also more likely to remain the same in
48 low-emission scenarios because the much of the warming with respect to preindustrial has already occurred
49 and ice sheets are less likely to become the dominant contributor.

1 Recent SEM-based studies show convergence towards the AR5 process-based assessment, and offer the
2 advantage of allowing a comparison between 1.5°C and 2°C worlds. Sanderson et al. (2017) use the
3 methodology developed by Kopp et al. (2016) with forcing from the CESM climate model to derive
4 estimates of GMSL rise of 0.5–0.8 and 0.6–0.9 m (90% confidence intervals, relative to preindustrial),
5 respectively for 1.5°C and 2°C. Schleussner et al. (2017) uses the MAGICC reduced-complexity carbon-
6 climate model with an Antarctic outflow contribution based on Levermann et al. (2014) to determine ranges
7 of 0.29–0.53 and 0.36–0.65 m (66% confidence, 2100 compared to 2000), respectively for 1.5°C and 2°C.
8 Using a similar procedure (due to Goodwin et al., 2017) Nicholls et al. (submitted) obtain GMSL rise ranges
9 of 0.30–0.48 and 0.39–0.49 m, for 1.5°C and 2°C respectively. All three studies are consistent in reporting a
10 ~0.1m difference in GMSL rise between 1.5°C and 2°C worlds.

11
12 Translating projections of GMSL to the scale of coastlines and islands requires two further steps. The first
13 accounts for regional changes in the Earth’s gravitational field associated with changing water and ice loads,
14 as well as accounting for spatial differences in ocean heat uptake and circulation. The second maps regional
15 sea level on to changes in the return periods of particular flood events. Kopp et al. (2014) present a
16 framework to achieve this and give an example application for nine sites (in the US, Japan, northern Europe
17 and Chile). Of these sites, seven (all except those in northern Europe) experience at least a quadrupling in the
18 number of years in the 21st century with 1-in-100 year floods under RCP2.6 compared to no future sea-level
19 rise. Rasmussen et al. use this approach to investigate the difference between 1.5°C and 2°C worlds up to
20 2200. They find that the reduction in the frequency of 1-in-100 year floods in 1.5°C compared to 2°C worlds
21 is greatest in the eastern US and Europe at around a half. Extending this analysis, they find that by 2150
22 roughly five million fewer people (including 40,000 living in SIDS) are inundated in a 1.5°C world in
23 comparison to a 2°C world. Schleussner et al. (2011) emulate the Atlantic Meridional Overturning
24 Circulation (AMOC) based on a subset of CMIP-class climate models. When forced using global
25 temperatures appropriate to the CP3-PD scenario (1°C warming at 2100 relative to 2000), the emulation
26 suggested an 11% median reduction in AMOC strength at 2100 (relative to 2000) with associated 0.04 m
27 dynamic sea-level rise along the New York City coastline. Increased meltwater production from the
28 Greenland ice sheet of 0.1 m sea-level equivalent weakens the AMOC by a further 4.5%.

29
30 Many contributors to GMSL change respond slowly (i.e., over decades to millennia) to changes in global
31 temperature and their contribution can be thought of as proportion to the integral over time of the
32 temperature anomaly (for instance, thermal expansion (Bouttes et al., 2013; Zickfeld et al., 2012). This has
33 two implications for projections of GMSL rise. First, that this rise is *virtually certain* (Church et al., 2013) to
34 continue well beyond 2100 so that the effect of mitigation may be to delay the year at which a particular
35 amount of sea-level rise occurs. Second, that worlds with a stabilized end-of-century climate may experience
36 continued GMSL rise over future centuries (Clark et al., 2016; Levermann et al., 2013). Various feedbacks
37 between the Greenland ice sheet and the wider climate system (most notably those related to the dependence
38 of ice melt on albedo and surface elevation) make irreversible loss of the ice sheet a possibility. Two
39 definitions have been proposed for the threshold at which this loss is initiated. The first is based on the global
40 mean temperature at which net SMB first becomes negative for the current ice-sheet geometry (i.e, there is
41 more mass loss by meltwater runoff than gain by snowfall). Church et al. (2013) assess this threshold to be
42 2°C or above (relative to pre-industrial). A second definition considers the impacts of future feedbacks
43 between lowered ice-sheet topography and SMB. Robinson et al. (2012) find a range for this threshold of
44 0.8–3.2°C (95% confidence). The timescale for eventual loss of the ice sheet could be a millennium to tens
45 of millennia, and depends strongly on the magnitude of the temperature forcing. Were temperature to cool
46 subsequently, the ice sheet may regrow. In which case, the amount of cooling required is likely to be highly
47 dependent on the duration and rate of the previous retreat.

48
49 The multi-centennial evolution of the Antarctic ice sheet is considered in papers by DeConto and Pollard

1 (2016) and Golledge et al. (2015). Both suggest that RCP2.6 is the only RCP scenario leading to long-term
2 contributions to GMSL of below 1.0 m. The long-term committed future of Antarctica (and GMSL
3 contribution at 2100) are complex and require further detailed process-based modelling, however a threshold
4 in this contribution may be present close to 1.5°C.
5

6 **[START BOX 3.4 HERE]**
7

8 **Box 3.4:** Paleontological evidence for understanding 1.5–2°C warmer worlds
9

10 The best studied examples of such warmer conditions (with essentially modern geographies) are the
11 Holocene Thermal Maximum (HTM) (broadly defined as ~10–5 kyr before present (BP), where present is
12 defined as 1950), the Last Interglacial (LIG ~129–116 kyr BP) and the Mid Pleistocene Warm Period
13 (MPWP, 3.3–3.0 Ma). Note that while the first two examples exhibited greenhouse concentrations similar to
14 preindustrial but different orbital parameters¹ compared to today, the MPWP is the most recent time period
15 in Earth history, where CO₂ concentrations were similar to today’s anthropogenically influenced levels. To
16 study CO₂ concentrations as high as expected for RCP 8.5 at the end of this century one has to look further
17 back to time periods as early as the Early Eocene Climatic Optimum (EECO, ~53–51 Ma) when CO₂ was in
18 the range 900–1900 ppm, but the continental configuration and ocean circulation, were significantly different
19 from today.
20

21 Although the guardrail concept of 1.5–2°C global warming is useful, it is important to ask whether these
22 global limits constitute a safe range for our complex planet. The assessment of the risks involved in a
23 warmer world is mainly based on climate models. However, climate models used for future climate
24 projections may underestimate both rates and extents of changes if they do not include processes important
25 on long timescales such as ice sheet dynamics or carbon cycle feedbacks (Valdes, 2011). An alternative
26 observation-based approach is to explore warm climate episodes in Earth’s history (Fischer et al.).
27 Understanding these past events may illuminate feedback mechanisms that define Earth System Sensitivity
28 (ESS), i.e. the long-term climate response to an increase in CO₂ including ice sheet and carbon cycle
29 feedbacks, enabling an assessment of possible impacts of warming on physical, biological, chemical, and
30 ecological services upon which humanity depends.
31

32 The global temperature response to changes in the insolation forcing during the HTM (Marcott et al.,
33 2013) and the LIG (Hoffman et al., 2017) was up to +1°C compared to preindustrial (1850–1900) with high
34 latitude warming being generally larger by a factor of 2–4 (Capron et al., 2017; Vinther et al., 2009).
35 Accordingly, the temperature changes during those times were similar albeit still somewhat smaller
36 compared to what is expected for the mitigation scenario RCP 2.6. During the MPWP, when greenhouse gas
37 forcing was similar to present, the global temperature response was >1°C and Arctic temperatures likely 8°C
38 warmer than preindustrial (Brigham-Grette et al., 2013; Dowsett et al., 2012) more in line with unmitigated
39 or weakly mitigated scenarios.
40

41 While there is no perfect analog for present day or future climate, similarities in regional changes allow us to
42 draw conclusions on the impacts of a 1.5–2.0°C warmer world on various components of the Earth System,
43 such as sea ice, ice sheets and sea-level, ecosystem and biome changes and therefore to perform a risk
44 assessment of thresholds or amplification processes in the Earth System (Box 3.4 Figure 1). Note however,

¹FOOTNOTE During the last millions of years, the glacial-interglacial alternations are driven by orbital parameters, which determine the orbit of the Earth around the Sun and the inclination of its rotation axis and then the insolation received in each point of the Earth. These changes are then amplified by covarying greenhouse gas concentrations

1 that the influence of other anthropogenic disturbances (such as air and water pollution, land use and water
2 use, etc.) or impacts exacerbated by the speed of change, such as rapid ocean acidification (Hönisch et al.,
3 2012) cannot be assessed using the paleorecord. Because of the uncertainties associated to the proxies, it is
4 also difficult to distinguish the impacts of 1.5°C and 2°C global warming.
5

6 In spite of some warming, the HTM and LIG show greenhouse gas concentrations similar to preindustrial
7 (Bereiter et al., 2015; Loulergue et al., 2008; Schneider et al., 2013) suggesting a relatively low risk of
8 runaway greenhouse gas effects for such limited global warming. Transient releases of CO₂ and CH₄ are
9 likely to occur when permafrost melts but may be partially compensated by a long-term increase in peatland
10 carbon storage (Yu et al., 2010). Paleoresearch on the change in CO₂ concentrations during historical times
11 suggests a stronger response of CO₂ release from soil respiration during CO₂ induced warming than on CO₂
12 fertilization of plants (Frank et al., 2010). When extending the range to even warmer periods such as the
13 MPWP, higher CO₂ concentrations provide circumstantial evidence of positive carbon cycle effects related
14 to land soil and vegetation feedbacks and the ocean's carbon storage capacity.
15

16 The risk derived from the paleorecord for a collapse of the Atlantic Meridional Overturning Circulation
17 during such limited warming is low, although evidence for centennial to millennial variations in overturning
18 strength are found (Galaasen et al., 2014; Winsor et al., 2012; Gottschalk et al., 2015).
19

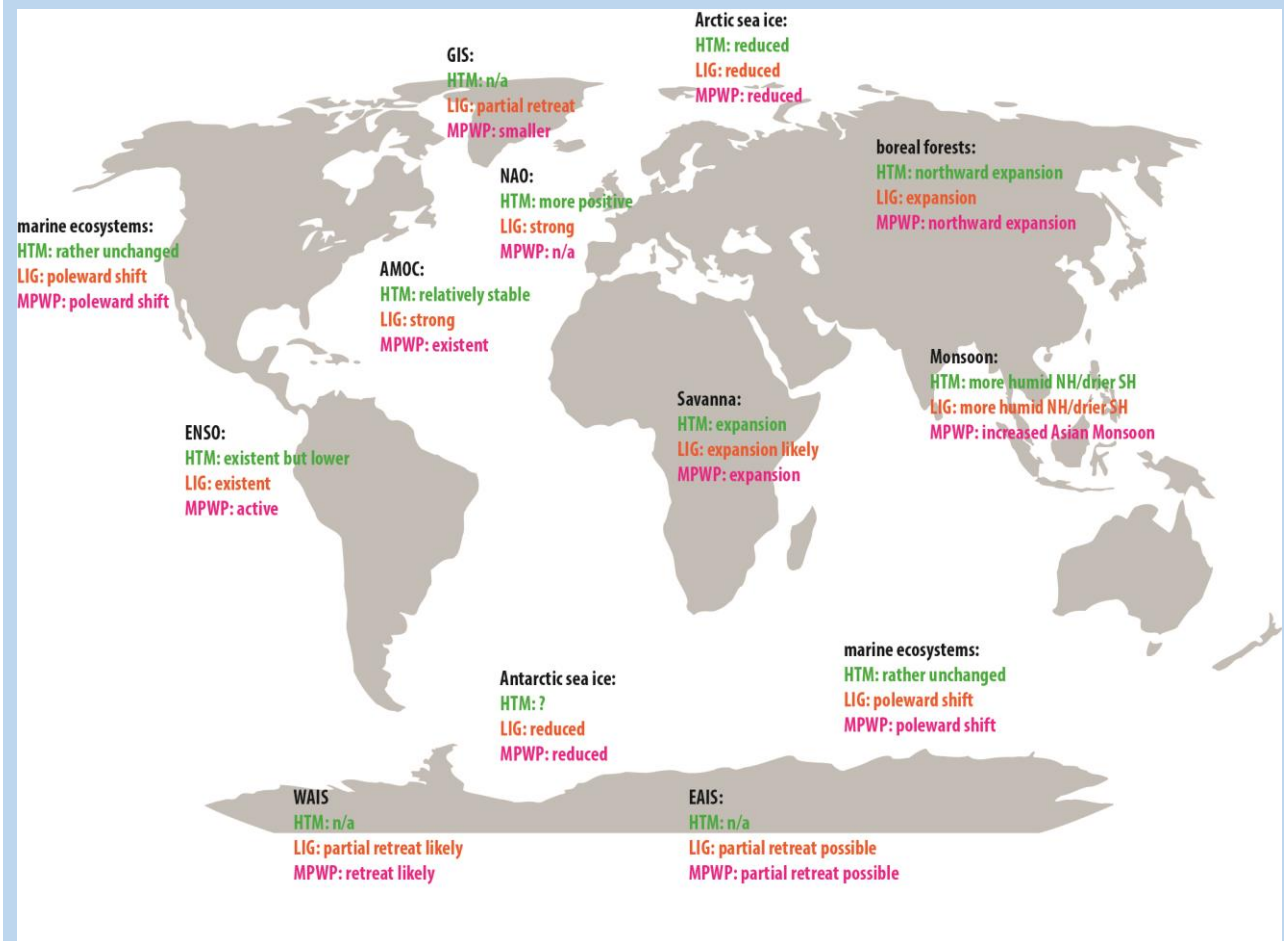
20 Shifts of ecosystems and biome distribution associated with warming are demonstrated in the ocean and on
21 land. While the paleorecord shows little evidence of species extinction in the marine record for the HTM and
22 LIG, it supports a poleward shift of marine ecosystems for warmer climate conditions. Such a shift is also
23 supported for the MPWP (Haywood et al., 2016). Overall, the diversity-temperature relationship stayed
24 relatively constant (Yasuhara et al., 2012). Similar shift in ecosystem and biome distribution is observed on
25 land, with a northward expansion of the Arctic treeline (Williams et al., 2009) and also an upward shift in
26 Alpine regions (Reasoner and Tinner, 2008). At the same time, rain forests and temperature forests show
27 reductions in areas where drought conditions increasingly prevail favouring an expansion of savanna biomes
28 (Dowsett et al., 2016; Urrego et al., 2015) both for HTM, LIG and MPWP.
29

30 Among the most severe impacts of past warming are evidenced for the cryosphere with decreasing summer
31 and winter sea ice in the Arctic for the LIG (Stein et al., 2017), causing a significant local albedo effect.
32 Paleoevidence does not support a complete melting of summer sea ice in the Arctic for the LIG. A similar
33 picture is derived for the Antarctic (de Vernal et al., 2013), however, robust spatial evidence is very limited.
34

35 While the HTM is a time when global sea level was still significantly below preindustrial levels because of
36 the slow retreat of residual Pleistocene ice sheets, the LIG reached higher than modern sea levels after
37 complete melting of the North American and Fennoscandian ice sheets. Accordingly, the LIG (and similar
38 Marine isotope Stage (MIS) 11.3 around 400 kyr BP) allow a reliable assessment of the long-term response
39 of the Greenland Ice Sheet (GIS) and the West and East Antarctic Ice Sheets (WAIS, EAIS) to a sustained
40 high latitude warming. Global sea level reconstructions of 6–9 m higher than present during the LIG (and
41 similar or higher for MIS11.3) require a substantial retreat of at least one of the Greenland and Antarctic ice
42 sheets, but likely a significant reduction of both, relative to their current volumes (Dutton et al., 2015). While
43 ice sheet and climate model simulations allow for a substantial retreat of the West Antarctic Ice Sheet
44 (WAIS) and potentially parts of East Antarctica (DeConto and Pollard 2016; Sutter et al. 2016) during the
45 LIG, direct observational evidence is still lacking. The sea level evidence of a partial collapse of the GIS,
46 however, is supported by direct geological observations (NEEM community members, 2013; Reyes et al.,
47 2014; Schaefer et al., 2016). Reduced ice sheets existed in Greenland and Antarctica also during the MPWP,
48 as reflected in sea-levels >6 m higher than present (Dutton et al., 2015), but their configuration is uncertain
49 (de Boer et al., 2015; DeConto and Pollard, 2016).

1
2 The paleorecord also provides an extended range of past rates of sea level rise compared to our historic
3 observations. In line with ice sheet melting, sea-level changes within the LIG were likely between 3 and
4 7 mm yr⁻¹ (1000-year average) (Kopp et al., 2013) i.e. likely two times larger than the highest rise rates
5 observed during the last two decades. Given these rate constraints from paleo observations, melting of parts
6 of the GIS and WAIS will take a long time. This implies that once melting is triggered such high sea level
7 rise rates will be sustained over many millennia and are likely unstoppable even within a 2°C warming
8 guardrail, a clear concern for policies related to long-term safeguarding coastal populations and
9 infrastructures.

10
11 Finally, the extended time scales of feedback processes available through the paleorecord also allow a
12 refined assessment of ESS. Many previous studies attempted to calibrate ESS based on the last
13 glacial/interglacial transition, but this time period may not be directly representative for the future ESS, due
14 to the melting of large continental ice sheets that do not exist anymore. Using the paleoevidence for the
15 warmer HTM, LIG, MPWP and the EECO a more robust estimate of ESS can be derived. This analysis
16 shows that current models that do not include these long-term feedbacks may underestimate the equilibrium
17 warming response of the Earth System to CO₂ climate forcing by up to a factor of 2 and, because the rate of
18 sea-level rise responds to the degree of warming, likely also underestimates the long-term rates of coastal
19 inundation (Clark et al., 2016; Fischer et al., 2017).



21
22 **Box 3.4, Figure 1: Impacts and responses of components of the Earth System: Summary of typical changes found**

1 for warmer periods in the paleorecord as discussed in (Fischer et al.) (all statements relative to
2 preindustrial). Note that significant spatial variability and uncertainty exists in the assessment of
3 each component and, therefore, this figure should not be referred to without reading the publication
4 Fischer et al. in detail.

5
6 **[END BOX 3.4 HERE]**

7 8 9 **3.3.11 Ocean chemistry**

10
11 Ocean chemistry includes pH, salinity, oxygen and a number of specific ions, and is fundamentally important
12 to marine organisms and ecosystems. It is influenced by factors such as precipitation, evaporation, river run-
13 off, coastal erosion, up-welling, ice formation, and the activities of organisms and ecosystems (Stocker et al.,
14 2013). Despite these many influences, ocean chemistry has been relatively stable for long periods of time
15 prior to the start of the Industrial Period (Hönisch et al., 2012). Ocean chemistry is changing under the
16 influence of human activities (*virtually certain*; Stocker et al. 2013; Rhein et al. 2013). Around 30% of CO₂
17 emitted by human activities, for example, has been absorbed by the ocean where it combines with water to
18 produce a dilute acid that dissociates and drives ocean acidification (Cao et al., 2007; Stocker et al., 2013).
19 These changes have resulted in a decrease in ocean pH of more than 0.1 pH units since the Pre-Industrial
20 Period.

21 The flux of CO₂ into the ocean has also increased the concentration of protons and has decreased that of
22 carbonate ions by 30% (Cao and Caldeira, 2008; Stocker et al., 2013) which is exceptional according to AR5
23 consensus (Pörtner et al., 2014a): “The current rate and magnitude of ocean acidification are at least 10
24 times faster than any event within the last 65 Ma (*high confidence*; Ridgwell and Schmidt, 2010) or even
25 300 Ma of Earth history (*medium confidence*; Hönisch et al., 2012).” Periods of high atmospheric
26 concentrations of CO₂ in the paleo-record have been accompanied by a reduction in calcifying ecosystems
27 such as corals and other invertebrates (e.g., PETM, 55.5 Ma, Mcinerney and Wing, 2011; Veron, 2008;
28 Pörtner et al., 2014) with reversal of these changes taking tens of thousands of years (Hönisch et al.,
29 2012). Consequently, consideration must be given to the irreversibility (on human timescales) of the
30 emerging risks associated with ocean acidification.

31
32 Ocean acidification varies with latitude with the greatest changes occurring where temperatures are lowest
33 (e.g. polar regions, due to increased CO₂ solubility at lower temperatures), or where CO₂ rich water is
34 brought to the ocean surface by upwelling (3.1.8; Feely et al. 2008). Acidification can also be influenced by
35 effluents from natural or disturbed coastal land use (Salisbury et al., 2008), plankton blooms (Cai et al.,
36 2011), and the atmospheric deposition of acidic materials (Omstedt et al., 2015). These sources may not be
37 directly attributable to climate change, yet may amplify ocean acidification due to increased atmospheric
38 CO₂ (Bates and Peters, 2007; Duarte et al., 2013). Ocean acidification also influences other aspects of the
39 ionic composition of seawater by changing the organic and inorganic speciation of trace metals, with
40 increases in the predicted free ion concentrations such as Al by 20-fold by the end of century. These changes
41 are of concern given the importance of these ions to biological systems in the ocean yet the impacts are
42 poorly understood (Stockdale et al., 2016).

43
44 The oxygen concentration of seawater is another centrally important component of ocean chemistry which
45 varies regionally and with depth, and is highest in polar regions and lowest in the eastern basins of the
46 Atlantic and Pacific oceans, and the northern Indian Ocean. Increasing temperatures in the upper layers of
47 the ocean have led to concentrations of oxygen declining by 2% since 1960 (Schmidtko et al., 2017). Altieri
48 and Gedan (2015) reviewed the literature and found evidence that oxygen levels are being affected by climate
49 variables such as temperature, ocean acidification, sea level rise, precipitation, wind, and storm patterns.

1 Changes in ocean mixing together with increased metabolic rates (due to increased temperature and
2 increased supply of organic carbon in the deep ocean has increased the frequency of ‘dead zones’. Dead
3 zones are where oxygen has fallen below levels that fail to sustain oxygenic life and are doubling in frequency
4 (risk) every decade (Diaz and Rosenberg, 2008). Drivers are complex and include both climate change and
5 other factors (Altieri and Gedan, 2015). Originally reported along temperate coastline, recent reports have
6 identified increasing risks of deoxygenation and dead zones in tropical regions (Altieri et al., 2017). Ocean
7 salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e.
8 evaporation and inundation; Hoegh-Guldberg et al., 2014). Some regions (e.g. northern oceans and Arctic
9 regions) have decreased salinity (i.e. due to melting glaciers and ice sheets) while others are increasing in
10 salinity due to higher sea surface temperatures and evaporation (Durack et al., 2012).

11
12 Changes in ocean chemistry occur in concert with increases in temperature, and most evidence indicates an
13 amplification of the impacts of global warming to 1.5°C and 2.0°C. Gattuso et al. (2015) based on Bopp et
14 al. (2013) illustrate the changes expected in the upper layers of the ocean in terms of the decrease in pH,
15 oxygen content, as well as the increasing sea level. Our understanding of how changes to ocean chemistry is
16 likely to influence the outcome of global warming is in its infancy although experiments indicate that
17 changes to temperature and ocean chemistry are likely to be synergistic in terms of overall impact (Dove et
18 al., 2013) as explored in the section below on Ocean Systems (3.4.3).

21 **3.3.12 Global synthesis**

22
23 This section summarises the various changes in the physical and biogeochemical realms associated with
24 1.5°C and 2°C global warming based on the preceding assessments in this section.

26 **3.3.12.1 Atmospheric change**

27 There are statistically significant differences in temperature means and extremes at 1.5°C vs. 2°C global
28 warming, both in global average (Schleussner et al., 2016e) and in most land regions (Wartenburger et al.
29 2017b; Seneviratne et al., Section 3.3.2). Increases of this magnitude in global mean temperature will have
30 an exaggerated effect on regional land-based heat extremes (Seneviratne et al., 2016), in particular in Central
31 and Eastern North America, Central and Southern Europe, the Mediterranean, Western and Central Asia, and
32 Southern Africa. These regions have a strong soil-moisture-temperature coupling in common (Vogel et al.,
33 2017) leading to increased dryness and consequent reduction in evaporative cooling. Some of these regions
34 also show a wide range of responses to temperature extremes, in particular Central Europe and Central North
35 America. The number of hot days is another index of temperature extremes, and shows the largest
36 differences between 1.5 and 2.0°C in the tropics because of their low interannual temperature variability
37 (Mahlstein et al., 2011). Published literature shows that impacts of global warming to 1.5°C and 2.0°C on
38 cities would include a substantial increase in the occurrence of deadly heatwaves compared to the present-
39 day (Matthews et al., 2017; Mitchell et al.). A study for megacities suggests that this effect would be similar
40 for warming of 1.5 and 2.0°C (Matthews et al., 2017), and increase substantially above 2°C global warming.
41 However, in some other urban regions, there would be significant changes between 1.5°C and 2°C global
42 warming as well (Mitchell et al.).

43
44 Projections for heavy precipitation (Section 3.3.3) are less robust than for temperature means and extremes.
45 However, several regions display statistically significant differences in heavy precipitation at 1.5°C vs 2°C
46 warming (with stronger increase at 2°C; Wartenburger et al., 2017; Seneviratne et al.), and there is a global
47 tendency towards increases in heavy precipitation on land between these two temperature levels (Fischer and
48 Knutti, 2015; Schleussner et al., 2016e). Southern Asia is a hot spot for increases in heavy precipitation
49 between these two global temperature levels (Schleussner et al., 2016e; Seneviratne et al., 2016). Overall,

1 regions that display statistically significant changes in heavy precipitation between 1.5°C and 2°C global
2 warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern
3 Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including
4 China and Japan) and in Eastern North America. Results are less consistent for other regions. Differences in
5 the statistics of tropical cyclones are thought to be small between 1.5 and 2°C worlds, although their total
6 number is expected to decrease and the most intense ones (category 4 and 5) occur more frequently (Wehner
7 et al., 2017).

10 3.3.12.2 *Land-surface changes*

11 In terms of drought (Section 3.3.4), limiting global warming to 1.5°C may substantially reduce the
12 probability of extremes changes in water availability in several regions (Greve et al., 2017). Studies and
13 analyses suggest strong increases in dryness and reduced water availability in the Mediterranean region
14 (including Southern Europe, northern Africa, and the near-East), in Northeastern Brazil, and in Southern
15 Africa at 1.5°C vs. 2°C (Schleussner et al. 2015; Lehner et al. 2017; Greve et al. 2017; Wartenburger et al.
16 2017a, Figures 3.15 and 3.16).Based on observations and model experiments, a drying trend is already
17 detectable in the Mediterranean region (Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017),
18 i.e. for a global warming of 1°C. Considering runoff and flooding, differences in decrease between 1.5°C and
19 2°C projection of runoff are highest around the Mediterranean (5–16% compared to 8–25%, 66% confidence
20 interval) but important over much of the northern high latitudes, and parts of India, the Sahel and East Africa
21 (Doell et al.; Schleussner et al., 2016b). At 1.5°C, low river flows are projected to become lower in the
22 Mediterranean, but increase in northern Europe and the Alps (Marx et al., 2017). Across most of China,
23 projected river flow increase more for 2°C than 1.5°C (Zhai et al., 2017). At the scale of catchments, there is
24 evidence that limiting global warming to 1.5°C could avoid some hazards in the Rhine, Tagus and Lena,
25 although other the picture for other large catchments is unclear (Gosling et al., 2017). Flood magnitudes are
26 thought to increase in much of Europe south of 60 °N, while decreasing in many parts of northern Europe
27 (Roudier et al., 2016).While at global scale, there is evidence of a decrease in the return period of extreme
28 floods in a 1.5°C world compared to the recent past (Alfieri et al., 2017). By 2100, the area of Arctic
29 permafrost is expected to decline by 21–37% in a 1.5°C world and 35–47% relative to the present (Chadburn
30 et al., 2017).

33 3.3.12.3 *Oceanic changes*

34 Many changes are already occurring in the global ocean and will continue to intensify as global warming
35 increases. Stabilising temperatures at 1.5°C will avoid significant added burdens from changes in ocean
36 temperature, stratification, deoxygenation, ocean acidification, intensification of storms, sea level rise and
37 many other factors (Hoegh-Guldberg et al., 2014). The relative influence of each of these factors varies as
38 consequence of latitude and ocean depth, and suggest regional challenges for organisms, livelihoods and
39 people (Gattuso et al., 2015). There is clear evidence and concern that some of these changes involve
40 tipping points that have been reached (Box 3.5). For example, numerous studies place the threshold for a
41 seasonally ice-free Arctic between 1.5 and 2.0°C global warming, both within this century and for long-term
42 equilibrium climate conditions. Year-round sea ice is much more likely to be maintained in a 1.5°C world
43 than a 2°C one (Jahn; Niederrenk and Notz; Ridley and Blockley; Screen and Williamson, 2017). Studies
44 do not find evidence of irreversibility or tipping points, and suggest that year-round sea ice could return with
45 years given a suitable climate (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011).

46
47 There is also a growing consensus between process-based modelling and semi-empirical modelling of Global
48 Mean Sea Level (GMSL) rise. Available studies suggest that GMSL rise by 2100 will be ~0.1m greater in a
49 2°C world than a 1.5°C (Kopp et al., 2016; Nicholls et al.; Schleussner et al., 2015). There is also an

1 indication that the frequency of large storm surges may be reduced at 1.5°C compared to 2°C, in particular it
2 may be halved in the eastern US and Europe (Rasmussen et al.). For the Greenland and Antarctic ice sheets,
3 significant thresholds are likely to exist in long-term (millennial-scale), committed GMSL rise for global
4 climate stabilization around 1.5–2°C exist (DeConto and Pollard, 2016; Golledge et al., 2015; Robinson et
5 al., 2012).

6
7 **[START BOX 3.5 HERE]**

8
9 **Box 3.5:** Climate tipping points in the climate system

10
11 The prospect of passing climate tipping points was considered as a ‘reason for concern’ in the IPCC WG2
12 report (IPCC, 2014a; Oppenheimer et al., 2014) and has been put forward by some authors as a motivation
13 for limiting global warming (Lenton et al., 2008; Smith et al., 2009). A tipping point occurs when a small
14 change in forcing (e.g. global temperature) leads to a qualitative change in the future state of a component of
15 the global climate system (Lenton et al., 2008). The resulting change may unfold rapidly or slowly and may
16 be in some cases difficult to reverse, depending on the component involved (Lenton et al., 2008). As
17 discussed in the IPCC SREX report, the possible future occurrence of low-probability, high-impact scenarios
18 associated with the crossing of poorly understood climate thresholds cannot be excluded, given the transient
19 and complex nature of the climate system (Seneviratne et al., 2012). However, the literature is still sparse on
20 the assessment of tipping points and their robustness, especially with a focus on 1.5°C vs. higher levels of
21 warming.

22
23 Studies have identified several potential climate tipping points that could be passed under different levels of
24 global warming. Techniques used in these studies include literature review (Lenton et al., 2008), expert
25 elicitation (Kriegler et al., 2009; Lenton et al., 2008) and scanning of the CMIP5 model database (Drijfhout
26 et al., 2015). Existing assessments agree that the likelihood of passing tipping points increases with global
27 temperature. However, whilst expert elicitation results suggest a roughly linear increase in the likelihood of
28 passing specific tipping points with global temperature (Kriegler et al., 2009; Lontzek et al., 2015), a recent
29 analysis of CMIP5 model projections suggests a clustering of abrupt changes in the interval of 1.5–2°C
30 warming (Drijfhout et al., 2015). Abrupt changes predicted at low levels of global warming involve sea ice,
31 land ice/snow and high-latitude ocean circulation (deep convection) (Drijfhout et al., 2015), consistent with
32 observations that the polar regions are particularly sensitive to global warming and proposals that they have
33 several potentially easily-triggered tipping points (Lenton, 2012; Lenton et al., 2008). The point in time at
34 which this warming is realized (e.g. within the 21st century or after several millennia, see also Section 3.2) is
35 also important for those associated with sea ice and sea level rise. We next discuss specific classes of tipping
36 point that could be passed or avoided by limiting warming to 1.5°C or 2°C.

37
38 **Sea-ice:** Arctic summer sea-ice cover has been declining over the last ~30 years, due to both warming and
39 atmospheric circulation changes (Ding et al., 2017). Abrupt sea-ice declines are projected in some models
40 under future forcing, with two of 37 model simulations showing this feature ~1.5°C (Drijfhout et al., 2015).
41 Consequences that have been proposed to result from crossing of sea-ice tipping points range from
42 amplification of regional warming and possible changes in mid-latitude weather patterns to major ecological
43 shifts (Bhatt et al., 2014; Vihma, 2014).

44
45 **Land-ice/snow:** Abrupt declines in snow volume on the Tibetan plateau are projected by some models,
46 with two related model simulations (out of 37) showing this feature at ~2.0°C (Drijfhout et al., 2015).
47 Potential remote impacts may include intensification of Eurasian heatwaves (Wu et al., 2016) and weakening
48 of the East Asian summer monsoon (Xiao and Duan, 2016). Regardless, the extent of permafrost loss is
49 expected to increase from 2.6–6.8 × 10⁶ km² at 1.5°C to 4.4–8.6 × 10⁶ km² at 2°C (Chadburn et al., 2017).

1 Consequences include amplification of global warming from CH₄ and CO₂ release, ecological changes, and
2 regional disruption of transport and infrastructure.
3

4 **Ocean circulation:** Deep convection in the Labrador Sea region has already switched on and off in the
5 observation record and is projected to collapse in some models (Drijfhout et al., 2015). Consequences
6 include sea-ice expansion, cooling of the N. Atlantic region, southward shift of the ITCZ (Drijfhout et al.,
7 2015) and increases in sea-level along the eastern seaboard of N. America (Yin et al., 2009). A full collapse
8 of the Atlantic meridional overturning circulation (AMOC) is predicted in one model (of 37) at low warming
9 (Drijfhout et al., 2015). The AMOC may be systematically biased to be too stable in current models (Liu et
10 al., 2017), meaning that the likelihood of collapse at low levels of warming may have been underestimated.
11

12 **Ice sheets:** Observations suggest that parts of the Antarctic Ice Sheet (AIS) and the Greenland Ice Sheet
13 (GIS) are in retreat. Paleo-climatic interpretations from the Eemian period (the last interglacial, MIS 5e)
14 can be used to assess the multi-millennial Global Mean Sea Level (GMSL) commitment for ~1°C. They
15 suggest GMSL rise of 6–9 m, of which 5–8 m was from polar ice sheets (Dutton et al., 2015). Models
16 estimate a 0.6–3.5 m Eemian contribution from the GIS, implying 1.5–7.4 m from AIS.
17

18 At 1.5°C, 2°C, or greater warming, recent models suggest the GIS and WAIS could become vulnerable to
19 irreversible loss. The entire GIS could be under threat at greater than 1.5°C warming, ultimately contributing
20 up to ~7 m to GMSL over multi-millennial timescales (IPCC, 2013; Knutti et al., 2016; Robinson et al.,
21 2012). Similarly, there are indications that sectors of the AIS may exhibit threshold behavior between
22 RCP2.6 and higher scenarios. For the higher scenarios, (Golledge et al., 2015) obtain near-equilibrium
23 contributions to GMSL of up to 9 m after 3000 years, and de (DeConto and Pollard, 2016) 12–14 m after 500
24 years, although this finding is highly dependent on model physics. Both studies suggest equilibrium
25 contributions of less than a metre for RCP2.6.
26

27 **Biomes:** Abrupt terrestrial biomes shifts are predicted in some models but only at greater than 2°C warming
28 (Drijfhout et al., 2015; Lenton et al., 2008). These shifts include greening of the Sahel, Amazon dieback,
29 expansion of the boreal forest into the tundra at its northern edge, and dieback of the boreal forest at its
30 southern boundary. Almost complete degradation of tropical coral reefs has been assessed to possibly
31 occur at ~2°C warming (Schleussner et al., 2016) but it is unclear at present if this could be fully irreversible.
32

33 In summary, existing studies have proposed that limiting global warming to 1.5°C could significantly reduce
34 the risk of passing some damaging tipping points, especially terrestrial biome loss. While the present
35 literature does not allow a probability to be assigned to the potentially most critical climate tipping points or
36 the levels of global warming at which they are most likely to be triggered, they need to be considered as the
37 associated consequences cannot be excluded at present, and could be major if realized.
38

39 **[END BOX 3.5 HERE]**
40
41

42 **3.4 Observed impacts and projected risks in natural and human systems**

44 **3.4.1 Introduction**

45 Understanding the observed impacts and projected risks on natural and human systems forms a crucial
46 element in understanding how the world is likely to change under global warming of 1.5°C above the
47 preindustrial period (versus 2.0°C and higher). Scientific literature is growing substantially in the three-year
48 period since AR5. In this section, we explore the new literature and update the assessment of observations of
49

1 impacts and our ability to project risks into the future.

2
3 The Working Group II contribution to the IPCC 5th Assessment Report (AR5) assessed the literature for
4 natural systems across systems and sectors, as well as for geographic regions evaluating the evidence of
5 changes in natural ecosystems and their impacts on humans and their communities and industry. While
6 impacts varied substantially between systems, sectors and regions, many changes over the past 50 years can
7 be attributed to human driven climate change and its impacts. In particular, risks are increasing for natural
8 systems, such as:

- 9
- 10 • Risks of changes to natural ecosystems as climate extremes increase in frequency and intensity.
- 11 • Risks associated with flora and fauna shifting their biogeographical ranges to higher latitudes and
- 12 altitudes, with consequences for ecosystems services and human dependents.
- 13 • Risks of increasing disease and invasive species as organisms shift their distribution, potentially
- 14 posing challenges for communities and industry as well as agricultural and fisheries food production.
- 15 • Risks of decreasing coastal protection against sea level rises and key species such as mangroves and
- 16 coral reefs are lost.
- 17 • Risks of changing ecosystem structure and function such that support for human communities and
- 18 planetary services erode.
- 19 • Risks of crossing tipping points in which maintaining or reversing changes due to climate change
- 20 become impossible on a human time scale.
- 21

22 There are many more examples of substantiated risks that are increasing for natural systems and the reader is
23 referred to the relevant chapters in Working Group II of AR5 for detailed assessment of the changes, their
24 causal attribution, and the associated risks. These changes also amplify risks associated with human
25 systems. Human systems that are also assessed in AR5 were urban areas; rural areas; key economic sectors
26 and services; human health; migration and conflict; and livelihoods and poverty. Key messages from the
27 AR5 assessment of reasons for concern / key vulnerabilities for human systems within the context of Article
28 2 of the UNFCCC (Cramer et al., 2014b) included.

- 29
- 30 • Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island
- 31 developing states and other small islands, due to storm surges, coastal flooding, and sea level rise;
- 32 • Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding
- 33 in some regions;
- 34 • Systemic risks due to extreme weather events leading to the breakdown of infrastructure networks
- 35 and critical services such as electricity, water supply, health, and emergency services;
- 36 • Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban
- 37 populations and those working outdoors in urban or rural areas;
- 38 • Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding,
- 39 and precipitation variability and extremes, particularly for poorer populations in urban and rural
- 40 settings;
- 41 • Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation
- 42 water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal
- 43 capital in semi-arid regions;
- 44 • Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and
- 45 services they provide for coastal livelihoods, especially for coastal communities in the tropics and
- 46 the Arctic; and
- 47 • Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods,
- 48 functions, and services they provide for livelihoods.

1 The literature assessed in the AR5 focused on describing and quantifying linkages between weather and
2 climate patterns and outcomes, with limited detection and attribution studies (Cramer et al., 2014b). The
3 observed changes in human systems are increased by the loss of ecosystem services (e.g. access to safe
4 water) that are supported by biodiversity (Cramer et al., 2014b). Limited research on the risks of warming of
5 +1.5 and +2°C was conducted subsequent to the 5th Assessment Report for most key economic sectors and
6 services, for livelihoods and poverty, and for rural areas. For these systems, climate is one of many drivers
7 that result in adverse outcomes. Other factors include patterns of demographic change, socioeconomic
8 development, trade, and tourism. Further, consequences of climate change for infrastructure, tourism,
9 migration, crop yields, and other impacts interact with underlying vulnerabilities, such as for individuals and
10 communities engaged in pastoralism, mountain farming, and artisanal fisheries, to affect livelihoods and
11 poverty (Dasgupta et al. 2014). Incomplete data and understanding of these cascading interactions across
12 sectors and regions currently limits exploration of the projected risks of warming of +1.5 and +2°C for rural
13 areas.

14
15

16 **3.4.2 Freshwater resources (quantity and quality)**

17

18 **3.4.2.1 Water availability**

19 IPCC WGII AR5 concluded that about 80% of the world's population already suffers serious threats to
20 water security as measured by indicators including water availability, water demand, and pollution
21 (Vörösmarty et al., 2010). Climate change can alter the availability of water, and threaten water security as
22 defined by (UNESCO, 2011).

23

24 Even observed physical changes to streamflow and continental runoff have been detected and attributed to
25 climate change (Section 3.3.5), water scarcity occurred in the past is still less well understood (Wada et al.,
26 2011). Over the past century, substantial growth in population, industrial and agricultural activities, and
27 living standards (i.e. per capita water use) have exacerbated water stress in many parts of the world
28 (AghaKouchak et al., 2015; Mehran et al., 2015), especially in semi-arid and arid regions. Due to increasing
29 population pressure, change in water consumption behavior, climate change, and particularly in the effects of
30 spatial distribution of population growth relative to water resources, the population under water scarcity
31 increased from 0.24 billion (14% of global population) in the 1900s to 3.8 billion (58%) in the 2000s
32 (Kummu et al., 2016).

33

34 Changes in population will generally have a greater effect on changes in water resource availability than will
35 climate change over the next few decades and for increases in global mean temperature of less than around
36 2°C above preindustrial. Climate change, however, will regionally exacerbate or offset the effects
37 of population pressure (Jiménez Cisneros et al., 2014b).

38

39 The reduction of water resource availability at 1.5°C global warming is smaller than the 2.0°C warming (see
40 Section 3.3.5). However, socioeconomic drivers could affect projected risks on water availability more than
41 the risks posed by the variation in global warming of 1.5°C and 2°C. (*limited evidence, medium agreement*).
42 Assuming a constant population in these models, (Gerten et al., (2013) demonstrates that an increase of 4%,
43 8%, and 10% of the world population who are exposed to new or aggravated water scarcity with 50%
44 confidence are projected at 1.5°C, 2°C, 3°C global warming, respectively. Gerten et al. (2013) reveal to be the
45 case, especially in Europe, Australia and southern Africa, which are projected to have impacts as a result
46 global warming of 1.5°C. Schewe et al. (2014) projected the reduction in water resources under SSP2
47 population scenario, by at least one of the two criteria (to experience a discharge reduction >20% and >1σ),
48 for about 8% and 14% of the global population under global warming of 1.7°C in 2021–2040 and 2.7°C in
49 2043–2071 (RCP 8.5), respectively. Exposure to increase of water scarcity would be globally reduced by

1 184–270 million people at 1.5°C global warming (RCP2.6 in 2050, SSP1–5) compared to the impacts under
2 the around 2°C (RCP4.5 in 2050, SSP1–5), however the variation between socioeconomic differences is
3 greater than the variation between levels of global warming (Arnell and Lloyd-Hughes, 2014). On many small
4 developing islands, there would be freshwater stress derived from projected aridity change, however,
5 constraining to 1.5°C global warming would avoid substantial fraction of water stress (~25%) compared to
6 2.0°C especially across the Caribbean region (Karnauskas et al.).

7
8 Increase of water demand at 2.0°C global warming is projected to be similar to the 1.5°C. Using 25 ensemble
9 projections (five GHMs by five GCMs), Wada et al. (2013) projects irrigation water demand in India, China,
10 Pakistan, USA and over the globe. It shows the changes are by around –1.7% (–1.5%), 10.3% (13.3%),
11 –0.6% (1.6%), –2.4% (2.4%) and 8.6% (9.4%) under 2.2°C (2.7°C) global warming (RCP2.6 and RCP4.5 in
12 2035–2065), respectively. Hanasaki et al. (2013) conclude that the projected ranges of changes in global
13 irrigation water withdrawal with human configuration fixing non-meteorological variables at circa 2000 are
14 1.8%, 1.1–2.3%, 1.4%, and 0.6–2.0% under 1.5°C, 1.6°C, 1.9°C, and 2.1°C global warming, respectively.

15 16 17 3.4.2.2 *Extreme hydrological events (floods and droughts)*

18 Socioeconomic losses from flooding since the mid-20th century have increased mainly due to greater
19 exposure and vulnerability (*high confidence*, IPCC WGII AR5), however there is *low confidence*, due to
20 *limited evidence*, that anthropogenic climate change has affected the frequency and magnitude of floods. It
21 also concluded that there is no evidence that surface water and groundwater drought frequency has changed
22 over the last few decades, although impacts of drought have increased mostly due to increased water
23 demand (Jiménez Cisneros et al., 2014b).

24
25 Since AR5, the number of studies related to river flooding and meteorological drought based on long-term
26 observed data has been gradually increasing (see Sections 3.3.4 and 3.3.5). The magnitude of flood
27 vulnerability has greatly depended on changes in population and economic statuses in accordance with time
28 and place. The vulnerability has also been affected by socioeconomic development conditions, such as flood
29 measures, topography and hydro-climatic conditions (Tanoue et al., 2016).

30
31 IPCC WGII AR5 assessed that global flood risk will increase in the future partly due to climate change
32 (*limited evidence, medium agreement*), however projected changes in the frequency of droughts longer than
33 12 months are more uncertain, because these depend on accumulated precipitation over long periods (Jiménez
34 Cisneros et al., 2014b).

35
36 Flooding hazards at 1.5°C of global warming are reduced compared to the hazards under the 2°C (see Section
37 3.3.5), although a few studies find that socioeconomic conditions might contribute to flood impacts more
38 than the warming scenarios do (Winsemius et al., 2016). Under 1.5°C and 2°C global warming (RCP8.5,
39 5GCMs, 10GHMs), direct global flood risk could increase by 63% and 80% and human losses by 73% and
40 98%, resulting in a welfare loss of 0.27% and 0.34%, respectively (Dottori et al.). Assuming constant
41 population sizes, impacts of global warming of 1.5°C and 2°C are projected to increase by 100% and 170% in
42 the proportion of populations affected, and 120% and 170% increase in the economic damage occurring at a
43 global scale (Alfieri et al., 2017). Alfieri et al. also study on the population affected by flood events in
44 European states, that is relative to the baseline period (1976–2005), and find the number would be limited to
45 86% at 1.5°C as compared to 93% at 2.0°C. Under SSP2 population scenario, Arnell et al. (2017) find that
46 36–46% of impacts on populations exposed to river flood would be globally avoided at 1.5°C compared to
47 2.0°C global warming, Warren et al. indicate significant benefits (84–564 million people) in the global
48 aggregate from constraining warming by 2100 (with 66% probability) to 1.5°C rather than 2°C, for fluvial
49 flooding.

1 Arnell and Lloyd-Hughes (2014) found that the number of people exposed to increased flooding at 1.5°C
2 (RCP2.6 in 2050, SSP1–5) would be reduced by 26–34 million compared to at the 2.0°C (RCP4.5 in 2050,
3 SSP1–5). Variation between socioeconomic differences, however, is greater than the variation between the
4 extent of global warming. Kinoshita et al. (2017) find that a significant increase in potential flood fatality
5 (+5.7%) is projected without any adaptation if global warming increases by 1.5°C to 2.0°C, whereas an
6 increase in potential economic loss (+0.9%) is less significant. Although in the study, socioeconomic changes
7 make the greater contribution to the potential increased consequences of future floods, about a half of the
8 increase of potential economic losses is mitigated by autonomous adaptation.
9

10 Hazards by droughts at 1.5°C global warming would be reduced compared to the hazards under the 2°C
11 warming (see Section 3.3.4). There is limited information about the global (and regional) projected risks
12 posed by droughts at 1.5°C and 2°C global warming. The global mean monthly number of population
13 exposed to extreme drought at around 1.5°C (RCP8.5 in 2021–2040) and around 2.0°C (RCP8.5 in 2041–
14 2060) is projected to be 114.3 and 190.4 million people under A2r population scenario (Smirnov et al.,
15 2016). Under SSP2 population scenario, Arnell et al. (2017) project that 36–51% of impacts on populations
16 exposed to drought would be globally avoided at 1.5°C as compared to 2.0°C global warming, Warren et
17 al. indicate significant benefits (17.3–34.0 million people) in the global aggregate from constraining
18 warming by 2100 (with 66% probability) to 1.5°C rather than 2°C, for drought.
19

20 Liu et al. study the changes in population exposure to severe drought both globally and in 27 regions at 1.5°C
21 and 2°C using SSP1 population scenario, and find that urban population in most regions would be decreased
22 at 1.5°C (+232.6±124.8 million) compared at 2.0°C (468.3±228.0 million), respectively. In the Haihe River
23 Basin in China, exposure of populations to droughts at the 1.5°C warming level is projected to be reduced by
24 30.4%, but increase by 74.8% at the 2°C relative to the 1986–2005 period (Sun et al., 2017).
25
26

27 3.4.2.3 Groundwater

28 IPCC WGII AR5 concluded that the detection of changes in groundwater systems, and attribution of those
29 changes to climatic changes, are rare owing to a lack of appropriate observation wells and an overall small
30 number of studies (Jiménez Cisneros et al., 2014b).
31

32 Since AR5, the number of studies based on long-term observed data continues to be limited. The
33 groundwater-fed lakes in north-eastern central Europe have been affected by climate and land use changes,
34 and show a predominantly negative lake-level trend in 1999–2008 (Kaiser et al., 2014).
35

36 IPCC WGII AR5 concluded from its assessment of the literature that climate change is projected to reduce
37 groundwater resources significantly in most dry subtropical regions (*robust evidence, high*
38 *agreement*; (Jiménez Cisneros et al., 2014b).
39

40 Very few studies project the risks of ground water under 1.5°C and 2.0°C global warming. Under 1.5°C
41 global warming (RCP 8.5), an ensemble mean (five GCMs) of around 1.6% (range 1.0–2.2%) of global land
42 area is projected to suffer from an extreme decrease in renewable groundwater resources of more than 70%,
43 while the affected areas increase to 2.0% (range 1.1–2.6%) at the 2°C (RCP8.5) (Portmann et al., 2013). In a
44 groundwater-dependent irrigated region in Northwest Bangladesh, the average groundwater level during the
45 major irrigation period (January–April) is projected to decrease by 0.15–2.01 m because of an increase in
46 temperature of around 1.6–5.6°C, the decreases project to cause an increase of irrigation costs by 0.05–0.54
47 thousand Bangladeshi Taka per hectare (Salemet et al., 2017).
48

3.4.2.4 Water quality

IPCC WGII AR5 concluded that most observed changes of water quality due to climate change are known from isolated studies, mostly of rivers or lakes in high-income countries, using a small number of variables (Jiménez Cisneros et al., 2014b). Since AR5, studies have detected climate change impacts on several indices of water quality in lakes, watershed and in region (e.g., Marszelewski and Pius 2016; Patiño et al. 2014; Capo et al. 2017; Aguilera et al. 2015; Watts et al. 2015).

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

Since AR5, the number of studies utilizing RCP scenarios at regional or watershed scale has been gradually increasing (e.g. Teshager et al. 2016; Boehlert et al. 2015; Marcinkowski et al. 2017). There are, however, few studies that explore projected impacts on water quality under 1.5°C versus 2.0°C global warming. Projected risks derived from the differences of at 1.5°C and at 2.0°C global warming would be smaller when comparing the risks posed by projected socioeconomic changes, which could pose greater factors. The daily probability of exceeding the chloride standard for drinking water taken from Lake IJsselmeer and (Andijk, the Netherlands) are projected to slightly increase at 1.5°C and further at 2.5°C global warming from the reference period (1997–2007) (Bonte and Zwolsman, 2010). Mean monthly dissolved oxygen concentrations and nutrient concentrations are projected to less decrease at 1.5°C (RCP2.6 in 2050–2055) global warming compared to the 2.0°C (RCP4.5 in 2050–2055) in the upper Qu'Appelle River (Hosseini et al., 2017). In the three river basins (Sekong, Sesan, and Srepok), (Trang et al., 2017) projects annual N (P) yield changes at around 1.5°C global warming (RCP4.5 in 2030s) and around 2°C (RCP8.5 in 2030s) as well as with combinations of two land-use change scenarios: 1) conversion of forest to agriculture and 2) of forest to agriculture. The projected changes under 1.5°C and 2.0°C scenarios are 7.3(5.1)% and –6.6(–3.6)%, whereas under the combination of land-use scenarios are 1) 5.2(12.6)% and 8.8(11.7)%, and 2) 7.5(14.9)% and 3.2(8.8)%, respectively.

3.4.2.5 Soil erosion and sediment load

IPCC WGII AR5 assessed that there is little or no observational evidence yet that soil erosion and sediment loads have been altered significantly due to changing climate (*limited evidence, medium agreement*) (Jiménez Cisneros et al., 2014b).

While there are increasing number of studies on climate change impacts on soil erosion, in which change of rainfall amount is the most important factor (Lu et al., 2013), it has been understood that the studies also have to consider the factors such as rainfall intensity (e.g. Shi and Wang 2015; Li and Fang 2016), snow melting and change of vegetation cover due to temperature rise (Potemkina and Potemkin, 2015), and crop management practices (Mullan et al., 2011).

IPCC WGII AR5 concluded that increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices (Jiménez Cisneros et al., 2014b).

Published papers in respect of climate change impacts on soil erosion have been increasing since 2000 over the world (Li and Fang, 2016), however there are few articles published with impacts at 1.5°C and 2°C global warming. The differences of average annual sediment load under 1.5°C and 2.0°C global warming are not clear because of complex interactions among climate change, land cover/surface and soil management (Cousino et al., 2015; Shrestha et al., 2016). Average annual sediment loads is projected to be similar under

1 1.5°C and 2.0°C global warming(Cousino et al., 2015; Shrestha et al., 2016).

2

3 Summary: Projected risks of water availability and extreme hydrological events (flood and drought) at 1.5°C
4 global warming would be reduced compared to the risks at 2°C, however, socioeconomic drivers could have
5 more risks than those posed by the differences between 1.5°C and 2°C global warming (*limited evidence,*
6 *medium agreement*)

1 **Table 3.1:** *[Placeholder. Table of risk for Freshwater resources. See summary and detailed tables in Annex 3.1, Table S3.4.2]*

Risk	Region (could be globe)	Metric (unit)	Baseline time period against which change in impact measured	Socio-economic scenario and date (make clear if uses present day population and assumes constant)	Baseline global T used in paper (pre-industrial, or other, and did you have to convert? Eg if your paper gives delta T relative to 1990 you add 0.5C)	Climate scenario used (e.g. RCP, SRES, HadCM3 in 2050s, etc)	Is it for transient (T) or equilibrium (E) (if known) ?	Is it an overshoot scenario? How long it is above 1.5C and what is the max temp and when?	Is the modelling approach used in that publication dynamic (Y/N)	Projected impact at 1.5C above pre-industrial	Projected impact at 2C above pre-industrial	Projected impact at delta T(°C)	Delta T relative to pre-industrial; delta T(°C) (deltaT1+column F)	Delta T relative to baseline temp(T1); delta T1(°C)

2

1 3.4.3 Terrestrial and wetland ecosystem

2

3 Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their
 4 projection into the future relies on three general approaches: (1) inference from analogous situations in the
 5 past or in the present; (2) manipulative experimentation, deliberately altering one of a few factors at a time;
 6 and (3) models with a mechanistic or statistical basis (Rosenzweig and Neofotis, 2013). Models include
 7 ecological niches, population dynamics, species interactions, spatially explicit disturbance, ecosystem
 8 processes, and plant functional responses, in addition to monitoring and experiments (Franklin et al., 2016).

9

10 This section considers several aspects of the ecosystem services in the light of observed changes and
 11 projected risks for various levels of global warming. Observation analysis intends to understand the
 12 sensitivity of the ecosystems to possible drivers and to understand their capacity of adaptation and, in the
 13 end, to attribute them to climate change, whether natural or anthropogenic (Cramer et al., 2014b). The
 14 absence of observed changes does not preclude confident projections of future change for three reasons:
 15 climate change projected for the 21st century substantially exceeds the changes experienced over the past
 16 century for 2°C (or more) global warming scenarios; ecosystem responses to climate change may be
 17 nonlinear; and change may be apparent only after considerable time lags (Settele et al., 2014).

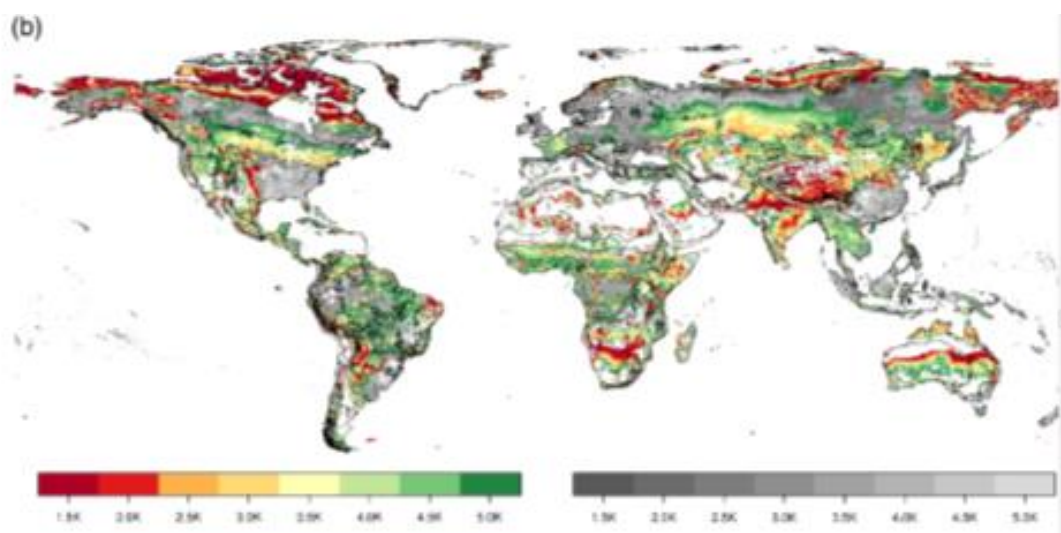
18

19

20 3.4.3.1 Biome Shifts

21 AR5 Chapter 4 (Settele et al., 2014) confirmed that field studies have detected elevational and latitudinal
 22 shifts of biomes in boreal, temperate, and tropical ecosystems (*high confidence*) and, that the biome shifts are
 23 attributable more to anthropogenic climate change than other factors (*medium confidence*). Using an
 24 ensemble of seven Dynamic Vegetation Models driven by projected climates from 21 alternative Global
 25 Circulation Models, Warszawski et al. (2013) show that approximately 25% more biome shifts are projected
 26 to occur under 2°C warming than under 1.5°C warming (Figure 3.17). Figure 3.17 maps the level of global
 27 warming at which biome shifts become significant regionally, and indicates that areas where biome shifts
 28 would be avoided by constraining warming to 1.5°C as compared with 2°C are located in the Arctic, Tibet,
 29 Himalayas, South Africa and Australia. The proportion of biome shifts is projected to approximately double
 30 for warming of 3°C.

31



32

33

34

Figure 3.17: Threshold level of 1Tg leading to significant local changes in water resources (a) and terrestrial

1 ecosystems (b). Coloured areas: river basins with new levels of water scarcity or aggravation of existing
2 scarcity (cases (1) and (2), see Section 2.3.1); greyish areas: basins experiencing lower water availability
3 but remaining above scarcity levels (case (3)); black areas: basins remaining water-scarce but without
4 significant aggravation of scarcity even at $1Tg = 5\text{ }^{\circ}\text{C}$ (case (4)). No population change is assumed here
5 (see also Annex 3.1 Figure S5. iop.org/ERL/8/034032/mmediafor maps including population scenarios).
6 Basins with an average runoff 50% of the simulations. Source: Gerten et al. (2013)
7
8

9 3.4.3.2 *Changes in phenology*

10 AR5 (Settele et al., 2014) suggests spring advancement of -2.8 ± 0.35 days per decade for plants and animals
11 of most of the North Hemisphere ecosystems (between 30°N and 72°N). Among the 4000 plant species
12 studied by (Parmesan and Hanley, 2015), 72% respond to spring warming with earlier flowering (maximum
13 probability of one day per decade), but they highlight the observation that the response is often more
14 complex and that community-level experiments are needed to resolve this. The latter has been confirmed for
15 some regions for vegetation (Amano et al., 2014; Buitenwerf et al., 2015; Crabbe et al., 2016; Dugarsuren
16 and Lin, 2016; Guo et al., 2015; Piao et al., 2015a), but some studies conclude that daytime temperature is a
17 better driver than the daily mean temperature (Piao et al., 2015a) and that, in some regions, for example on
18 the Tibet Plateau (Liu et al. 2016) the situation is more complex. For animals, although a number of non-
19 climatic factors influence phenology, warming has contributed to the overall spring advancement egg laying
20 dates for birds in the north hemisphere (high agreement and medium evidence, AR5 Section 4.3.2.1.2, p292),
21 which is confirmed for the migratory birds in China (Wu and Shi, 2016) and butterflies in UK (Roy et al.,
22 2015). Seddon et al. (2016) quantitatively identified ecologically sensitive regions to climate change in most of
23 the continents from tundra to tropical rainforest. For Africa, available data are less numerous (Adole et
24 al., 2016). Remote sensing data reveal significant advance of growth by 4 to 8 days for croplands and about
25 two weeks for rangeland vegetation (Begue et al., 2014).
26

27 Mid-Century projections of plant and animal phenophases in UK (Thackeray et al., 2016) clearly indicate
28 that the timing of phenological events could change more for primary consumers (6.2 days on average) than
29 for species of higher trophic levels (2.5–2.9 days on average), but the variability between taxa is high with
30 insects being the most sensitive terrestrial taxa. As the sensitivity of the taxa is up to 2.5 ± 1.5 days/ $^{\circ}\text{C}$, it is
31 expected that the difference between a 2°C and 1.5°C warming could be up to 1.25 ± 0.75 days. This is
32 confirmed by Tansey et al., (2017). Within the butterfly population in UK (Roy et al., 2015), the time rate of
33 adult emergence is 6.4 days/ $^{\circ}\text{C}$, a significant value as compared with the inter-population variability. In UK
34 also, the temperate forest phenology will gain 14.3 days in the near term (2010–2039) and 24.6 days in the
35 medium term (2040–2069), so in first approximation the difference between 2°C and 1.5°C global warming
36 is about 10 days. In Northern China (Luo et al., 2014), the start date of growing season advances by 0.65 to
37 1.79 days per decade. Up to 2050, RCP4.5 and RCP8.5 scenarios provide quite similar evolution (-6.5 to $-$
38 7.4 days according to 1961–1990), which could correspond to something between the 1.5°C and 2°C global
39 warming scenario, but at the end of the 21st century, the RCP4.5 (about 3°C global warming), the advance
40 should be about 12 days. This phenological plasticity is not always adaptive (except at the range limits) and
41 must be taken cautiously (Duputié et al., 2015). For example, too early leaf unfolding and flowering increase
42 the risk of frost damage and compromise the possibility of fruits, especially at the margins of a species'
43 distribution. In summary, avoiding a 2°C global warming may reduce advance in spring phenology by a few
44 days and decrease the risk of maladaptation coming from the larger sensitivity of many species to increased
45 climate variability.
46

3.4.3.3 *Changes in species range, abundance and extinction*

AR5 (Settele et al., 2014) concluded that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming: approximately 17 kilometres poleward and 11 metres up in altitude per decade (57 kilometres over 50 years in Canada (McKenney et al., 2014)). In a recent meta-analysis of 27 studies concerning a total of 976 species in of the 20th century, Wiens (2016) found that 47% of local extinctions reported across the globe could be attributed to climate change, especially in tropical regions, and in freshwater habitats. The analysis included plants, mammals, insects, birds, marine invertebrates, amphibians, and molluscs, and found a higher proportion of local extinctions noted for animals. The proportion of species at increased risk of global (as opposed to local) commitment to extinction as a result of climate change has however been estimated (Thomas et al., 2004) to be significantly greater (24%; range 15–37% across studies of limited sets of plants, mammals, birds and butterflies in selected regions) for a warming of 2.2°C above pre-industrial levels than for warming of 1.6°C (18%; range 9–31%). The spatial and interspecific variance in bird populations in Europe and the North America since 1980 are well predicted by trends in climate suitability (Stephens et al., 2016). IUCN (2015) lists 305 terrestrial animal and plant species from Pacific island developing nations as being threatened by climate change and severe weather. Pecl et al. (2017) summarize at the global level the consequences (for economic development, livelihoods, food security, human health and culture) of the species redistribution and concluded that, even if greenhouse gas emissions stopped today, the effort for human systems to adapt to the most crucial effects of climate-driven species redistribution will be far reaching and extensive.

Fischlin et al. (2007) estimated that 20–30% of species would be at increasingly high risk of extinction if global temperature rise exceeds 2–3°C above pre-industrial levels. (Settele et al., 2014) state more generally that large magnitudes of climate change will ‘reduce the populations and viability of species with spatially restricted populations, such as those confined to isolated habitats and mountains’. Warren et al. (2013) simulated climatic range loss for 50,000 plant and animal species using 21 alternative projected climates derived from GCM output, allowing for a realistic rate of species dispersal. It was projected that with 4°C warming, and realistic dispersal rates taken from the literature, 34±7% of the animals, and 57±6% of the plants, would lose 50% or more of their climatic range by the 2080s. By comparison, these projected losses were reduced by 60%, if levels of warming were constrained to 2°C. This earlier study has now been updated and expanded to incorporate 105,501 species, including 19,848 insects, with increased spatial resolution and updated climate change scenarios (Warren et al.). This new study finds that a warming of 4.5°C by 2100 would lead to projected geographic range losses of >50% in 64±6% of 19,848 insects species, 44±14% of 12,429 vertebrate species, and 67±15% of 73,224 plant species studied (thus consistent with the earlier study). This is reduced to 20±10% insects, 8±5% vertebrates, and 16±10% plants; and at 1.5°C to 9±6% insects, 4±3% vertebrates and 8±5% plants, at global warming of 2°C. Hence the number of insect, vertebrate and plant species projected to lose over half their geographic range is halved when warming is limited to 1.5°C as compared with 2°C. Both studies account for the potential ability of species to disperse naturally in an attempt to track their geographically shifting climate envelope, using published estimates of dispersal. This is consistent with estimates made from the earlier study which that range losses at 1.5°C were 50% lower (range 46–56%) than those at 2°C warming (Smith et al.). All these studies exclude species with ranges smaller than 3200 square km.

Bamboo has a high industrial value, but its extension in Japan under temperature increase is at the expense of native plants (Takano et al., 2017). Takana et al. (2017) show an increase of potential habitat from 35% of central/northern Japan in 1980-2000 to 46-48% under a 1.5°C global warming (1.3 times increase) and 51-54% under a 2°C global warming. In Europe, cork oak is also a socio- economically important forest ecosystem protected by the European Union Habitats Directive, but under approximately 1.9°C global warming 5% of its current environmentally suitable areas may be lost, mainly in northern Africa and

1 southern Iberian Peninsula (Correia et al., 2017). These losses can be compensated by afforestation in new
2 suitable areas (twice the present area), but this implies considerable policy and socio-economic challenges
3 including competition with current land uses and alternative management options. By constraining warming
4 to 1.5°C losses would be expected to be further reduced.
5
6

7 3.4.3.4 *Changes in ecosystem function, biomass and carbon stocks*

8 The net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era
9 (Settele et al., 2014)(AR5-Chap4, *high confidence*), with most studies speculate that this increase is due to
10 rising CO₂ concentrations driving increased photosynthetic activity. There is, however, no clear signal in this
11 respect. Spring warming has largely stimulated ecosystem productivity at latitudes between 30°N and 90°N,
12 but suppressed productivity in other regions (Xia et al., 2014). From a meta-analysis covering all
13 ecosystems, Slot and Kitajima (2015) found that leaf respiration of most terrestrial plants can acclimate to
14 gradual warming (decreased respiration of new leaflets), and can potentially reduce the magnitude of the
15 positive feedback between climate and the carbon cycle in a warming world. A greening effect due to CO₂
16 fertilization is often observed in the tropics (Murray-Tortarolo et al., 2016; Zhu et al., 2016) and in China
17 [LAI increase of 0.0070 yr⁻¹, between 0.0035 yr⁻¹ to 0.0127 yr⁻¹](Piao et al., 2015b). The extreme events are a
18 particular point of concern. Frank et al.(2015) found that ecosystem responses can exceed the duration of the
19 climate impacts of extreme events via their lagged effects on the carbon cycle, depending on changes in their
20 frequency and severity, on their compound effects, timing. Droughts are the most impacting events and
21 forests are the most vulnerable ecosystems.
22

23 WGII AR5 concluded that deforestation has slowed over the last decade (even if this is now reversing),
24 including in the tropical regions, and that biomass and soil carbon stocks in terrestrial ecosystems are
25 currently increasing (*high confidence*), but are vulnerable to loss to the atmosphere as a result of rising
26 temperature, drought, pests, storms, and fire projected in the 21st century. In the tropical regions, Anderegg
27 et al. (2015) show that the total ecosystem respiration, at the global scale, has decreased in response to
28 increase of nighttime temperature (1 Pg C / year /°C, p=0.02). Munoz-Rojas et al. (2016) demonstrated
29 increased rates of soil respiration in semi-arid ecosystems in burnt areas versus unburnt ones. There is now
30 additional evidence for attribution of increased forest fire in North America to anthropogenic climate change
31 during 1984-2015, via the mechanism of increasing fuel aridity almost doubling the western US forest fire
32 area compared to what would have been expected in the absence of climate change (Abatzoglou and
33 Williams, 2016). Grassland carbon storage in China has shown an increasing trend, with the average annual
34 growth rate of 9.62 Tg C yr⁻¹ during 1961 - 2013, and temperature was the main determinant factor,
35 explaining about 72.3% of its variation(Zhang et al., 2016a).
36

37 Yang et al. (2015) showed a reduction of the carbon sink of global terrestrial ecosystems by 0.57 PgCyr⁻¹ in
38 ecosystems with high carbon storage, such as peatlands and tropical forests. Forest must be seen as prime
39 regulators within the water, energy and carbon cycles and so a powerful adaptation tool (Ellison et al., 2017).
40 Soil is a key compartment for carbon sequestration(Lal, 2014; Minasny et al., 2017) depending on the net
41 biome productivity, the soil quality (Bispo et al., 2017)and that some of this productivity can be retained in
42 the soil to offset emissions and also enhance the resilience of soil and agro-ecosystems to climate change.
43 The increase of total ecosystem respiration in spring and autumn, in relation with higher temperature, may
44 turn boreal forest from carbon sink to carbon source (Hadden and Grelle, 2016). This is confirmed for the
45 boreal peatlands where increased temperature may diminish the carbon storage and compromise the stability
46 of the peatland (Dieleman et al., 2016).
47

48 AR5 assessed that there remains large uncertainty in the land carbon cycle behavior in the future (Ciais et
49 al., 2013a), with most, but not all, CMIP5 models simulating continued terrestrial carbon uptake under all

1 four RCP scenarios (Jones et al., 2013). Disagreement between models outweighs differences between
2 scenarios even up to 2100 (Hewitt et al. 2016; Lovenduski and Bonan 2017). Increased CO₂ will drive
3 further increases in land carbon sink (Ciais et al., 2015; Schimel et al., 2015), which could persist for
4 centuries (Pugh et al. 2016). Nitrogen, phosphorus and other nutrients, will limit terrestrial carbon cycle
5 response to both CO₂ and climate (Ellsworth et al., 2017; Goll et al., 2012; Wieder et al., 2015; Yang et al.,
6 2014; Zaehle et al., 2015). Climate change may accelerate plant uptake of carbon (Gang et al., 2015), but also
7 decomposition processes (Crowther et al., 2016; Koven et al., 2015; Todd-Brown et al., 2014). Ahlström et
8 al. (2012) found a net loss of carbon in extra-tropics and largest spread across model results in the tropics.
9 The net effect of climate change is to reduce the carbon sink expected under CO₂ increase alone (AR5).
10 Friend et al. (2014) found substantial uptake of carbon by vegetation under future scenarios when considering
11 the effects of both climate change and elevated CO₂.

12
13 There is little published literature examining modelled land carbon changes specifically under 1.5°C
14 warming, but here existing CMIP5 models and published data are used to draw some conclusions. For
15 systems with significant inertia, such as vegetation or soil carbon stores, changes in carbon storage will
16 depend on the rate of change of forcing and so are dependent on the choice of scenario (Ciais et al., 2013a;
17 Jones et al., 2009; Sihi et al., 2017). Therefore, the focus is on GPP – the rate of photosynthetic carbon
18 uptake – by the models, rather than by changes in their carbon store, as this will be less dependent on legacy
19 effects of the choice of scenario. For a number of reasons, we draw on idealized simulations with coupled
20 carbon cycle models where atmospheric CO₂ is prescribed to increase at 1% per year. Firstly, simulations
21 exist with a range of models, and two simulations have been run which allow for the explicit separation of
22 the role of CO₂ and the role of climate on the carbon cycle. Secondly, there are no confounding effects of
23 land-use. Land-use forcing is a significant driver of changes in land carbon storage but is not simply linked
24 with global temperature change (Ciais et al., 2013a), and so analysis of model results from future scenarios
25 that include both climate change and land-use change effects are difficult to interpret in terms of the role of
26 these drivers individually (Hewitt et al., 2016).

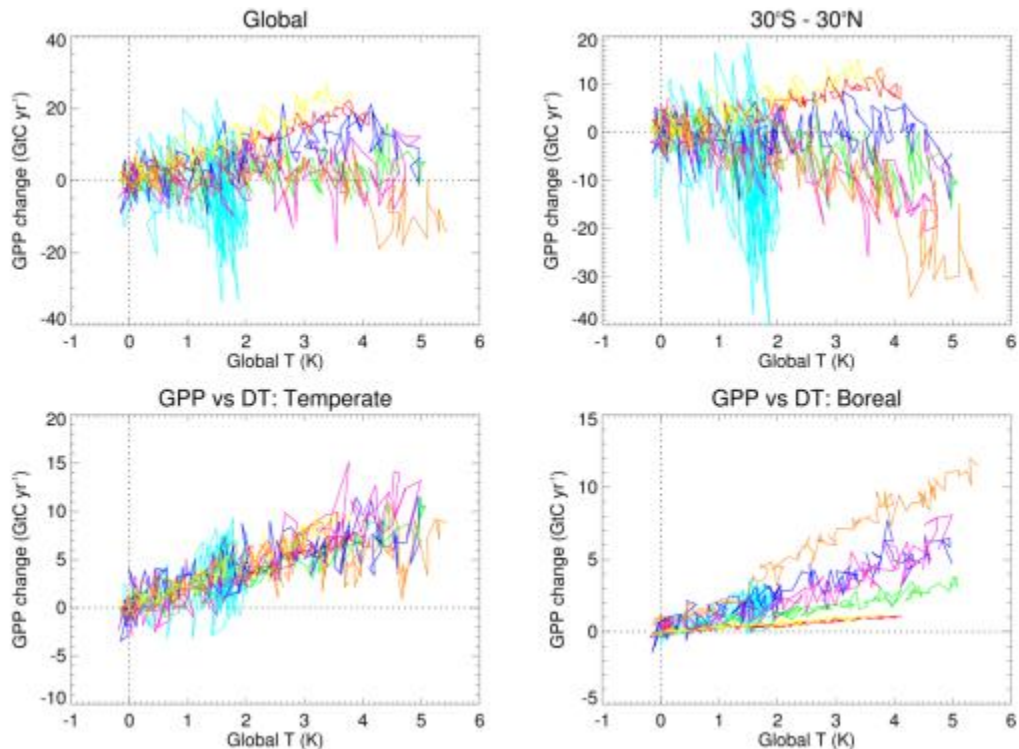
27
28 Results show (Figure 3.18) different responses of the terrestrial carbon cycle to climate change in different
29 regions. The models show a consistent response of increased GPP in temperate latitudes of approximately
30 2.0 Gt Cyr⁻¹ K⁻¹. This is in agreement with Gang et al. (2015) who also projected a robust increase in NPP of
31 temperate forests, however Ahlström et al. (2012) show this could be offset or reversed by increases in
32 decomposition. CMIP5 models also project an increase in high-latitude productivity, but in the tropics, there
33 is marked disagreement between models even over the sign of response, and sufficiently weak signal to noise
34 ratio to allow confident assessment of the future changes. Two models with increased tropical productivity
35 also show lower high latitude gains. These are the two CMIP5 models that include treatment of terrestrial
36 nitrogen cycling, highlighting the important role of nutrient limitations on future terrestrial carbon uptake.
37 Globally, GPP increases or remains approximately unchanged in most models. This confirmed by (Sakalli et
38 al., 2017) for Europe using Euro-Cordex regional models under a 2°C global warming for the 2034-2063
39 period (storage will increase by +5% in soil and by +20% in vegetation).

40
41 AR5 assessed high confidence in thawing of permafrost but low confidence in the amount of carbon that
42 may be released. Observational constraints suggest limiting global warming to 1.5°C would avoid
43 approximately 2 million km² of permafrost compared with stabilisation at 2°C (Chadburn et al., 2017), but
44 the timescale for release of thawed carbon as CO₂ or CH₄ is likely to be many centuries (Burke et al., 2017).

45
46 There is no clear evidence of strong non-linearities or thresholds between 1.5°C and 2°C, so impacts on
47 terrestrial carbon storage will be greater at 2°C than at 1.5°C. If global CO₂ concentrations and temperatures
48 stabilise, or peak and decline, then both land and ocean carbon sinks – which are primarily driven by the
49 continued increase in atmospheric CO₂ – will also decline, and may even reverse (Cao and Caldeira, 2010;

1 Jones et al., 2016).

2



3

4 **Figure 3.18:** The response of terrestrial productivity (GPP) to climate change, globally (top left) and for three
 5 latitudinal regions: 30S-30N; 30-60N and 60-90N. Data was used from the CMIP5 model archive
 6 (<http://cmip-pcmdi.llnl.gov/cmip5/>). Seven Earth System Models used: NorESM-ME (yellow); CESM
 7 (red); IPSL-CM5-LR (dark blue); GFDL (pale blue); MPI-ESM (pink); HadGEM2-ES (orange);
 8 CanESM2 (green). Results are differences in GPP from model simulations with ('1pctCO₂') and without
 9 ('esmfixclim1') the effects of climate change. Data is plotted against global mean temperature increase
 10 above pre-industrial from simulations with 1% per year increase in CO₂ ('1pctCO₂').

11

12 Sui and Zhou (2013) found that the regional temperate grasslands in China acted as a small carbon sink in the
 13 study area of 64.96 million hectares during the period of 1951-2007. The sink of temperate grasslands will
 14 be reduced if the climate gets warmer and drier during this century since the increasing net primary
 15 production does not keep up with the increase of heterotrophic respiration.

16

17 AR5 also highlighted projected increases in the intensity of storms, wildfires and pest outbreaks (Settele et
 18 al., 2014), which can potentially lead to forest dieback. This would contribute to a decrease in the terrestrial
 19 carbon sink. The increased amount of evidence that anthropogenic climate change has already caused
 20 significant increases in fire area in N America (see 3.4.1), is in line with projected fire risks. Fire risks are
 21 projected to increase further at 1.5°C warming relative to the present day: in one study, projections on the
 22 basis of the CMIP3 ensemble of climate models (SRES A2 scenario) indicated with high agreement that fire
 23 frequency would increase over 37.8% of global land areas during 2010-2039 (Moritz et al., 2012),
 24 corresponding to a global warming level of approximately 1.2°C; as compared with over 61.9% of the global
 25 land area in 2070-2099, corresponding to a warming of approximately 3.5°C (Figure 10.5 panel A, Meehl et
 26 al. 2007), which indicates an ensemble average projection of 0.7°C or 3°C above 1980-1999, which is itself
 27 0.5°C above pre-industrial (Figure 10.5 panel A, Meehl et al. 2007). Romero-Lankao et al. (2014) (Box 26-1)
 28 also indicated significantly lower wildfire risks in North America for near term warming (2030-2040, which

1 may be considered a proxy for 1.5°C) than at 2°C.

2 3.4.3.5 *Regional and Ecosystem-Specific Risks*

3 A large number of threatened systems including mountain ecosystems, highly biodiverse tropical wet and
4 dry forests, deserts, freshwater systems and dune systems are assessed in the AR5. These include
5 Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the
6 Fynbos and succulent Karoo areas of S. Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe.
7 In all these systems, impacts accrue with greater warming. Consequently, impacts at 2°C would be expected
8 to be greater than those at 1.5°C (*medium confidence*). These systems are interconnected. Huang et al. (2017)
9 demonstrated that the drylands have warmed during the last century at rates that are 20-40% more than the
10 humid lands while their CO₂ emissions (250 Gt) were one third of those of the humid lands. For the end of
11 this century, when global warming will reach 2°C, the warming will be 3.2-4°C on drylands and if it is
12 limited to 1.5°C, the mean warming on drylands will be 3°C. So the world's population living on drylands
13 will suffer from emission primarily from humid lands, especially due to decreased crops, water resources and
14 malaria transmission.

15 16 17 3.4.3.5.1 *Arctic and alpine ecosystems*

18 According to AR5 (Settele et al., 2014) the High Arctic region, with tundra-dominated landscapes, has
19 warmed more than the global average over the last century. Seven of 19 sub-populations of the polar bear are
20 declining in number. The Arctic tundra biome is experiencing increasing fire disturbance and permafrost
21 degradation (Bring et al., 2016; DeBeer et al., 2016a; Jiang et al., 2016; Yang et al., 2016). Both of these
22 processes facilitate conditions for woody species establishment in tundra areas. In the arctic ecosystems,
23 Mortensen et al. (2014) indicate that among the 114 abiotic, performance and phenological variables related
24 to several tens of taxa, 32 showed a delay and 51 an advance in phenology, the most negative concerning
25 specific trophic levels (plants, arthropods, predators, zooplankton). Cooper (2014) show that the main causes
26 of Arctic terrestrial ecosystem disruption are delays in winter onset and mild winters. Long-term absence of
27 snow reduces vascular plant cover in the understorey by 92%, reduces fine root biomass by 39% (Blume-
28 Werry et al., 2016). See also the latest Arctic Report Card (<http://www.arctic.noaa.gov/Report-Card>).

29
30 Using RCP scenarios, CMIP5 ensemble simulations and a statistical model of periglacial processes, (Aalto et
31 al., 2017) predict a 72% reduction of cryogenic land surface processes in Northern Europe for RCP2.6 in
32 2040-2069 (corresponding to a global warming of approximately 1.6°C, with only slightly larger losses for
33 RCP4.5 (2°C global warming).

34
35 Grassland net primary productivity (NPP) on the Qinghai-Tibet Plateau caused decreased from 1.2 gCm⁻²yr⁻¹
36 during the 1982-2001 period to -92gCm⁻²yr⁻² during the 2001-2011 period, as a result of climate change.
37 This was, however, compensated for by an equivalent increase resulting from changes in human activities
38 (stopping degradation of grassland and reducing livestock number) (Chen et al. 2014). Hence an adequate
39 adaptation policy was in this case able to compensate for the negative effects of climate change to date.

40 41 42 3.4.3.5.2 *Forest and woodland ecosystems*

43 Projected impacts on forests including increases in the intensity of storms, wildfires and pest
44 outbreaks (Settele et al., 2014), potentially leading to forest dieback. Romero-Lankao et al. (2014, Box 26-1)
45 indicate significantly lower wildfire risks in North America for near term warming (2030-2040, which may
46 be considered a proxy for 1.5°C) than at 2°C.

47
48 Amazon tropical forest has been shown to be close to its climatic threshold (Good et al., 2011; Hutyrá et al.,
49 2005), but this threshold may move under elevated CO₂ (Good et al., 2011). Future changes in rainfall,

1 especially dry season length, will determine response of Amazon forest (Good et al., 2013; Sombroek, 2001).
2 The forest may be especially vulnerable to combined pressure from multiple stressors: namely changes in
3 climate and continued anthropogenic disturbance (Borma et al., 2013; Nobre et al., 2016). Modelling
4 (Huntingford et al., 2013) and observational constraints (Cox et al., 2013) suggest large scale forest dieback
5 less likely than suggested under early coupled modelling studies (Cox et al., 2000; Jones et al., 2009)
6 estimate climate threshold of 4°C and a deforestation threshold of 40%. In Central America (Lyra et al.,
7 2017) showed that under progressive warming and drying simulated in that region, that vegetation
8 productivity and biomass steadily decline.

9
10 Boreal forests are likely to experience higher local warming than the global average (AR5, Collins et al.
11 2013). Northward expansion of the treeline and enhanced carbon storage is seen in dynamic vegetation
12 models and coupled climate models (Jones et al. 2010; Ciais et al. 2013). Increased disturbance from fire,
13 pests and heat related mortality may affect the southern boundary of the boreal forest (Gauthier et al., 2015,
14 and references therein). Thawing permafrost will affect local hydrology on small heterogeneous scales,
15 which may increase or decrease soil moisture and waterlogging. Thawing of organic matter may liberate
16 nutrients, which in turn may stimulate enhanced vegetation productivity and carbon storage.

17 18 19 3.4.3.5.3 *Dryland ecosystems: Savannas, shrublands, grasslands, deserts*

20 Globally, according to AR5 (Settele et al., 2014), the savanna boundary is moving into former grasslands
21 with woody encroachment, and tree cover and biomass have increased over the past century. It has been
22 attributed to changes in land management, rising CO₂, climate variability and change (often in combination).
23 Rangelands are highly responsive to changes in water balance. Guan et al. (2014) found that the rainy season
24 length has strong nonlinear impacts on tree fractional cover of dry forests and savannas.

25
26 Observed shifts in phenology, range, and the health of plant species in the Mediterranean region have been
27 observed as precipitation has decreased and temperatures have increased. In semi-arid biomes of the SW
28 USA, recent drought conditions had a strong negative impact on fire incidence and intensity and vegetation
29 productivity (Barnes et al., 2016). Recent prospective studies using independent complementary approaches
30 now show that there is a regional-scale tipping point in the Mediterranean between 1.5°C and 2°C warming
31 (Guiot and Cramer, 2016; Schleussner et al., 2016d). Using a large ensemble of climate and hydrological
32 model projections the former identifies that at 1.5°C warming, median water availability is projected to
33 decline by 9% relative to the period 1986-2005 (by which time warming of 0.6°C above pre-industrial levels
34 had occurred, see IPCC (2013) in comparison to 17% at 2°C, whilst the length of dry spells increases by 7%
35 under 1.5°C warming compared to 11% under 2°C warming. The latter finds that only 1.5°C warming
36 constrains the region's climate to lie within the variability of the Holocene climate— whilst 2°C warming
37 results in transformation of 12-15% of the Mediterranean biome area. Global warming of 4°C is projected to
38 transform Southern Spain into a desert. Sánchez-Salguero et al. (2017) anticipate an abrupt reduction in
39 plant growth toward the end of the 21st century for the water-limited fir forest sites and an increase in moist
40 refugia due to higher temperature.

41
42 Song et al. (2016) examined the photosynthetic responses of *Stipa baicalensis* to relative long-term exposure
43 (42 days) to the predicted elevated temperature and water availability changes in Inner Mongolia, China. The
44 elevated temperature (+4°C) and partial irrigation reduced the net photosynthetic rate, and the reduction in
45 V_{cmax} increased with increasing temperature. Although climate warming (+4°C) caused reductions in the
46 light use efficiency and photosynthetic rate, a self-photoprotection mechanism in *Stipa baicalensis* resulted in
47 its high ability to maintain normal live activities.

48
49 Lü et al. (2016) pointed out that warming and changing precipitation had significant interactive effects,

1 different from the accumulation of single-factor effects, on functional traits of *Stipa* species. The correlation
2 and sensitivity of different plant functional traits to temperature and precipitation differed. Precipitation is
3 the key factor determining the growth and changes in plant functional traits in *Stipa* species, and that
4 temperature mainly influences the quantitative fluctuations of the changes in functional traits.
5

6 A comparison of vegetation in Mongolian sites in 2013 and in 1994-1995 (Khishigbayar et al., 2015) does
7 not show any important change in biomass, except for mountain-steppe sites, while the diversity declined
8 significantly everywhere. The study shows also a strong resilience to degradation except in grazing pressure
9 sites, so that adaptation is possible with appropriate governance that permits collective possession and
10 management of pastures by self-organized groups of herders.
11

12 The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under
13 increasing temperatures and drier winters. It is projected to lose ~20%, ~45% and ~80% of its current
14 suitable climate area under 1°C, 2°C and 3°C of global warming, respectively (Engelbrecht and Engelbrecht,
15 2016). The global temperature anomalies have been calculated with respect to present-day climate.
16
17

18 3.4.3.5.4 *Wetlands and freshwater ecosystems*

19 According to AR5 (Settele et al., 2014), freshwater ecosystems are considered to be among the most
20 threatened on the planet. Although peatlands cover only about 3% of the land surface, they hold one-third of
21 the world's soil carbon stock (400 to 600 Pg). In the Congo Basin (Dargie et al., 2017) and in the Amazonian
22 Basin (Draper et al., 2014), the peatlands store the equivalent of the tropical forest. Carbon stored in these
23 systems is vulnerable to land use change and future reduction in precipitation. At the global scale, they are
24 undergoing rapid major transformations through drainage and burning in preparation for oil palm and other
25 crops or through unintentional burning. Wetland salinization, a widespread threat to the structure and
26 ecological functioning of inland and coastal wetlands, is currently occurring at an high rate and large
27 geographic scale (Herbert et al., 2015). The water conservation of the alpine ecosystem of the Source Region
28 of the Yellow River had a slightly decreasing trend of -1.15 mm yr⁻¹ during the period of 1981-2010 (Yunhe
29 et al., 2016). Peatbogs, coastal lagoons also may be threatened at mid-latitudes (Munoz-Sobrinho et al., 2016).
30

31 Settele et al. (2014) find that rising water temperatures are projected to lead to shifts in freshwater species
32 distributions and worsen water quality. Some of these ecosystems respond non-linearly to changes in
33 temperature, for example it has been found that the wetland function of the Prairie Pothole region in North
34 America is projected to decline beyond a local warming of 2-3°C above present (a 1°C local warming,
35 corresponding to a 0.6°C global warming). If the ratio of local to global warming remains similar for these
36 small levels of warming, this would indicate a global temperature threshold of 1.2-1.8°C warming. Hence
37 constraining global warming to approximately 1.5°C warming would maintain the functioning of the prairie
38 pothole ecosystem in terms of their productivity and biodiversity (Johnson and Poiani, 2016).
39

1 **Table 3.2:** [Placeholder. Table of risk for Terrestrial and wetlands ecosystems. See summary and detailed tables in Annex 3.1, Table S3.4.3]

Risk	Region (could be globe)	Metric (unit)	Baseline time period against which change in impact measured	Socio-economic scenario and date (make clear if uses present day population and assumes constant)	Baseline global T used in paper (pre-industrial, or other, and did you have to convert? Eg if your paper gives delta T relative to 1990 you add 0.5C)	Climate scenario used (e.g. RCP, SRES, HadCM3 in 2050s, etc)	Is it for transient (T) or equilibrium (E) (if known)?	Is it an overshoot scenario? How long it is above 1.5C and what is the max temp and when?	Is the modelling approach used in that publication dynamic (Y/N)	Projected impact at 1.5C above pre-industrial	Projected impact at 2C above pre-industrial	Projected impact at delta T(°C)	Delta T relative to pre-industrial; delta T(°C) (deltaT1+column F)	Delta T relative to baseline temp(T1); delta T1(°C)

2

1 3.4.4 Oceans systems

2
3 The ocean plays a central role in regulating atmospheric gas concentrations, global temperature and climate.
4 It is also home to a vast number of organisms and ecosystems that provide ecosystem goods and services that
5 are worth trillions of USD per year (e.g. Costanza et al. 2014; Hoegh-Guldberg et al. 2015). Some of the
6 most vulnerable human communities depend on the ocean for food and income, with inequities projected to
7 increase as ocean and coastal resources experience growing impacts from climate change and other human
8 activities (Halpern et al., 2015).

9
10 In assessing the evidence for climate change, AR5 separated the Ocean into regions such as up-welling
11 zones, semi-enclosed seas, coastal boundary systems, sub-tropical gyres, polar seas, and the deep sea
12 (Hoegh-Guldberg et al., 2014). Knowledge of climate related risks and challenges facing the ocean has
13 increased substantially since AR5, although knowledge about how the ocean and its ecosystems have, and
14 are, responding to climate change continue to lag behind that of terrestrial ecosystems. The world's largest
15 habitat for example, the deep sea, is the least understood region of our planet yet may includesome of the
16 greatest risks of irreversible climate change. Understanding ocean components, processes, and tipping points,
17 as well as human responses to change across the ocean is becoming increasingly important. Background
18 information on ocean systems and climate change can be found in AR5, particularly Rhein et al. (2013),
19 Hoegh-Guldberg et al. (2014), and Pörtner et al. (2014a).

20
21 Previous sections of the present chapter have described the evidence for changes in ocean temperature down
22 to 700 m due to climate change (see 3.3.8). Anthropogenic carbon dioxide has also resulted in a decrease in
23 pH, as well as both increases and decreases in other crucial ions (see 3.3.11), over a similar depth range.
24 Increased ocean temperature has also increased ocean volume and sea level (see 3.3.10), loss of sea ice, and
25 storm activity (see 3.3.7), as well as decreasing the solubility of oxygen (see 3.3.11). Table 3.3 summarises
26 a broad set of changes expected in sea surface temperature, pH, oxygen content, sea level and ocean volume
27 with respect to the saturation of the key form of calcium carbonate, aragonite, by the end of the century.
28 Three Representative Concentration Pathways (RCP) scenarios were used to drive CMIP5 model ensembles
29 that were compared to the 1990s (1990-1999) as well as the pre-industrial period (1870-1899). While no
30 specific scenario was modelled for 1.5°C, RCP2.6 and RCP4.5 scenarios essentially bracket many 1.5°C
31 scenarios. This information will be used later in this chapter to inform specific projected risks as well as
32 adaptation options.

33
34 Importantly, risk factors really operate in isolation. Consequently, the effect of global warming at 1.5°C
35 versus 2°C, must be considered in the light of multiple, interactive factors that may accumulate over time to
36 produce complex impacts on human and natural systems.
37

1 **Table 3.3:** Changes in SST, pH, oxygen content, sea level and ocean volume with respect to aragonite (Ω_a) in CMIP5
 2 models and RCP emission scenarios. Originally from Bopp et al. (2013) and as presented by (Gattuso et al.,
 3 2015a).
 4

A. Changes relative to 1990-1999						
	Δ SST	Δ pH	Δ O ₂	Sea level	Vol Ω_a	Vol Ω_a
	(°C)	(units)	(%)	(m)	(>1%)	(>3%)
2090-2099 (RCP 8.5)	2.73	-0.33	-3.48	0.67	9.4	0
2090-2099 (RCP 4.5)	1.28	-0.15	-2.37	0.49	15	0.57
2090-2099 (RCP 2.6)	0.71	-0.07	-1.81	0.41	17.3	1.22
1990s (1990-1999)	0	0	0	0	24	1.82
Pre-industrial (1870-1899)	-0.44	0.07	-	-	25.6	2.61
Pre-industrial (1870-1879)	-0.38	0.07	-	-	25.6	2.67
B. Changes relative to 1870-1899 (except sea level, relative to 1901)						
2090-2099 (RCP 8.5)	3.17	-0.4	-	0.86	-	-
2090-2099 (RCP 4.5)	1.72	-0.22	-	0.68	-	-
2090-2099 (RCP 2.6)	1.15	-0.14	-	0.6	-	-
2010s (2005-2014)	0.83	-0.11	-	-	-	-
Past 10 years (2005-2014)	0.72	-0.1	-	0.19*	-	-
1990s (1990-1999)	0.44	-0.07	-	-	-	-
Pre-industrial (1870-1899)	0	0	-	0	-	-
<i>*Value for 2010 obtained from instrumental records</i>						

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3.4.4.1 Observed impacts

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3.4.4.1.1 Warming and stratification of the surface ocean

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The average temperatures of the surface layers of the ocean are expected to increase by an average of 1.15°C to 1.72°C above the pre-industrial period by end of century for RCP2.6 and RCP4.5 scenarios respectively (Table 1). Patterns of ocean warming are complex and have been detected across a number of levels from species to regions. The range of marine organisms, from phytoplankton to sharks, are tracking local

1 temperatures as they relocate, with biogeographical ranges shifting to higher latitudes as ocean waters warm,
2 at rates of up to 40 km/year (Bruge et al., 2016; Chust et al., 2014). These changes have major implications
3 for biodiversity, food webs, ecosystem structure, fisheries, and human livelihoods (Poloczanska et al., 2016).
4 As biogeographical ranges of many organisms shift to higher latitudes, equatorial regions are projected to
5 experience enhanced elevated local extinction rates while biodiversity will increase at higher latitudes
6 (Burrows et al., 2011; García Molinos et al., 2015; Hoegh-Guldberg et al., 2014; Poloczanska et al., 2013a,
7 2016).

8
9 Net Primary Productivity (NPP, net fixation of CO₂ by phototrophic organisms) of the ocean represents half
10 of the global NPP and is driven by both atmospheric and ocean processes including sea ice, wind, waves,
11 currents, thermal stratification and upwelling, among other factors (Bakun et al., 2015; Boyd et al., 2014;
12 Capone and Hutchins, 2013; Di Lorenzo, 2015; Sydeman et al., 2014). Changes to global temperature are
13 driving decreases in NPP in some regions (e.g. reduced equatorial up-welling, and increased stratification)
14 with *low to medium confidence* (Boyd et al., 2014; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014b;
15 Signorini et al., 2015). Similar levels of confidence can be assigned to the increased fish catch being
16 reported at high latitude sites in the northern hemisphere where ice retreat and warming are stimulating
17 primary productivity through greater light levels and nutrients from increased water column mixing (Cheung
18 et al., 2016a; Poloczanska et al., 2014; Weatherdon et al., 2016).

19
20 Not all organisms have biogeographical ranges that are as flexible as plankton in response to rapidly shifting
21 isotherms (Poloczanska et al., 2016). Organisms that are physically fixed to the ocean floor for much of
22 their life cycle (e.g. corals, seaweeds and bivalves) have lower rates of re-location and hence experience high
23 rates of mortality as conditions within locations change. In these cases, temperature extremes can result in
24 the mass mortality of key organisms such as reef-building corals or kelp plants (Hughes et al., 2017;
25 Krumhansl et al., 2016) (Babcock et al. 2018). Organisms may also differ markedly in their sensitivity to
26 increased temperatures, which may vary with life-history stage or size (Pörtner et al., 2014a). Changes in
27 temperature can also lead to changes in the timing of key events such as spawning or migration (Poloczanska
28 et al., 2016). Modifications to the distribution and abundance of organisms are likely to result in permanent
29 changes to ecosystems, which may include the appearance of novel ecosystems, food webs, and rates of
30 productivity (Hobbs et al., 2009). In some cases, these changes are very likely to present substantial
31 challenges and have negative implications for societies, industry, and millions of people world-wide (see
32 Box 3.6).

33 34 35 3.4.4.1.2 *Storms and coastal run-off*

36 Coastal ecosystems and communities are vulnerable to the impact of wind, waves and inundation (IPCC,
37 2012a; Seneviratne et al., 2012). The number of very intense tropical cyclones across the world's ocean has
38 increased, with an associated decrease in the overall number of tropical cyclones (3.3.7, Elsner et al. 2008;
39 Holland and Bruyère 2014). The direct force of wind and waves associated with larger storms increases the
40 risks of physical damage to coastal ecosystems such as mangroves (Long et al., 2016; Primavera et al., 2016;
41 Villamayor et al., 2016) and coral reefs (Bozec et al., 2015; Cheal et al., 2017; De'ath et al., 2012) leading,
42 in some case, to increased exposure to additional impacts. These changes are associated with increases in
43 maximum wind speed, wave height, and the inundation, although trends in these variables vary from region
44 to region (3.3.5). Sea level rise has amplified these impacts with storm surge and damage already penetrating
45 further than a few decades ago, changing conditions for coastal ecosystems and human communities
46 (3.3.10).

47
48 The balance between the frequency of impacts and the time frame for recovery will determine whether
49 ecosystems will persist or not. The increasing frequency of extremes affecting the Great Barrier Reef (e.g.

1 storms, heat-related mass mortalities) plus local factors (coastal pollution), for example, has overwhelmed
2 the capacity for communities of reef-building corals to recover, resulting in the rapid loss of corals (over
3 50% in 30 years) across this vast ecosystem (Cheal et al., 2017; De'ath et al., 2012). Increasing storm
4 strength and precipitation (*medium confidence*) are projected to occur (3.3.3), further challenging both
5 natural and human systems as conditions change. These factors are also likely to influence water quality
6 along coastlines globally through greater climate extremes, erosion and loss of crucial coastal ecosystems
7 within river catchment such as forests and mangroves (Burt et al., 2016; Serpa et al., 2015, 2017). In some
8 regions, the incident of droughts may increase (IPCC SREX, *medium confidence*) reducing soil retention and
9 thereby contributing greater amounts of sediment and nutrients during subsequent rainfall and flood events
10 (3.3.4). These changes in water quality are likely to have negative impacts on many coastal ecosystems,
11 especially those that require clear and nutrient depleted waters (Brodie et al., 2012; Kroon et al., 2016;
12 Muscatine and Porter, 1977).

13
14 Adaptation to the impacts of changes to storms and run-off include reducing exposure to storms as well as
15 long-term planning for the combined challenges of increased storms intensity, sea level rise and salinization
16 of coastal water resources. Integrating the expected shoreward migration of key coastal ecosystems (e.g.
17 mangroves, salt marsh) across coastal area will be important in terms of protecting key ecological services
18 such as fisheries habitat and coastal protection for human communities and infrastructure provided by these
19 ecosystems (Saunders et al., 2014, BOX 3.6, 3.7). Increased management of vegetation under the challenges
20 of climate related erosion will help reduce erosion and associated water quality issues (Mehdi et al., 2015).

21 22 23 3.4.4.1.3 *Ocean circulation*

24 The movement of water within the ocean, whether it be geographic or depth-related plays a central part of
25 the biology and ecology of the ocean. Ocean currents can connect regions across thousands of kilometres of
26 ocean through the transport of nutrients, heat, oxygen, carbon dioxide, physical materials, human
27 infrastructure (ships), and marine organisms. Similarly, the upwelling of cold nutrient rich waters in some
28 regions brings important inorganic nutrients to the surface, boosting productivity and supporting fisheries
29 that provide the protein needs of hundreds of millions of people (Bakun et al., 2015; FAO, 2016; Kämpf and
30 Chapman, 2016). Other regions have highly stable water columns, which have very low amounts of
31 inorganic nutrients due to the sinking of particles out of the upper layers of the ocean and the associated loss
32 of nutrients from the photic zone. As a result, primary productivity in these regions is extremely low (e.g.
33 sub-tropical gyres, STP). Firmly attributing recent changes in the strength and direction of ocean currents to
34 climate change, however, is complicated by long-term variability (e.g. Pacific Decadal Oscillation, Signorini
35 et al., 2015) and the lack of matching long-term records in many cases (Lluch-Cota et al. 2014). Since AR5,
36 however, a meta-analysis undertaken by Sydeman et al. (2014b) reveals that (overall) upwelling-favourable
37 winds have intensified in the California, Benguela, and Humboldt upwelling systems, but have weakened in
38 the Iberian system, over 60 years of record. The same analysis was equivocal with respect to the Canary up-
39 welling system. These conclusions are consistent with the developing consensus that winds favourable to
40 upwelling are likely to intensify under climate change for most systems (Bakun et al., 2015; Di Lorenzo,
41 2015; Sydeman et al., 2014).

42
43 Changes in ocean circulation can have profound impacts on marine ecosystems by connecting regions and
44 enabling the entry of alien species (i.e. 'tropicalization', Verges et al., 2014; Vergés et al., 2016; Wernberg et
45 al., 2012; Zarco-Perello et al., 2017) and disease (Burge et al., 2014) into new regions. The sea urchin,
46 *Centrostephanus rodgersii*, for example, has been able to reach Tasmania where it was previously unknown
47 (from the Australian continent), due to the strengthening of the East Australian Current (EAC). As a
48 consequence, the distribution and abundance of kelp forests have rapidly decreased with implications for
49 fisheries and other ecosystem services (Ling et al., 2009). At regional scales, changes to ocean circulation

1 can have regional implications. Weakening of the Atlantic Meridional Overturning Circulation (AMOC), for
2 example, is likely to be highly disruptive to natural and human systems as the delivery of heat via this
3 current system to higher latitudes is reduced (Rahmstorf et al., 2015).

4 5 3.4.4.1.4 Acidification

6 While many aspects of climate change and ocean chemistry are not understood, numerous risks from ocean
7 acidification to biological systems have been identified (Albright et al., 2016; Dove et al., 2013; Gattuso et
8 al., 2015a; Kroeker et al., 2013; Pörtner et al., 2014a). A comprehensive meta-analysis (Kroeker et al., 2013)
9 synthesized the results and conclusions of 228 studies and revealed risks to the survival, calcification,
10 growth, development, and abundance of a broad range of taxonomic groups (i.e. from algae to fish) with
11 considerable evidence of predictable trait-based sensitivities (Kroeker et al., 2013). Organisms with shells
12 and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a
13 broad number of organisms, although there are examples of taxa that did not show the same sensitivity to
14 changes in CO₂, pH and carbonate concentrations (Kroeker et al., 2013). By comparison, there is a smaller
15 list of examples of unambiguous impacts of ocean acidification on organisms in the field. This list, however,
16 is increasing as studies expand and includes community scale impacts on bacterial assemblages and
17 processes (Endres et al., 2014), coccolithophores (Meier et al., 2014a), pteropods and polar food webs
18 (Bednarsek et al., 2014; Bednaršek et al., 2012), phytoplankton (Richier et al., 2014; Riebesell et al., 2013),
19 seagrass (Garrard et al., 2014), macroalgae (Ordonez et al., 2014; Webster et al., 2013), as well as excavating
20 sponges and reef-building corals in flow-through coral field located mesocosms (Dove et al., 2013; Fang et
21 al., 2014). Ocean acidification is projected to further reduce the resilience of organisms to disturbances. For
22 example, coral reefs may be increasingly brittle as a result of reduced calcification and hence even more
23 vulnerable to intensifying storms, from which they may take longer to recover from due to the impact of
24 other factors (pollution), tipping the balance toward the loss of viable reefs. Adaptation options include
25 reducing local sources of coastal acidification (e.g. coastal run-off and pollution, Duarte et al., 2013; Feely et
26 al., 2016) or involve interventions in coastal and catchment management (i.e. build structures to replace
27 those normally provided by coastal ecosystems, (Barton et al., 2015).

28 29 30 3.4.4.1.5 Deoxygenation

31 Oxygen concentrations in the ocean are declining due to three main factors: (1) heat related stratification of
32 the water column (less ventilation and mixing), (2) reduced oxygen solubility as ocean temperature
33 increases, and (3) impacts of warming on biological processes that produce or consume oxygen such as
34 photosynthesis and respiration (Pörtner et al., 2014a; Shepherd et al., 2017). Similarly, a range of processes
35 (see Section 3.1.11) can also act in synergy, including non-climate change factors such as run-off and coastal
36 eutrophication (e.g. from coastal farming, intensive aquaculture), which increase the metabolic rate of
37 coastal microbial communities by supplying greater amounts of organic carbon (Bakun et al., 2015). The
38 number of dead zones has been increasingly exponentially over the past few decades (Altieri and Gedan,
39 2015; Diaz and Rosenberg, 2008; Schmidtoko et al., 2017). While attribution is difficult due to the
40 complexity of the climate and non-climate change-related processes involved, recent impacts related to
41 deoxygenation (*medium confidence*) include the expansion of the oxygen minimisation zones (Acharya and
42 Panigrahi, 2016; Carstensen et al., 2014; Lachkar et al., 2017; Turner et al., 2008), physiological impacts
43 (Pörtner et al., 2014a), and mortality of oxygenic organisms such as fish (Jacinto, 2011; Thronson and
44 Quigg, 2008) (Hamukuaya et al., 1998) and invertebrates (Altieri et al., 2017; Bednaršek et al., 2016; Hobbs
45 and McDonald, 2010; Seibel, 2016). The impact of the deoxygenation, especially when it occurs together
46 with ocean acidification, may have substantial challenges for aquaculture and fisheries (e.g. Bakun et al.,
47 2015; Feely et al., 2016). Managing both of these industries has the potential to stabilise or reverse trends in
48 oxygen concentrations and shifts in the OMZ. Maintaining sustainable levels of fish, and reducing intensive
49 and unsustainable aquaculture methods, are two ways that the impacts of climate change on the solubility of

1 oxygen and the metabolic rates of organisms can be countered as temperatures increase. The cost benefits
2 have been explored in some regions (Rabotyagov et al., 2014a, 2014b) and point favourable outcomes of
3 action on addressing some of the drivers (i.e. nutrient levels in large rivers).
4
5

6 3.4.4.1.6 *Sea Ice*

7 Sea ice provides habitat for a considerable number of organisms both above and below the ice, as well as
8 livelihoods for Arctic communities. The recent loss of sea ice has been rapid and unprecedented in both polar
9 oceans (Bring et al., 2016; Notz and Stroeve, 2016a; Stuecker et al., 2017). Increased warming increases the
10 risk of the Arctic Ocean being nearly ice free in September, with it being possible at 1.5°C in the 21st century
11 (Sanderson et al., 2017) and ‘*virtually certain*’ (Niederdrenk and Notz) with 2°C of warming (RCP2.6,
12 RCP4.5). The observed and modelled decline of sea ice suggest that temperature targets of 2.0°C and above
13 will be insufficient to prevent the total loss of Arctic sea ice (Screen and Williamson, 2017). This, and other
14 coasts are subject to water-based ice melt has implications for increased significant wave heights nearer to
15 land (Ruest et al., 2016), flooding, erosion, land use and shipping.
16

17 A survey of the literature reveals that major impacts have already occurred and that these are accelerating
18 (see 3.1.9). At this point, a fundamental transformation will have occurred in organisms, systems, and
19 services (*very high confidence*). Photosynthetic communities such macroalgae, phytoplankton and algae
20 dwelling on the underside of sea ice are likely to be transformed as light, temperature and nutrients undergo
21 fundamental changes as sea ice retreats, mixing increases, and phototrophs have access to seasonally high
22 levels of solar radiation (Meier et al., 2014b). These changes may stimulate fisheries productivity as has been
23 reported in the northern hemisphere spring bloom system (Cheung et al., 2009, 2016a; Lam et al., 2014).
24 Losing sea ice will result, however, in the loss of critical habitat for organisms such as seals, seabirds, whales
25 and polar bears among others. Sea ice loss together with sea level rise, increasing temperatures, thawing
26 permafrost, and changing weather patterns will increasingly impact people and infrastructure as well as
27 industries (Meier et al., 2014b). Rates of change currently exceed the ability of many communities to keep
28 up with the many associated challenges. Options surround adapting to new resources while dealing with the
29 challenges of maintaining infrastructure in the face of a rapidly changing Arctic. These aspects will be
30 explored in later chapters of this report.
31
32

33 3.4.4.1.7 *Sea level*

34 Rising sea levels are already having serious impacts. These changes are interacting with other factors such
35 as strengthening storms, together which drives greater storm surge, erosion and habitat loss (Church et al.,
36 2013; Stocker et al., 2013, see 3.3.10). Minimal differences exist between RCP2.6 versus RCP4.5
37 (bracketing a 1.5°C scenario) in terms of sea level rise (0.6 m versus 0.63 m respectively, Table 3.3). End of
38 century sea level rise for RCP 8.5 is much greater than these two. While some ecosystems (e.g. mangroves
39 sea grasses) may be able to move shoreward as sea levels increase, coastal development often curtails these
40 opportunities (Saunders et al., 2014). Options for responding to these challenges include reducing the impact
41 of other stresses such as those arising from tourism, fishing, coastal development, and unsustainable
42 aquaculture/agriculture. In some cases, restoration of coastal habitats and ecosystems can be a cost-effective
43 way of responding to changes arising from rising sea levels, intensifying storms, coastal inundation and
44 salinization (3.3.10).
45

3.4.4.2 Projected risks and adaptation options for a global warming of 1.5°C and 2°C above pre-industrial levels

Gattuso and colleagues explore risks from climate change to ocean systems by adding new information after AR5 on the impacts, risks and adaptation options across key marine organisms and ecosystems, as well as ocean related services for human communities and industry (Gattuso et al., 2015a). Given the rapidly expanding literature, we further review and add to Gattuso et al. (2015)'s assessment by examining new literature (from 2015-2017) and adjusting levels of risk where appropriate. To do this, we use input from the original expert group's assessment (see Annex 3.1, S3-4-4_Supplementary Information on Oceans Systems) and focus particularly on the implications of global warming of 1.5°C as compared to 2.0°C. We also provide a list of potential adaptation options, the details of which will be further explored in later chapters of this special report. This section refers heavily to the review, analysis and literature presented in the Supplementary On-Line Material that accompanies the special report (SOM-Ch3).

3.4.4.2.1 Framework organisms (corals, mangroves and seagrass)

A number of marine species (e.g. seagrass meadows, kelp forests, oyster reefs, salt marsh, mangrove forests and coral reefs) play especially important roles in terms of providing the physical framework and habitat for large numbers of other organisms. Here, we assess the risks from climate change for a subset of framework species (i.e. seagrass meadows, mangrove forests and coral reefs). Framework building organisms are often referred to as ecosystem engineers (Gutiérrez et al., 2012) and are critically important to ecosystems in terms of structure, function and habit.

Evidence has strengthened over the past two years as to the impact of climate change on seagrass meadows, mangrove forests and coral reefs. During the past 3 years (2015-2017), tropical coastal regions experienced unprecedented mass coral bleaching and mortality across a large number of sites globally (Normile, 2016). In the case of the Great Barrier Reef, two successive years of bleaching events removed 50% of all reef-building corals from the Great Barrier Reef (Hughes et al., 2017). While studies are still being written up and analysed, the escalating impacts of the third global mass bleaching event was much larger than that reported for previous global events of 1998 and 2010. These changes to coral reefs were accompanied by similar impacts of climate change on other coastal ecosystems such that 40% of Australia's coral reefs, mangroves and seagrass were removed (Babcock et al.). The latter represents a loss of Australia's coastal resources that is unprecedented in the European history of Australia.

Risks of climate change impacts on seagrass and mangrove ecosystems have recently been assessed by an expert group led by Short et al. (2016). Impacts of climate change were similar across a range of submerged and emerged plants. Submerged plants such as seagrass were affected mostly by temperature and indirectly by turbidity, while emerged communities such as mangroves and salt marshes were most susceptible to sea level variability and temperature extremes, which is consistent with evidence and concern of others (Di Nitto et al., 2014; Osorio et al., 2016; Sasmito et al., 2016; Sierra-Correa and Cantera Kintz, 2015), especially in the context of human activities that reduce soil supply (Lovelock et al., 2015) or interrupt the shoreward movement of mangroves by coastal infrastructure (Saunders et al., 2014). Projection of the future distribution of seagrasses suggest a poleward shift, with concern that low latitude seagrass communities may contract due to increasing stress levels (Valle et al., 2014).

Present-day risks from climate change are *moderate* for seagrass, to *low* for mangroves, and *moderate to high* for reef building corals (Figure 3.19). As average global warming reaches 1.5°C above pre-industrial period, both seagrass and mangroves are expected to experience *moderate* risks, while coral reefs experience high risks of impacts. At global warming of 2°C above the preindustrial, seagrasses are projected to reach

1 *moderate to high* levels of risk (e.g. sea level rise, damage from extreme temperatures, storm damage), while
2 climate change risks to mangroves remain *moderate* (e.g. risks of not keeping up with sea level rise). By this
3 point, coral reefs reach a *very high risk* of impact (Figure 3.19) with most available evidence suggesting that
4 they will not be coral dominated ecosystems at this point (e.g. coral abundance near zero in most locations,
5 intensifying storms ‘flattening’ reef 3-D structure; Alvarez-Filip et al., 2009). Impacts at this point are likely
6 to have undermined the ability to provide habitat for biodiversity as well as a range of ecosystem services
7 important for millions of people (e.g. food, livelihoods, coastal protection, cultural services). Further
8 analysis and literature references can be found in the SOM material accompanying this chapter.

9
10 Adaptation options include reducing non-climate change pressures (e.g. coastal pollution, overfishing,
11 destructive coastal development) to ensure that these ecosystems are as resilient and robust as possible for
12 recovery from accelerating climate change impacts (Anthony et al., 2015; Kroon et al., 2016; O’Leary et al.,
13 2017; Sierra-Correa and Cantera Kintz, 2015; World Bank, 2013). In addition, concentrating adaptation
14 efforts in locations where organisms may be more robust to climate change than others or less exposed to
15 climate change (Bongaerts et al., 2010; van Hooijdonk et al., 2013), may have benefits in terms of efficient
16 and effective use of resources. In this case, this could involve areas of cooler conditions due to upwelling,
17 deep water communities that experience less extreme conditions and impacts, or variable conditions that lead
18 to more resilient organisms. Given the potential value of these regions for surviving climate change and
19 helping repair ecosystems, efforts for preventing their loss to non-climate stresses are likely to be important
20 (Bongaerts et al., 2010; Cacciapaglia and van Woesik, 2015; Chollett et al., 2013, 2014; Fine et al., 2013;
21 van Hooijdonk et al., 2013) but see (Pim Bongaerts et al. 2017; Chollett, Mumby, and Cortés 2017).

22
23 Integrating coastal infrastructure such that it allows the shore-ward relocation of coastal ecosystems such as
24 mangroves, seagrasses and salt marsh will be important as will be maintaining sediment supply to coastal
25 areas in order to enable mangroves can keep pace with sea level rise (Lovelock et al., 2015; Sasmito et al.,
26 2016; Shearman et al., 2013). The impact of damming rivers on sediment supply to mangrove habitat, and
27 hence the ability of mangroves to persist without drowning as sea level increases, should be carefully
28 explored and avoided where possible (Lovelock et al., 2015). In addition, integrated coastal zone
29 management should recognise the importance and economic expediency of using natural ecosystems such as
30 mangroves and coral reefs to protect coastal human communities (Arkema et al., 2013; Elliff and Silva, 2017;
31 Ferrario et al., 2014; Hinkel et al., 2014; Temmerman et al., 2013). High levels of adaptation will be
32 required to prevent impacts on food security and livelihoods in general. Adaptation options include
33 developing alternative livelihoods and food sources, ecosystem restoration, and construction of infrastructure
34 aiming to reduce the impacts of rising seas and intensifying storms.

35 36 37 3.4.4.2.2 *Ocean food webs (pteropods, bivalves, krill, and fin fish)*

38 An integral part of ocean ecosystems is the flow of energy and nutrients through complex food webs. These
39 vast interconnected systems ultimately drives solar energy trapped by phytoplankton through trophic levels
40 and interactions and ultimately provide resources for larger organisms and eventually that apex predators
41 such as sharks, marine mammals and humans. Here, we take four representative types of marine organisms
42 which are important within food webs across the globe, and which illustrate the impacts and ramifications of
43 1.5°C or greater warming.

44
45 Pteropods are pelagic molluscs that produce a calcium carbonate shell and which are highly abundant in
46 temperate and polar waters, where they form an important trophic linkage between phytoplankton and a
47 range of other organisms including fish, whales and birds. Changing water chemistry and temperature,
48 however, is affecting the ability of pteropods to produce their shells, as well as swim and survive (Bednaršek
49 et al., 2016). Shell dissolution is now 19-26% higher, for example, than both nearshore and offshore

1 populations since the pre-industrial period (Feely et al., 2016). There is considerable concern as to whether
2 these organisms are undergoing further reductions in abundance, especially given their central importance in
3 ocean food webs (David et al., 2017).

4
5 Bivalves (e.g. clams, oysters and mussels) are also filter-feeding molluscs that underpin the basis of
6 important fisheries and aquaculture industries (from the polar to tropical regions), and are important as food
7 sources for a range of organisms including humans. Bivalves are also at risk from ocean warming and
8 acidification, with differences between larval versus adult phases. Climate change impacts a wide range of
9 life history stages of bivalve molluscs (e.g. Asplund et al., 2014; Castillo et al., 2017; Lemasson et al., 2017;
10 Mackenzie et al., 2014; Ong et al., 2017; Rodrigues et al., 2015; Shi et al., 2016; Velez et al., 2016;
11 Waldbusser et al., 2014; Wang et al., 2016; Zhao et al., 2017; Zittier et al., 2015). Impacts on adult bivalves
12 include decreased growth, increased respiration, and reduced calcification with larval stages tending to show
13 greater developmental abnormalities and mortality after exposure (Lemasson et al., 2017; Ong et al., 2017;
14 Wang et al., 2016c; Zhao et al., 2017b).

15
16 Another globally significant group of invertebrate are euphausiid crustaceans known as krill. This abundant
17 Antarctic food source grazes on phytoplankton and thereby represents is a major link between primary
18 producers and higher trophic levels (e.g. fish, mammals, sea birds). Polar regions, however, are among the
19 fastest changing areas globally, with rates of change in ocean warming and acidification that are double that
20 of the planetary average (Notz and Stroeve, 2016b; Turner et al., 2017). Record levels of sea ice loss in the
21 Antarctic directly translates as the loss of habitat and hence abundance of krill. Other influences such as high
22 rates of ocean acidification, coupled with the shoaling of the aragonite saturation horizon, are likely to play
23 key roles. (Kawaguchi et al., 2013; Piñones and Fedorov, 2016).

24
25 Fish are vitally important components of ocean food webs, and contribute to the income of coastal
26 communities, industry and nations, and are important to food security and livelihoods globally (FAO, 2016).
27 Impacts and responses identified in Gattuso et al. (2015) and AR5 regarding the relative risk of climate
28 change to finfish have strengthened. In this regard, there is a growing number of studies indicating that
29 different stages of development may also be made more complex by fish having life-cycle stages in different
30 habitats, which may each be influenced by climate change in different ways and to different extents, as well
31 as evidence of differing sensitivities to change between different stages (Esbaugh, 2017; Ong et al., 2015,
32 2017).

33
34 The biogeographical ranges of an increasing number of fish species are shifting to higher latitudes, with
35 tropical species relocating into temperate zones (driving ‘tropicalization’, Horta E Costa et al., 2014; Verges
36 et al., 2014; Vergés et al., 2016)) and temperate species moving into high latitude and polar regions (driving
37 ‘Borealization’, Fossheim et al., 2015). Concern has been raised that greater number of extinctions will
38 occur in the tropics as species relocate (Burrows et al., 2014; García Molinos et al., 2015; Poloczanska et al.,
39 2016). Changing conditions in polar regions carry a high risk due to the rapid rates of warming (Notz and
40 Stroeve, 2016b; Turner et al., 2017). One of the consequences of this is that an increasing number of fish
41 species are expanding their distributional ranges into the Arctic, being followed by large, migratory fish
42 predators. The borealization of fish communities in the Arctic is leading to a reorganization of species, food
43 webs and ecological processes which is not well understood (Fossheim et al., 2015).

44
45 There is a moderate risk of impact across the four different components of ocean food webs under present
46 day conditions (Figure 3.19, *medium to high confidence*). As temperatures increase to 1.5°C, risk of impacts
47 remains *moderate* except in the case of bivalves where the risks of impact become *moderate to high*.
48 Reviewing the literature (see SOM-CH3) reveals that pteropods face *moderate* risks of impact at 1.5°C and
49 increasing risks of impacts at average global temperatures of 2°C or more. Risks accumulate at higher rates

1 for bivalve molluscs, with *high* risks of impacts at 1.5°C, and *very high* risks at 2°C or more. This general
2 pattern continues with bivalves and fin fish acquiring *high* risks of impact (*high confidence*) when average
3 global surface temperatures achieve by 2°C above the pre-industrial period (Figure 3.19). As with many
4 risks associated with impacts at the ecosystem scale, most adaptation options focus on the management of
5 non-climate change stresses from human activities. Reducing non-climate change stresses such as pollution
6 and destruction of habitat will be important in maintaining this important food web components. Fisheries
7 management at local to international scales will be important in reducing stress on food web organisms such
8 as those discussed here, as well as helping communities and industries adapt to changing food web structure
9 and food resources (see further discussion of fisheries *per se* below).

10 11 3.4.4.2.3 *Key ecosystem services (e.g. carbon uptake, coastal protection, and coral reef recreation)*

12 The ocean provides a vast array of ecosystem services that are important to humanity. Regulation of
13 atmospheric composition involves gas exchange across the boundary between ocean and atmosphere, and a
14 series of physicochemical processes which are influenced by ocean chemistry, circulation, oceanography,
15 temperature and biogeochemical components. The ocean is a net sink for carbon dioxide, absorbing
16 approximately 30% of human emissions from the burning of fossil fuels and modification of land use. Recent
17 evidence has revealed that carbon uptake by the ocean is decreasing (Iida et al., 2015), with concern growing
18 from observations and models regarding changes in ocean circulation (Rahmstorf et al., 2015). Biological
19 components of carbon uptake by the ocean are also changing with observations of varying net primary
20 productivity (NPP) in equatorial (*medium confidence*) and coastal upwelling systems (*low confidence*, Bakun
21 et al., 2015; Lluch et al., 2014; Sydeman et al., 2014b) as well as subtropical gyre systems (Signorini et al.,
22 2015, *low confidence*). These changes are complex, however, as discussed in the previous section on
23 warming and stratification of the surface ocean.

24
25 Coastal protection is another ecosystem service which is important for protecting human communities and
26 infrastructure against rising sea levels, waves and the effect of intensifying storms (Hauer et al., 2016b).
27 Both natural and human coastal protection have the potential to reduce impacts (Fu and Song, 2017). Coral
28 reefs, for example, provide effective protection by dissipating around 97% of wave energy, with 86% of the
29 energy being dissipated by reef crests alone (Ferrario et al., 2014). Natural ecosystems, when healthy, also
30 have the ability to repair themselves after being damaged, which sets them apart from coastal hardening and
31 other human responses that require constant maintenance (Barbier, 2015; Elliff and Silva, 2017).
32 Recognising and restoring coastal ecosystems such as coral reefs, mangroves and coastal vegetation in
33 general may be more cost-effective than human remedies such as the installation of seawalls and coastal
34 hardening, where costs of creating and maintaining structures is generally expensive (Temmerman et al.,
35 2013).

36
37 Risks of impacts from reduced coastal protection is particularly high for low-lying areas, such as low-lying
38 atoll islands in the tropical Indo-Pacific where land for food, dwelling, and water can be limited. The effect
39 of rising seas and intensifying storms create circumstances that may make many of these islands
40 uninhabitable within decades (Storlazzi et al., 2015). Even in advantaged countries such as the United States,
41 these factors will place millions at serious risk (e.g. 4.2 million people, 90 cm sea level rise, Hauer et al.,
42 2016). The escalation of serious coastal impacts such as Super Storm Sandy and Typhoon Haiyan (Long et
43 al., 2016; Villamayor et al., 2016) have increased our understanding of the future of coastal areas in terms of
44 impacts and their mitigation (Rosenzweig and Solecki, 2014; Shults and Galea, 2017). Further discussion of
45 the importance of the coastal protection is provided in the SOM material associated with this special report
46 (SOM-CH3).

47
48
49 Tourism is one of the largest industries globally. A substantial part of the global tourist industry is

1 associated with tropical coastal regions and islands where coral reefs and related ecosystems play important
2 roles. Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries,
3 particularly small island developing states (SIDS, Box 3.7, Spalding et al., 2017; Weatherdon et al., 2016b).
4 The direct relationship between increasing global temperatures, intensifying storms, elevated thermal stress,
5 and the loss of coral reefs has raised concern about the risks of climate change for local economies and
6 industries based on coral reefs. Risks to coral reef recreational services from climate change are considered
7 here as well as in Box 3.6, main text, and on-line material (SOM-CH3).

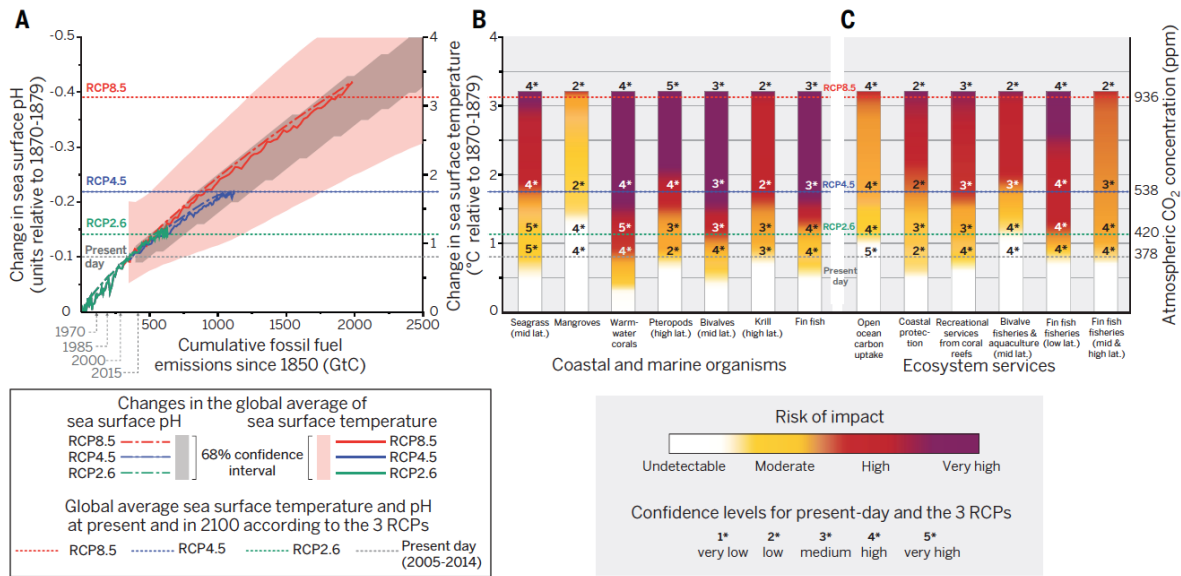
8
9 The recent heavy loss of coral reefs at tourist locations worldwide has prompted concern over the relationship
10 between increasing sea temperatures, degrading coral reefs, and tourist revenue (Normile, 2016). About
11 30% of the world's coral reefs support tourism which generates close to \$36 billion (USD) on an annual basis
12 (Spalding et al., 2017). Tourist expenditure, in this case, represents economic activity which supports jobs,
13 revenue for business and taxes (e.g. \$6.4 billion AUD and 64,000 jobs annually to the Australian economy in
14 2015-16; Deloitte Access Economics. 2017). Climate change in turn can influence the quality of the tourist
15 experience through such aspects through changing weather patterns, physical impacts such as those from
16 storms, and coastal erosion, as well as the effects of extremes on biodiversity within a region. Recent impacts
17 on Caribbean countries in 2017 highlights the risks and impacts of climate change on coastal tourism, with
18 the prospect that many businesses will take years to recover from impacts such as the recent hurricanes
19 Harvey, Irma and Maria (Gewin, 2017; Shults and Galea, 2017)

20
21 Risks of impacts from reduced carbon uptake, coastal protection, and services contributing to coral reef
22 recreation are *moderate* in today's setting and at 1.5°C (*medium confidence*). At 2°C, risks of impacts
23 associated with changes to carbon uptake remain *moderate*, while those associated with reduced coastal
24 protection and the capacity for recreation on coral reefs have *high* risks of climate related impacts, especially
25 given the vulnerability of this ecosystem and others (e.g. seagrass, mangroves) to climate change (Figure
26 3.19).

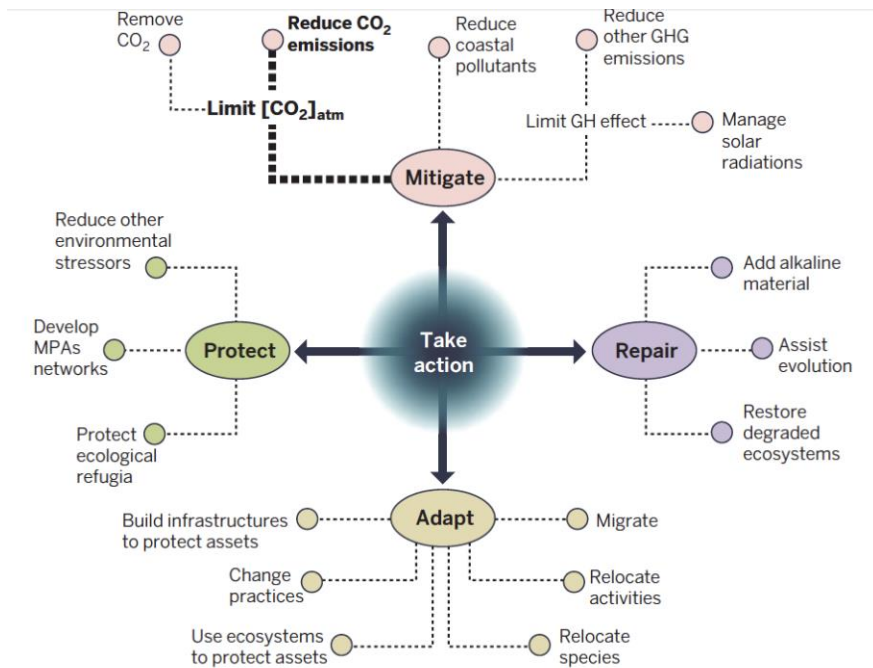
27
28 Adaptation options for the three ecosystem components considered here illustrate the different adaptation
29 needs (Figure 3.20). Adapting to the broad global changes in carbon uptake by the ocean are limited and are
30 discussed with respect to the changes in NPP and their implications for fishing industries (next section).
31 These are broad scale and indirect, with the only other solution at scale being reducing the entry of CO₂ into
32 the ocean. Strategies for adapting to reduced coastal protection involve avoidance of vulnerable areas,
33 managed retreat from threatened locations, and/or accommodation of impacts and loss of services. Within
34 these broad options, there are strategies that involve direct human intervention (e.g. coastal hardening,
35 seawalls and artificial reefs), while there are others that exploit the opportunities for increasing coastal
36 protection by involving a naturally occurring oyster banks, coral reefs, mangroves, seagrass, and other
37 ecosystems (Cooper et al., 2016; Ferrario et al., 2014).

38
39 Recent studies have increasingly stressed the need for coastal protection to be considered within the context
40 of new ways of managing coastal land, including protecting and ensuring that coastal ecosystems are able to
41 undergo shifts in their distribution and abundance (André et al., 2016). Facilitating these changes will require
42 new tools in terms of legal and financial instruments, as well as integrated planning that involves not only
43 human communities and infrastructure, but also ecosystem responses and value. In this regard, the
44 interactions between climate change, sea level rise and coastal disasters are being increasingly informed by
45 models (Bosello and De Cian, 2014) with a widening appreciation of the role of natural ecosystems as an
46 alternative to hardened coastal structures (Cooper et al., 2016). Adaptation options for coral reef recreation
47 include: (1) Protecting and improving biodiversity and ecological function by minimizing the impact of non-
48 climate change stresses (e.g. pollution, overfishing), (2) Ensuring adequate levels of coastal protection by
49 supporting and repairing ecosystems that protect coastal regions, (3) ensuring fair and equitable access to the

1 economic opportunities associated with recreational activities, and (4) seeking and protecting supplies of
 2 water for tourism, industry, and agriculture alongside community needs.
 3



4
 5
 6 **Figure 3.19:** Observed impact and risk scenarios of ocean warming and acidification for important organisms and
 7 critical ecosystem services. “Present day” (gray dotted line) corresponds to the period from 2005 to 2014.
 8 Impact levels are for the year 2100 under the different projections shown and do not consider genetic
 9 adaptation, acclimatization, or human risk reduction strategies (mitigation and societal adaptation).
 10 RCP4.5 is shown for illustrative purposes as an intermediate scenario between the business-as-usual high
 11 emissions scenario (RCP8.5) and the stringent reduction scenario (RCP2.6). (A) Changes in global
 12 average SST and pH versus cumulative fossil fuel emissions. Realized fossil emissions are indicated for
 13 different years below the horizontal axis, whereas the lines are based on allowable emissions estimated
 14 from ensemble means of the CMIP5 simulations for the industrial period and the 21st century following
 15 RCP2.6, RCP4.5, and RCP8.5. Cumulative emission of 1000 GtC causes a global SST change of about
 16 1.7°C and a surface pH change of about –0.22 units. The colored shadings indicate the 68% confidence
 17 interval for pH (gray) and SST (pink) from observation-constrained, probabilistic projections using 55
 18 multi-gas emissions scenarios. (B) Risk of impacts resulting from elevated CO₂ on key organisms that are
 19 well documented in the literature. (C) Risk of impacts resulting from elevated CO₂ on critical ecosystem
 20 services. The levels of confidence in the risk levels synthesize the author team’s judgments (see materials
 21 and methods) about the validity of findings as determined through evaluation of evidence and agreement
 22 (Modified from Gattuso et al. 2015).
 23
 24



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Figure 3.20: Four clusters of action against climate change including ocean acidification. For each cluster, a nonexhaustive list of actions is shown. [CO₂] at mis concentration of atmospheric CO₂ ; GH, greenhouse ; GHG, greenhouse gases ; MPAs, marine protected areas. The mitigation pathway leading to CO₂ reductions is represented in bold, consistent with the consensus view that significant reductions in CO₂ emissions is presently the only actual ‘solution’ to the ocean impacts of climate change and ocean acidification (see main text). To be developed further from Gattuso et al. (2015)

1 **Table 3.4:** [Placeholder. Table of risk for ocean systems. See summary and detailed tables in Annex 3.1, Table S3.4.4]

Risk	Region (could be globe)	Metric (unit)	Baseline time period against which change in impact measured	Socio-economic scenario and date (make clear if uses present day population and assumes constant)	Baseline global T used in paper (pre-industrial, or other, and did you have to convert? Eg if your paper gives delta T relative to 1990 you add 0.5C)	Climate scenario used (e.g. RCP, SRES, HadCM3 in 2050s, etc)	Is it for transient (T) or equilibrium (E) (if known)?	Is it an overshoot scenario? How long it is above 1.5C and what is the max temp and when?	Is the modelling approach used in that publication dynamic (Y/N)	Projected impact at 1.5C above pre-industrial	Projected impact at 2C above pre-industrial	Projected impact at delta T(°C)	Delta T relative to pre-industrial; delta T(°C) (deltaT1+column F)	Delta T relative to baseline temp(T1); delta T1(°C)

2

1 **[START BOX 3.6 HERE]**2
3 **Box 3.6: Coral reefs in a 1.5°C warmer world**

4
5 Tropical coral reefs are found along coastlines between latitude 30° S and 30°N where they provide habitat
6 for thousands of species as well as food, livelihoods and coastal protection for millions of people (Burke et
7 al., 2011; Cinner et al., 2012; Pendleton et al., 2016). Shallow water tropical coral reefs are found down to
8 depth of 150m and are dependent on light, as distinct from the cold deep-water reef systems that extend
9 down to depths of 2000 m or more (Hoegh-Guldberg et al., 2017). The difficulty in accessing deep water reef
10 systems also means that the literature on impacts of climate change is sparse by comparison to tropical coral
11 reefs (Hoegh-Guldberg et al., 2017). Consequently, this box focuses on the impacts of climate change on
12 tropical coral reefs, particularly on their prospects under average global surface temperatures of 1.5°C
13 and 2°C.

14
15 Scleractinian (reef-building) corals build reefs in warm, shallow and sunlit waters of the tropics by
16 depositing large quantities of calcium carbonate over time (Kennedy et al., 2013). Their ability to do this is a
17 consequence of an ancient mutualistic symbiosis between corals and dinoflagellate microalgae from the
18 genus *Symbiodinium*. In this intracellular relationship, *Symbiodinium* spp. provide the coral host with
19 abundant photosynthetic energy and receive inorganic nutrients (e.g. phosphate, ammonia) from the host in
20 return (Muscatine and Porter, 1977; Reaka-Kudla and Wilson, 1997). As a result of the inherent efficiencies
21 of this mutualistic relationship, corals have flourished in the otherwise nutrient poor waters of tropical and
22 subtropical seas for millions of years (Stanley, 2003). The resulting calcium carbonate frameworks provide
23 habitat for large proportion of ocean biodiversity (as much as 25% of all life in the ocean). The resulting
24 ecosystem provides food, income, coastal protection, cultural context, and many other services for millions
25 of people along tropical coastal areas (Pendleton et al., 2016).

26
27 Despite their importance, the distribution and abundance of coral reefs is declining due to local factors such
28 as pollution, overfishing and unsustainable coastal development (Burke et al., 2011; Halpern et al., 2015). As
29 a result of these combined impacts, at least 50% of coral reefs have been lost over the past 30 years from many
30 regions (Bruno and Selig, 2007; De'ath et al., 2012; Gardner et al., 2005), with an increasing signature of
31 ocean warming and other climate change related stresses (Hoegh-Guldberg, 1999). Thermal stress of just
32 1°C above the long-term summer maximum for an area (1985-1993) is enough to cause the symbiosis
33 between reef-building corals and *Symbiodinium* to disintegrate, resulting in "coral bleaching". While corals
34 may recover from coral bleaching, increasingly elevated temperatures for longer periods will cause corals to
35 starve, be out competed, get diseased and in many cases, die in large numbers (Eakin et al., 2010; Hughes et
36 al., 2017). As corals disappear, so do the fish and the many other reef dependent species, directly impacting
37 industries such as tourism and fisheries, as well as coastal livelihoods for many, often disadvantaged, people
38 (Cinner et al., 2016; Graham, 2014; Graham et al., 2015; Wilson et al., 2006).

39
40 There is substantial evidence that the impacts of climate change reach further than the impacts of extreme
41 temperatures within tropical and subtropical seas. In addition to mass coral bleaching and mortality,
42 intensifying storms are affecting coral reefs through destructive waves that can damage the framework of
43 coral reefs (Gardner et al., 2005) and associated ecosystems such as mangroves (Long et al., 2016; Primavera
44 et al., 2016). The impacts of rising sea temperature are also exacerbated by ocean acidification (see section of
45 Ocean Chemistry) which reduces the ability of corals and other calcifiers (e.g. foraminifera, macroalgae,
46 molluscs) to produce their skeletons and shells, and grow and reproduce (Gattuso et al., 2015a; Hoegh-
47 Guldberg et al., 2014; Pörtner et al., 2014b). Ocean acidification reduces the ability of coral reefs to recover,
48 and leads to greater activity by decalcifying organisms such as excavating sponges (Dove et al., 2013; Fang et
49 al., 2013a, 2014; Kline et al., 2012; Reyes-Nivia et al., 2013, 2014). As the frequency of coral bleaching and

1 mortality events increase, the time available for recover is reduced, resulting in the steady contraction of
2 coral dominated ecosystems over time(Kennedy et al., 2013). This trend is amplified by ocean acidification
3 which slows the rate of calcification and growth, and further increases the net rate of loss of coral reefs.
4

5 Paleontological studies confirm the sensitivity of coral reefs to past changes in atmospheric CO₂, with
6 carbonate coral reefs disappearing for long periods of time when CO₂ levels were high (Pörtner et al., 2014b;
7 Veron, 2008).Building insights from past responses enables insights into how reefs are likely to change
8 under the influence of perturbations to ocean temperature and chemistry(Hoegh-Guldberg et al., 2007).
9

10 Evidence strongly supports the detection and attribution of mass coral bleaching and mortality as a
11 consequence of climate change (*very high confidence*, AR5 Box 18-2, Cramer et al. 2014). This close
12 relationship between temperature, and mass coral bleaching and mortality, provides insights into the future
13 of coral reefs when combined with projections of changes in sea temperatures. Predictions of back-to-back
14 bleaching events (Hoegh-Guldberg, 1999) have become reality in 2015-2017 (e.g. Hughes et al., 2017) as
15 have projections of declining coral cover (*high confidence*). Models have also become increasingly detailed,
16 predicting the large-scale loss of coral reefs by mid-century under even low emission scenarios (Donner,
17 2009; Donner et al., 2005; Frieler et al., 2012; Hoegh-Guldberg, 1999; Hoegh-Guldberg et al., 2014; van
18 Hooijdonk et al., 2016; van Hooijdonk and Huber, 2012) Even achieving emission reduction goals consistent
19 with the Paris Agreement (“*well below 2°C*”) will result in the further loss of 90% of reef-building corals
20 found on reefs today, with 99% of corals being removed under warming by 2°C or more above the pre-
21 industrial period (Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b). In some of the latest analyses, the
22 risk of losing coral reefs under 1.5°C increases up until mid-century at which point 90% of coral reefs will
23 have been eliminated. Under this scenario, the loss decreases to 70% by late century, as conditions stabilize.
24 In a 2°C scenario, however, most coral reefs have been eliminated by mid-to-late century.
25

26 The assumptions underpinning these grim assessments are considered to be highly conservative. In some
27 hypothetical cases, ‘optimistic’ assumptions adopted by modelers include rapid thermal adaptation by corals
28 (0.2-1.0°C per decade and 0.4°C per decade, Donner et al., 2005; Schleussner et al., 2015, respectfully) as
29 well as very rapid recovery rates from impacts (i.e. 5 years, Schleussner et al., 2015). Adaptation to climate
30 change at these high rates (if at all) has not been documented and rates of recovery from mass mortality tend
31 to be much longer (> 15 years, Baker et al., 2008). Probability analysis also reveals that the underlying
32 increases in sea temperatures that drive coral bleaching and mortality are 25% less likely under 1.5°C versus
33 2°C (King et al., 2017). Differences between rates of heating suggest the possibility of temporary climate
34 refuges (Cacciapaglia and van Woesik, 2015; Caldeira, 2013; Keppel and Kavousi, 2015; van Hooijdonk et
35 al., 2013) which may play an important role in terms of the regeneration coral reefs once the climate has
36 been stabilized. Similar proposals have been made for the potential role of deep water (30 to 150 m) or
37 mesophotic coral reefs (Bongaerts et al., 2010; Holstein et al., 2016)avoiding shallow water extremes (i.e.
38 heat, storms) although the ability of these ecosystems to repopulate damaged shallow water areas may be
39 limited (Bongaerts et al., 2017).
40

41 The prospect for coral reefs in a 1.5°C world is better than that of a 2°C world where coral reefs will largely
42 disappear (Schleussner et al., 2016b). Losing 90% of today's coral reefs, however, will decrease resources
43 and increase poverty levels across the world's tropical coastlines in the short term, highlighting the key issue
44 of equity for the millions of people that depend on these valuable ecosystems (Halpern et al., 2015; Spalding
45 et al., 2014). Anticipating these challenges to food and livelihoods for coastal communities will become
46 increasingly important, and might include diversification of livelihoods and industry such as fisheries in
47 order to reduce the dependency of coastal communities on threatened coastal ecosystems such as coral reefs
48 (Cinner et al., 2012, 2016; Pendleton et al., 2016). At the same time, coastal communities will need to pre-
49 empt changes to other services provided by coral reefs such as coastal protection (Gattuso et al., 2015a;

1 Hoegh-Guldberg et al., 2014; Kennedy et al., 2013; Pörtner et al., 2014b). Given the scale and cost of these
2 interventions, implementing them earlier rather than later would be expedient.

3
4 **[END BOX 3.6 HERE]**

8 **3.4.5 Coastal and low lying areas, and sea level rise**

9
10 Observations have been felt through salinity changes (e.g., groundwater or estuaries) and in sensitive
11 environments such as small islands. Sea-levels will not stop rising with temperature stabilisation at 1.5°C or
12 2°C, leading to salinisation, flooding, permanent inundation, erosion and pressure on ecosystems. Over
13 multi-centennial timescales, adaptation remains essential and climate change mitigation provides greater
14 time to adapt. The unconstrained response of natural coastal systems is still being understood: Whilst some
15 coasts will be overwhelmed with sea-level rise or adversely react to warmer temperatures, other natural
16 coasts may be able to respond positively by vertical accretion of sediment or by landward migration of
17 wetlands. Small islands are projected to experience multiple inter-related impacts, but there remain large
18 knowledge gaps in understanding the present observations and future impacts and response, and in aligning
19 these with wider development needs.

21 **3.4.5.1 Introduction**

22 Due to the commitment to sea-level rise (where sea levels rise for centuries until reaching equilibrium
23 conditions even if climate forcing is stabilized, due to a delay between sea level rise response to global
24 warming Wong et al. 2014; Mengel et al.) there is not a clear relationship between temperature rise and
25 subsequent sea-level rise and impacts. Maintaining temperatures at 1.5°C or 2°C will slow the rate of rise.
26 Due to multiple factors of change there is a large and overlapping uncertainty in impacts at 1.5°C and
27 2°C (Brown a et al.; Brown b et al.; Nicholls et al.), but these are distinct from rises of 4.0°C or more over
28 centennial scales (Brown a et al.). Thus the benefits of climate change mitigation will not be realized for
29 coastal impacts until after the 21st century (Brown a et al.; Nicholls et al.; Nicholls and Lowe, 2004). There is
30 high confidence that adaptation can reduce impacts in human settings (Hinkel et al., 2014; Wong et al.,
31 2014), but less certainty for ecosystems.

35 **3.4.5.2 Impacts**

38 **3.4.5.2.1 Global / sub-global scale**

39 Impacts and exposure at 1.5°C and 2°C reinforce findings from AR5 (Wong et al., 2014), but further focus on
40 the longevity of impacts, even with climate change mitigation. With a 1.5°C stabilization scenario, global
41 mean sea-levels are projected to rise leading to 574 x 10³km² (in 2050), 620 x 10³km² (in 2100), 666 x
42 10³km² (in 2200) and 702 x 10³km² (in 2300) of land exposed (assuming there is no adaptation). With a
43 2°C stabilization scenario, this increases to 575 x 10³km² (in 2050), 637 x 10³km² (in 2100), 705 x 10³km² (in
44 2200) and 767 x 10³km² (in 2300). Thus, even with temperature stabilization, exposure increases. In contrast
45 land area exposed is projected to at least double by 2300 using a RCP8.5 scenario (Brown a et al.). In the 21st
46 century, land area exposed to sea-level rise (assuming there is no adaptation) is an order of magnitude larger
47 than the cumulative land loss due to submergence (taking into account defences) (Brown a et al.; Warren et
48 al., 2013) regardless of sea-level rise scenario. This will affect human and ecological systems, including
49 health, heritage, freshwater, agriculture and other services. Adaptation can substantially reduce impacts, and

1 slow rates of rise provide greater opportunity for adaptation.

2
3 At 1.5°C in 2100, 31.87–68.83 million people world-wide could be exposed to flooding assuming no
4 adaptation (and 2010 population values), compared with 31.99–78.38 million people at 2°C in 2100
5 (Rasmussen et al.). With a 1.5°C stabilization scenario in 2100, 55–94 million people / year are at risk from
6 flooding increasing to 115–188 million people per year in 2300 (50th percentile, SSP1-5, no socio-economic
7 change after 2100), assuming no upgrade to present adaptation levels (Nicholls et al.). The number of people
8 at risk increases by approximately 18% using a 2°C scenario and 266% using a RCP8.5 scenario in 2300.
9 Through prescribed SRES sea-level rise scenarios, Arnell et al. (2016) also found people flooded increased
10 substantially after 2°C without further adaptation, particularly in the second half of the twentieth century. Sea
11 flood costs could cost thousands on billions of dollars annually, with damage costs under constant protection
12 0.3–5.0% of global GDP in 2100 for a RCP2.6 scenario. Risks are projected to be highest in south and south-
13 east Asia (Arnell et al., 2016; Warren b et al.). Countries with large populations exposed to sea-level rise
14 based on a 1,280 Pg C emission scenario include Egypt, China, India, Indonesia, Japan, Philippines, United
15 States and Vietnam (Clark et al., 2016).

16 17 18 *3.4.5.2.2 Cities*

19 Urban areas are projected to result in increased flooding, salinization of groundwater and potential damage
20 of infrastructure from extreme events, which may be enhanced through localized subsidence (Wong et
21 al., 2014). Due to high population, a large number of the cities projected to be affected are likely to be in
22 south and south-east Asia (Cazenave and Cozannet, 2014; Hallegatte et al., 2013; Hanson et al., 2011).
23 Jevrejeva et al. (2016) report with 2°C of warming by 2040, more than 90% of global coastlines will
24 experience sea-level rise greater than 0.2 m (RCP8.5). Under climate change mitigation scenarios where 2°C
25 is stabilized later in time, this figure would differ due to the commitment to sea-level rise.

26
27 Cities can financially justify adaptation such as dikes to reduce flooding. Nicholls et al. projected the fraction
28 of population protected in 136 world cities (population > 1 million) with sea-level rise and socio-economic
29 change. In 2005, 50% of the cumulative population of those cities was estimated to be protected by a 2.9 m
30 dike. Under 1.5°C and 2°C stabilization scenarios, mean dike height increase to approximately 3.75m in
31 2300, but for an RCP8.5, this increases to 6.3m. Hence climate change mitigation is advantageous.

32 33 34 *3.4.5.2.3 Deltas and estuaries*

35 Observations of sea-level rise and human influence are felt through salinization leading to mixing in deltas
36 and estuaries, flooding (also enhanced by precipitation and river discharge), erosion land degradation,
37 threatening freshwater sources and posing risks to ecosystems and human systems (Wong et al., 2014). For
38 instance, in the Delaware River Estuary on the USA east coast, upward trends of streamflow adjusted salinity
39 (measured since the 1900s) have been detected (Ross et al., 2015), accounting for the effects of streamflow
40 and seasonal variations. Through modelling it is suggested that sea-level rise may be the cause of increased
41 salinity.

42
43 Yang et al. (2015b) found that in the Snohomish River estuary, Washington, USA future climate scenarios
44 (A1B 1.6°C and B1 2°C in the 2040s) had a greater effect on salinity intrusion than future land use/land
45 cover change. This resulted in a shift in the salinity both upstream and downstream in low flow conditions.

46
47 The mean annual flood depth when 1.5°C is first reached in the Ganges-Brahmaputra delta may be less than
48 the most extreme annual flood depth seen today (Brown b et al.). Furthermore increased river salinity and
49 saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C, projected in 2038 (RCP8.5, SMHI)

1 or 2045 (RCP8.5, CNRM)(Zaman et al., 2017). 1.5°C or 2°C stabilization conditions in 2200 or 2300
2 indicate a large proportion of any delta's land elevation would be inundated unless sedimentation occurs
3 (Brown b et al.). However, dike building to reduce flooding restricts sediment deposition leading to
4 enhanced subsidence, which can be at a greater rate than sea-level rise (Auerbach et al., 2015; Takagi et al.,
5 2016). Similarly dam / barrage building restricts sediment movement (Gupta et al., 2012) and/or river flow
6 and beach mining provokes erosion (Appeaning Addo, 2015). Promoting sedimentation is an advisable
7 strategy and transformative decisions regarding the extent of sediment restrictive infrastructure may need to
8 be considered over centennial scales (Brown b et al.).
9

10 3.4.5.2.4 *Small islands*

11 Small islands are well recognized to be at risk and very sensitive from climate change and other stressors
12 (AR5, Nurse et al. 2014; Ourbak and Magnan 2017; Rasmussen et al.), such as sea-level rise, oceanic
13 warming, precipitation, cyclones and coral bleaching (see Box 3.7). Qualitative observations of climate
14 change (and other stresses) include land degradation due to saltwater intrusion in Kiribati and Tuvalu
15 (Wairiu, 2017), access to freshwater due to variable precipitation in Fiji (Pearce et al., 2017) and shoreline
16 change in French Polynesia (Yates et al., 2013), Tuvalu (Kench et al., 2015) and Hawaii (Romine et al.,
17 2013). Observation, models and other evidence indicate Pacific atolls have kept pace with sea-level rise with
18 little reduction in size or experienced a net gain in land (Beetham et al., 2017; Kench et al., 2015; McLean
19 and Kench, 2015). Thus, whilst islands are highly vulnerable, they are also reactive to change and it is not a
20 foregone conclusion that all low-lying islands will drown with sea-level rise.
21

22
23 Climate change is, and will, affect fundamental livelihoods by changing rainfall patterns (Pearce et al., 2017;
24 Taylor et al.) affecting groundwater, freshwater resources and availability, impacting upon diet and
25 livelihoods (Pearce et al., 2017), or increased sea-levels and wind-driven water levels affecting flooding and
26 increasing salinization of freshwater resources (Storlazzi et al., 2015). Extreme events today (e.g. hurricane,
27 storms) damage essential infrastructure (including those used by tourists who are essential for income),
28 potentially affecting whole communities (Mycoo, 2017). Even small changes in temperature (differentiating
29 1.5°C and 2°C regardless of timeframe) could make significant differences to impacts (Benjamin and
30 Thomas, 2016) beyond adaptive capacity (e.g., for corals see Box 3.6, 3.4.3, and Schleussner et al. 2016).
31 Largely, multi-sectoral impacts are projected, but often not quantified (at 1.5°C or 2°C regardless of
32 timeframe) partly to a lack of projections or appropriate data (e.g., Pearce et al. 2017).
33

34 Adaptation to multiple drivers of change is underway. People have migrated internally due to flooding (e.g.,
35 Vunidogoloa, Fiji, McNamara and Des Combes 2015) or preparing to do so internationally evidence through
36 land purchase or arrangements with other nations (Constable, 2017; Kelman, 2015; Thomas and Benjamin,
37 2017b; Yamamoto and Esteban, 2017). For example, Kiribati has purchasing land from Fiji (Kelman, 2015).
38 Migration is not preferable for all: A Philippine small island community prefers in-situ adaptation in
39 response to flooding (Jamero et al., 2017). Migration also occurs with development, such as in the Maldives
40 (Speelman et al., 2017), meaning that climate change is one of many factors potential migrants consider.
41

42 National adaptation plans along side development are starting to include climate change, but are competing
43 with other government priorities (Mycoo, 2017). Adaptation needs to combine local scientific knowledge,
44 historical responses and traditional cultures (Nunn et al., 2017), knowledge (Weir et al., 2017) in light of
45 social, political and economic development and change (Sealey-Huggins, 2017). In small island developing
46 states, an approved understanding of how aid is spent relating to adaptation is required (Betzold, 2015).
47 Today there are gaps in knowledge, finance and policies targeting loss and damage for small island
48 developing States, plus projections for slow onset events under temperature rises of 1.5°C (Thomas and
49 Benjamin, 2017a). There is a need to develop risk management frameworks, financial provision and

1 response to small islands undergoing climate change (Ourbak and Magnan, 2017).

4 3.4.5.2.5 *Ecosystems*

5 Ecosystems such as coral reefs, saltmarshes and mangrove forests are disrupted by changing conditions. For
6 example, saltmarshes in Connecticut and New York measured from 1900 to 2012, have accreted with sea-
7 level rise, but have lost marsh surface relative to tidal datums, leading to increased marsh flooding and
8 further accretion (Hill and Anisfeld, 2015). This stimulated marsh carbon storage, and aided climate change
9 mitigation. (Raabe and Stumpf, 2016) analyzed tidal marshes in the Gulf of Mexico, US over 120 years and
10 found a net gain of land, with wetlands transgressing from one type to another, despite sea-level rise.

11 Wetlands are threatened by sea-level rise particularly where there is a lack of accommodation space or
12 sediment supply (e.g., due to urbanisation, land use change Martínez et al. 2014), resulting in coastal squeeze
13 (Pontee, 2013; Spencer et al., 2016). Sediment supply remains crucial for wetland areas (Spencer et al.,
14 2016), and feedback between plant growth and geomorphology may allow wetlands to resist sea-level rise
15 (Kirwan and Megonigal, 2013). Depending on model assumption, some studies indicates a net wetland loss
16 to sea-level rise (e.g., Cui et al. 2015 with a 2.6 mmyr⁻¹ rise (aligning with AR5) in the Yangtze Estuary;
17 Blankespoor et al. 2014a 1m rise in multiple countries; Arnell et al. (2016) using an A1 SRES scenario of up
18 to 0.48m by 2050 on a global scale). Alternatively, Payo et al. (2016) suggests erosion may be dominant over
19 inundation in 2100, for all but the highest scenario analyzed (of 1.48m relative sea-level rise by 2100) in the
20 Bangladeshi Sundarbans. Salinisation may also lead to shifts in wetland communities and their ecosystems
21 functions, including freshwater wetlands (Herbert et al., 2015). Rather, Kirwan and Megonigal (2013) and
22 Kirwan et al. (2016) argue human interaction and the ability to migrate in land is of great importance. Thus
23 the relationship between wetlands and sea-level is complex and is still being understood, and this would
24 apply to conditions of 1.5°C and 2°C at any timeframe.

25
26
27 Further discussion of the impacts of climate change on coastal ecosystems (at 1.5°C versus 2°C) can be
28 found in Section 3.4.4 and subsections.

31 3.4.5.2.6 *Morphology and oceanography*

32 Sea-level rise can result in changes to sediment movement, shoreline change (erosion and accretion) and cliff
33 erosion (Wong et al., 2014). Le Cozannet et al. (2014) reviewed shoreline change observations due to sea-
34 level rise through case studies and found no overall clear effect, but some local studies (e.g., Romine et al.
35 2013)) suggest that erosion has increased due to sea-level rise. Beach volumes could also be locally affected
36 by sea-level rise, particularly where infrastructure or geological constraints reduces shoreline movement
37 causing coastal squeeze. In Japan, beach losses due to sea-level rise are projected with a RCP2.6 scenario,
38 and are projected to increase under RCP8.5 (Udo and Takeda, 2017).

39
40 Tide gauge observations indicate annual exceedance rates are linearly increasing along the United States
41 west coast (Sweet and Park, 2014), potentially leading to increased nuisance flooding, unless there is an
42 adaptive response. The amplification of flooding, for high and/or low frequency events (Buchanan et al.,
43 2017a) and different forcing factors, including waves (Arns et al., 2017; Storlazzi et al., 2015; Vitousek et al.,
44 2017), compound flooding (e.g., Moftakhari et al. 2017) is also cause for concern even with sea-level rise
45 associated with a rise in temperatures of 2°C, or within the next few decades.

1 *3.4.5.3 Adaptation*

2 There is high confidence that adaptation to sea-level rise is occurring today. Retreat and human migration are
3 increasingly being considered in management response (Geisler and Currens, 2017; Hauer et al., 2016a),
4 particularly in low-lying or island settings. Adaptation pathways (e.g., Barnett et al. 2014; Buurman and
5 Babovic 2016; Rosenzweig and Solecki 2014; Ranger et al. 2013) assist long-term thinking, but are not
6 widespread practice in coastal zones despite knowledge of long-term risk. Since AR5, there are few studies
7 on the adaptation limits to sea-level rise (IPCC, 2014a; Nicholls et al., 2015) where transformation change
8 may be required. This is pertinent for centennials sea-level rise, even with climate change mitigation.

1 **Table 3.5:** *[Placeholder. Table of risk Coastal and low lying areas. See summary and detailed tables in Annex 3.1, Table S3.4.5]*

Risk	Region (could be globe)	Metric (unit)	Baseline time period against which change in impact measured	Socio-economic scenario and date (make clear if uses present day population and assumes constant)	Baseline global T used in paper (pre-industrial, or other, and did you have to convert? Eg if your paper gives delta T relative to 1990 you add 0.5C)	Climate scenario used (e.g., RCP, SRES, HadCM3 in 2050s, etc)	Is it for transient (T) or equilibrium (E) (if known)?	Is it an overshoot scenario? How long it is above 1.5C and what is the max temp and when?	Is the modelling approach used in that publication dynamic (Y/N)	Projected impact at 1.5C above pre-industrial	Projected impact at 2C above pre-industrial	Projected impact at delta T(°C)	Delta T relative to pre-industrial; delta T(°C) (deltaT1+column F)	Delta T relative to baseline temp(T1); delta T1(°C)

2

[START BOX 3.7 HERE]**Box 3.7: Small Island Developing States (SIDS)**

1.5°C will likely prove a challenging state for small island developing states (SIDS) which are already facing significant threats from climate change and other stressors. At 1.5°C, the compounding impacts from changes in rainfall and temperature patterns and frequency of extremes, more intense tropical cyclones and higher sea levels (which will increase even at temperature stabilisation) will be evident across multiple natural and human systems. This will likely contribute to loss of, or change in, critical ecosystems, freshwater resources and associated livelihoods, economic stability, coastal settlements and infrastructure. There are potential benefits to SIDS from avoided risks at 1.5°C versus 2.0°C, especially when coupled with adaptation efforts.

IPCC AR5 reaffirmed that small islands are highly vulnerable to the impacts of climate change. Small islands face several unique challenges in relation to climate change due to physical exposure, limited options for livelihood diversification and resource constraints (Lissner et al., 2017). Small islands rank highest in terms of relative population exposure and economic damage related to extreme weather events, especially since a large proportion of the population lives in coastal zones; and individual events (e.g., tropical cyclones) may inflict damages exceeding double digit percentages in affected infrastructure, population and GDP (Moore et al., 2017; Nurse et al., 2014).

The key drivers for climate risks for small islands identified with high confidence and high agreement in the AR5 include sea level rise, increasing air and sea surface temperatures, tropical cyclones, ocean acidification and extreme precipitation (Nurse et al., 2014). Changes to these key drivers have already been observed with resulting impacts on SIDS (see Section 3.4.2). For example, interactions between sea-level rise and wave exposure is leading to coastal erosion and shoreline recession in some places, including French Polynesia, Tuvalu and Hawaii (Section 3.4.2). Between 1947-2014, five vegetated reef islands in the Solomon Islands vanished (Albert et al., 2016). The abundance of reef-building corals which form unique and threatened marine biodiversity hot spots is in steep decline: by about 1- 2% per year for the 1968–2004 period in many Pacific and Southeast Asian regions, and by more than 80% on many Caribbean reefs since 1977 (Gatusso et al., 2014). 44% of all small islands are currently under freshwater stress (Holding et al., 2016). The risk of major disruption to rainfall patterns over the Pacific Ocean lasting up to ~ 1 year increased up to the end of the 20th century, resulting in major impacts on severe weather, agricultural production, ecosystems, and disease within the Pacific, and in many countries beyond (Power et al., 2017). The risk to terrestrial biodiversity hotspots on small islands is increasing due to sea level rise (Bellard et al., 2014).

Changing climate hazards for SIDS at 1.5°C

There is limited literature projecting changes in the key drivers of climate risks for small island states at 1.5°C. An assessment of what is available suggests that 1.5°C will likely prove a challenging state for SIDS.

Regional climate changes

Mean surface temperature is projected to increase on most small islands at 1.5°C. As oceans warm slower than large land masses, the projected increase is below the average for the global land mass (Nurse et al., 2014). The Caribbean region will experience 0.5°C–1.5°C warming compared to 1971-2000 baseline (Taylor et al.), with largest warming over the larger land masses including in the north Caribbean. Under the RCP 2.6 scenario, the western tropical Pacific is projected to experience warming of 0.5–1.7°C relative to 1961–1990 (Wang et al., 2016a). Relevant threshold exceeding temperature extreme weather indices will likely also increase, with

1 the potential for elevated impact as a result of comparably small natural variability(Reyer et al., 2017a). Up to
2 50% of the year is projected to be very warm in the Caribbean using the warm spell duration index (wsdi) for
3 1.5° C, with a further increase by up to 70 days for 2°C versus 1.5°C(Taylor et al.).

4
5 Changes in precipitation patterns differ between the different small island regions and so do the resulting
6 changes in freshwater availability. While some islands in the Western Pacific and the northern Indian ocean
7 may see increased freshwater availability, most other regions, including the South Pacific, the Southern Indian
8 ocean and the Caribbean are projected to see a substantial decline in freshwater availability(Holding et al.,
9 2016; Karnauskas et al., 2016). For several SIDS, particularly across the Caribbean region, a substantial
10 fraction (~25%) of the large overall freshwater stress projected under 2°C at 2030 can be avoided by limiting
11 global warming to 1.5°C. Future per capita freshwater availability is strongly dependent on future population
12 growth(Karnauskas et al.). In accordance with an overall drying trend, an increasing drought risk is projected
13 for the Caribbean region(Lehner et al., 2017). The time spent in moderate to extreme drought is expected to
14 increase on average by ~9% for the land areas bordering on the Caribbean Sea, including the Caribbean SIDS,
15 for 2°C vs 1.5°C(Taylor et al.).

16
17 There are uncertainties with respect to regional changes in sea level at 1.5°C or 2°C (Section 3.3.10). Jevrejeva
18 et al. (2016)report that with 2°C of warming, more than 70% of global coastlines will experience sea-level rise
19 greater than 0.2m, with the highest sea-levels projected for small island nations in low to mid latitude Pacific
20 and Indian Ocean islands. For SIDS, it is important to note that sea-levels will not stop rising with temperature
21 stabilisation at either warming target (Section 3.3.10). Associated threats e.g., from salinisation, flooding,
22 permanent inundation, erosion and pressure on ecosystems, will therefore persist well beyond the 21st century
23 (Nicholls et al.).

24
25 Extreme precipitation in small island regions is often linked to tropical storms and cyclones and contributes to
26 the climate hazard posed by such storms (Khouakhi et al. 2017). Similarly, extreme sea levels for small islands
27 in particular in the Caribbean are linked to tropical cyclones occurrence (Khouakhi and Villarini 2017).
28 Tropical regions including small islands will experience the largest increases in coastal flooding frequency,
29 and the frequency of extreme water-level events in small islands may double no later than 2050 (Vitousek et
30 al. 2017). For sea level rise of 50cm, present day one-in-50-year events may occur annually. By limiting
31 warming to 1.5°C instead of 2°C in 2050, risks of coastal flooding (measured as the flood amplification factors
32 (AFs) for 100-yr flood events) are reduced between 20 and 80% for SIDS (Rasmussen et al.).

33
34 Other sections of this report point to projected changes in the ocean system at higher warming targets (Section
35 3.4.3), including potential changes in circulation (Section 3.3.8) and increases in both surface temperatures
36 (Section 3.3.8) and ocean acidification (Section 3.3.11) including for tropical oceans. Most of the studies cited
37 are not specific to 1.5°C, but compare RCP2.6 with higher RCP4.5 scenarios i.e. essentially bracketing the
38 1.5°C target. They, nonetheless, suggest steadily increasing risks for SIDS associated with changing ocean
39 chemistry at warming levels close to and exceeding 1.5°C (Section 3.4.3).

40 41 **Changes in Climate Phenomena affecting SIDS**

42
43 Wehner et al. (2017), using a high resolution global atmospheric model, project a decrease in the frequency of
44 weaker tropical storms and an increase in the number of intense cyclones under a 1.5°C stabilization scenario.
45 Other studies, though not specifically devoted to 1.5°C, are consistent in projecting an increase in very intense
46 tropical cyclones and simultaneous decrease in frequency of tropical cyclones by the end of the century under
47 global warming (Section 3.3.7). There are, however, uncertainties associated with the projections at the ocean
48 basin scale. For example, one study projects decreases in tropical cyclone systems including decreases in the
49 most intense systems under 1.5°C warming over the southwest Indian Ocean(Mavhungu et al.). There are

1 insufficient studies to assess differences in tropical cyclone statistics for 1.5°C vs 2°C, however no reversal of
2 tendencies is projected (Section 3.3.7).

3
4 As a result of their location in tropical regions, changes in ENSO will affect in particular Pacific and Caribbean
5 SIDS. The frequency of extreme El Niño events is projected to increase with global mean temperature(Cai et
6 al., 2014; Wang et al., 2017b), with a possible doubling of events at 1.5°C warming(Wang et al., 2017b).
7 Increases in the frequency of extreme El Niño events will likely continue long after temperatures have
8 stabilized, in part due to a deepening oceanic thermocline and sustained faster warming in the eastern
9 equatorial Pacific than in the off-equatorial region(Wang et al., 2017b). Extreme La Niña events are projected
10 to double in frequency under 4.5°C warming scenario (Cai et al., 2015), however, the extent of change at 1.5°C
11 or 2°C may be small or negligible (Wang et al., 2017b). Prolonged interannual sea level inundations may
12 become more likely throughout the tropical Pacific with ongoing warming and in the advent of the increased
13 frequency of extreme La Niña events, regionally exacerbating the coastal impacts of projected global mean
14 sea level rise(Widlansky et al., 2015).

15 16 **Impacts on key natural and human systems**

17
18 AR5 notes that the future risks for SIDS associated with changes in climatic drivers include loss of ecosystems,
19 ecosystem services, critical livelihoods, economic stability, coastal settlements and infrastructure (Nurse et al.,
20 2014). The few studies that assess the impact of 1.5°C or higher warming on key natural and human systems
21 of importance to SIDS support the AR5 conclusion of increased risk at higher surface temperatures, and also
22 point to avoided risk compared to 2.0°C.

23
24 An increase in global temperatures from 1.5°C to 2°C is expected to result in increased aridity, especially in
25 the Caribbean and eastern Atlantic (Karnauskas et al.,) (Box3.7, Figure 1) and decreased freshwater
26 availability in SIDS regions (Gosling and Arnell, 2016). The results of Karnauskas et al. do not account for
27 additional risks from sea-level rise or from increased wave-induced run-up that may leave several atoll
28 islands uninhabitable and affect the freshwater lens in others, particularly in the Pacific (Storlazzi et al.,
29 2015). Limited freshwater on many small islands and potential changes in availability and quality linked to a
30 combination of changes in climate drivers will likely have adverse impacts on water supply and the
31 economies of SIDS(Holding and Allen, 2015; Terry and Chui, 2012; White and Falkland, 2010), including
32 on associated industries such as hydropower (Donk et al.).

33
34 Increased intensity of tropical rainfall that is projected for some SIDS as temperatures increase (e.g., Mclean
35 et al. 2015) has implications for flooding with detrimental effects on livelihoods, damages to infrastructure
36 and loss of life. Modeling of flood inundation in Jamaica shows increased probability of flood risk at 2.5°C
37 as compared to 1.5°C (Mandal et al.).

38
39 Many SIDS are dependent on their coastal resources, particularly coral reefs and fisheries, for livelihoods,
40 economic survival and coastal protection. Mass coral bleaching and mortality are projected to increase under
41 rising ocean temperatures, and corals to become brittle under ocean acidification, as well due to destructive
42 waves from intensifying storms which also destroy associated ecosystems such as mangroves (Section 3.4.3,
43 Box 3.6). At 1.5°C, approximately 70-90% of global coral reefs are projected to be at risk of long-term
44 degradation due to coral bleaching. This increases to 99% at 2.0°C of warming(Schleussner et al., 2016d).
45 Warmer temperatures are also associated with an increase in pathogens that favor disease development in
46 corals and lead to coral degradation that is in addition to coral bleaching (Maynard et al., 2015). Wave driven
47 coastal flooding risks for reef-lined islands will increase as a result of coral reef degradation and sea level rise
48 (Quataert et al., 2015). Limiting warming to 1.5°C is projected to come with large benefits to marine fisheries
49 in particular in tropical regions (Cheung et al., 2016b). Small islands in the Indo-Pacific region are particularly

1 at risk to declines in maximum catch potential and species turnover at higher levels of warming than 1.5°C.

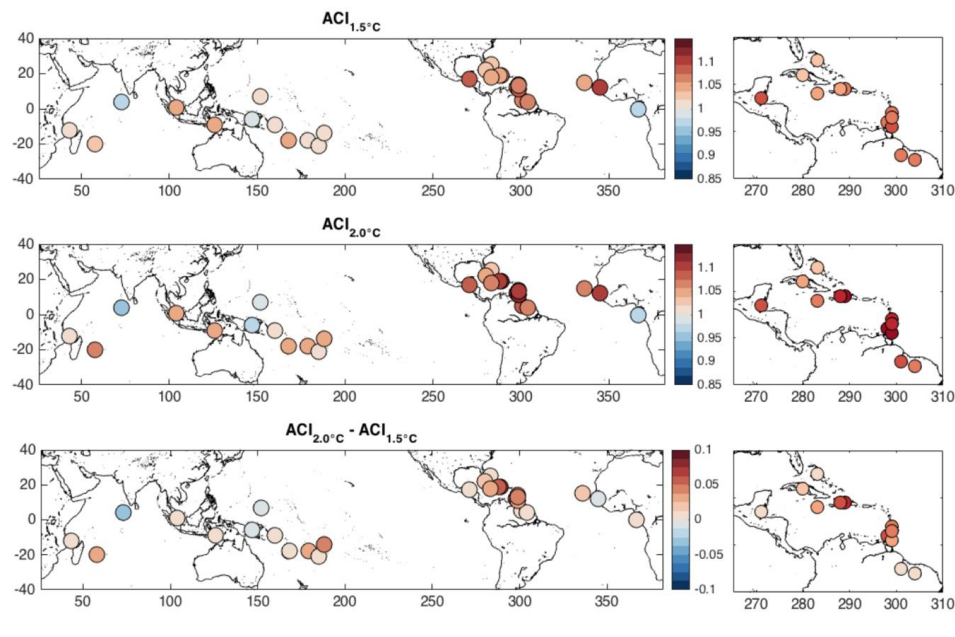
2
3 Agriculture is a key sector for many small islands, and is imperative to achieving local food security. A case
4 study of Jamaica with lessons for other Caribbean SIDS shows that the difference in heat stress for livestock
5 between 1.5 and 2.0°C will likely exceed the limits for normal thermoregulation and result in persistent heat
6 stress for animals (Lallo et al.). Another case study, also for Jamaica, projects a reduction in the range of
7 viable agricultural crops for 1.5°C (Rhiney et al.). Small islands are also recognized as major food importing
8 countries and are therefore strongly susceptible to food price shocks linked to climate impacts elsewhere
9 (Puma et al., 2015).

10
11 Exposure of infrastructure to coastal impacts is particularly high for SIDS, placing a significant share of
12 population and assets at risk. For example, 57% of built infrastructure for a group of 12 Pacific islands is
13 located within 500m of their coastline (Kumar and Taylor, 2015). Similarly, over 65% of hotel rooms in the
14 Commonwealth Caribbean are located in low-lying coastal areas (Rhiney, 2015). Sea level rise of 1m may
15 place up to 60% of tourism facilities in the Caribbean at risk to beach erosion and inundation, with potential
16 significant impacts on national economies (Scott et al. 2012, Section 3.4.9). Rasmussen et al. project that for
17 a 2.0°C stabilization scenario, a significant amount of the coastal areas occupied by SIDS inhabitants may be
18 at risk of being permanently submerged by 2150, with gains to be had if stabilization is instead at 1.5°C. The
19 study does not however account of shoreline response (see Section 3.4.2) or adaptation.

20
21 Other recent studies of natural and human systems that are critical to SIDS project that at 1.5°C there will be
22 increased incidents of internal migration (Albert et al., Section 3.5.5), limited capacity to monitor and assess
23 loss and damage (Thomas and Benjamin, 2017a), significant increases in financial damages associated with
24 climate impacts (Burgess et al.), and substantial increases in risk to critical transportation infrastructure from
25 marine inundation (Monioudi et al.). While these studies do not offer a comparison to impacts at higher
26 levels of warming, they suggest that SIDS will already face significant challenges at 1.5°C.

27
28 In comparison to other regions, the number of studies focusing specifically on differential impacts between
29 1.5°C and higher levels of global warming for systems of importance to small islands is limited. Globally
30 scaled studies often exclude SIDS due to their small size and limited data availability, while limited or
31 scattered observational evidence hampers attribution of sectoral climate impacts in SIDS (Huggel et al.,
32 2016). Key research gaps identified in relation to SIDS include food production (Machovina and Feeley,
33 2013), tourism (Section 3.4.9) and coastal infrastructure (Kumar and Taylor, 2015), public health (Rhiney,
34 2015), and ecosystem response.

35
36 There will likely be significant potential benefits to SIDS from avoided risks at 1.5°C versus 2.0°C especially
37 when coupled with adaptation efforts. Adaptation in SIDS, however, needs to be considered in light of
38 sustainable development (Box 5).



Box 3.7, Figure 1: Aridity Change Index (Karnauskas et al.,)

[END BOX 3.7 HERE]

3.4.6 Food security and food production systems (including fisheries and aquaculture)

3.4.6.1 Observed impacts

Quantifying the observed impacts of climate change can be a difficult task for food security and food production systems, requiring assumptions about the many non-climate variables that interact with climate change variables. Implementing specific strategies can partly alleviate the impacts of climate change on these systems, whilst the degree of resilience is mainly dependent on geographical area and crop (Rose et al., 2016).

3.4.6.2 Crop production

Impact studies on agricultural crops were focused on several components that contribute to food productions (crop suitability and yield, CO₂ fertilization, biotic and abiotic stresses).

Observed changes in climate parameters have already affected the crop suitability in many areas. These changes have produced effects on the main agricultural crops (e.g., wheat, rice, maize) determining shift of the cultivated areas or changes on crop production. These impacts are evident in many areas of the world ranging from Asia (Chen et al., 2014b; He and Zhou, 2016; Sun et al., 2015c); to America (Cho and McCarl, 2017) and Europe (Ramirez-Cabral et al., 2016), affecting particularly typical local crops cultivated in specific climate conditions (e.g., Mediterranean crops like olive and grapevine, Moriondo et al. 2013a,b).

Concerning impacts of observed mean climate changes on crop yields, several studies have estimated highest negative impacts on wheat and maize (Lobell et al., 2011); whilst the effects on rice and soybean yields have

1 been smaller(Kim et al., 2013). Warming has produced positive effects on crop yield in some high-latitude
2 areas (Jaggard et al. 2007; Chen et al. 2014b; Supit et al. 2010; Gregory and Marshall 2012; Sun et al. 2015;
3 He and Zhou 2016; Daliakopoulos et al., 2017), also leading to the possibility of more than one harvest per
4 year (Chen et al., 2014a; Sun et al., 2015c).

5
6 Ray et al. (2015), using detailed crop statistics time series for assessing climate variability and the related
7 variations in maize, rice, wheat and soybean production worldwide, found that climate change explains more
8 than >60% of the yield variability in the main global breadbaskets areas. Similarly, Moore and Lobell (2015)
9 found that climate trends explain 10% of the slowdown in wheat and barley yields in Europe. Schauburger et
10 al. (2017), using an ensemble of nine crop models, revealed that when temperatures are above 30°C, US
11 maize, soybean and wheat yields decline, and the increased CO₂ can only weakly reduce these yield losses.
12 For northern latitude areas (e.g., Canada), Qian et al. (2010) found a significant lengthening of the growing
13 season during 1895-2007 due to a significantly earlier start and a significantly later end of the growing
14 season.

15
16 However, increases in atmospheric CO₂ would be expected to increase yields by enhancing radiation and
17 water use efficiencies(Elliott et al., 2014). In open-top chamber experiments Abebe et al. (2016) reported a
18 maize grain yield increase by 45.7% and 0.5% at 550 ± 20 ppm and +1.5°C and +3.0°C, respectively,
19 compared to ambient conditions. Similarly Singh et al. (2013), observed a potato yield increase of 11% at
20 elevated CO₂ (i.e. 550 ppm) and +1°C but a yield decrease of 13.7% when a further increase in CO₂ has been
21 combined with a rise in temperature of +3°C. Despite observed increases in atmospheric CO₂ concentration,
22 however, observations of decreasing crop yields as a result of climate change remain more common than
23 crop yield increases (Porter et al., 2014). At the same time, a meta-analysis of 143 comparisons of the edible
24 portions of crops grown at ambient and elevated [CO₂] from seven different experimental locations in Japan,
25 Australia, and the United States involving six food crops found 5-10% decreases in zinc and iron, elements
26 important for human nutrition. The rise in tropospheric ozone has reduced yields of wheat, rice, maize of
27 soybean ranging from 3 and 16% globally (Van Dingenen et al., 2009). The modelling study (McGrath and
28 Lobell, 2013) indicated that stimulation of production at increased atmospheric CO₂ concentration is mostly
29 driven by differences in climate and the crop considered, specifying that the variability in yield due to the
30 variable response to elevated CO₂ is about 50–70% of the variability in yield due to the variable response to
31 climate. Also, an ensemble of 21-models(Durand et al., 2017) found that the simulated impact of elevated
32 CO₂ on maize yield under water deficit may be significantly underestimated.

33
34 Crop productions are also strongly affected by increases in extreme events, but the quantification of these
35 changes is more difficult. There is evidence that changes in the frequency of extreme events have affected
36 cropping systems (e.g., changes in rainfall extremes, Rosenzweig et al. (2014); increases in hot nights,
37 Welch et al. 2010, Okada et al. 2011; extremely high daytime temperature, Schlenker and Roberts 2009, Jiao
38 et al. 2016; drought, Jiao et al. 2016 Lesk et al. 2016; heat stress, Deryng et al. 2014; chilling damage, Jiao et
39 al. 2016). Lesk et al. (2016) identified global losses due to extreme weather disasters during 1964–2007,
40 particularly droughts and extreme heat, significantly reduced cereal production by 9–10%.

41
42 Finally, the impacts on the occurrence, distribution and intensity of pest and disease on crop yields produced
43 a general increase in pest and disease outbreaks related to higher winter temperatures that allows pests to
44 survive(van Bruggen et al., 2015). Jiao et al. (2014) observed that climate warming and agricultural pests and
45 diseases produced decrease in grain yield for winter wheat, maize and double cropping paddy rice in China.

46
47 Considering now projected impacts of climate change on crop yields, studies for major cereals showed that
48 yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics(Porter et al.,
49 2014). Temperate maize and tropical rice yields are less clearly affected at these temperatures, but are

1 significantly affected with warming of 3°C to 5°C. However, all crops showed negative yield impacts for
2 3°C of warming without adaptation (Porter et al., 2014) and at low latitudes under nitrogen stress conditions
3 (Rosenzweig et al., 2014).

4
5 A few studies since AR5 have focused on the impacts on cropping systems for scenarios where global mean
6 temperatures increase within 1.5°C. Schleussner et al. (2016c) projected that constraining warming to 1.5°C
7 rather than 2°C would avoid significant risks of tropical crop yield declines in West Africa, South East Asia,
8 and C&S America. Ricke et al. (2015) highlight how globally, cropland stability declines rapidly between 1
9 and 3°C warming. Similarly, Bassu et al. (2014) suggested that an increase of air temperature negatively
10 influence the modeled maize yield response of $-0.5 \text{ t ha}^{-1} \text{ per } ^\circ\text{C}$ and even a conservative target of 2°C global
11 mean warming would lead to losses of 8-14% in global maize production. Challinor et al. (2014), using multi-
12 model ensemble projections, indicated high vulnerability of wheat and maize production in tropical regions,
13 whilst Niang et al. (2014), using the near term (2030-2040) as a proxy for 1.5°C warming, projected
14 significantly lower risks to crop productivity in Africa compared to 2°C warming. Warren b et al. use an
15 empirical approach to project a global average decline in crop yields of 5% associated with a warming of 2°C,
16 25% of which is avoided if warming is constrained to 1.5°C.

17
18 The modelling study for assessing yield stability of hybrid maize cultivars to abiotic stresses (Lana et al.,
19 2017) indicated that the impact of temperature increases on crop failure was not so pronounced as the impact
20 of precipitation, thus suggesting higher responsiveness only if temperatures are above +1°C, and yields
21 decrease by 20% or more as temperatures increase to +2°C in conjunction with reduction in precipitation, due
22 to faster development and increase in water demand. Huang et al. (2017) found that while over drylands a
23 2°C warming would result in 3.2–4°C warming, resulting in decreased maize yields and runoff, increasing
24 long-lasting drought, these effects may be prevented by limiting warming at 1.5 °C. Rosenzweig et al. (2017)
25 found that, at the global scale, simulated yield showed a general declines in some breadbasket regions led to
26 overall declines in productivity at both +1.5°C and +2°C. Lizumi et al. (2017), in a modeling study linking
27 the global mean temperature change from preindustrials to global mean yields of major crops, found that
28 impacts on maize and soybean yields are lower at +1.5°C than at +2°C. They also indicated an increase in
29 rice production under +2°C than at +1.5°C warming, whilst no clear differences were observed for wheat at
30 global mean basis. Asseng et al. (2015) indicated as for each °C increase in global mean temperature can be
31 observed a reduction in global wheat grain production between –4.2% and –8.2%. (Zhao et al., 2017a),
32 combining four different methods for assessing the impact of each degree Celsius increase in global mean
33 temperature on yields of wheat, rice, maize, and soybean, showed a global average reduction of $6.0 \pm 2.9\%$,
34 $3.2 \pm 3.7\%$, $7.4 \pm 4.5\%$ and 3.1% , respectively. Li et al. (2017) indicated a significant reduction in rice yields
35 by about 10.26% for each 1°C increase in temperature compared to the baselines the Indochina peninsula
36 region.

37
38 A 1.5°C warming by 2030 is projected to reduce the present Sub-Saharan maize cropping areas by 40%
39 making them no longer suitable for current cultivars, with significant negative impacts projected as well for
40 the suitability for sorghum in the western Sahel and southern Africa (World Bank 2013). An increase in
41 warming (2°C) by 2040 would result in further yields losses and damage to the main African crops (i.e.
42 maize, sorghum, wheat, millet, groundnut, cassava). Sultan and Gaetani (2016) indicated a robust evidence of
43 yield loss in West Africa mainly due to increased mean temperature, while potential wetter conditions or
44 elevated CO₂ concentrations partly or totally counteract this effect both for C3 and C4 crops. For South East
45 Asia a 2°C warming by 2040 will result in one third decline in per capita crop production (Nelson et al.,
46 2010) associated with a general crop yield decreases. Schleussner et al. (2016) emphasized the uncertainty
47 related to the CO₂ fertilization effects, showing results for fertilization and non-fertilization of rice and
48 soybean. Läderach et al. (2013), analyzing the expected distribution of cocoa growing areas based on climate
49 change predictions from 19 Global Circulation Models for 2050, found that current areas producing cash

1 crops like cocoa will become unsuitable (Lagunes and Sud-Comoe in Côte d'Ivoire) and will require change
2 to when and where cropping occurs, while other areas will become increasingly suitable for growing cocoa
3 (Kwahu Plateau in Ghana and southwestern Côte d'Ivoire).

4
5 Ghude et al. (2014) quantified the potential impact of ozone on district-wise cotton, soybeans, rice, and
6 wheat crops in India for the first decade of the 21st century found that wheat is the most impacted crop with
7 losses of 3.5 ± 0.8 million tons (Mt), followed by rice at 2.1 ± 0.8 Mt. Tai et al. (2014) showed an integrated
8 analysis of the individual and combined effects of 2000–2050 climate change and ozone trends on the
9 production of four major crops (wheat, rice, maize and soybean) worldwide excluding the effect of rising
10 CO_2 , found that warming reduces global crop production by over 10% by 2050 with the potential to
11 substantially worsen global malnutrition in all scenarios considered. They also indicated as, depending on the
12 region, some crops are primarily sensitive to either ozone (for example, wheat) or heat (for example, maize).
13 Anderson et al. (2015) showed the importance of the joint effect of water availability and temperature to
14 understand crop yield response, finding for long growing season regions a yield reduction per $^{\circ}\text{C}$ of 10% at
15 high water availability and 32.5% at low water availability, and in a shorter growing season regions yield
16 reduction per $^{\circ}\text{C}$ is 6% for high water availability and 27% for low water availability. Zhang et al. (2017)
17 assessed the response of rice yield to an increased heat extreme temperature stress, and a decreased cold
18 extreme temperature stress showed a large spatial variability of rice yield loss in the future in many areas of
19 China.

20 21 22 3.4.6.3 *Livestock production*

23 Studies of the impact of climate change on livestock production are relatively few in number. Climate
24 change is expected to directly affect yield quantity and quality (Notenbaert et al., 2017), beside indirectly
25 impacting the livestock sector through pest and disease (Kipling et al., 2016). Increasing heat extremes is one
26 of the major issues, leading to distress, sweating and increased respiratory rate (Mortola and Frappell, 2000).
27 Severe heat stress is highly detrimental effects on productivity, growth, development (Collier and
28 Gebremedhin, 2015) and reproduction (De Rensis et al., 2015). Attention has largely been dedicated to
29 ruminant diseases (e.g., liver fluke, Fox et al. 2011; blue-tongue virus, Guis et al. 2012; Foot-and-mouth
30 disease (FMD) Brito et al. 2017; or zoonotic diseases Njeru et al. 2016; Simulundu et al. 2017). In both cases,
31 climate change has facilitated the recent and rapid spread of the virus or ticks.

32
33 Future climate change impacts on livestock will include direct effects on animal health due to higher
34 temperatures, lack of water availability, etc., but also impacts on quantity and quality of forage and feed, and
35 on livestock diseases spreading.

36
37 In temperate climates, warming is expected to lengthen forage growing season but decrease forage quality,
38 with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurrealde et al.,
39 2011). Similar studies confirmed decrease in forage quality both for natural grassland in France (Graux et al.,
40 2013) and sown pastures in Australia (Perring et al., 2010). Lee et al. (2017) found that elevated temperatures
41 besides to reduce grass nutritive value also increase methane production, moving from 0.9% at $+1^{\circ}\text{C}$
42 temperature to +4.5% at $+5^{\circ}\text{C}$. This relation has been found also by Knapp et al. (2014) under controlled
43 conditions.

44
45 High temperatures also reduce animal feeding and growth rates (André et al., 2011; Renaudeau et al., 2011).
46 Wall et al. (2010), observed as the impact of climate change on dairy cow production over some UK regions,
47 reduced milk yields and increased cows mortality, mainly due to heat stress. The impact of climate change
48 can also affect water supply for livestock. This will affect the increased livestock populations, as reported by
49 Masike and Urich (2008), the expected warming will lead to an annual increase in cattle water demand.

1
2 Recent work indicated that heat stress can be responsible for the increase in mortality and economic losses
3 (Vitali et al., 2009); it affects a wide range of parameters (e.g., embryonic development and reproductive
4 efficiency in pigs, Barati et al. 2008; ovarian follicle development and ovulation in horses, Mortensen et al.
5 2009).

6 7 8 3.4.6.4 Fisheries and Aquaculture Production

9 Currently, global fisheries and aquaculture contributes for a total of 88.6 and 59.8 million tons from capture
10 and aquaculture, respectively (FAO, 2016). While the total annual catch from global fisheries has plateaued,
11 aquaculture has become one of the fastest growing food sectors and is becoming increasingly essential to
12 meeting the demand for protein by a growing global population (FAO, 2016). Studies published over the period
13 2015-2017 showed a steady increase in the risks associated with bivalve fisheries and aquaculture at mid-
14 latitude locations coincident with increases in temperature, ocean acidification, introduced species, disease and
15 other associated risks (Clements et al., 2017; Clements and Chopin, 2016; Lacoue-Labarthe et al., 2016; Parker
16 et al., 2017). These have been met with a range of adaptation responses by bivalve fishing and aquaculture
17 industries (Callaway et al., 2012; Weatherdon et al., 2016). Risks are also likely to increase as a result of sea
18 level rise and intensifying storms which pose a risk to hatcheries and other infrastructure (Callaway et al.,
19 2012; Weatherdon et al., 2016). Some of the least predictable yet potentially most important risks are
20 associated with the invasion of parasites and pathogens (Asplund et al., 2014; Castillo et al., 2017), which may
21 be mitigated to a certain extent by active intervention by humans. Many of these have reduced the risks from
22 these factors although costs have increased in at least some industries. By the end of century, risks are likely
23 to be *moderate* under RCP 2.6 although *very high* under RCP 8.5, similar to the evidence and conclusions
24 of Gattuso et al. (2015).

25
26 Low latitude fin fisheries, or small-scale fisheries, provide food for millions of people along tropical coastlines
27 and hence play an important role in the food security of a large number of countries (McClanahan et al. 2015;
28 Pauly and Charles 2015). In many cases, populations are heavily dependent on these sources of protein given
29 the lack of alternatives (Cinner et al., 2012, 2016; Pendleton et al., 2016). The climate related risks for fin fish
30 (3.4.4 and subsections), however, are producing a number of challenges for small scale fisheries based on these
31 species (e.g., Pauly and Charles 2015; Bell et al. 2017; Kittinger 2013). Recent literature (2015-2017) has
32 continued to describe growing threats from the rapid shifts in the biogeography of key species (Burrows et al.,
33 2014; García Molinos et al., 2015; Poloczanska et al., 2013b, 2016) and the ongoing rapid degradation of key
34 habitats such as coral reefs, seagrass and mangroves (see Section 3.4.5 above as well Box 3.6, main report).
35 As these changes have accelerated, so have the risks to the food and livelihoods associated with small-scale
36 fisheries (Cheung et al., 2010). These risks have compounded with non-climate stresses (e.g., pollution,
37 overfishing, unsustainable coastal development) to drive many small-scale fisheries well below the sustainable
38 harvesting levels required to maintain these resources as a source of food (McClanahan et al., 2015;
39 McClanahan et al., 2009; Pendleton et al., 2016). As a result, projections of climate change and the growth
40 in human populations increasingly project scenarios that include shortages of fish protein for many regions
41 (e.g., Pacific, e.g., Bell et al., 2013, 2017; Indian Ocean, e.g., McClanahan et al., 2015). Mitigation of these
42 risks involves marine spatial planning, fisheries repair, sustainable aquaculture, and the development of
43 alternative livelihoods (Kittinger, 2013; McClanahan et al., 2015; Song and Chuenpagdee, 2015; Weatherdon
44 et al., 2016). Threats to small-scale fisheries have also come from the increasing incidence of alien (nuisance)
45 species as well as an increasing incidence of disease, although the literature on these threats is limited (Kittinger
46 et al., 2013; Weatherdon et al., 2016).

47
48 Risks of climate change related impacts on small-scale fisheries are *medium* today, but are expected to reach
49 *very high* levels at under RCP 2.6 and higher scenarios. The research literature plus the growing evidence that

1 many countries will have difficulty adapting to these changes, especially at low latitudes (*high confidence*).

2
3 While the risks and reality of decline are *high* for low latitude fin fisheries, projections for mid to high latitude
4 fisheries include increases in fishery productivity in some cases (Cheung et al., 2013; FAO, 2016; Hollowed
5 et al., 2013; Lam et al., 2014) These changes are associated with the biogeographical shift of species towards
6 higher latitudes ('borealization', Fossheim et al., 2015) which brings benefits as well as challenges (e.g.,
7 increased risk of disease and invasive species). Factors underpinning the expansion of fisheries production to
8 high latitude locations include warming as well as increased light levels and mixing due to retreating sea
9 ice (Cheung et al., 2009). As a result of this, fisheries in the cold temperate regions of the North Pacific and
10 North Atlantic are undergoing substantial increases in primary productivity and consequently in the increased
11 harvest of fish from Cod and Pollock fisheries (Hollowed and Sundby, 2014). At more temperate locations,
12 intensification of some upwelling systems is also boosting primary production and fisheries catch (Shepherd
13 et al., 2017; Sydeman et al., 2014), although there are increasing threats from deoxygenation as excess biomass
14 falls into the deep ocean, fueling higher rates metabolism that decrease concentrations of oxygen (Bakun et al.,
15 2015; Sydeman et al., 2014).

16
17 Specific risks to bivalve aquaculture and fisheries based on finfish vary with industry and region. However,
18 based on recent literature, there appear to be a number of general risks that allow us to assess a number of
19 broad patterns. Present day risks for mid latitude bivalve fisheries and aquaculture (e.g., oysters, mussels) are
20 *low to moderate*, and are *moderate* at 1.5°C, and *moderate to high* at 2.0°C (Figure 3.19). Low latitude finfish
21 fisheries have higher risks of impacts, with present day risks being *moderate* and becoming *high* risks at 1.5°C
22 and 2°C. High latitude fisheries are undergoing major transformations, and while production is increasing,
23 present day risk is *moderate*, and remains at *moderate* at 1.5°C and 2°C (Figure 3.3).

24
25 The ability of fishing industries to adapt to these challenges is considerable although the economic costs of
26 adapting can be high in terms of gear, fuel and infrastructure. Adaptation options for responding to increased
27 climate change impacts on the global production of shellfish (*high confidence*) include protecting reproductive
28 stages and brood stock from periods of high ocean acidification (and chemical buffering) as well as selecting
29 stock for high tolerance to OA (Clements and Chopin, 2016; Ekstrom et al., 2015; Handisyde et al., 2016; Lee,
30 2016; Rodrigues et al., 2015b; Weatherdon et al., 2016). Adapting to threats from climate change to the
31 redistribution of large pelagic highly migratory fish resources such as the tropical Pacific tuna fisheries (*high*
32 *confidence*) could involve governance instruments such as international fisheries agreements that accommodate
33 the relocation of stocks and maintain shared fishery benefits even after stock have shifted away from particular
34 signatories (Lehodey et al., 2015; Matear et al., 2015). Adaptation options to decreasing catch and species
35 diversity in small-scale fisheries on coral reefs include restoration of overexploited fisheries, protection and
36 regeneration of reef habitats, and the reduction of other non-climate change stresses on coral reefs, as well as
37 the development of alternative livelihoods and food sources (e.g., aquaculture, Bell et al., 2013, 2017).

38
39 Synthesizing information on observed and modelled responses by fisheries to climate change has the
40 potential to outline potential benefits from constraining global warming to particular levels. Cheung et al.,
41 (2016b) examined the potential benefits to marine fisheries of meeting the Paris Agreement long-term goal
42 of 1.5°C and used the output of 19 Earth system models from AR5 to derive oceanic conditions, biological
43 responses and impacts on marine ecosystems. Using the projected maximum catch potential and species
44 turnover as indicators of risk for fisheries, Cheung et al. (2016) were able to estimate the loss in fishery
45 productivity for different amounts of global warming (i.e. 1.5°C, 2°C and 3.5°C above the preindustrial
46 period). From this analysis, Cheung et al. (2016) concluded that the potential global catch for marine
47 fisheries was likely to decrease by more than 3 million metric tons for every degree of warming. As has been
48 discussed above, some regions do better than others in the shorter term (e.g., northern hemisphere high
49 latitude fisheries versus low latitude fisheries). This is a very significant proportion of the estimated 100

1 million tonnes (FAO) caught annually by global fisheries all of which is headed in wrong direction in terms
2 of producing food for a growing global population.

3 4 5 3.4.6.5 *Food security*

6 Food security includes food production and diversification, distribution, and the access, all of which are
7 affected by climate change. The impacts of observed climate change on food production are discussed in
8 previous sections (see sections above), but quantification of the resulting impacts on food security is
9 relatively poor due to (a) uncertainties in the regional projection of climate change (b) uncertainties in CO₂
10 fertilisation (c) uncertainties in extreme weather events, effects of pests and diseases, and tropospheric
11 ozone (d) uncertainties in the adaptation which may be implemented in food production systems (e) food
12 trade policies. Countries in the Middle East, Central America and Western Africa are relatively sensitive to
13 changes to the supply of foods such as wheat, maize, and rice yield, respectively (Porter et al., 2014)

14
15 Changes in temperature and precipitation, irrespective of climate change, are projected to contribute to
16 increased global food prices by 2050, with estimated increases ranging from 3 to 84% (IPCC, 2013).

17 Projections including the effects of CO₂ changes on crops over and above O₃ effects and those of pests and
18 disease, indicate that global price increases are contrasting, with a nonlinear range of projected impacts
19 which range from -30% to +45% by 2050. Lobell et al. (2011) estimated that prices of traded food
20 commodities increase due to the role of temperature and rainfall trends on food supply (+19%), but, was
21 lower when increased CO₂ was considered (+6%). D'Amour et al. (2016) indicated the presence of many
22 countries often clustered geographically which are vulnerable to supply shocks of specific crops and small
23 numbers of supplier, thus suggesting that climate change will further aggravate the situation. Concerning
24 bioenergy crops, the increased demand due to increased use in biofuel production influenced both energy
25 policy and oil price fluctuations, thus leading crop price fluctuations (Mueller et al., 2011; Roberts and
26 Schlenker, 2013; Wright, 2011). The diversification of diets can also reduce risks to sudden supply shocks
27 (d'Amour et al., 2016).

28
29 Fisheries and aquaculture provide 3 billion people with 20% of their daily protein requirements. Impacts of
30 climate change are also strongly affecting this sector, leading to negative consequences on abundance and
31 distribution of harvested aquatic species, both freshwater and marine, and aquaculture production
32 systems. Food security is an important issue along tropical coastal areas where communities depend on small-
33 scale fisheries and other sources of coastal livelihoods. As climate change has reduced the health and
34 complexity of coral reefs, for example, habitat underpinning small-scale fisheries has eroded. Similar
35 problems have arisen from the degradation of other ecosystems such as mangroves and seagrass
36 meadows. As these resources have decreased, tropical coastal communities have been exposed to increasing
37 levels of food insecurity and poverty (see Section 3.4.6.5

38
39 The overall impact of climate change on food security is considerably more complex and greater than
40 impacts on agricultural productivity. Several components of food security will be affected by climate change,
41 ranging from food availability, accessibility, utilization and stability.

42
43 Global temperature increases at 1°C or 2°C above preindustrial levels, combined with increasing food demand,
44 would pose large risks to food security globally and regionally, and risks to food security are generally greater
45 in low latitude areas (Rosenzweig et al., 2013; Rosenzweig and Hillel, 2015). For the major crops (wheat, rice,
46 and maize), the highest negative impacts are expected at +2°C or more warming in the late-20th-century levels
47 especially over tropical and temperate regions.

48
49 Lehner et al. (2017) using multiple drought metrics and a set of simulations with the CESM (Community

1 Earth System Model) at +1.5°C and +2°C above preindustrial global mean temperatures, found that in the
2 Mediterranean, central Europe, the Amazon, and southern Africa, will cause drier mean conditions and
3 higher risk of consecutive drought years the additional 0.5°C warming from 1.5°C to 2°C. This may
4 negatively affect the whole agricultural sector of these regions, with negative effects on food security. Sultan
5 and Gaetani (2016) indicated for the African Sahel a high risk of food shortage and low nutrition at +2°C
6 warming or more due to substantial decrease in crop yield. This pattern poses at high risk of food shortage an
7 area where many rural people are subsistence farmers.

8
9 Under no carbon fertilization effect, von Lampe et al. (2014) reports that the average annual rate of change of
10 real global producer prices for agricultural products lies between -0.4% and +0.7% between 2005 and 2050,
11 whilst Nelson et al. (2014a) argued that differences in price impacts of climate change are accompanied by
12 differences in land use change. Nelson et al. (2014a) also reported higher prices on average for almost all
13 commodities in all regions, using ensemble global economic models, with lower yields and reduced
14 consumption depending on the climate stress involved. Thamo et al. (2017), in a study focusing on the
15 potential impacts of future climate change on production and profitability in the West Australian Wheatbelt
16 using 72 scenarios combining rainfall reduction, temperature increase and CO₂ concentration, showed that at
17 +2.5°C temperature increase or 20% rainfall reduction farm profit falls compared to the base-case. By
18 contrast, when changes in climate variables are lower, farm profit can be positive as a result of the joint
19 interaction between CO₂ concentration increase and warmer temperatures. Schmitz et al. (2014), comparing
20 several global agro-economic models with harmonized drivers of population, GDP, and biophysical yields
21 for different socioeconomic and climate scenarios, projected an increase of cropland of 10–25% by 2050
22 especially for sub-Saharan Africa and South America. Hasegawa et al. (2014), using a set of climate
23 scenarios (RCPs) and socio economic condition for assessing the effects of climate change and adaptation on
24 the food security and hunger risk, found that the degree of the impacts is mainly driven by population growth
25 and economic development, but this impact can be strongly reduced by applying adaptation measures.
26 Hasegawa et al. (2015) also indicated that the effects of mitigation measures (i.e. high cost of
27 implementation, heavy use of bioenergy) can negatively impact on food calorie intake and the risk of hunger
28 especially under RC2.6 than RCP8.5.

29
30 In countries where agriculture is the major source of livelihood (e.g., West African countries) several studies
31 have concluded that there are existing inefficiencies in agriculture which contribute to short-falls in addition
32 to climate change. It appears that climate change will unequivocally decrease agricultural yield and that
33 yields could be improved with appropriate investment (Muller, 2011; Neumann et al., 2010; Roudier et al.,
34 2011). There is also a need for appropriate awareness-raising to inform often illiterate farmers as to the use
35 of technologies that improve efficiency as well as ensure benefits flow to farming and associated
36 communities. Improved understanding of various agricultural subsectors and their respective current
37 adaptation strategies will also be important, with policy developments and institutional settings helping
38 foster the adoption of sustainable agricultural systems that effectively mainstream climate change in
39 regions (Zougmore et al., 2016).

1 **Table 3.6:** *[Placeholder. Table of risk for Food security and food production See summary and detailed tables in Annex 3.1, Table S3.4.6*

Risk	Region (could be globe)	Metric (unit)	Baseline time period against which change in impact measured	Socio-economic scenario and date (make clear if uses present day population and assumes constant)	Baseline global T used in paper (pre-industrial, or other, and did you have to convert? Eg if your paper gives delta T relative to 1990 you add 0.5C)	Climate scenario used (e.g., RCP, SRES, HadCM3 in 2050s, etc)	Is it for transient (T) or equilibrium (E) (if known)?	Is it an overshoot scenario? How long it is above 1.5C and what is the max temp and when?	Is the modelling approach used in that publication dynamic (Y/N)	Projected impact at 1.5C above pre-industrial	Projected impact at 2C above pre-industrial	Projected impact at delta T(°C)	Delta T relative to pre-industrial; delta T(°C) (deltaT1+column F)	Delta T relative to baseline temp(T1); delta T1(°C)

2

3.4.7 Human health

3.4.7.1 Observed impacts from AR5

Climate change is adversely affecting human health by increasing exposure and vulnerability to climate-related stresses (Cramer et al., 2014a). Observed and detected changes in climate change that affect human health include:

- Extreme weather events: climate-change-related risks from extreme events, such as heatwaves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).
- Distribution of risks: risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium to high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*).

Furthermore, climate change has the potential to adversely affect human health by increasing exposure and vulnerability to a variety of stresses. For example, the interaction of climate change with food security can exacerbate malnutrition, increasing the vulnerability of individuals to a range of diseases (*high confidence*).

While noting that there are multiple social, environmental, and behavioral factors that influence heat-related mortality, Cramer et al. (2014) concluded that climate change has contributed to increased heat-related mortality in recent decades in Australia, England, and Wales (*medium confidence*). Further, there is increasing evidence that high ambient levels of CO₂ concentrations will affect human health by increasing the production and allergenicity of pollen and allergenic compounds and by decreasing nutritional quality of important food crops. Cramer et al. (2014) concluded that changes in the latitudinal and altitudinal distribution of disease-carrying ticks in North America is consistent with observed warming trends but there was a lack of evidence of any associated changes in the distribution of Lyme disease.

3.4.7.2 Detected impacts of climate change on adverse health outcomes

There is strong evidence that changing weather patterns associated with climate change are shifting the geographic range, seasonality, and intensity of transmission of selected climate-sensitive infectious diseases (e.g., Semenza and Menne 2009), and increasing morbidity and mortality associated with extreme weather and climate events (e.g., Smith et al. 2014). Health detection and attribution studies conducted since the AR5 provided evidence using multi-step attribution that climate change is adversely affecting adverse health outcomes associated with heatwaves; Lyme disease in Canada; and *Vibrio* emergence in northern Europe (Ebi et al., 2017; Mitchell, 2016; Mitchell et al., 2016). Changes in the rates and geographic distribution of adverse health outcomes were detected, and, in each instance, a proportion of the observed changes could be attributed to changes in weather patterns associated with climate change.

Heatwaves: There is robust evidence that climate change is affecting the frequency, intensity, and duration of heatwaves (IPCC, 2013); and that exposure to high ambient temperatures is associated with excess morbidity and mortality (e.g., Gasparrini et al. 2015). Climate change increased the risks of heat events in Egypt and Europe (Mitchell et al., 2016). Mortality in Stockholm, Sweden, in recent decades from heat extremes doubled that which would have occurred without climate change, adjusting for urbanization and the urban heat island effect (Astrom et al., 2013).

1 Lyme disease in Canada: Climate could impact Lyme disease, a tick-transmitted zoonotic disease caused by
2 the bacterium *Borrelia burgdorferi*, by affecting tick vector distributions and abundance; *B. burgdorferi*
3 transmission; and the likelihood of transmission to humans. Until the early 2000's there was only one known
4 tick population in Canada. Since then, studies have confirmed that tick vector populations and Lyme disease
5 risk in Canada emerged in a spatial pattern strongly associated with climate. Consistent positive associations
6 have been found between the presence and abundance of ticks on animal hosts (rodents and deer) and
7 temperature, accounting for a range of alternative potential drivers for tick occurrence (Bouchard et al.,
8 2013a, 2013b; Gabriele-Rivet et al., 2015; Ogden et al., 2008, 2010). Passive tick surveillance data identified
9 strong associations between the spatial occurrence of tick populations and the speed with which tick
10 populations can become established with temperature changes at a sub-national scale (Koffi et al., 2012;
11 Leighton et al., 2012). Temperature increase was considered a key driver of emergence, with temperature
12 change attributed to climate change (Vincent et al., 2012) while other possible drivers of emergence were
13 ruled out over most of the affected area (Ogden et al., 2014a). Over recent years, the spread of the tick vector
14 was associated with steadily increasing numbers of Lyme disease cases, confirming the climate change-
15 driven spread of the tick, accompanied by *B. burgdorferi* transmission cycles, with public health
16 consequences in Canada (Ogden et al., 2014b, 2015).

17
18 Vibrio emergence in the Baltic Sea: *Vibrio* are bacteria that are typically found in marine environments and
19 which cause foodborne outbreaks and wound infections (Semenza et al., 2012a). Brackish saltwater and
20 elevated sea surface temperature (SST) are ideal environmental growth conditions for certain *Vibrio* species
21 (Semenza et al., 2012b). Between 1977-2010, 272 *Vibrio* cases were identified in the Baltic Sea region
22 (Baker-Austin et al., 2013) with the vast majority reported from 1997 onwards (85%). Significant and
23 sustained warm water anomalies corresponded with increases in reported *Vibrio*-associated illness; each
24 increase in the maximum annual sea surface temperature (SST) increased by 1.93 times the number of
25 observed cases (Baker-Austin et al., 2013). In July and August 2014, the SST in the northern part of the
26 Baltic exceeded historic records; exceeding the long-term average in some places by approximately
27 10°C. *Vibrio* infections during the summer and autumn of 2014 in Sweden and Finland exceeded the number
28 previously recorded (Baker-Austin et al., 2016).

31 3.4.7.3 Projected risk at 1.5°C and 2°C

32 Smith et al. (2014) concluded that if climate change continues as projected, major changes in ill health would
33 include the following:

- 35 • Greater risks of injuries, diseases, and death due to more intense heatwaves and fires (*very high confidence*);
- 36 • Increased risk of undernutrition resulting from diminished food production in poor regions (*high confidence*);
- 37 • Consequences for health of lost work capacity and reduced labor productivity (*high confidence*);
- 38 • Increased risks of food- and waterborne diseases (*very high confidence*) and vectorborne diseases (*medium confidence*);
- 39 • Modest reductions in cold-related morbidity and mortality in some areas due to fewer cold extremes (*low confidence*), geographic shifts in food production, and reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds (*medium confidence*). These positive effects will be increasingly outweighed, worldwide, by the magnitude and severity of the negative effects of climate change (*high confidence*).

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47 Tables S7, S8 and S9 (supplementary material) summarize the projected risks to human health of warming of
48 1.5 and 2°C from studies of temperature-related mortality, vectorborne diseases, and undernutrition assessed
49 in and since the AR5. Table S6 provides the conversions used to translate risks projected at particular time

1 slices to temperature change.

2
3 Temperature-related mortality: The associations between high and low ambient temperatures and mortality
4 are generally described using linear relationships (e.g., Gasparrini et al. 2015; Hales et al. 2014), although
5 very high ambient temperatures can be associated with non-linear increases in mortality in some regions
6 (Rocklöv and Ebi, 2012). Therefore, more recent quantifications using non-linear models to describe the
7 relationships. The magnitude of projected heat-related mortality and hazardous heat conditions at +2°C is
8 greater than at +1.5°C (Anderson et al., 2016; Astrom et al., 2013; Benmarhnia et al., 2014; Dong et al.,
9 2015; Doyon et al., 2008; Eun Chung et al., 2017; Garland et al., 2015; Gasparrini et al., 2017; Guo et al.,
10 2016; Hajat et al., 2014; Hales et al., 2014; Hanna et al., 2011; Honda et al., 2014; Huynen and Martens,
11 2015; Jackson et al., 2010; Kendrovski et al., 2017; Kingsley et al., 2016; Li et al., 2016b; Marsha et al.,
12 2016; Martinez et al., 2016; Mitchell et al.; Mora et al., 2017; Oleson et al., 2015b; Petkova et al., 2013;
13 Schwartz et al., 2015; Vardoulakis et al., 2014; Vicedo-Cabrera et al.; Voorhees et al., 2011; Wang et al.,
14 2015b, 2016d; Weinberger et al., 2017; Wu et al., 2014). The extent to which mortality increases varies by
15 region, presumably because of acclimatization, population vulnerability, the built environment, access to air
16 conditioning, and other factors. Populations at highest risk include older adults, children, women, those with
17 chronic diseases, and people taking certain medications.

18
19 In some regions, cold-related mortality is projected to decrease with warmer temperatures, although
20 increases in heat-related mortality generally are projected to outweigh any reductions in cold-related
21 mortality with warmer winters, with the heat-related risks increasing with greater degrees of warming
22 (Gasparrini et al., 2015; Hajat et al., 2014; Huang et al., 2012; Huynen and Martens, 2015; Oleson et al.,
23 2015a; Schwartz et al., 2015; Vardoulakis et al., 2014; Weinberger et al., 2017). Evidence suggests recent
24 adaptation reduced the impacts of heatwaves (Arbuthnott et al., 2016; Astrom et al., 2013; de' Donato et al.,
25 2015; Sheridan and Dixon, 2016). Assumptions of additional adaptation reduce the projected magnitude of
26 risks under different warming scenarios (Anderson et al., 2016; Hales et al., 2014; Huynen and Martens,
27 2015; Li et al., 2016b; Petkova et al., 2017).

28
29 Occupational health: Higher ambient temperatures and humidity levels place additional stress placed on
30 individuals engaging in physical activity. The wet bulb globe temperature (WBGT) enable monitoring of
31 environmental conditions during work, to determine when heat exposure could affect productivity; they were
32 not designed to predict adverse health outcomes(Niosh 2016). Heat stress can occur with exposure to high
33 ambient temperatures. With prolonged exposure, and without interventions to lower core body temperature,
34 heat stress can progress through heat stroke to death (Hanna and Tait, 2015). Characteristics of the individual
35 (e.g., age, health status, and level of physical fitness), type of activity (e.g., degree of exertion), clothing, and
36 other factors determine disease progression. Heat stress can be reduced by modifying metabolic heat
37 production or heat exchange by convection, radiation, or evaporation.

38
39 The conclusion of Smith et al. (2014) that safe work activity and worker productivity during the hottest
40 months of the year would be increasingly compromised with additional climate change is supported by
41 recent publications (Kjellstrom et al. 2013; Kjellstrom et al. 2017; Sheffield et al. 2013). In Nicaragua by
42 2050, the percent of days with high heat stress is projected to increase from 10% to 15% when outdoor
43 afternoon WBGT increase 3°C (Sheffield et al., 2013). In South East Asia by 2050, WBGT as high as 34-
44 35°C are projected, with associated loss of productivity (Kjellstrom et al., 2013). WBGT also are projected
45 to increase in Tehran, Iran (Habibi Mohraz et al., 2016). Global warming of +1.5°C is projected to reduce
46 working hours worldwide because of heat stress by 6% (Kjellstrom et al., 2017). Environmental heat stress
47 in 2050 is projected to reduce worldwide labor capacity by 20% in hot months from a 10% reduction today,
48 assuming no change in worker behavior or workplace conditions (Dunne et al., 2013).

49
50 Other studies, instead of projecting worker productivity, projected other measures of the future risks higher
51 temperatures. Worldwide projections of the costs of preventing workplace heat-related illnesses through

1 worker breaks suggest that GDP losses in 2100 could range from 2.6-4.0%, with higher costs under scenarios
2 of higher greenhouse gas emissions and SSP3 (Takakura et al., 2017). Because the relationship between the
3 costs of heat-related illness prevention and temperature is approximately linear, the different in economic
4 loss between the 1.5°C and 2°C goal in 2100 is projected to be approximately 0.3% global GDP. In China,
5 taking into account population growth and employment structure, high temperature subsidies for employees
6 working on extremely hot days are projected to increase from 38.6 billion yuan yr⁻¹ in 1979-2005 to 250
7 billion yuan yr⁻¹ in the 2030s and 1,000 billion yuan yr⁻¹ in 2100 (Zhao et al., 2016), with higher costs under
8 RCP8.5 than under RCPs 4.5 and 2.6.

9
10 Without considering the complex drivers of heat stress or the potential for acclimatization and adaptation,
11 studies project a significant increase in areas of the world that could experience increasing heat stress as
12 defined by a wet bulb globe temperature and/or may become inhospitable for human health and well-being
13 as temperatures continue to increase (Matthews et al., 2017; Pal and Eltahir, 2015; Sherwood and Huber,
14 2010).

15
16 Air quality: Air pollution significantly affects morbidity and mortality, with approximately 7 million excess
17 deaths annually across the world, most due to exposure to high concentrations of particulate matter (PM)
18 (WHO, 2012). Climate change could alter the dispersion of primary air pollutants, particularly
19 particulate matter, and intensify the formation of secondary pollutants, such as near-surface ozone (Orru et al.
20 2017). There is *low confidence* in projected changes in the atmospheric concentrations of ground-level ozone
21 and particulate matter because of limits of understanding and with large regional variations in projected
22 changes (Section 3.7). Because ozone formation is temperature dependent, projections focusing only on
23 temperature increase generally conclude that ozone-related mortality will increase with additional warming,
24 with the risks higher at +2°C than at 1.5°C (Fang et al. 2013; Fann et al. 2014; Silva et al. 2016; Likhvar et
25 al. 2015; Orru et al. 2013; Geels et al. 2015; Heal et al. 2013; Sun et al. 2015; Garcia-Menendez et al. 2015;
26 Alexeeff et al. 2016; Wilson et al. 2016; Chang et al. 2014; Physick et al. 2014; Dionisio et al. 2017; Lee et
27 al. 2017; table S3.9). Reductions in precursor emissions would reduce future ozone concentrations (and
28 associated mortality). Changes in projected PM-related mortality could increase or decrease, depending on
29 climate projections and emissions assumptions
30 ((Fang et al. 2013; Silva et al. 2016; Geels et al. 2015; Goto et al. 2016; Likhvar et al. 2015; Liu et al. 2016;
31 Sun et al. 2015; Garcia-Menendez et al. 2015; Tainio et al. 2013; Table S10)

32
33 Undernutrition: Studies since the AR5 support the conclusions that climate change will negatively affect
34 childhood undernutrition, particularly stunting, through reduced food availability, and will negatively affect
35 undernutrition-related childhood mortality and disability-adjusted lives lost (DALYs), with the largest risks
36 in Asia and Africa (Ishida et al. 2014; Hasegawa et al. 2016; Springmann et al. 2016; Table S3.5). Climate
37 change is projected to constrain trends in increasing food security, such that the avoided number of
38 childhood deaths will be smaller (Springmann et al., 2016). Climate change-related changes in dietary and
39 weight-related risk factors will increase mortality due to global reductions in food availability, fruit and
40 vegetable consumption, and the consumption of red meat (Springmann et al., 2016). The projected health
41 risks are greater at 2° vs 1.5°C warming. For example, under SSP3 in 2100, the projected global mean per-
42 capita food intake is 2950-2960 kcal/person/day at 1.5°C and 2930-2960 kcal person⁻¹ day⁻¹ at 2°C. The
43 projected global undernourished population is 530-550 million at 1.5°C and 540-590 million at 2°C
44 (Hasegawa et al., 2016). Furthermore, climate change is reducing the protein and micronutrient content of
45 major cereal crops, which is expected to further affect food security (Myers et al., 2017). Socioeconomic
46 conditions are the primary driver of vulnerability.

47
48 Malaria: Recent projections of the potential impacts of climate change on malaria globally and for China,
49 Asia, Africa, and South America (supplementary materials), confirm the conclusions reached in the AR5
50 (Smith et al., 2014) that weather and climate are among the drivers of the geographic range, intensity of
51 transmission, and seasonality of malaria, and that the influences of temperature and precipitation are

1 nonlinear (Caminade et al. 2014; Song et al. 2016b; Tompkins and Caporaso 2016; Khormi and Kumar
2 2016; Kwak et al. 2014; Ren et al. 2016; Semakula et al. 2017; Yamana et al. 2016; Zorello Laporta et al.
3 2015). Many projections suggest the burden of malaria could increase with climate change because of a
4 greater geographic range of the *Anopheles* vector, longer season, and/or increase in the number of people at
5 risk, with larger burdens with greater amounts of warming, with complex regional patterns. Relationships
6 between temperature and disease incidence are not necessarily linear, resulting in complex patterns of
7 changes in risk with additional warming. Some regions are projected to become too hot and/or dry for the
8 *Anopheles* mosquito, such as in northern China and parts of south and southeast Asia (Khormi and Kumar
9 2016; Semakula et al. 2017; Yamana et al. 2016; Tompkins and Caporaso 2016). Vector populations are
10 projected to shift with climate change, with expansions and reductions depending on the degree of local
11 warming, the ecology of the mosquito vector, and other factors (Ren et al., 2016).

12
13 *Aedes* (mosquito vector for dengue fever, chikungunya, yellow fever, and Zika virus): Projections focus on
14 the geographic distribution of *Aedes aegypti* and *Ae. albopictus* (principal vectors) or on the prevalence of
15 dengue fever, generally concluding there will be an increase in the number of mosquitos and a larger
16 geographic range in the 2030s and beyond than at present, and suggesting more individuals at risk of dengue
17 fever, with regional differences (Butterworth et al. 2017; Campbell et al. 2015; Khormi and Kumar 2014;
18 Proestos et al. 2015; Butterworth et al. 2016; Colón-González et al. 2013; Fischer et al. 2013, 2011; Bouzid
19 et al. 2014; Liu-Helmersson et al. 2016; Williams et al. 2016; Williams et al. 2014; Jia et al. 2017; Ryan et
20 al. 2017; Tagaris et al. 2017; Teurlai et al. 2015; Banu et al. 2014; Mweya et al. 2016; Ogden et al. 2014a).
21 Projections are at global and regional levels, and include North America, Europe, Australia, China, Asia,
22 New Caledonia, and Tanzania. The risks increase with greater warming and under higher greenhouse gas
23 emission pathways. Projections suggest that climate change will expand the geographic range of
24 chikungunya, with greater expansions with higher degrees of warming (Tjaden et al., 2017).

25
26 West Nile Virus: Projections in North America and Europe suggest a latitudinal and altitudinal expansion of
27 regions climatically suitable for West Nile Virus transmission, particularly along the current edges of its
28 transmission areas, and extension of the transmission season, with the magnitude and pattern of changes
29 varying by location and degree of warming (Harrigan et al. 2014; Belova et al. 2017; Brown et al. 2015;
30 Morin and Comrie 2013; Chen et al. 2013; Semenza et al. 2016).

31
32 Lyme disease and other tick-borne diseases: Most projections conclude that climate change will expand the
33 geographic range and seasonality of Lyme and other tick-borne diseases in parts of North America and
34 Europe (Feria-Arroyo et al., 2014; Lorenz et al., 2014; Monaghan et al., 2015; Ogden et al., 2014b; Porretta
35 et al., 2013; Simon et al., 2014; Williams et al., 2015). The changes are larger with greater warming and
36 under higher greenhouse gas emission pathways.

37
38 Other vector-borne diseases: Projections of the impacts of climate change on leishmaniasis, Chagas disease,
39 and other vector-borne and zoonotic diseases indicate climate change could increase or decrease future
40 health burdens, with greater impacts at higher degrees of warming (Carvalho et al., 2015; Ceccarelli and
41 Rabinovich, 2015; Domşa et al., 2016; Garza et al., 2014; González et al., 2014; Kartashev et al., 2014;
42 McIntyre et al., 2017; Medone et al., 2015; Ochieng et al., 2016).

43
44 **Summary: Global warming of 2°C poses greater risks to human health than warming of 1.5°C, often**
45 **with complex regional patterns and a few exceptions.** Each additional unit of warming will *very*
46 *likely* increase heat-related mortality, will *very likely* increase ozone-related mortality if precursor emissions
47 remain the same, and *likely* increase undernutrition. Warmer temperatures are *likely* to affect the
48 transmission of infectious diseases, with increases and decreases projected depending on disease (e.g.,
49 malaria, dengue, West Nile virus, and Lyme disease), region, and degree of temperature change. The
50 magnitude and pattern of future impacts will *very likely* depend on the extent and effectiveness of additional
51 adaptation and vulnerability reduction, and on mitigation for risks past mid-century.

1 3.4.8 *Urban areas*

2 3 3.4.8.1 *Observed impacts*

4 Urbanization, development patterns, geography, and other factors can generate systemic risks that
5 exceed the capacities of cities to prepare for and manage the risks of climate variability and change;
6 for example, in low-lying coastal zones and for urban transport, energy, and water
7 infrastructure (Revi et al. 2014; Birkmann et al. 2014; Rosenzweig et al. 2015; Bader et al. 2018;
8 Morton et al. 2014). Weather and climate variability can impact populations living in urban areas by
9 affecting water quality and quantity; functioning of critical infrastructure; and urban ecosystems,
10 biodiversity, and ecosystem services. Extreme weather and climate events can increase the risks of
11 injuries, illnesses, and deaths and can disrupt livelihoods and incomes, by, for example, the inland
12 and coastal flooding of 3.4 m above 2012 mean sea level observed in New York City during
13 Hurricane Sandy (Brandon et al., 2014). Droughts, temperature extremes exacerbated by urban heat
14 islands, and reductions in air quality also can adversely affect urban populations. These can be
15 compounded by geo-hydrological hazards, such as soil composition, landslides, and saltwater
16 intrusion. The coupled systems within cities can lead to novel, interacting hazards. The effects of
17 weather and climate variability on rural and peri-urban agriculture, ecosystem services, and other
18 sources of resources (e.g., firewood) affect cities through urban-rural interactions.

19 20 3.4.8.2 *Projected risks at 1.5°C versus 2°C*

21 Many large urban agglomerations in almost all continents will be exposed to a temperature rise of greater
22 than 1.5°C by mid-century under RCP2.6 (see Section 3.3).

23
24 Climate models are better at projecting implications of varying levels of greenhouse gas forcing on the
25 physical systems than assessing differential risks associated with achieving a specific temperature target
26 (James et al., 2017). These challenges in parsing differential risks at 1.5 versus 2°C are amplified when
27 combined at the scale of urban areas with assumptions about socio-economic pathways (Jiang and Neill,
28 2017; Kamei et al., 2016; Krey et al., 2012). New methods may be necessary to address uncertainties
29 associated with non-linearities, innovations, local scales, latent or lagging responses in climate (James et al.,
30 2017), and by extension, associated natural and human systems. Vahid Moussavi (2012) offers an example
31 of downscaling through a combination of GCMs and RCMs to address spatial and temporal uncertainties for
32 the building sector in Sweden. Likewise, Yu et al. (2016) distinguish different effects between 1.5°C or 2°C
33 warming on temperature and precipitation extremes for major urban agglomeration in China. For further
34 details on downscaling consideration see Section 3.2.2.

35
36 In urban areas, risks will differ between warming of + 1.5°C and 2°C (Schleussner et al. 2015,) (Figure
37 3.21). Direct risks are associated with heat related extreme events (Pfeifer et al, submitted), variability in
38 water supply, and sea-level rise (Bader et al., 2018). Indirect risks may be due to variability in agricultural
39 yields and loss of coral reefs.

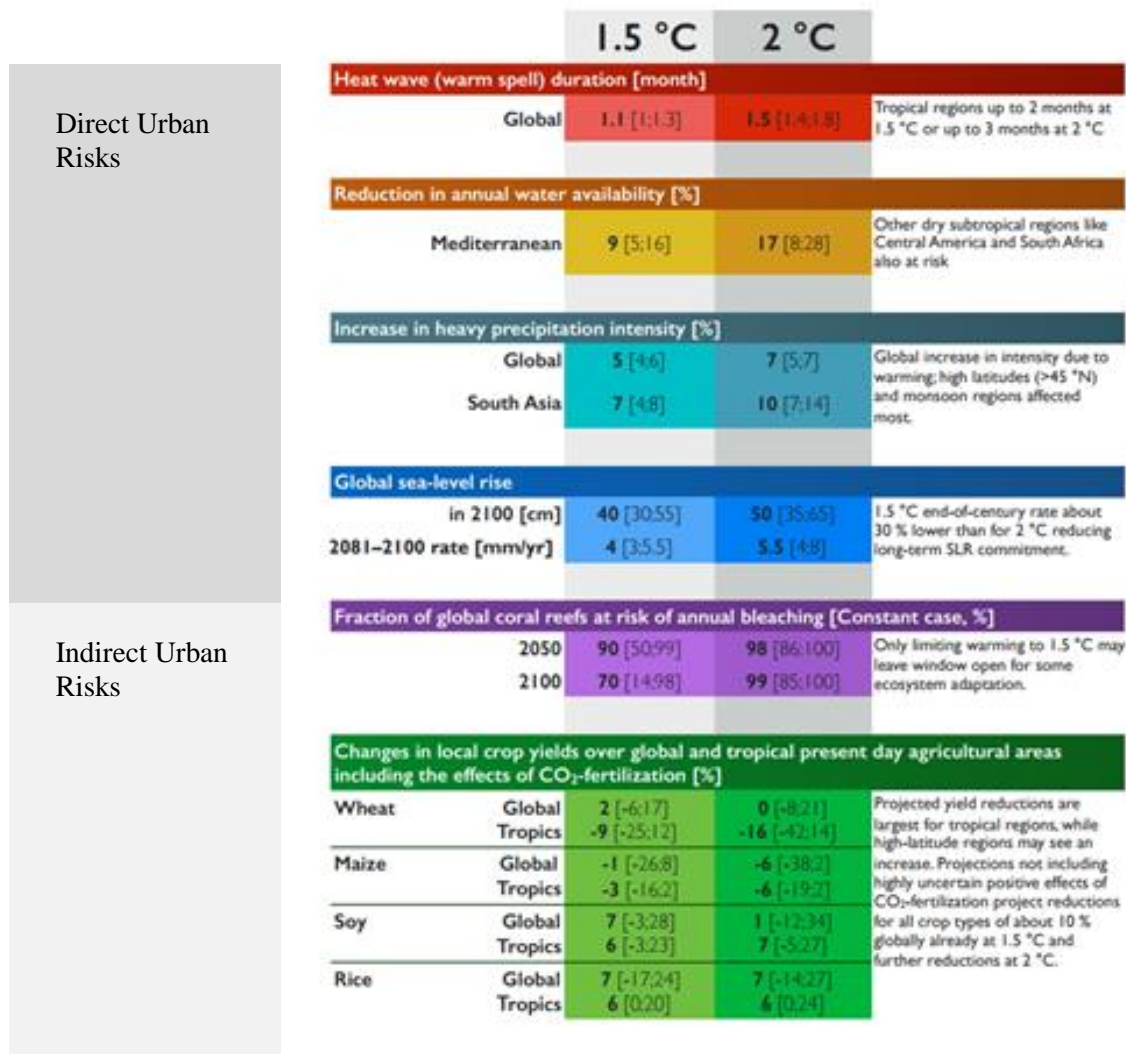


Figure 3.21: Summary of key differences in climate impacts at + 1.5°C and + 2°C and stylized 1.5°C 2°C scenarios over the 21st century. The 66% ranges are in square brackets. Source: (Schleussner et al., 2016b)

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Increases in the mean and variability of ambient temperature are of growing concern. In urban areas, the urban heat island is expected to increase the impact of ambient temperature. The UHI intensity is projected to decrease overall by 6% for a doubling of CO₂, with a range of up to a 30% increase (McCarthy et al., 2010). These simulations do not account for many of the differences between cities, and demonstrate substantial errors in many locations. A small number of studies used km-scale regional climate models to investigate these interactions for selected cities, finding, in general, that the urban health island remains in a future warmer climate with increases in UHI intensity occurring due to increases in population and city size. (Argüeso et al., 2014; Conlon et al., 2016; Georgescu et al., 2012; Grossman-Clarke et al., 2017; Kusaka et al., 2016). Future warming and urban expansion could lead to more extremes in heat stress conditions (Argüeso et al., 2015; Suzuki-Parker et al., 2015). Projection of near surface temperature in Israeli cities due to urbanization by mid-century are expected to exceed 3°C in several urban jurisdictions (Kaplan et al., 2017). Incremental warming of +2°C is expected to increase the risks of heat waves in China’s five major urban agglomerations - Bohai Ring, Yangtze River Delta, Pearl River Delta, Mid-reach of the Yangtze River, and the Chengyu - under RCP2.6, RCP4.5, RCP8.5 scenarios (Yu, Zhai, and

1 Lu, 2017). Urban morphology, water, and vegetation are factors affecting the differential warming
2 between urban and rural areas in the United States, suggesting managing albedo is an adaptive
3 mechanism (Li et al., 2016a; Zhao et al., 2014). Land-use changes due to urbanization in eastern
4 China are altering the regional land-sea temperature difference and may be a contributing factor to
5 changes in the East Asian Subtropical Monsoon (Yu et al., 2016).

6
7 For extreme heat events, +0.5°C of global warming implies a robust shift from the upper-bounds of
8 observed natural variability to a new global climate regime (Schleussner et al., 2016b). This has
9 differential implications for the urban poor. Adverse impacts of extreme events could arise in
10 tropical coastal areas of Africa, South America, and South East Asia (Schleussner et al., 2016b),
11 where large slum and other vulnerable urban populations reside. Heat-related regional variance in
12 median water supply has implications for Mediterranean cities. Mediterranean water stress is
13 projected to increase from 9% to 17% in a +1.5°C versus +2°C world. Likewise, regional dry spells
14 are projected to expand from 7% to 11%. Sea-level rise is expected to be lower for 1.5°C versus
15 2°C lowering risks for coastal metropolitan agglomerations.

16
17 If climate change is held below 2°C, taking into consideration urban heat island effects, there could
18 be a substantial increase in the occurrence of deadly heatwaves in cities, with the impacts similar at
19 1.5°C and 2°C, but substantially larger than under the present climate (Matthews et al., 2017). At
20 +1.5°C, twice as many megacities (such as Lagos, Nigeria, and Shanghai, China) could become
21 heat stressed as to present, exposing more than 350 million more people to deadly heat by 2050
22 under a midrange population growth scenario. At +2°C warming, Karachi (Pakistan) and Kolkata
23 (India) could expect annual conditions equivalent to their deadly 2015 heatwaves. However, these
24 projections do not integrate adaptation to projected warming, for instance, cooling that could be
25 achieved with more reflective roofs and urban surfaces overall (Akbari et al., 2009; Oleson et al.,
26 2010).

27
28 Summary: In most cases, warming of +2°C poses greater risks to urban areas than warming of
29 +1.5°C, varying with the vulnerability of the location (coastal and non-coastal), infrastructure
30 sectors (energy, water, transport), and levels of poverty. Linear associations between temperature
31 and adverse impacts, including due to heat waves, floods, droughts, and storms, mean that
32 additional warming of +0.5°C enhances risks to cities. Scale and distribution of future impacts
33 depend on the scope and effectiveness of additional adaptation by cities of its vulnerable assets and
34 people, and on mitigation for risks from warming later in the century.

37 **3.4.9 Key economic sectors and services**

38
39 Climate change will affect tourism, energy and water services through direct impacts on operations (e.g., sea
40 level rise) and through impacts on supply and demand, with the risks varying significantly across geographic
41 region, season, and time. Projected risks also depend on assumptions with respect to population growth, the
42 rate and pattern of urbanization, and investments in infrastructure. Cramer et al. (2014)
43 concluded that in low-income countries, higher annual temperatures and higher temperatures averaged over
44 15-year periods result in substantially lower per capita income and lower economic growth. Portions of the
45 energy sector are sensitive to higher temperatures (e.g., increasing demand for cooling and decreasing
46 demand for heating), and many energy technologies are sensitive to weather and climate. Tourism also is
47 sensitive to weather and climate, particularly winter sports, beach resorts, and nature resorts. Overall, the
48 impacts of climate change will be small relative to other drivers of economic sectors and services, such as

1 changes in population, regulations, governance, and many other aspects of socioeconomic development
2 (Cramer et al., 2014a).

3
4 Table S11 in the supplementary materials provides a further summary of the knowledge to date.

5 6 7 *3.4.9.1 Energy systems*

8 9 *3.4.9.1.1 Observed impacts*

10 The operations of energy systems can be affected by ambient temperature and extreme weather and climate
11 events, including increased (and in some areas decreased) demand for air conditioning and heating; impacts
12 on operational requirements and infrastructure; water runoff, river flow, and temperature (hydropower and
13 power plant cooling); solar radiation (solar power); wind and storms (wind energy and network infrastructure
14 risk); and other weather variables linked to agriculture and forestry for biofuel production (Arent et al.,
15 2014).

16 A wide range of weather variables can affect energy technologies (thermal and nuclear power plants,
17 hydropower, solar energy, wind power), and the effectiveness of adaptation options(Arent et al., 2014).

18 19 20 *3.4.9.1.2 Projected risks at 1.5 vs 2°C*

21 Climate change will likely increase the demand for energy in most regions(Arent et al., 2014). At the same
22 time, increasing temperature will decrease the thermal efficiency of fossil, nuclear, biomass, and solar power
23 generation technologies, as well as buildings and other infrastructure. Most impacts will be related to
24 increased temperatures. For example, air temperature in Korea is the principal variable associated directly
25 with electricity demand with variations with season and time scale (Hong and Kim, 2015). In warm regions,
26 demand for air conditioning is expected to increase (Arent et al., 2014). Projecting risks is complex because
27 of uncertainties in climate projections, and because of the interactions of climate change with population
28 growth and other factors. For example, in Ethiopia, capital expenditures through 2050 may either decrease
29 by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario
30 (Block and Strzepek, 2012). In the Zambezi river basin, hydropower may fall by 10% by 2030, and by 35%
31 by 2050 under the driest scenario (Strzepek et al., 2012). Annual hydroelectric power production in Ecuador
32 is projected to vary between -55 and +39% of the mean historical output when considering future inflow
33 patterns to hydroelectric reservoirs covering one standard deviation of the CMIP5 RCP4.5 climate ensemble
34 (Carvajal et al., 2017).

35
36 Impacts on energy systems can affect gross domestic product (GDP). The economic damage in the United
37 States from climate change is estimated to be roughly 1.2% cost of GDP per +1°C increase on average under
38 RCP8.5 (Hsiang et al., 2017a). Petris et al. (2017) suggest the impact of +1.5°C would be indistinguishable
39 compared with current conditions, while +2°C implies significantly lower projected economic growth for
40 many countries, with higher losses for low-income countries and a greater impact on countries around the
41 equator and Southern Hemisphere. Projections of the GDP negative impacts of energy demand associated
42 with space heating and cooling in 2100 are highest (median: -0.94%) under 4.0°C (RCP8.5)compared with a
43 GDP change (median: -0.05%) under 1.5°C, depending on the socioeconomiccondition(Park et al., 2017).
44 Additionally, at the global scale total energy demands for heating and cooling changes little with increases
45 up to 2°C, however there is high variability between regions (Arnell et al., 2017).

46
47 Evidence for the impact of climate change on energy systems is limited since AR5. Globally, gross
48 hydropower potential is projected to increase (+2.4% under RCP2.6; +6.3% under RCP8.5 for the 2080s)
49 with the most growth in central Africa, Asia, India, and northern high latitudes(Van Vliet et al. 2016). At
50 minimum and maximum increases in temperature of 1.35° and 2°C, the overall stream flow in Florida, USA

1 is projected to increase by an average of 21% with pronounced seasonal variations, resulting in increases in
2 power generation in the winter (72%) and autumn (15%) and decreases in summer (-14%; Chilkoti et al.
3 2017). Changes are greater at the higher projected temperature. In a reference scenario with global mean
4 temperatures rising by 1.7°C from 2005 to 2050, U.S. electricity demand in 2050 is 1.6 to 6.5% higher than a
5 control scenario with constant temperatures (McFarland et al., 2015). Decreased electricity generation of -
6 15% is projected for Brazil starting in 2040, declining to -28% later in the century (de Queiroz et al., 2016).
7 (de Queiroz et al. 2016). In large parts of Europe electricity demand is projected to decrease mainly due to
8 reduced heating demand, with exception of Italy (+2°C more than in +1.5°C warming) (Jacob et al.).
9

10 In Europe, no major differences in large-scale wind energy resources, inter-annual or intra-annual variability
11 are projected for 2016-2035 (Carvalho et al., 2017). However, in 2046-2100, wind energy density is
12 projected to decrease in Eastern Europe and increase in Baltic regions (-30% vs. +30%). Intra-annual
13 variability is expected to increase in Northern Europe and decrease in Southern Europe. Under RCP4.5 and
14 RCP8.5, the annual energy yield of European wind farms as a whole as projected to be installed by 2050 will
15 remain stable (± 5 for all climate models). However, wind farm yields will undergo changes up to 15% in
16 magnitude at country and local scales and a 5% change in magnitude at regional (Tobin et al., 2015, 2016).
17

18 The impacts of solar radiation and temperature changes on energy yields of photovoltaic (PV) systems under
19 RCP8.5 indicates statistically significant decreases in PV outputs in large parts of the world with exceptions
20 in parts of Europe and South-East China (Wild et al., 2015). Limited change in solar PV production in
21 Europe is projected by 2100 (range -14%; +2%, using EURO-CORDEX) with the largest decreases in
22 Northern countries (Jerez et al., 2015).
23

24 3.4.9.2 *Tourism*

25 3.4.9.2.1 *Observed impacts*

26
27 The implications of climate change for the tourism sector are far-reaching and are impacting
28 tourism sector investments, destination assets (environment and cultural), operational costs, and
29 tourist demand (Scott et al., 2016a, Scott and Gossling 2017). With its strong reliance on specific
30 climatic conditions, the ski industry is the tourism market most directly and immediately affected
31 by climate change. Reduced natural snowfall had a limited impact on skier visits in high-elevation
32 ski areas in France and high-latitude ski areas in Finland (Falk, 2015; Falk and Vieru, 2017), but
33 had a significant impact on overnight stays in 55% of European regions analyzed by (Damm et al.,
34 2017). Reduced snowfall between 1970 and 2007 contributed to ski area closures in the New
35 England region (US) (Beaudin and Huang, 2014), while no effect of poor natural snow seasons on
36 closures were detected in Austria (Falk, 2013). Observed changes in skier visits during recent
37 record warm winters were largely consistent in the regional markets of North America and Western
38 Europe where snowmaking is widely implemented (Steiger et al., 2017). Skier visits decline
39 between 10-15% market-wide, but vary greatly between individual ski areas, with higher elevation
40 and larger ski areas less sensitive (even gaining market share). Record warm winter conditions in
41 the Ontario (Canada) market reduced the ski season (17%), total skiable terrain (9%), days with
42 high quality snow conditions (46%), and skier visits (15%), while increasing water usage for
43 snowmaking (300% in December) versus recent climatically normal winter (for the 1981-2010
44 period) (Rutty et al., 2017). With continued investment in snowmaking, average ski season length
45 in all regional markets of the US continued to grow from the 1980s to the 2000s, despite warming
46 temperatures (Scott et al., 2017). This trend was reversed in five of six regions from 2010-2016,
47 signifying the adaptive capacity provided by snowmaking may be nearing its limits.
48
49

1 Observed impacts on other tourism markets are not as well analyzed, despite many analogue
2 conditions (e.g., heatwaves, major hurricanes, wild fires) anticipated to occur more frequently with
3 climate change. Examples of diverse tourism impacts include a four-day shift forward in peak
4 attendance at US national parks experiencing climate change (warmer spring and fall months) since
5 1979 (Buckley and Foushee, 2012) closures of national park areas in the US, India, and Canada due
6 to major flooding and extreme and unseasonal wildfires; access restrictions and closures of diving
7 sites in Thailand and compromised tourism in Australia because of severe coral bleaching; and the
8 severe impact of category 5 hurricanes on the tourism infrastructure of several islands in the
9 Caribbean (see 3-4-3 and Box 3.7 for detailed discussion). Early estimates from the Caribbean
10 Tourism Organization (CTO, 2017) are that reduced tourism revenue to storm damaged destinations
11 will exceed \$US600 in 2017 and early 2018. There is some evidence that the prevalence of
12 observed impacts on tourism assets (environmental and cultural heritage) is leading to the
13 development of ‘last chance to see’ tourism markets where travellers visit destinations before they
14 are substantially degraded by climate change impacts or to view the impacts of climate change on
15 landscapes (e.g., melting glaciers, bleaching and dying coral reefs) (Lemelin et al., 2017; Piggott-
16 McKellar and McNamara, 2017; Stewart et al., 2016)

17

18

19 3.4.9.2.2 *Projected risks at 1.5 vs 2°C*

20 There is limited research on the projected risks of +1.5° vs 2°C temperature increase and resultant
21 environmental and socio-economic impacts in the tourism sector. Growing evidence indicates that the
22 magnitude of projected impacts is temperature-dependent and sector risks will be much greater with higher
23 temperature increases (Markham et al., 2016; Scott et al., 2015; Steiger et al., 2017)

24

25 Climate is an important ‘push and pull’ factor influencing the geography and seasonality of tourism demand
26 and spending globally. The changing distribution of climate resources will directly impact climate dependant
27 tourism markets, including sun and beach and snow sports tourism, with lesser impact on other tourism
28 markets that are less climate sensitive (e.g., urban sightseeing) (Scott et al., 2016a). Several studies
29 addressed regional gaps in projected spatial and temporal changes in tourism climate resources (Australia –
30 (Amelung and Nicholls, 2014); China –(Fang and Yin, 2015; Li and Chi, 2014) ; Hungary – (Kovács et al.,
31 2017; Kovács and Unger, 2014); Iran – (Olya and Alipour, 2015; Roshan et al., 2016; Yazdanpanah et al.,
32 2016a); Japan – (Kubokawa et al., 2014); Serbia - (Anđelković et al., 2016); South Africa – (Fichett et al.,
33 2016; Fichett et al., 2017)t , broadly reinforcing the impact patterns established before the AR5 (Rosselló-
34 Nadal, 2014; Scott et al., 2016a). These studies utilized a tourism climate index that has been subject to
35 substantial critiques (Dubois et al., 2016; Scott et al., 2016b). Studies of tourist climate preferences for sun-
36 beach and urban markets revealed thermal tolerances to be much higher than previously assumed (Rutty and
37 Scott, 2013, 2015). When tourist preferences are accounted for, the projected impacts on the distribution of
38 tourism climate resources in Europe are reduced (Scott et al., 2016b), and the contention that summer
39 conditions in Southern Europe will significantly deteriorate under +2°C climate futures is not supported.
40 Tourism impacts projected on the basis of climate indices not informed by tourist preference and adaptive
41 capacity may not yield robust results (Rosselló-Nadal, 2014; Scott et al., 2016a). Analysis of the tourism
42 impacts of recent heat waves in Europe, India and other destinations as analogues for future climate remains
43 limited (Gómez-Martín et al., 2014; Scott et al., 2016a)

44

45 The translation of changes in climate resources for tourism, together with other major drivers of tourism, into
46 projections of tourism demand and spending remains geographically limited. Using an econometric analysis
47 of the relationship between regional tourism demand and regional climate conditions, Ciscar et al. (2014)
48 projected a +2°C world would reduce European tourism by -5% (€15 billionyr-1), with losses up to -11% (€6
49 billionyr-1) for southern Europe and a potential gain of €0.5 billion/year in the UK. Tourist visits to the US

1 National Parks under low-high visitation growth and RCP 4.5-8.5 scenarios were projected to change in
2 almost all parks (95%), increasing total annual visits across the park system by 8 to 23%) and expanding the
3 visitation season at individual parks by 13 to 31 days (Fisichelli et al., 2015). Very warm months at some
4 parks may see decreases in future visitation. The climate-induced environment changes in the parks further
5 impact visitation, with compounding impacts for management and local economies.

6
7 Studies from 27 countries consistently project substantially decreased reliability of ski slopes that are
8 dependent on natural snow, increased snowmaking requirements and investment in snowmaking systems,
9 shortened and more variable ski seasons, a contraction in the number of operating ski areas, altered
10 competitiveness among and within regional ski markets, and subsequent impacts on employment and the
11 value of vacation properties (Steiger et al., 2017). In all regional markets, the extent and timing of these
12 impacts depends on the magnitude of climate change and the types of adaptive responses by the ski industry,
13 skiers, and destination communities.

14
15 In the European Alps region, a 2°C warming and associated changes in natural snow is projected to result in
16 a decline of 10.1 million ski tourism overnight stays in Austria, France, Italy and Switzerland (Damm et al.,
17 2017). 1.9 mill annual winter overnight stays are being saved in Europe when global warming is limited to
18 +1.5°C (Jacob et al.). However, this study did not account for the extensive and growing snowmaking
19 capacity in the region and therefore does not represent the current operating realities of the ski industry or the
20 snow conditions that ski tourists respond to. In studies that fully incorporate the adaptive capacity of
21 snowmaking, major differences in the impacts of 2°C vs. 4°C warming are projected. In the eastern
22 European Alps, the proportion of snow reliable ski areas (able to maintain 100 day ski season, with
23 snowmaking) declines slightly under 1°C warming in the Vorarlberg, Tyrol, Salzburg, Lower Austria, Styria,
24 Upper Bavaria, and Allgäu regions. The number of snow reliable ski areas declines further under 2°C
25 warming with significant losses in Vorarlberg (-30%), Tyrol (-22%), Lower Austria (-91%), Styria (-71%),
26 Upper Bavaria (-54%), and Allgäu (-38%) regions (Steiger and Abegg, 2017). In the Ontario (Canada)
27 market, losses in average ski season can be limited to between 8% and 16% (large and small resorts
28 respectively) under RCP 2.6, which is analogous to recent record warm winters (Scott et al., 2017). Season
29 losses under RCP 8.5 increase to 18-50% by mid-century and 60-90% by late-century. The same modeling
30 approach found differential impacts on the suitability of former Olympic Winter Games locations to host the
31 Games in a warmer future (Scott et al. 2014). By the 2050s, the number of climate reliable former host
32 locations would decline from 19 to 11 (RCP 2.6) or 10 (RCP 8.5). By the 2080s only six to ten locations
33 (RCP 2.6 vs 8.5) would be climatically suitable to host the Games. A georeferenced agent-based model that
34 accounted for snowmaking similarly projected highly differential impacts on skier visitation to ski resorts in
35 the Pyrenees region under 2°C (less than 25% loss) and 4°C (50% and 100% loss) warming (Pons et al.,
36 2015).

37
38 The tourism sector is also impacted by climate-induced changes in environmental systems that are critical
39 assets for tourism, including biodiversity, beaches, glaciers and other environmental and cultural heritage.
40 Limited analyses of projected risks associated with 1.5° vs. 2°C are available. A global analysis of sea level
41 rise risk to 130 UNESCO cultural World Heritage sites found that if the current global temperatures was
42 sustained, about 6% (40 sites) of the sites will be affected, increasing to 19% (136 sites) under warming of
43 2°C (Marzeion and Levermann, 2014). Similar risks to coastal tourism infrastructure and beach assets remain
44 unquantified in most small-island developing states that depend on coastal tourism. One exception is the
45 projection that a 1-metre sea-level rise would partially or fully inundate 29% of 900 coastal resorts in 19
46 Caribbean countries, with a substantially higher proportion (49–60%) vulnerable to associated coastal
47 erosion (Scott and Verkoeyen, 2017). If recent patterns of severe coral reef bleaching continue, Great Barrier
48 Reef tourism areas are projected to be at risk of losing over 1 million visitors per year and 10,000 tourism
49 jobs (Australia Institute 2016; see Section 3-4-3 and Box 3.6 for discussion on specific adaptation options).

50
51 One of the largest barriers to understanding the risks of climate change for tourism (from the destination

1 community global scale) has been the lack of integrated sectoral assessments that analyze the full range of
2 potential impacts and their interactions (Scott et al., 2016a). Using a vulnerability index approach with 15
3 indicators, summer oriented tourism in Europe under 2°C warming and a range of socioeconomic scenarios
4 was projected to increase the vulnerability of summer tourism in the most European countries, but especially
5 in the southern regions of Spain, France, Italy, Greece (Koutroulis et al.) with less risks of changes for
6 +1.5°C global warming (Jacob et al.). Central and northern European countries such as Romania, Germany
7 and UK are amongst the future beneficiaries. A comparable global vulnerability index using 27 indicators of
8 internal and transnational climate change risks and tourism sector and destination country adaptive capacity
9 in 181 countries found that countries with the lowest risk are found in western and northern Europe, central
10 Asia, as well as Canada and New Zealand, while the highest sector risk is found in Africa, the Middle East,
11 South Asia and Small Island Developing States in the Caribbean as well as Indian and Pacific Oceans (Scott
12 and Gossling 2017). Countries with highest risk and where tourism represents a significant proportion of the
13 national economy (more than 15% GDP) include many SIDS (Maldives, Seychelles, Mauritius, Antigua and
14 Barbuda, Bahamas, Saint Lucia, Grenada, Barbados, Jamaica, Vanuatu, Fiji, and Kiribati) as well as Costa
15 Rica, Belize, Honduras, Laos, Thailand, Cambodia, Vietnam, Mexico, Namibia, and Gambia. Climate
16 change risk also aligns strongly with regions where tourism growth is projected to be the strongest over the
17 coming decades, including the sub-regions of Sub-Saharan Africa and South Asia; representing an important
18 barrier to long-term tourism growth in these regions. The transnational implications of these impacts on the
19 highly interconnected global tourism sector and the contribution of tourism to achieving the 2030
20 Sustainable Development Goals remain important uncertainties.

21 22 Key Message

23
24 Climate is an important ‘push and pull’ factor influencing the geography and seasonality of tourism demand
25 and spending globally (*very high confidence*). Increasing temperatures will directly impact climate
26 dependant tourism markets, including sun and beach and snow sports tourism, with lesser impact on other
27 tourism markets that are less climate sensitive (*high confidence*). The translation of changes in climate
28 resources for tourism, together with other major drivers of tourism, into projections of tourism demand and
29 spending remains geographically limited.

30 31 32 3.4.9.3 Transportation

33 34 3.4.9.3.1 Observed impacts

35 Road, air, rail, shipping, and pipeline transportation can be impacted directly or indirectly by weather and
36 climate, including increases in precipitation and temperature; extreme weather events (flooding and storms);
37 sea level rise; and incidence of freeze-thaw cycles (Arent et al., 2014). Much of the published research on the
38 risks of climate change for the transportation sector has been qualitative. Risks depend on the location of the
39 infrastructure (within three major climatic zones) and vulnerabilities:

- 40
41 • Freezing/frost zone: Permafrost, freeze-thaw cycles, precipitation, flooding, sea level rise, and
42 storms (coastal);
- 43 • Temperate zone: Precipitation intensity, flooding, maximum daily precipitation, sea level rise, and
44 storms (coastal); and
- 45 • Tropical zone: Precipitation intensity, flooding, maximum daily precipitation, sea level rise, and
46 storms (coastal)

47 48 49 3.4.9.3.2 Projected risks at 1.5 vs 2°C

50 Limited new research since the AR5 supports that increases in global temperatures will impact the
51 transportation sector. Increases in mean (2-4°C) and extreme (4-8°C) temperatures under RCP4.5 and

1 RCP8.5 till 2100 are projected to impact weight restrictions for aircraft takeoff, which may lead to increased
2 costs for airlines (Coffel et al., 2017). Warming is projected to result in increased days of ice-free navigation
3 and a longer shipping season in cold regions, thus impacting shipping and reducing transportation cost
4 (Arent et al., 2014). In the North Sea Route (NSR) large-scale commercial shipping might not be possible
5 until 2030 for bulk shipping and 2050 for container shipping under RCP 8.5, but more shipping is expected
6 to contribute to a mean temperature rise of 0.05% (Yumashev et al., 2017). By 2100, CMIP5 ensemble-mean
7 estimates show an increase of the NSR transit window by about 4 and 6.5 months under RCP4.5 and 8.5,
8 respectively (Khon et al., 2017). Climatic losses are projected to offset 33% of the total economic gains from
9 NSR under RCP8.5, with the biggest losses projected to occur in Africa and India. Decline in Arctic sea ice
10 is projected to open shorter trade routes across the Arctic Ocean with transit times from Europe to East Asia
11 declining to 22 days under RCP2.6 and 17 days under RCP8.5 through the 21st century. Further, for a low-
12 emissions scenario, with global mean temperature stabilization of less than 2°C above preindustrial, the
13 frequency of open water vessel transits has the potential to double by midcentury with a season ranging from
14 2 to 4 months (Melia et al., 2016)

15
16 Arent et al. (2014) concluded that impacts of climate change on inland navigation and shipping will vary
17 widely due to projected rise or fall in water levels. Overall, the effects on inland navigation are projected to
18 be negative and are region specific.

19 20 21 3.4.9.4 *Water*

22 23 3.4.9.4.1 *Observed impacts*

24 Arent et al. (2014) concluded that flooding and droughts may have significant economic impacts on water
25 systems and infrastructure, with adaptation costs ranging from relatively modest to relatively high. Most
26 studies examining the economic impacts of climate change on the water sector were carried out at the local,
27 national, or river-basin scale; the distribution of such studies is skewed toward high-income countries.
28 However, water-related impacts are typically more pronounced in low- and middle-income countries, with
29 significant associated economic costs. Increasing costs globally are expected to promote climate-resilient
30 municipal and industrial water supply economic systems to prepare for anticipated future changes.

31 32 33 3.4.9.4.2 *Projected risks at 1.5 vs 2°C*

34 The costs of flooding are expected to increase due to climate change in low-, middle- and high-income
35 countries, with greater risks at higher warming levels. Continental U.S. mean annual flood damages are
36 projected to increase by US\$1.5 billion by 2100 under a business as usual scenario and a moderate climate
37 sensitivity of 3°C (Wobus et al., 2014). In the UK, climate change could increase the annual cost of flooding
38 almost 15-fold by 2080 under high emissions scenarios (ABI, 2005). By 2050, Bangladesh could face
39 incremental costs of flood protection (against sea and river floods) of US\$2.6 billion initial costs and US\$54
40 million annual recurring costs (Dasgupta et al., 2010). Floods and droughts are projected to cost Kenya about
41 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka et al., 2005).

42 43 44 3.4.10 *Livelihoods and poverty, and the changing structure of communities*

45
46 Multiple drivers and embedded social processes influence the magnitude and pattern of livelihoods and
47 poverty, and the changing structure of communities related to migration, displacement, and conflict (Adger et
48 al., 2014a). In the AR5, evidence of a climate change signal was limited, with more evidence of impacts of
49 climate change on the places where indigenous people live and on traditional ecological knowledge (Olsson
50 et al. 2014).

1 3.4.10.1 *Livelihoods and poverty*

2 Risks to livelihoods and poverty are expected to worsen with additional climate change because of
3 interactions with non-climate stressors and entrenched structural inequities that shape vulnerabilities (Olsson
4 et al., 2014). Multi-dimensional poverty is expected to increase in most low- and middle-income countries
5 with climate change, including high mountain states, countries at risk of sea level rise, and countries with
6 indigenous populations(Olsson et al., 2014). Poor people are poor for different reasons, so are not uniformly
7 affected, and not all vulnerable people are poor. The impacts of climate-related hazards are felt through
8 losses in food, water, and household security, and through a loss of sense of place. Changes in weather
9 patterns can alter rural livelihoods, with consequences for development, including poverty traps. The general
10 high vulnerability of marginalized and disadvantaged groups means climate-related hazards can worsen
11 poverty and inequalities, creating new vulnerabilities and opportunities.

12
13 By 2030, climate change will be a poverty multiplier that makes poor people poorer, and increases the
14 poverty head count (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Poor people may be heavily
15 affected by climate change even when impacts on the rest of population remain limited. Climate change
16 could force more than 100 million people into extreme poverty by 2030, and the number of people in
17 extreme poverty only because of climate change is projected to be between 3 million and 16 million, mostly
18 through impacts on agriculture and food prices (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017).
19 Warming of + 1°C could reduce labour productivity by 1-3%, at least for people working outdoors without
20 air conditioning (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). The association between
21 economic productivity and temperature is non-linear, with productivity peaking at an annual average
22 temperature of 13°C and declining strongly at higher temperatures(Burke et al., 2015b). Unmitigated
23 warming could reshape the global economy by reducing average global incomes roughly 23% by 2100 and
24 widening global income inequality (Burke et al., 2015b). The extent to which climate change could slow
25 economic growth and poverty reduction, further erode food security, and create new poverty traps would
26 affect the number and distribution of poor individuals and communities between now and 2100(Hallegatte et
27 al., 2016; Hallegatte and Rozenberg, 2017). Most severe impacts are projected for urban areas and some
28 rural regions in sub-Saharan Africa and Southeast Asia.

31 3.4.10.2 *The changing structure of communities*

33 **Migration:**

34
35 The potential impacts of climate change on migration and displacement was identified in the AR5 as an
36 emerging risk (Oppenheimer et al. 2014). The social, economic, and environmental factors underlying
37 migration are complex and varied; therefore, it was not possible to detect the effect of observed climate
38 change or assess its possible magnitude with any degree of confidence (Cramer et al. 2014).

39
40 Migration is a widely used and recognized adaptive response to climate variability and environmental change
41 generally(Adger et al., 2014b; Afifi et al., 2016; Gharbaoui and Blocher, 2016; Hummel, 2016; McLeman,
42 2016; Milan et al., 2016; Sow et al., 2016). Migration can be voluntary, planned (e.g., relocation), and forced
43 displacement (IOM, 2016). Labour migration also occurs among individuals with high resilience and
44 adaptive capacity (Brzoska and Fröhlich, 2016; Mueller et al., 2014; Warner and Afifi, 2014). Those who
45 can not move can adapt in-situ or become immobile/trapped(Brzoska and Fröhlich, 2016; Mueller et al.,
46 2014; Warner and Afifi, 2014). Planned, safe, dignified and orderly migration is a viable adaptation strategy
47 to cope with the adverse effects of environmental and climate change (IOM, 2014).

48
49 No studies specifically explored the difference in risks between 1.5°C and 2°C on human migration. The
50 literature consistently highlights the complexity of migration decisions and the difficulties in attributing

1 causation (e.g., Baldwin and Fornalé 2017; Constable 2017a; Bettini 2017; Islam and Shamsuddoha 2017;
2 Nicholson 2014; Suckall, Fraser, and Forster 2017). The studies on migration that most closely explore the
3 probable impacts of 1.5°C and 2.0°C tend to focus on past migration behaviour and the effect of temperature
4 and precipitation anomalies. Studies related to migration examine the effects of changing rainfall,
5 temperature, and natural disasters directly on migration, or indirectly through examining migration due to
6 changing agriculture yield and livelihood sources (Mastrorillo et al., 2016; Mueller et al., 2014; Piguet and
7 Laczko, 2014; Sudmeier-Rieux et al., 2017).

8
9 Some studies reconstructed historical migration of populations over hundreds or thousands of years. For
10 example, Jennings and Gray (2015) used longitudinal individual-level demographic data to explore 20th
11 century migration in Netherlands. They concluded that the effect of temperature was most pronounced
12 (although still weak) in the case of short-term, within country movement. For longer-term migration, there
13 was no overall climate effect. For international migration, the effect of extreme rainfall was strong and
14 negative. Pei and Zhang (2014) explored the relationship between nomadic migration in China and climate
15 variability over a 2000-year period, concluding that most nomadic migration peaks occurred during periods
16 of low temperature, or little rainfall or both with the role of precipitation being more significant.

17
18 Global: Temperature has a positive and statistically significant effect on out migration over recent decades in
19 163 countries, but only for agricultural-dependent countries (Cai et al., 2016a). A 1°C increase in temperature
20 in the OECD's International Migration Database was associated with a 1.9% increase in bilateral migration
21 flows from 142 sending countries and 19 receiving countries (Backhaus et al. 2015). An additional
22 millimeter of precipitation was associated with an increase in migration by 0.5%. An increase in
23 precipitation anomalies in the same database, but over a different time period, was strongly associated with
24 an increase in out-migration while there are no significant effects for temperature anomalies (Coniglio and
25 Pesce, 2015).

26
27 South America: Exposure to monthly temperature shocks in South America had the most consistent effect on
28 migration relative to monthly rainfall shocks (Thiede, Gray, and Mueller 2016). Nawrotzki et al.
29 (2017) explored international migration from Mexico and concluded that an increase in temperature generally
30 increases outward migration. For example, an increase in the warm spell duration by one standard deviation
31 unit increased international migration by 22%. The relationship between heat months and migration in
32 Mexico is non-linear, with moderate increases in temperature depressing rural to urban migration until a
33 threshold is reached and migration becomes positive and progressively increases in strength (Nawrotzki et
34 al., 2017).

35
36 Africa: In South Africa, migration flows increase with larger positive maximum temperature anomalies
37 whilst negative temperature anomalies do not engender a similar effect (Mastrorillo et al., 2016). The effect of
38 precipitation on migration is much more inconsistent (Bohra-Mishra et al., 2014a; Mastrorillo et al., 2016;
39 Nawrotzki et al., 2017; Thiede et al., 2016). Gray and Wise (2016), utilizing the World Bank's African
40 Migration and Remittances Survey data for five African countries over a six-year period, concluded that the
41 effect of temperature on migration was important although the direction of the relationship changes
42 depended on the country context, although not all studies report an association between climate and
43 migration (Nawrotzki et al., 2017). In Mali and Senegal, severe droughts increased seasonal and internal
44 migration, with the intention to return to their original places. The majority had migrated in the past and
45 considered migration as a part of everyday/ traditional life (Sow et al., 2016), rather than as a last resort
46 (Hummel, 2016). Ocean warming, reduced precipitation, overfishing and fish migration are the common
47 drivers for migration of fishermen from West African countries to Morocco (Sow et al., 2016). A study
48 examining climate variability and its influence on internal migration within South Africa between 1997-2001
49 and 2007-2011 suggested that an increase in positive temperature extremes as well as positive and negative
50 excess rainfall act to enhance out-migration, and agriculture could be the channel through which adverse
51 climatic conditions affect migration (Mastrorillo et al., 2016).

1 Asia: Temperature has a significant positive effect on outmigration in the Philippines with each 1°C increase
2 in average summer temperature increasing outmigration by 0.6% for the period 1990 – 2000(Bohra-Mishra
3 et al. 2014a). An increase in temperature in Indonesia due to natural variability and climate change are likely
4 to have greater effect on permanent outmigration of households, compared to that due to variations in rainfall
5 or sudden natural disasters (Bohra-Mishra et al., 2014a). There are nonlinear effects of temperature and
6 precipitation on annual migration, with lower crop revenues in relatively warm districts and higher revenues
7 in cooler districts,such that above 25°C, a rise in temperature leads to an increase in outmigration, mostly
8 through changes in agricultural productivity (Bohra-Mishra et al. 2014a; Lohano 2017). A 1% weather-
9 related decrease in the crop revenue per hectare induces, on average, around 2% decrease in the district in-
10 migration rate (Lohano, 2017). In rural Pakistan, heat stress consistently increases the long-term migration of
11 men, driven by a negative effects on farm and non-farm income, while flooding had modest to insignificant
12 impacts on migration(Mueller et al., 2014).

13
14 Pathways: Theorising on the pathways through which climate will impact on migration appears most
15 strongly supported in literature for a pathway through agriculture, suggesting that countries that are most
16 likely to see a climate signal in migration are those from the global south with high rural unemployment
17 (Coniglio and Pesce, 2015; Maurel and Tuccio, 2016; Nawrotzki et al., 2015a, 2015b, 2017; Nawrotzki and
18 Bakhtsiyarava, 2017; Nawrotzki and DeWaard, 2016). Temperature increasescan reduce migration and traps
19 people into poverty in low income countries, strengthen the incentives to migrate to cities or abroad in
20 middle income countries warming, and encouragea transformation towards more urban and productive
21 economies and increase emigration (Cattaneo and Peri 2016;Thiede et al 2016, Nawrotzki et al
22 2017).Socially-differentiated groups can and do use migration in different ways for different reasons(Adams
23 2016; Arnall and Kothari 2015). For example, changes in temperature in South Africa appeared to have
24 greater effect on black and other ethnic minorities as well as those on low incomes (Mastrorillo et al 2016).

25 Disasters:

26
27
28 Islam and Shamsuddoha (2017) concluded that rapid onset disasters such as cyclones, tidal water incursion,
29 and river bank erosion in low lying coastal districts in Bangladesh can lead to mass migration. In contrasts,
30 Lu et al. (2016) and Ayeb-Karlsson et al. (2016) (drawing on data from Bangladesh) assert that the impact of
31 extremes such as typhoons is much more mixed and unclear. The literature is almost unanimous in asserting
32 that such rapid onset disasters do effect migration but the nature of the impact remains uncertain and often
33 contradictory emphasising the multi-causality of migration decisions.

34
35 Displacement:Over the 21st century climate change, is projected to increase the displacement of people
36 (Cramer et al., 2014a). Displacement associated with disasters and conflicts is a global issue, with three
37 times more individuals displaced because of disasters than because of conflict (IDMC, 2017). Almost 230
38 million displacements were recorded since 2008, an average of 25.3 million a year, with 165.9 million
39 people newly displaced in the five-year period of 2008–2013 (IDMC, 2017). In 2015, weather-related
40 disasters displaced around 14.7 million people, almost twice the number of people (8.6 million) that fled
41 conflict and violence (IDMC, 2015). In 2016, there are 31.1 million new cases of internally displaced
42 individuals due to conflict, violence, and/or disasters, with 31 events accounting for 86% per cent of disaster-
43 related displacements (IDMC and NRC, 2017). New internal displacements occur more often in low and
44 lower-middle income countries (IDMC and NRC, 2017).

45
46 Global: Between 2011 to 2015, over 90% of displacement was related to climate and weather disasters. Since
47 2009, an estimated one person every second was displaced by a disaster (IDMC, 2015). Ninety-eight per cent
48 of new displacements associated with disasters in 2016 were triggered by climate or weather-related hazards
49 such as storms, floods, wildfires, and severe winter conditions; more than half were associated with
50 storms(IDMC and NRC, 2017). Storms triggered seven of the ten largest displacement events in absolute
51 terms, and nine out of ten relative to population size (IDMC and NRC, 2017).Over the period 2008-2015, an

1 average of 22.5 million people was displaced from their homes each year by disasters brought on by climate-
2 related hazard events, mostly floods and storms, that is equivalent to 62,000 people every day (IDMC, 2015).
3

4 Asia, the Pacific and Caribbean, and Africa and Middle East and North Africa (MENA): East Asia and the
5 Pacific accounted for two-thirds of the displacement associated with disasters. There were 16.4 million new
6 displacements across the region as a whole in 2016, almost double the number for 2015, and 7.4 million in
7 China alone (IDMC and NRC, 2017). New displacements in South Asia more than halved compared with
8 2015, from 7.9 million to 3.6 million. India accounted for 67% of the total, mostly from monsoon flooding in
9 Bihar that caused 1.6 million displacements (IDMC and NRC, 2017). In 2013, about 7.3 million people were
10 newly displaced by sudden-onset disasters such as typhoon Haiyan in the Philippines (IDMC and NRC,
11 2017).
12

13 Fiji and Tonga in the Pacific, and Haiti, Belize, and Cuba in the Caribbean were among the ten countries
14 with the largest per capita displacements (IDMC and NRC, 2017). Following Hurricane Matthew, more than
15 a million people (10% of total population) in Cuba were evacuated. Cyclone Winston displaced more than
16 62,000 people in Fiji and 3,000 people in Tonga (IDMC and NRC, 2017).
17

18 There were 6.9 million new internal displacements associated with conflict and violence in 37 countries in
19 2016, primarily in sub-Saharan Africa and the Middle East (IDMC and NRC, 2017). New displacements in
20 Greater Horn of Africa from January through December 2016, are due to conflict and violence 827,000, and
21 sudden-onset disasters 635,000 (IDMC and UNISDR, 2017). In Ethiopia, drought led to the displacement
22 of 9,400 to 22,000 people in Afar and from 78,000 to 294,000 in Somali between September 2016 to June
23 2017 (IDMC and UNISDR, 2017).
24

25 Using ascenario of a +2 °C warming, there is a potential for significant population displacement concentrated
26 in the tropics (Hsiang and Sobel 2016a). Tropical populations may have to travel distances greater than 1000
27 km if global mean temperature rises by 2 °C from the period of 2011-2030 to the end of the century.
28 A disproportionately rapid evacuation of the tropics could cause migrants to concentrate in tropical margins
29 and the subtropics, where population densities would increase 300% or more (Hsiang and Sobel, 2016).
30

31 **Conflict:**

32
33 The AR5 concluded the detection of a climate change effect and an assessment of the importance of its role
34 in the collapse of civilizations and large-scale climate disruptions could only be made with low confidence
35 because of the limits of understanding and data (Cramer et al. 2014, see also Box 3.2 for Middle East). The
36 situation has not changed materially with respect to evidence for direct pathways from climate change to
37 violence, especially for group-level violence and armed conflict (Gilmore, 2017). There is stronger evidence
38 for indirect effects in agricultural and other vulnerable settings and for exacerbating ongoing violence
39 (Gilmore, 2017). Literature is increasing on the link between climate change and conflicts, with inconsistent
40 results (e.g., Buhaug 2015, 2016; Hsiang et al. 2013a; Hsiang and Burke 2014a; Carleton and Hsiang; Hsiang
41 and Burke 2014b; Carleton et al. 2016; Hsiang et al. 2013b). There also are inconsistent results from studies
42 examining the relationships between climate change, migration, and conflicts (e.g. Christiansen 2016; Selby
43 2014; Theisen et al. 2013; Buhaug et al. 2014; Burrows and Kinney 2016; Waha et al. 2017; Reyer et al.
44 2017; Brzoska and Fröhlich 2016). While some studies report a consistent and robust relationship between
45 climatic variables and a range of forms of human conflict and violence (Hsiang et al. 2013a; Hsiang and
46 Burke 2014a; Carleton and Hsiang; Bohra-Mishra et al. 2014b; Hsiang and Burke 2014b; Hsiang et al. 2011,
47 2017; Burke et al. 2015b; Carleton and Hsiang 2016; Hsiang and Sobel 2016b; Carleton et al. 2016; Burke et al.
48 2015c), others found the relationships weak and inconsistent (Buhaug, 2014, 2015, 2016; Buhaug et al.,
49 2014b). Some studies warn against deterministic positivist approaches towards linking extreme weather or
50 climate change directly with human security issues in general (Raleigh et al., 2014; Selby, 2014).
51

1 Global: Studies of the relationships among water scarcity, drought and conflict at different world regions and
2 from the international to micro levels suggest the impact of drought on conflict under most circumstances is
3 limited (Buhaug, 2016; von Uexkull et al., 2016). However, for nations or groups that are particularly
4 vulnerable due to their livelihood dependence on agriculture, drought significantly increases the likelihood of
5 sustained conflict. This is particularly relevant among groups in the least developed countries (von Uexkull
6 et al., 2016), Africa (Serdeczny et al., 2016) and those in the Middle East (Waha et al., 2017). Hsiang et al.
7 (2013b) find causal evidence and convergence across studies that climate change is linked to human conflicts
8 across all major regions of the world, and across a range of spatial and temporal scales. A 1°C increase in
9 temperature or more extreme rainfall increases the frequency of intergroup conflicts by 14%. If the world
10 warms by 2 - 4°C by 2050, then rates of human conflict could increase. Some causal associations between
11 violent conflict and socio-political stability were reported from local to global scales and from hours to
12 millennium, (Hsiang and Burke, 2014). A one-standard deviation increase in temperature increased the risk
13 of interpersonal conflict by 2.4% and intergroup conflict by 11.3% (Burke et al. 2015c), Schleussner et al.
14 (2016) established the relationships between armed-conflict risks and climate-related disasters in ethnically
15 fractionalized countries, indicating there is no clear signal that environmental disasters directly trigger armed
16 conflicts. They however found that globally, between 1980-2010, there was a 9% coincidence rate regarding
17 armed-conflict outbreak and disasters such as heat waves or droughts, with 23% of conflict coinciding with
18 climatic calamities such as those occurring in ethnically highly fractionalized countries in North and Central
19 Africa and Central Asia (Schleussner et al. 2016). Assessment of the sensitivity of civil conflict to growing-
20 season drought in Asia and Africa between 1989 and 2014 suggested that for agriculturally dependent and
21 politically excluded groups in very poor countries, drought can contribute to sustaining conflict, and
22 environmental shocks and violent conflict create a cycle that can undermine the groups (von Uexkull et al.
23 2016). A decrease in GDP per capita growth rates, induced by short-run weather shocks, significantly
24 increased the probability of a coup attempt in 148 countries between 1960 and 2005 (Kim, 2016).

25

26 Asia: There is little evidence that climate variability is linked to civil violence (Wischnath and Buhaug,
27 2014a). Water conflicts between upper and lower riparian basins in South Asia contribute to inter and intra-
28 state conflicts. In South Asia, agricultural sectors are projected to be adversely affected by the climate
29 changed-related changes in productivity, leading to food shortages by 2030 (Bandara and Cai, 2014).
30 Wischnath and Buhaug (2014b) examined food production and conflict severity in India and found that a
31 food production loss was associated with more severe civil violence, suggesting that food insecurity was the
32 intermediate link between climate and conflict. Processes by which lower food production can escalate
33 existing conflicts include lower opportunity costs for rebelling, increased opportunities for recruitment, and
34 widespread social grievances.

35

36 The Mediterranean: The Mediterranean region is a hot-spot for decreases in water availability and increases
37 in dry spells between 1.5°C and 2°C (Schleussner et al., 2016d). In Syria, water and climatic conditions
38 directly contributed to the deterioration of Syrian's economic conditions, which compounded with the
39 complex religious and ethnic diversity that escalated violence and conflict in Syria today (Gleick, 2014). The
40 2007-2010 drought in Syria was 2-3 times more severe than would have been expected based on historic
41 trends, causing large crop failure and a mass migration of farmers to the city centers, and contributing to the
42 current Syrian conflict (Kelley et al. 2015; Kelly et al. 2015b). Overall, climate change was an intermediate
43 variable, not a major driver of conflict around the Euphrates and Lower Jordan basins (Feitelson and Tubi,
44 2017).

45

46 Africa: A mapping of climate security vulnerability in Africa suggest that the Horn of Africa, South Sudan,
47 Coastal Madagascar and Mozambique, northern Nigeria and southern Mali, Sierra Leone and Guinea are the
48 most vulnerable areas (Busby et al., 2014). In Kenya and Uganda, high exposure, high vulnerability, and
49 high general risk of violent conflict onset are the three main components determining the risk of conflict (Ide
50 et al. 2014). A cohesive social structure provides the means for conflict resolution, as does political and
51 economic development. While there is a robust link between changes in weather pattern and food

1 production in Sub-Saharan Africa, there is weak and often inconsistent connection between food production
2 and violent conflict (Buhaug et al. 2015). The proposed linkages are that adverse weather patterns cause
3 agricultural loss that could lead to the loss of state revenues, which in turn may lead to coup d'état and civil
4 conflict. These patterns also can lead to food price shocks and to hunger and livelihood loss, which in turn
5 lead to mal-distribution or aid corruption, leading to urban unrest. Hunger can trigger migration that can in-
6 turn lead to non-state conflict. Therefore, violent conflict in contemporary Africa is more closely associated
7 with the wider socioeconomic and political context than about drought and crop failures (Buhaug et al.,
8 2015). In colonial Nigeria, there was a robust and significant curvilinear (U-shaped) relationship between
9 rainfall deviations and conflict intensity, with a 1.5 standard deviation in rainfall associated with an increase
10 in conflict (Papaioannou, 2016). The results tended to be stronger in agro-ecological zones that were the least
11 resilient to climatic variability (such as Guinean Savannah) and where (pre-) colonial political structures
12 were less centralized. Climate shocks enhanced competition over scarce resources, which led to disputes and
13 clashes on a communal scale (Papaioannou, 2016).
14
15

16 **3.4.11 Rural areas**

17
18 Limited research on the risks of warming of +1.5 and +2°C was conducted subsequent to the AR5 for rural
19 areas, where climate is one of many drivers of adverse outcomes. Other factors include patterns of
20 demographic change, socioeconomic development, trade and tourism. Further, consequences of climate
21 change for infrastructure, tourism, migration, crop yields, and other impacts interact with underlying
22 vulnerabilities, such as for individuals and communities engaged in pastoralism, mountain farming, and
23 artisanal fisheries, to affect livelihoods and poverty (Dasgupta et al., 2014). Incomplete data and
24 understanding of these cascading interactions across sectors and regions currently limits exploration of the
25 projected risks of warming of +1.5 and +2°C for rural areas.
26
27

28 **3.4.12 Interacting and cascading risks**

29
30 The risks of climate change will not operate on individual sectors in isolation. Hazards will occur
31 simultaneously or in close sequence, affecting multiple sectors; some of the impacts can then cascade across
32 sectors and regions. Global exposure to fourteen impact indicators covering water, energy, and land sectors
33 from changes in drought intensity and water stress index, cooling demand change and heatwave exposure,
34 habitat degradation, and crop yields, will increase about 2.5-fold between +1.5°C and +3.0°C (Byers et al.).
35 The land area affected by climate risks increases as warming progresses. For individuals vulnerable to
36 poverty (income <\$10/day, currently 4.2 billion people globally), exposure is an order of magnitude greater
37 under a high level of poverty and inequality development pathway (SSP3) compared with a sustainable
38 socioeconomic development pathway (SSP1). Asian and African regions are projected to experience 75% of
39 global exposure with 85-90% of the exposed and vulnerable population, approximately half of which are in
40 South Asia. Figure 3.22 shows that moderate and high multi-sector impacts are prevalent where vulnerable
41 people live, predominantly in South Asia at 1.5°C, but spreading to sub-Saharan Africa, the Middle East and
42 East Asia at higher levels of warming. The world's poorest are projected to be disproportionately affected.
43

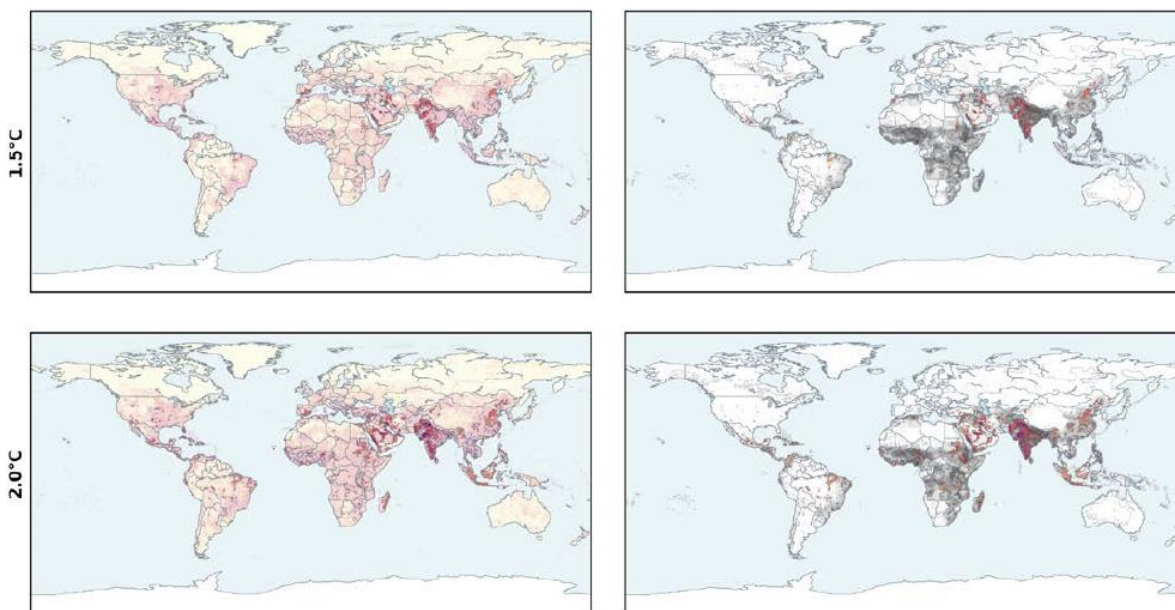


Figure 3.22: Multi-sector risk maps for 1.5 and 2°C. The left column shows the full range of the multi-sector risk score (range 0-9) with transparency and the scores ≥ 5.0 in full color. The right column greyscale overlays the 2050 vulnerable populations under SSP2 with the multi-sector risk score ≥ 5.0 in full color, indicating the concentrations of exposed and vulnerable populations.

[START BOX 3.8 HERE]

Box 3.8: Cascading and interacting impacts

In the 1990s, livelihoods in the Chiloe archipelago in southern Chile changed with the introduction of industrial scale aquaculture (Daughters, 2016). Each of the more than 400 salmon farms in the region produces concentrations of fish feces equivalent to a town of 60,000 people. That contamination, mixed with unused fishmeal and antibiotics, is flushed into the open ocean, facilitating the growth of harmful algae and toxic red tides (Cabello and Godfrey, 2016; Daughters, 2016). In January and February 2016, toxic blooms of *Pseudochattonella marina* resulted from unprecedented high sea surface temperatures associated with El Niño and climate change combined with pollution from the aquaculture farms. The toxic blooms caused the death of 23 million farmed salmon, costing nearly USD1 billion in exports; hundreds of salmon-farm employees were laid off. The dead fish were dumped into the open ocean, causing further damage to the marine ecosystem that led to further losses of livelihoods and to human health hazards (Cabello and Godfrey, 2016). In April and May, a bloom of *Alexandria catenella*, an organism producing a paralytic neurotoxin, covered the southernmost part of the Chiloe Interior Sea and the Reloncavi Gulf to the north, and extending into the open Pacific to 300 to 400 km to the north. This toxic algal bloom was accompanied by massive shellfish mortality, including millions of contaminated mollusks. As a result, the government curtailed harvesting and consumption of wild and cultured shellfish for several weeks, increasing unemployment and economic disruptions. Social and political unrest followed, resulting in authorities declaring a state of emergency in the affected areas.

[END BOX 3.8 HERE]

3.5 Avoided impacts and reduced risks at 1.5°C compared with 2°C

3.5.1 Introduction

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

The five reasons for concern, for which risks are aggregated, are:

1. Unique and threatened systems
2. Extreme weather events
3. Distribution of impacts
4. Global aggregate impacts
5. Large scale singular events

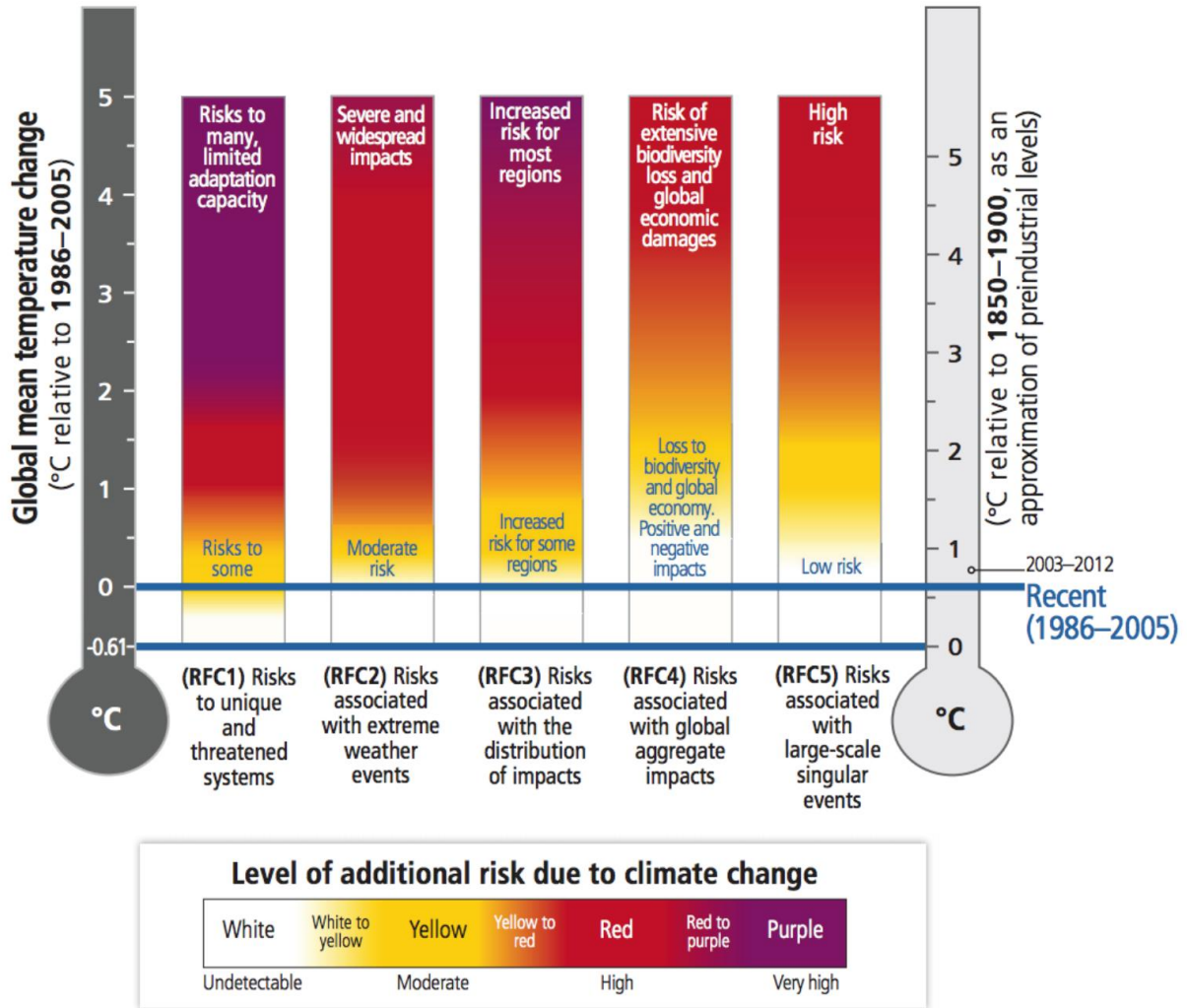
The economic benefits to be obtained by achieving the global temperature goal of 1.5°C, as compared to 2°C (or higher) are discussed (Section 3.6.3) in the light of the five reasons for concern (explored in Section 3.6.2). Regional benefits from reducing the global temperature increase to 1.5°C are discussed in Section 3.6.4, with the climate change hot spots that can be avoided or reduced by achieving the 1.5°C target summarised in Section 3.6.5. The section concludes with a discussion of regional tipping points that can be avoided at 1.5°C compared to higher degrees of global warming (Section 3.6.6).

[Placeholder: Summary table of risks based on risk tbales found in Annex 3.1]

3.5.2 Aggregated avoided impacts and reduced risks at 1.5°C versus 2°C of global warming

A brief summary of the accrual of RFC with global warming as assessed in IPCC WGII AR5 is provided in the following sections, followed by an update of pertinent literature published since AR5. The new literature is used to confirm the levels of global warming at which risks are considered to increase to *moderate*, and from *moderate to high*, and from *high to very high*. Figure 3.23 modifies figure 19.4 from AR5 WGII with the ensuing text in this subsection provides the justification for the modifications. It should be noted that in the AR5, this assessment was initially provided using a scale of global warming levels expressed relative to recent temperatures (1986-2005). However, the requirement in this report to express warming levels relative to pre-industrial leads to an artificial impression of precision in the AR5 statements: since transitions which take place at 1°C above recent temperatures, now occur at 1.5°C above pre-industrial levels.

[Placeholder: A graphical presentation of how the five reasons of concern accrue with global warming between 0°C and 2°C above pre-industrial levels is provided in Figure 3.23. Placeholder: Update to AR5 WGII Ch 19 Figure 19.4 (subject to authors feeling sufficient literature available by SOD to justify update). Note that this follows the analysis of Oppenheimer et al. (2014), but with the risk assessments based on the most recent literature.]



1
 2 **Figure 3.23:** Figure 19.4 of AR5 WGII [To be updated and developed to highlight more clearly the recent literature on
 3 the differences between risks for 1.5°C/2°C warming]. [Placeholder caption] The dependence of risk
 4 associated with the Reasons for Concern (RFCs) on the level of climate change, updated and adapted from
 5 WGII AR5 Ch 19, Figure 19.4 and highlighting the nature of this dependence between 0 and 2°C warming
 6 above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The
 7 shading of each ember provides a qualitative indication of the increase in risk with temperature for each
 8 individual ‘reason’. The transition from red to purple, introduced for the first time in AR4, is defined by
 9 very high risk and the presence of significant irreversibility or persistence of climate-related hazards
 10 combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the
 11 increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMT. As was done
 12 previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation (RFC
 13 1, 3, 5) independently of development pathway. The rate and timing of impacts were taken into account in
 14 assessing RFC 1 and 5. The levels of risk illustrated reflect the judgements of the Ch 3 authors. [Note to
 15 reviewers: In WGII AR5 Ch 19 and more recently in O’Neill et al. 2017 the need to detail how how these
 16 kinds of figures vary with socioeconomic pathway is noted and suggestions are made therein as to how
 17 this might be done. That is seen as a task for IPCC AR6, and beyond the scope of what is feasible to do
 18 for SR1.5]
 19

3.5.2.1 RFC 1- Unique and threatened systems

AR5 Ch 19 found that some unique and threatened systems are at risk from climate change at current temperatures, with increasing numbers of systems at risk of severe consequences at global warming of 1.6°C above pre-industrial levels. It was also observed that many species and systems have limited ability to adapt to the very large risks associated with warming of 2.6°C or more, particularly Arctic sea ice and coral reef systems (*high confidence*). A transition from white to yellow indicating the onset of *moderate* risk was therefore located below present day global temperatures (*medium confidence*); a transition from yellow to red was located at 1.6°C, and a transition to purple at around 2.6°C. This AR5 analysis already implies a significant reduction in risks to unique and threatened systems if warming is limited to 1.5°C as compared with 2°C.

3.5.2.1.1 Coral reefs

New literature since AR5 provides a closer focus on the comparative levels of risk at 1.5°C versus 2°C global warming. As assessed in Section 3.4.4 and Box 3.6, reaching 2°C will increase the frequency of mass coral bleaching and mortality to a point at which it will result in the total loss of coral reefs from the world's tropical and subtropical regions. Restricting overall warming to 1.5°C will still be see a downward trend in average coral cover (70-90% decline by mid-century), but will prevent the total loss of coral reefs, projected with warming of 2.0°C. The remaining reefs at 1.5°C will also benefit from increasingly stable ocean conditions by the mid-to-late 21st century. Limiting global warming to 1.5°C during the course of the century may, therefore, open the window for many ecosystems to adapt or reassort geographically past climate change. This indicates a transition in risk in this system from high to very high (red to purple) at 1.5°C warming and contributes to a lowering of the transition from red to purple in this RFC1 compared to AR5. Further details of risk transitions for ocean systems are described in Figure 3.19.

[Placeholder: *temperature level to which this transition from red to purple is to be reduced, cannot be determined until all of the literature is available related to the other unique and threatened systems.*]

3.5.2.1.2 Arctic ecosystems

Substantial losses of Arctic Ocean summer ice were projected in AR5 WGI for global warming of 1.6°C, with a nearly ice-free Arctic Ocean being projected for global warming of greater than 2.6°C. Since AR5, the importance of a threshold between 1°C and 2°C has been further emphasized in the literature, with sea ice persisting throughout the year for global warming less than 1.5°C but having a vanishingly small probability of persisting for global warming greater than 2°C (Section 3.3.9).

Reduced thawing of permafrost would be expected to occur at 2°C vs. 1.5°C, which would be expected to reduce risks to both social and ecological systems in the Arctic.

[Placeholder: *A discussion is expected to follow, pending the available literature, analysing impacts at 1.5°C vs. 2°C in the Arctic, and concluding whether this affects the position of the yellow to red or red to purple transitions in the ember.*]

3.5.2.1.3 Other unique ecosystems

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

1 would maintain the functioning of the prairie pothole ecosystem (N America) in terms of its productivity and
2 biodiversity, whilst a warming of 2°C would not do so (Carter Johnson et al., 2016)

3
4 *[Placeholder: Pending the availability of literature, this section will assess whether transitions from moderate
5 to high, and high to very high risk, needs adjusting or not since AR5: this is particularly relevant for the range
6 of interest of this report, 1.5°C - 2°C.]*

9 3.5.2.1.4 Small island states

10 Small island states may often contain unique socioecological systems (having unique cultural traditions
11 and/or unique endemic biodiversity). AR5 identified a key risk of death, injury, disruption to livelihoods,
12 food supplies and drinking water in small island developing states and also identified tropical island
13 biodiversity as vulnerable to climate change (see Box 3.7).

14
15 *[Placeholder: Pending the availability of literature, this section will assess whether transitions from moderate
16 to high, and high to very high risk, needs adjusting or not since AR5: this is particularly relevant for the range
17 of interest of this report, 1.5°C - 2°C.]*

20 3.5.2.1.5 Unique socioecological systems dependent on glacier melt

21 The AR5 Ch 19 notes how experienced and projected loss of glacier ice and changes in melt-water regimes
22 create risks for socioecological systems in the Andes and Asia, where those systems are dependent on melt-
23 water rather than precipitation. It also noted the large uncertainties in projections of ice cover and dynamics.

24
25 *[Placeholder: Pending the availability of literature, this section will assess whether transitions from moderate
26 to high, and high to very high risk, needs adjusting or not since AR5: this is particularly relevant for the range
27 of interest of this report, 1.5°C - 2°C.]*

30 3.5.2.2 RFC 2- Extreme weather events

31 In this sub-subsection reduced risks in terms of the likelihood of occurrence of extreme weather events are
32 discussed for 1.5°C as compared to 2°C of global warming – for those extreme events where current evidence
33 is available. For some extreme events of significant potential impact, such as tropical cyclones, there is either
34 limited reporting in the peer-reviewed literature on reduced risks (by achieving the 1.5°C target) in terms of
35 frequency of occurrence and intensity, or the current state of climate science cannot distinguish between
36 risks due to 0.5°C of additional global warming.

37
38 AR5 assigned a moderate (‘yellow’) level of risk due to extreme weather events at recent temperatures
39 (1986-2005) due to the attribution of heat and precipitation extremes to climate change, and a transition to
40 high (‘red’) beginning below 1.6°C global warming based on the magnitude, likelihood and timing of
41 projected changes in risk associated with extreme events, indicating more severe and widespread impacts.
42 The AR5 analysis already suggests a significant benefit of limiting warming to 1.5°C, since this might keep
43 risks closer to the ‘moderate’ level. New literature since AR5 provides greater confidence in a reduced level
44 of risks due to extreme weather events at 1.5°C versus 2°C for some types of extremes (see Section 3.3. and
45 below).

48 3.5.2.2.1 Temperature

49 It is very likely that further increases in number of warm days/nights and decrease in number of cold
50 days/nights and in overall temperature of hot and cold extremes will occur under 1.5°C of global warming
51 compared to present-day climate (1°C warming), with further increases towards 2°C of warming (section

3.3). As assessed in Sections 3.3.1 and 3.3.2, impacts of a 0.5°C global warming can be identified for temperature extremes at global scales, based on observations and the analysis of climate models. At 2°C of global warming, it is likely that temperature increases of more than 2°C will occur over most land regions in terms of extreme temperatures (on average between 3-8°C depending on region and considered extreme index) (see Figure 3.3.2, Section 3.3.2). Regional increases in temperature extremes under 1.5°C of global warming, can be reduced to 2 – 6°C (see Figure 3.3.2, Section 3.3.2). Benefits to be obtained from this general reduction in extremes depends to a large extent on whether the lower range of increases in extremes at 1.5°C is sufficient for critical thresholds to be exceeded, within the context of wide-ranging aspects such as crop yields, human health and the sustainability of ecosystems.

Section 3.4. 7 assesses the evidence for increasing human mortality from heat extremes. Heat-related morbidity and mortality are generally described using linear relationships; therefore, higher temperatures will result in greater impacts (Section 3.5.4.3). Mortality in Stockholm, Sweden in recent decades from heat extremes doubled what would have occurred at pre-industrial temperatures (Astrom et al., 2013), highlighting that even if the Paris targets are realized, there could still be a significant adaptation needed for vulnerable populations.

3.5.2.2.2 Heavy precipitation

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

3.5.2.2.3 Droughts

When considering the difference between precipitation minus evaporation as a function of global temperature changes, the subtropics generally display an overall trend towards drying, whilst the northern high latitudes display a robust response towards increased wetting (Section 3.3.4, Figure 3.12).

Limiting global mean temperature warming to 1.5°C as opposed to 2°C could substantially reduce the risk of reduced regional water availability (Section 3.3.4). Regions that are to benefit include much of South America, southern Africa, Australia and the Mediterranean.

3.5.2.2.4 Fire

The increased amount of evidence that anthropogenic climate change has already caused significant increases in fire area in N America (Section 3.4.1), is in line with projected fire risks. Fire risks, which are generally associated with extremes of high temperature and/or low precipitation, are projected to increase further at 1.5°C warming relative to the present day (Section 3.4.3, Section 3.4.10). In one study, projections on the basis of the CMIP3 ensemble of climate models (SRES A2 scenario) indicated (with a high level of agreement) that fire frequency would increase over 37.8% of global land areas during 2010-2039 (Moritz et al., 2012), corresponding to a global warming level of approximately 1.2°C; as compared with over 61.9% of the global land area in 2070-2099, corresponding to a warming of approximately 3.5°C (Figure 10.5 panel A, Meehl et al. 2007, which indicates an ensemble average projection of 0.7°C or 3°C above 1980-1999, which is itself 0.5°C above pre-industrial) (Figure 10.5 panel A, Meehl et al. 2007). Romero-Lankao et al. (2014),

1 Box 26-1) also indicated significantly lower wildfire risks in North America for near term warming (2030-
2 2040, which may be considered a proxy for 1.5°C) than at 2°C.
3

4 *[Placeholder: Once more literature available, this section will discuss whether global temperature rise at*
5 *which transition from yellow to red occurs needs to be adjusted or not relative to AR5, and discuss whether a*
6 *transition from red to purple can be introduced by exploring if sufficient literature about limits to adaptation*
7 *to extreme weather events exists, see Table 10.1 and 10.2 IPCC WGII AR5 Ch 10 for a starting point on*
8 *some aspects.]*
9

10 3.5.2.3 RFC 3- Distribution of impacts

11 Risks are unevenly distributed and are generally greater for disadvantaged people and communities in
12 countries at all levels of development. Risks are already moderate because of regionally differentiated
13 climate-change impacts on crop production in particular and because of high underlying vulnerabilities
14 (AR5, *medium to high confidence*). Based on projected decreases in regional crop yields and water
15 availability, risks of unevenly distributed impacts are high for additional warming above 2°C (AR5 *medium*
16 *confidence*). The lower regional temperatures implied by 1.5°C warming as compared with 2°C imply
17 reduced global risks in terms of impacts such as water losses through evaporation, enhanced energy demand
18 (towards achieving human comfort in air conditioned buildings) and decreases in crop yield – although
19 global reduced risks at 1.5°C still need to be better quantified.
20

21
22 Climate change is projected to reduce renewable surface water resource significantly in most dry subtropical
23 regions (robust evidence, *high agreement*), in contrast, water resources are projected to increase at high
24 latitudes (AR5-WGII Chapter 3). Reduction in the availability of water resource for less than 2°C is
25 projected to be greater than 1.5°C of global warming, although changes in socioeconomics could have a
26 greater influence (Section 3.4.2).
27

28 Globally millions of people may be at risk from sea-level rise during the 21st century (Hauer et al., 2016b;
29 Hinkel et al., 2014), particularly if adaptation is limited. By 2030, 400 million people could be living in 23
30 coastal megacities, 370 million in Asia, Africa and South America, if sea level increases by 0.3m.
31 Subsidence of coastal areas as erosion increases will enhance those exposed (Jevrejeva et al., 2016).
32 Jevrejeva et al. (2016). At 2°C of warming, more than 70% of global coastlines will experience sea-level rise
33 greater than 0.2m. With 4°C of warming, 80% coastlines could experience 0.6m of sea-level rise (by 2083
34 under RCP8.5). The highest sea-levels are projected for small island nations in low to mid latitude Pacific
35 islands and India Ocean islands. The amplification of flooding, for high and/or low frequency events
36 (Buchanan et al., 2017b) and different forcing factors, including waves (Arns et al., 2017; Storlazzi et al.,
37 2015; Vitousek et al., 2017) is also cause for concern even with sea-level rise associated with a rise in
38 temperatures of 2°C, or within the next few decades.
39

40 Given the lack of literature regarding adaptation to extreme weather events, the level of global warming at
41 which there would be a transition to very high risk (purple) could not be identified in AR5. Additional
42 information reveals how the projected distribution of impacts compares at 1.5°C versus 2°C, and further
43 discussion of the location of appropriate levels for the transitions from moderate to high and high to very
44 high risks (purple) in RFC3 is needed.
45

46 3.5.2.4 RFC 4 - Global aggregate impacts

47 Oppenheimer et al. (2014) explain the inclusion of non-economic metrics related to impacts on ecosystems
48 and species at the global level, in addition to economic metrics in global aggregate impacts. The degradation
49 of ecosystem services by climate change and ocean acidification were in general excluded from previous
50 global aggregate economic analyses
51

1 3.5.2.4.1 *Global economic impacts*

2 The WGII AR5 found that overall global aggregate impacts become moderate between 1-2°C of warming
3 and the transition to *moderate* risk levels was therefore located at 1.6 °C above pre-industrial levels. This
4 was based on the assessment of literature using model simulations which indicate that the global aggregate
5 economic impact will become significantly negative between 1-2°C of warming (*medium confidence*), whilst
6 there will be a further increase in the magnitude and likelihood of aggregate economic risks at 3°C warming
7 (*low confidence*).
8

9 Since AR5, literature has emerged indicating that economic damages in the USA are projected to be higher
10 by 2100 if warming reaches 2°C than if it is constrained to 1.5°C (mean difference 0.35%, range 0.2-0.65%).
11 Further, the avoided risks compared to a ‘no policy’ baseline are greater in the 1.5°C case (4%, range 2-7%)
12 compared to the 2°C case (3.5%, range 1.8-6.5%, Section 3.5). This analysis (based on a single region only)
13 suggests that the point at which global aggregate of economic impacts become negative could be lower than
14 in AR5 (*low confidence*), and that there is a possibility that this is below 1.5°C warming.
15

16 Oppenheimer et al. (2014) note that the global aggregated damages associated with large scale singular
17 events has not been explored, and reviews of integrated modelling exercises have indicated a potential
18 underestimation of global aggregate damages due to the lack of consideration of the potential for these
19 events in many studies. A small number of studies and reviews indicated that higher values of aggregate
20 economic damage, and/or social costs of carbon, accrue in modelling calculations that take into account the
21 potential for catastrophic climate change associated with large scale singular events (AR5, Stern 2006),
22 Since AR5, a further analysis of the potential economic consequences of triggering these large scale singular
23 events (Cai et al., 2016b), also indicates a much larger economic impact associated with a warming of 3°C
24 than most previous analyses, which is in line with earlier critiques (Dietz, 2011; Lenton and Ciscar, 2013;
25 Revesz et al., 2014). Specifically, Cai et al. (2016) modifies a well established modelling approach to
26 incorporate the prospect of future multiple interacting tipping points. Combining this with realistic
27 assumptions about policymakers’ preferences under uncertainty, increases the social cost of carbon in the
28 model from \$15/tCO₂ to \$116/tCO₂. This results in the conclusion that global warming would need to be
29 constrained to 1.5°C above pre-industrial levels, if welfare impacts are to be minimised. This increases the
30 confidence since AR5 that there is a significant further increase in the magnitude and likelihood of aggregate
31 economic risks at global warming of 3°C.
32
33

34 3.5.2.4.2 *Biome shifts, risks of species extinction and ecosystem functioning and services*

35 Using an ensemble of seven dynamic vegetation models driven by projected climates from 21 alternative
36 Global Circulation Models, Warszawski et al. (2013) show that approximately 25% more biome shifts are
37 projected to occur under 2°C warming than under 1.5°C. The proportion of biome shifts is projected to
38 approximately double for warming of 3°C.

39 Oppenheimer et al. (2014) reports on the large amount of evidence for escalating risks of species range loss,
40 extirpation and extinction based on studies for global temperatures exceeding 2°C above pre-industrial
41 levels. Fischlin et al. (2007) estimated that 20-30% of species would be at increasingly high risk of
42 extinction if global temperature rise exceeds 2-3°C above pre-industrial levels. Settele et al. (2014) (AR4 Ch
43 4) state more generally that large magnitudes of climate change will ‘reduce the populations and viability of
44 species with spatially restricted populations, such as those confined to isolated habitats and mountains. New
45 evidence attributing extirpations (local extinctions) to climate change has accrued since AR5 (Section 3.4.3,
46 Wiens 2016). Warren et al. (2013) simulated climatic range loss for 50,000 terrestrial species and projected
47 that with 4°C warming, and realistic dispersal rates, 34±7% of the animals, and 57±6% of the plants, would
48 lose 50% or more of their climatic range by the 2080s. By comparison, these projected losses are reduced by
49 60% if warming is constrained to no more than 2°C. Since the AR5, information relating to 1.5°C warming
50 has now been estimated from this earlier study, indicating that with 1.5°C warming, and realistic dispersal
51 rates, the losses are projected to be reduced by approximately 80% (79-82%) compared to those at 4°C

1 warming) and 50% (range 46-56%) (compared to those at 2°C warming). Hence at 1.5°C, 7±2% animals and
2 10±2% plants are projected to lose 50% or more of their climatic range (Smith et al.).
3

4 Oppenheimer et al. (2014) assessed risks to marine fish stocks and resultant global aggregate losses of marine
5 ecosystem services. Since AR5 new literature indicates that impacts on marine fish stocks and fisheries are
6 lower in 1.5-2.0°C global warming relative to pre-industrial level when compared to higher warming
7 scenarios (Section 3.4.6). Sensitivity to the 1.5-2°C relative to other warming scenarios differ between
8 regions, with fish stocks and fisheries being highly sensitivity in tropical and polar systems. Direct benefits
9 of achieving the 1.5°C global warming target can be substantial (Cheung et al., 2016b) from increases in
10 fisheries revenues as well as the contribution of fishery and aquaculture to protein and micronutrients needs,
11 particularly those of the most vulnerable coastal communities (tropical developing countries and SIDS)
12 (Section 3.4.6).
13

14 Hence since AR5 there is additional evidence for lower biome shifts, lower species range losses, and hence
15 lower risks of extinction and ecosystem degradation in both terrestrial and marine ecosystems, at 1.5°C than
16 at 2°C. These lower risks translate into lower risks to ecosystem function and services (see AR5 Ch 19,
17 Gaston and Fuller 2008).
18
19

20 3.5.2.5 RFC 5 - Large scale singular events

21 Large scale singular events are components of the global earth system that are thought to hold the risk of
22 reaching critical tipping points under climate change, and that can result in or be associated with major shifts
23 in the climate system include:
24

- 25 • The cryosphere: West-Antarctic ice sheet, Greenland ice sheet
- 26 • The thermohaline circulation (slowdown of the Atlantic Meridional Overturning Current).
- 27 • The El Niño Southern Oscillation (ENSO) as a global mode of climate variability
- 28 • The Southern Ocean as a carbon sink in terms of its role in the global carbon cycle.
29

30 AR5 assessed that the risks associated with these events becomes moderate between 0.6 and 1.6°C above
31 pre-industrial levels due to early warning signs and that risk becomes high between 1.6 and 4.6°C due to the
32 potential for commitment to large irreversible sea level rise from the melting of land based ice sheets
33 (*medium confidence*). The increase in risk between 1.6 and 2.6°C above pre-industrial levels was assessed to
34 be disproportionately large. New findings since AR5 are detailed below (see also Box 3.5 on tipping
35 points).
36
37

38 3.5.2.5.1 Greenland and West-Antarctic ice sheets

39 Various feedbacks between the Greenland ice sheet and the wider climate system (most notably those related
40 to the dependence of ice melt on albedo and surface elevation) make irreversible loss of the ice sheet a
41 possibility. Two definitions have been proposed for the threshold at which this loss is initiated. The first is
42 based on the global mean temperature at which net SMB first becomes negative for the current ice-sheet
43 geometry (i.e, there is more mass loss by meltwater runoff than gain by snowfall). Church et al. (2013)
44 assess this threshold to be 2°C or above (relative to pre-industrial). A second definition considers the impacts
45 of future feedbacks between lowered ice-sheet topography and SMB. Robinson et al. (2012) find a range for
46 this threshold of 0.8-3.2°C (95% confidence). The timescale for eventual loss of the ice sheet varies between
47 millennia and tens of millennia, and assumes constant surface temperature forcing during this period. Were
48 temperature to cool subsequently, the ice sheet may regrow although the amount of cooling required is likely
49 to be highly dependent on the duration and rate of the previous retreat.
50

1 The multi-centennial evolution of the Antarctic ice sheet is considered in papers by DeConto and Pollard
2 (2016) and Golledge et al. (2015). Both suggest that RCP2.6 is the only RCP scenario leading to long-term
3 contributions to GMSL of below 1.0 m. The long-term committed future of Antarctica (and GMSL
4 contribution at 2100) are complex and require further detailed process-based modelling, however a threshold
5 in this contribution may be present close to 1.5°C (Section 3.3.10).
6
7

8 *3.5.2.5.2 Thermohaline circulation*

9 Evidence that thermohaline circulation is slowing has been building over the past years, including the
10 detection of the cooling of surface waters in the north Atlantic plus substantial evidence that the Gulf Stream
11 has slowed by 30% since the late 1950s. These changes have major implications for northern Europe and
12 America from the associated reduction in the movement of heat to many higher latitude countries
13 (Cunningham et al., 2013; Kelly et al., 2016; Rahmstorf et al., 2015). Increasing average surface temperature
14 to 1.5°C will increase these risks although precise quantification of the added risk due to an additional
15 increase to 2°C is difficult to access. The surface layers of the ocean will continue to warm and acidify but
16 rates will continue to vary regionally. Ocean conditions will eventually reach stability around mid-century
17 under scenarios that represent stabilization at or below 1.5°C (Section 3.3.8).
18
19

20 *3.5.2.5.3 Role of the Southern Ocean in global carbon cycle*

21 The critical role of the Southern Ocean as a net sink of carbon may reduce under global warming, and
22 assessing this effect under 1.5°C to 2°C of global warming is a priority. Changes in ocean chemistry
23 (oxygen, ocean acidification), especially that associated with the deep sea, are linked concerns (3.3.8)
24

25 *[When more literature is available it will be compared with the AR5 assessment of each tipping point in CH*
26 *19 section 19.6.3.6 to assess whether transition points in RFC5 need to be adjusted or not.]*
27
28

29 **3.5.3 Regional economic benefit analysis for the 1.5°C vs 2°C global temperature goals**

30
31 Limited research on the risks of warming of 1.5 and 2°C has been done since AR5 for key economic sectors
32 and services. Studies that differentiate at regional scales between the impacts of 1.5°C versus 2°C of global
33 warming are also rare. It should be noted that a myriad of additional factors (in addition to the direct
34 impacts/costs of additional global warming on regional economies) may determine response measures and
35 vulnerabilities, and consequently future net economic growth. These additional factors include patterns of
36 demographic change, socioeconomic development and trade, each which have to be analysed at regional
37 scales in order to understand regional benefits and costs (e.g., Kamei et al. 2016; Jiang and Neill 2017; Krey
38 et al. 2012). This section reviews recent literature that estimates the economic benefits for constraining
39 global warming to 1.5°C as compared to 2°C. The focus here is evidence pertaining to specific regions,
40 rather on global aggregated benefits (see 3.5.2).
41

42 Globally, the projected impacts on economic growth of 1.5°C of global warming are very similar to current
43 impacts at 1°C of global warming. At 2°C of global warming, however, lower economic growth is projected
44 for many countries, with low-income countries projected to experience the greatest losses (Petris et al.,
45 2017). Advantages in some sectors are projected to be offset by the increasing mitigation costs – with food
46 production being a key factor. That is, although restraining the global temperature increase to 2°C is
47 projected to reduce crop losses under climate change, relative to higher levels of warming, the associated
48 mitigation costs may increase the risk of hunger in low-income countries. It is plausible that the even more
49 stringent mitigation measures required to restrict global warming to 1.5°C will further increase these
50 mitigation costs and impacts. International trade in food may be a key response measure for alleviating
51 hunger in developing countries under 1.5 and 2°C stabilization scenarios (Hasegawa et al., 2016).

1 Although warming is projected to be the highest in the northern hemisphere under 1.5 or 2°C of global
2 warming, regions in the Southern Hemisphere and tropics that are projected to experience the largest impacts
3 on economic growth (Gallup et al., 1999; Petris et al. 2017). Taking into account uncertainties associated
4 with climate change and econometrics, large scale differences exist between projected growth under 1.5 and
5 2°C of global warming for developing versus developed countries. Statistically significant reductions in GDP
6 per capita growth are projected across much of the African continent, southeast Asia, India, Brazil and
7 Mexico. However, no statistically significant changes in GDP are projected to occur over most of the
8 developed world (Petris et al., 2017). Countries in the western parts of tropical Africa are projected to benefit
9 most from restricting global warming to 1.5°C as opposed to 2°C, in terms of future economic growth (Petris
10 et al., 2017). A caveat of the analysis of (Petris et al., 2017) is that the effects of sea-level rise are not
11 included in the estimations of future economic growth. However, the costs of coastal flooding may produce
12 very significant economic costs annually, with damage and response measures reaching 0.3–5.0% of global
13 GDP in 2100 under low range scenarios such as RCP2.6. Risks are projected to be highest in south and
14 south-east Asia (Arnell et al., 2016; Warren b et al.). Countries with large populations exposed to sea-level
15 rise based on a 1,280 Pg C emission scenario include Egypt, China, India, Indonesia, Japan, Philippines,
16 United States and Vietnam (Clark et al., 2016). Estimates of regional costs distinguishing between impacts at
17 1.5 vs 2C of global warming are not available at the time of preparing the SOD of SR1.5.
18
19

20 **3.5.4 Benefits of achieving the 1.5°C and 2°C of global warming as opposed to lower mitigation futures**

21 **3.5.4.1 Summary of benefits of 1.5°C or 2°C of global warming compared to temperature increases** 22 **associated with the Paris Agreement Nationally Determined Contributions**

24 A number of studies quantify the risks avoided from constraining warming to various levels. For example
25 Arnell et al. (2017) concludes that 1.8°C warming avoids 32-88% of the impacts accruing by 2100
26 (depending on sector) as compared to impacts for 4°C of warming. Similarly, 2°C warming avoids 24-82%
27 of the risks accruing by 2100 (primarily costs associated with human exposure to water stress, fluvial
28 flooding, coastal flooding, and heatwaves; loss of crop suitability; and biodiversity loss). Moreover, (Warren
29 et al.) provides an update to (Arnell et al., 2017) and quantifies the impacts avoided at 1.5°C relative to the
30 same 4°C baseline, encompassing a slightly wider set of risk metrics.
31

32 Some impacted sectors/systems display a non-linear relationship between the magnitude of the risks and the
33 extent of global warming, in which impacts increase rapidly during lower levels of warming, slowing at
34 higher global warming, as most of the sector has already been impacted. The most prominent examples are
35 coral reef bleaching, which increases very rapidly between 1° and 2°C warming, at which point most of the
36 impacts that could occur are realised; water scarcity, which increases rapidly between 0° and 2°C warming,
37 and more slowly as warming continues; and cropland stability, which decreases rapidly between 1° and 3°C
38 warming, decreasing slowly thereafter. This means that the benefits of constraining warming to 1.5°C are
39 projected to be disproportionately large for coral reefs, water availability, and cropland stability (Ricke et al.
40 2015)
41

42 Projections of risks for major cereals reveal that yields of maize and wheat begin to decline with 1° to 2°C of
43 local warming in the tropics. Temperate maize and tropical rice yields are less clearly affected at these
44 temperatures, but significantly affected with warming of 3° to 5°C. However, all crops showed negative
45 yield impacts for 3°C of warming without adaptation (Porter et al., 2014) and at low latitudes under nitrogen
46 stress conditions (Rosenzweig et al., 2014).
47

48 Warming of +2°C relative to +1.5°C will lead to greater temperature-related mortality and to greater
49 occupational heat stress that is projected to reduce safe work activity and worker productivity (Section 3.4.7
50 and supplementary tables). The difference in economic loss between 1.5°C and 2°C because of the cost of
51 heat-related illness is projected to be approximately 0.3% global GDP (Takakura et al., 2017). In China, high

1 temperature subsidies for employees working on extremely hot days are projected to increase from 38.6
2 billion yuan yr⁻¹ in 1979-2005 to 250 billion yuan yr⁻¹ in the 2030s (Zhao et al., 2016).

3.5.4.2 *Interpretation of different definitions of the 1.5°C temperature increase to benefits analysis*

3
4 The current analysis in Section 3.3 to 3.5 is largely based on impacts of the transient definition of 1.5 vs 2°C
5 (that is, the global temperature reaches thresholds of 1.5°C or 2°C of warming and then continues to
6 increase), whilst the analysis of impacts for stabilisation at 1.5° and 2°C (as strictly per the Paris Agreement
7 definition) are still is being done. To what extent do impacts calculated for a 20-year period (for example)
8 around the year when a 1.5°C increase first occurs differ from impacts associated with a 1.5°C stabilisation
9 scenario? This question is important to answer from a pragmatic perspective, since most studies on climate
10 change impacts under different global temperature goals are based on the CMIP5 GCMs and CORDEX
11 RCMs make use of exactly this latter definition.
12

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

13
14
15 This sub-section provides a summary of Sections 3.3 to 3.5, in terms of climate change induced hot-spots in
16 the physical climate system, ecosystems and socio-economic human systems that can be avoided or reduced
17 by achieving the 1.5°C global temperature target as opposed to the 2°C target. Similarly, an analysis of hot-
18 spots avoided by keeping the global temperature increase to between 1.5°C - 2°C as opposed to less
19 ambitious temperature goals (e.g., 3°C and 4°C) is presented. Moreover, hot spots that may result from
20 aggregated risks across the physical, natural and human systems are also analysed in relation to different
21 global temperature goals, in addition to hot spots that relate specifically to the physical climate system,
22 ecosystems or socio-economic human systems. Findings are also summarised in Table 3.7.
23
24

3.5.5.1 *Arctic sea-ice*

25
26
27 Early studies indicated that the threshold of ice-free Arctic Ocean summers to be ~ 3° C relative to
28 preindustrial temperatures (Mahlstein and Knutti, 2012), with subsequent work estimating the threshold to be
29 ~2.6 to 3.1°C(Collins et al., 2013). More recent work has indicated that these estimates, if anything, have
30 been too conservative, and that ice-free Arctic Ocean summers are likely in the case of failure of the Paris
31 Agreement (Niederrenk and Notz; Notz and Stroeve, 2016a; Rosenblum and Eisenman, 2016; Screen and
32 Williamson, 2017). Some studies are even indicative of the entire Arctic Ocean summer period becoming
33 ice-free under 2° C of global warming (Jahn). Ridley and Blockley, however, estimate this probability to be
34 just less than 50%, whilst Sanderson et al. (2017) estimates this probability to be about 50%.
35

36
37 The probability for an ice-free Arctic in September at 1.5°C of global warming is low (Niederrenk and
38 Notz; Screen and Williamson, 2017)(Jahn; Ridley and Blockley). There is, however, a single study that
39 questions the validity of the 1.5°C threshold in terms of maintaining summer Arctic Ocean sea-ice. Using a
40 combination of model for internal variability and observed sea-ice sensitivity, Niederrenk and Notz
41 concludes that the Arctic most likely becomes ice free at a warming of 1.7±0.2°C global warming above pre-
42 industrial levels. This implies that even at 1.5°C global warming, there is a several percent chance that Arctic
43 summer sea ice will be lost in some years (that is, some but not all years may be ice-free). Finally, during
44 winter, only little ice is projected to be lost for either 1.5°C or 2.0°C global warming (Niederrenk and
45 Notz).
46

47 It may be noted that the retreat of Arctic sea ice results in advantages for shipping and trade. The cruise
48 industry in Arctic Canada has grown 115% between 2005 and 2015, largely because of increasing
49 access(Dawson et al., 2014). While the current trade and marine regulations have been able to manage the
50 increased flow, it is expected that the need to manage the sector in the future will be more complex which
51 call for complex multi-jurisdictional regulatory frameworks to avoid human, environmental and security

1 issues in the near-and medium-term future (Dawson et al., 2014). The relative economic opportunities and
2 security risks at 1.5 versus 2°C of global warming remain to be further explored.
3
4

5 3.5.5.2 *Arctic land regions*

6 Snow-albedo-temperature feedbacks result in the Arctic regions having significant temperature sensitivity
7 (i.e. Amplification of Arctic warming) relative to a given a certain degree of global warming (Hall and Qu,
8 2006; Seneviratne et al., 2016; Serreze and Barry, 2011). In some regions and for some model simulations,
9 the warming of TNn (annual minimum temperature) at 1.5°C global warming can reach up to 8°C regionally
10 (e.g., Northern Europe, Figure 3.3) and thus may be much larger than increases in average global surface
11 temperatures. Moreover, over much of the Arctic, a further increase of 0.5°C in the global surface
12 temperature, from 1.5 to 2°C relative to the preindustrial period, leading to increased regional temperatures
13 of 2 -2.5°C (Figure 3.3). Projected biome shifts are already extremely pronounced in the Arctic and in alpine
14 regions (3.5.5.3) at 1.5°C warming and will increase for 2°C of global warming (Gerten et al., 2013).
15

16 3.5.5.3 *Alpine regions*

17 Alpine regions are generally regarded as climate change hot spots given their generally cold and harsh
18 climates in which a rich biodiversity has evolved, but which are vulnerable to increases in temperature.
19 Under regional warming, alpine species have been found to migrate upwards against mountain slopes
20 (Reasoner and Tinner, 2008), an adaptation response with obvious limited by mountain height and
21 habitability. Moreover, many of the world's Alpine regions are important from a water security perspective
22 through associated glacier melt, snow melt and river flow (see Section 3.3.10 for a discussion of these
23 aspects). The area percentage of actual grassland net primary productivity (NPP) change on Tibet Plateau
24 caused by climate change strongly declined from 79.6% in the 1982-2001 period to 56.6% over the last 10
25 years (temperature increase of 0.6°C) (Chen et al., 2014a). Projected biome shifts are already extremely
26 severe in alpine regions at 1.5°C warming and increase further for 2°C warming (Gerten et al. 2013 Figure
27 1b).
28
29

30 3.5.5.4 *Southeast Asia*

31 Southeast Asia is a region highly vulnerable to increased flooding in the context of sea-level rise (Arnell et al.,
32 2016; Warren c et al.). Countries in this region with large populations exposed to sea-level rise include
33 Indonesia, the Philippines and Vietnam (Clark et al., 2016), with large slum and urban populations in these
34 countries being particularly vulnerable (Cazenave and Cozannet, 2014; Hallegatte et al., 2013; Hanson et al.,
35 2011; Schleussner et al., 2016c). Risks from increased flooding rise from 1.5°C to 2°C of warming, with
36 substantial increases beyond 2°C (Arnell et al., 2016). Southeast Asia display statistically significant
37 differences in projected changes in heavy precipitation at 1.5°C vs 2°C warming (with stronger increase at
38 2°C; Wartenburger et al. 2017; Seneviratne et al.; Section 3.3.3), and thus is thought to be a hot spot in terms
39 of increases in heavy precipitation between these two global temperature levels (Schleussner et al., 2016d;
40 Seneviratne et al., 2016). Moreover, under high-concentration scenarios, a large increase in flood frequency is
41 expected in Southeast Asia (Hirabayashi et al., 2013). For South East Asia a 2°C warming by 2040 indicated
42 a one third decline in per capita crop production (Nelson et al., 2010) associated with general decreases in crop
43 yields. However, under 1.5°C of warming significant risks for crop yield reduction in the region are avoided
44 (Schleussner et al., 2016c). In South East Asia by 2050, wet bulb globe temperatures as high as 34-35°C are
45 projected, with associated loss of productivity (Kjellstrom et al. 2013; Schleussner et al. 2016b).
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3.5.5.5 *Southern Europe/Mediterranean*

Stronger warming of the regional land-based hot extremes compared to the mean global temperature warming is projected to occur in the Mediterranean (e.g., Seneviratne et al. 2016). Moreover, the Mediterranean is projected to experience substantial decreases in mean precipitation with associated substantial increases in dry spells (from 7% to 11%) when comparing regional impacts at 1.5°C versus 2°C of global warming (Schleussner et al., 2016c)

Recent studies show that at 1.5°C low river flows are projected to decrease in the Mediterranean (Marx et al., 2017) with associated significant decreases in high flows and floods (Thober et al.), largely in response to reduced precipitation. However, there is a known contradiction showing that with a decrease in mean precipitation extreme precipitation is increasing (eg. (Jacob et al. 2014; Jacob et al.), which leads to an increase in floods in some regions of the Mediterranean (Roudier et al., 2016). In association with the region being a hot spot of temperature increases from 1.5°C of global warming to 2°C of global warming, riverflows and runoff display similar sensitivities. The median reduction in annual runoff almost double from about 9% (likely range: 4.5–15.5%) at 1.5°C to 17% (likely range: 8–25%) at 2°C (Schleussner et al., 2016c). Similar results are found by Doell et al. with decreases of 10–30% in the mean annual streamflow that become significant with a global warming increase from 1.5°C to 2°C. Sea-level rise is expected to be lower for 1.5 versus 2°C lowering risks for coastal metropolitan agglomerations. The risks (with current adaptation) related to water deficit in the Mediterranean are high for a global warming of 2°C, but can be substantially reduced if global warming is limited to 1.5°C (Donnelly et al., 2017b; Guiot and Cramer, 2016) Schleussner et al., 2016c, see also Section 3.3.4). Risks are very high for a global warming of +4°C (AR5 WGII Table 23.5).

3.5.5.6 *West Africa and the Sahel*

West Africa and the Sahel are projected to experience increases in hot nights and longer and more frequent heat waves, even if the global temperature increase is constrained to 1.5°C, with further increase at 2°C of global warming and beyond (Weber et al.). Moreover, the daily rainfall intensity is expected to increase towards higher global warming scenarios (Weber et al.). Projected runoff changes show increases in much of the Sahel for 2°C of global warming relative to 1.5°C of warming (Schleussner et al., 2016c). It may be noted that under low mitigation towards the end of the century, plausible projections show an increased risk of floods associated with very wet events in West Africa and the Sahel (Sylla et al., 2015). Moreover, increased risks are projected in terms of drought, particularly for the premonsoon season (Sylla et al., 2015). Based on World Bank (2013) study for Sub-Saharan Africa, a 1.5°C warming by 2030 may reduce the present maize cropping areas by 40% making them no longer suitable for current cultivars, with significant negative impacts projections also on sorghum suitability in the western Sahel and southern Africa. Increase in warming (2°C) by 2040 would result in further yields losses and damages to the main African crops (i.e. maize, sorghum, wheat, millet, groundnut, cassava).

3.5.5.7 *Southern Africa savannahs*

Temperatures have been rising in subtropical regions of southern Africa at approximately twice the global rate over the last five decades (Engelbrecht et al., 2015). Elevated warming of the regional land-based hot extremes has occurred as a result (Section 3.3; Engelbrecht et al. 2015; Seneviratne et al. 2016). Increases in hot nights as well as longer and more frequent heat waves even if the global temperature increase is constrained to 1.5°C, with further increase at 2°C of global warming and beyond (Weber et al.).

Moreover, the region is likely to become generally drier with reduced water availability under low mitigation (Engelbrecht et al., 2015; James et al., 2017; Karl et al., 2015; Niang et al., 2014), with this particular risk also prominent under 2°C of global warming. Risks are significantly reduced, however, under 1.5°C of global warming (Schleussner et al. 2016c). There are consistent and statistically significant projected

1 increases in risks of increased meteorological drought (based under the number of consecutive dry days) at
2 2°C vs 1.5°C in southern Africa. Despite the general reductions projected for southern Africa, daily rainfall
3 intensities are expected to increase over much of the region, increasingly with further amounts of global
4 warming.

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6 The accumulated cyclonic energy is projected to decrease over the southern Indian Ocean (Wehner et al.,
7 2017) with associated projected decreases in landfalling tropical cyclones over southern Africa (Mavhungu
8 et al.). The decreases in cyclone frequencies under 2°C of global warming are larger than under 1.5°C of
9 global warming. There are no further decreases projected under 3°C of global warming and higher. This
10 suggests that 2°C of warming, at least in terms of the downscaling here, represent a type of stabilization
11 (Mavhungu et al.). This may imply an advantage for Mozambique posed by 2C of warming over 1C of
12 warming, although it should be noted that the general reduction in landfalling tropical cyclones over the
13 region are also occurring in association with general rainfall reductions and an increasing likelihood for
14 drought (Malherbe et al., 2013).

15 16 17 3.5.5.8 *Tropics*

18 The tropics is a hot-spot in terms of the projected increases in the number of hot days, since the largest
19 increases in the number of hot days are projected to occur in the tropics (Figure 3.10). Moreover, the
20 largest differences in the number of hot days to occur under 1.5°C of global warming versus 2°C of global
21 warming are found in the tropics (Mahlstein et al., 2011). In tropical Africa, increases in the number of hot
22 nights, as well longer and more frequent heat waves, are projected under 1.5°C of global warming, with
23 further increases under 2°C of global warming (Weber et al.). Generally, statistically insignificant changes
24 are projected for tropical land areas between 1.5°C and 2°C of global warming (Figure 3.6), but there is
25 some evidence of increases in extreme precipitation events with an additional 0.5°C of warming (e.g.,
26 (Weber et al.). Impact studies for major tropical cereals reveal that yields of maize and wheat begin to
27 decline with 1°C to 2°C of local warming in the tropics. Schlessner et al. (2016) project that constraining
28 warming to 1.5°C rather than 2°C would avoid significant risks of tropical crop yield declines in West Africa,
29 South East Asia, and Central and South America. Challinor et al. (2014) also found a high level of
30 vulnerability of wheat and maize production to climate change in tropical regions

31 32 33 3.5.5.9 *Islands*

34 Small islands, and in particular SIDS, are well recognized to be very sensitive from climate change and other
35 stressors (Nurse et al., 2014; Ourbak and Magnan, 2017), such as sea-level rise, oceanic warming,
36 precipitation, cyclones and coral bleaching. Even at 1.5°C of global warming, the compounding impacts of
37 changes in rainfall, temperature, tropical cyclones and sea levels are evident across multiple natural and
38 human systems. This will likely to contribute to loss of or change in critical ecosystems, freshwater resources
39 and associated livelihoods, economic stability, coastal settlements and infrastructure. There are potential
40 benefits to SIDS from avoided risks at 1.5°C versus 2.0°C, especially when coupled with adaptation efforts.

41
42 In terms of sea-level rise, by 2150 roughly 40 000 less people living in SIDS will be inundated in a 1.5C
43 world in comparison to a 2°C world (Rassmussen). On many small developing islands, there is already stress
44 on freshwater resources from projected changes in aridity. Constraining global warming to 1.5°C global
45 warming would significantly reduce water stress (~25%) as compared to the projected water stress at 2.0°C
46 (e.g., Caribbean region, Karnauskas et al.). Even with small changes in temperature (differentiating 1.5°C
47 and 2.0°C) could make significant differences in terms of the impacts (Benjamin and Thomas, 2016) the
48 ability of SIDS to adapt. Up to 50% of the year is projected to be very warm in the Caribbean using the
49 warm spell duration index (WSDI) for 1.5 C, with a further increase by up to 70 days for 2°C versus
50 1.5°C (Taylor et al.). By limiting warming to 1.5°C instead of 2°C in 2050, risks of coastal flooding
51 (measured as the flood amplification factors (AFs) for 100-yr flood events) are reduced between 20 and 80%

1 for SIDS (Rasmussen et al.). Agriculture is a key sector for many small islands, and is imperative to
2 achieving local food security. A case study of Jamaica with lessons for other Caribbean SIDS demonstrates
3 that the difference in heat stress for livestock between 1.5 and 2.0°C is likely to challenge livestock
4 thermoregulation resulting in persistent heat stress for animals (Lallo et al.).
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7 *3.5.5.10 Fynbos and shrubbiomes*

8 The Fynbos and succulent Karoo biomes of South Africa are threatened systems that have been assessed in
9 AR5. Similar shrublands exist in the southwestern semi-arid regions of other continents, the Sonora-Mojave
10 Creosotebush-White Bursage Desert Scrub ecosystem in the USA being a prime example. Impacts accrue
11 across these systems with greater warming, with impacts at 2°C likely to be greater than those at 1.5°C
12 (*medium confidence*). Under 2°C of global warming, regional warming in drylands will be 3.2-4°C and
13 under 1.5°C of global warming, mean warming in drylands will still be ~3°C. The Fynbos biome in
14 southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and
15 drier winters. The Fynbos biome is projected to lose ~20%, ~45% and ~80% of its current suitable climate
16 area under 1°C, 2°C and 3°C of warming with respect to present-day climate (Engelbrecht and Engelbrecht,
17 2016), demonstrating the value of climate change mitigation in protecting this rich centre of biodiversity.
18 The Sonora-Mojave Creosotebush-White Bursage Desert Scrub ecosystem is projected to lose 31% of its
19 suitable climate area by 2070 under RCP8.5.
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22 *3.5.5.11 Transboundary Kailash Sacred Landscape*

23 Large and substantial shifts in bioclimatic conditions can be expected throughout the area of the
24 transboundary Kailash Sacred Landscape (KSL) of China, India and Nepal by the year 2050 under CIMP5
25 Scenarios, within all bioclimatic zones and ecoregions. Over 76% of the total area may shift to a different
26 stratum, 55% to a different bioclimatic zone, and 36.6% to a different ecoregion. Potential impacts include
27 an upward shift in mean elevation of bioclimatic zones (357 m) and ecoregions (371 m), decreases in area of
28 the highest elevation zones and ecoregions, large expansion of the lower tropical and sub-tropical zones and
29 ecoregions, and the disappearance of several strata representing unique bioclimatic conditions within the
30 KSL, with potentially high levels of biotic perturbation by 2050 (Zomer et al., 2014). The extent to which
31 impacts on this region can be reduced at 1.5°C vs. 2°C of global warming remains to be analysed.
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34 *3.5.5.12 Urban areas*

35 Cities are likely to experience greater heat stress than the regional warming under 1.5 and 2°C scenarios
36 because of urban heat island effects. Projection of near surface temperature in Israeli cities due to
37 urbanization are expected to exceed 3°C in several urban jurisdictions (Kaplan et al., 2017). Land-use
38 changes due to urbanization in eastern China are altering the regional land-sea temperature difference and
39 may be a contributing factor to changes in the East Asian Subtropical Monsoon (Yu et al., 2016). Incremental
40 warming of 0.5°C above 1.5°C are expected to increase extreme risks of heat waves in China's five major
41 urban agglomerations—Bohai Ring, Yangtze River Delta, Pearl River Delta, Mid-reach of the Yangtze
42 River, and the Cheng-Yu—under RCP2.6, RCP4.5, RCP8.5 scenarios (Yu and Zhai). Urban morphology,
43 water, and vegetation are factors affecting the differential warming between urban and rural areas in the
44 United States and suggest managing albedo as a mechanism to adapt (Li et al., 2016a; Zhao et al.,
45 2014). Mortality in Stockholm, Sweden, in recent decades from heat extremes doubled what would have
46 occurred without climate change, adjusting for urbanization and the urban heat island effect (Astrom et al.,
47 2013).
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1 **Table 3.7:** Emergence and intensity of climate change hot-spots under different degrees of global warming
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Region and/or Phenomena	Warming of 1.5°C or less	Warming of 1.5°C-2°C	Warming of 2°C - 3°C	Warming of more than 3°C
Arctic sea-ice	Arctic summer sea-ice is likely to be maintained.	The risk of an ice free Arctic in summer is ~ 50% or higher.	Arctic is highly likely to be ice-free in summer.	Arctic is highly likely to be ice-free in summer
Arctic land regions	Regional warming up to 8°C is plausible	Regional warming 2-2.5°C higher than under 1.5°C of global warming		
Alpine regions	Severe shifts on biomes Reduced grassland net primary productivity	Even more severe shifts Increased risks for reduced grassland net primary productivity		
Southeast Asia	Risks for increased flooding related to sea-level rise Increases in heavy precipitation events Significant risks of crop yield reductions are avoided Decreases in labour productivity due to increases in oppressive temperatures Loss of 70-90% of coral reefs	Higher risks for increased flooding related to sea-level rise Stronger increases in heavy precipitation events One third decline in per capita crop production Larger decreases in labour productivity due to increases in oppressive temperatures Loss of most coral reefs – remaining structures weaker due to ocean acidification	Substantial increases in risks related to flooding from sea-level rise Loss of coastal protection as reef structures eroded by intensifying storms	Substantial increases in risks related to flooding from sea-level rise Risks for large-scale flooding
Small Islands	Land of 40 000 less people inundated by 2150 on SIDS Risks for coastal flooding reduced by 20-80% for SIDS Fresh water stress reduced by 25%	Tens of thousands displaced due to inundation of SIDS High risks for coastal flooding Fresh water stress from projected aridity		

Region and/or Phenomena	Warming of 1.5°C or less	Warming of 1.5°C-2°C	Warming of 2°C - 3°C	Warming of more than 3°C
	<p>Increase in the number of warm days for SIDS in the tropics</p> <p>Persistent heat stress in cattle avoided</p> <p>Loss of 70-90% of coral reefs</p>	<p>Further increase of ~ 70 warm days per year</p> <p>Persistent heat stress in cattle in SIDS</p> <p>Loss of most coral reefs – remaining structures weaker due to ocean acidification</p>		
Mediterranean	<p>7% increase in dry-spells</p> <p>Reduction in runoff about 9% (likely range: 4.5–15.5%)</p> <p>Risk of water deficit</p>	<p>11% increase in dry spells</p> <p>Reduction in runoff doubles to 17% (8–28%)</p> <p>High risk for water deficit</p>	Very high risks for water deficit	Very high risks for water deficit
West African and the Sahel	<p>Significant impacts in terms of avoided impacts on agriculture.</p> <p>High risks for under-nutrition</p>	<p>Significant negative impacts on sorghum production.</p> <p>Higher risks for undernutrition; Reduced malaria burden in a western sub-region and insignificant impact in an eastern sub-region</p>		
Southern African savannahs and drought	<p>Likely reductions in water availability; high risks for increased mortality from heat-waves; high risk for undernutrition; increase in the regional extent and length of malaria transmission season</p>	<p>Even larger reductions in water availability likely; higher risks for increased mortality from heat-waves; higher risks for undernutrition; increase in the regional extent and length of transmission season</p>	Reduced regional extent and length of malaria transmission season (too hot)	Reduced regional extent and length of malaria transmission season (too hot)
Tropics	Accumulated heat-wave duration up to two months;	Accumulated heat-wave duration up to three months;		

Region and/or Phenomena	Warming of 1.5°C or less	Warming of 1.5°C-2°C	Warming of 2°C - 3°C	Warming of more than 3°C
	3% reduction in maize crop yield.	7% reduction in maize crop yield.		
Fynbos biome	~ 20% of suitable climate area lost	~20-40% of suitable climate area lost	More than 40% of suitable climate area lost	As much as 80% of suitable climate area lost
Transboundary Kailash Sacred Landscape	To be investigated	To be investigated	To be investigated	To be investigated

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3.5.6 Avoiding regional tipping points by achieving more ambitious global temperature goals

Tipping points refer to critical thresholds in a system, that when exceeded may lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as ecosystems and human systems, is essential for understanding the risks and opportunities from mitigation. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C vs. 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems is also analysed. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming – note that tipping points in the global climate system, referred to as large scale singular events, have already been discussed in Section 3.6.2. A summary of regional tipping points is provided in Table 3.8.

3.5.6.1 Arctic sea-ice

Collins et al. (2013) discuss the loss of Arctic sea ice in the context of potential tipping points. Observed rapid declines in sea ice extent are not necessarily indicative of the existence of a tipping point, and could well be a consequence of large inter-annual natural climate variability combining with anthropogenically-forced change (Holland et al., 2006). Climate models have been used to assess whether a bifurcation exists that would lead to the irreversible loss of Arctic sea ice (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) and to test whether Summer sea ice extent can recover after it has been lost (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011). These studies do not find evidence of bifurcation and find that sea ice returns within a few years of its loss, leading Collins et al. (2013) to conclude that there is little evidence for a tipping point in the transition from perennial to seasonal ice cover. The transition from seasonal to year-round ice-free conditions in the Arctic is, however assessed as *likely* to be rapid on the basis of several modelling studies. Numerous studies place the threshold for a seasonally ice-free Arctic between 1.5 and 2°C global warming, both within this century and for long-term equilibrium climate conditions. Year-round sea ice is much more likely to be maintained in a 1.5°C world than a 2°C one (Jahn; Niederrenk and Notz; Ridley and Blockley; Screen and Williamson, 2017). Studies do not find evidence of irreversibility or tipping points, and suggest that year-round sea ice could return with years given a suitable climate (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011).

3.5.6.2 Tundra

Tree-growth in tundra-dominated landscapes is strongly constrained the number of days above 0°C. A potential tipping points exists, where the number of days below 0°C decrease to the extent that tree fraction increases significantly. Tundra-dominated landscapes have warmed more than the global average over the last century (Settele et al., 2014), with associated increases in fires and permafrost degradation (Bring et al.,

1 2016; DeBeer et al., 2016b; Jiang et al., 2016; Yang et al., 2016). Both of these processes facilitate
2 conditions for woody species establishment in tundra areas. Moreover, Cooper (2014) have demonstrated
3 that delays in winter onset and mild winters are key in Arctic terrestrial ecosystem disruption. The number
4 of investigations into how the tree-fraction may respond in the Arctic to different degrees of global warming
5 is limited although those available indicate that abrupt increases may only occur at levels of warming greater
6 than 2°C (Drijfhout et al., 2015; Lenton et al., 2008).

9 3.5.6.3 *Permafrost*

10 It is *virtually certain* that projected warming in the high latitudes of the northern hemisphere, combined with
11 changes in snow cover, will lead to shrinking near-surface permafrost (Collins et al., 2013). The areal extent
12 of permafrost is projected to decline by 21-37% (1 σ uncertainty) and 35-47% relative to 1960-1990 levels,
13 under 1.5°C and 2°C of global warming, respectively (Chadburn et al., 2017). This implies that a 1.5°C world
14 would have roughly 4×10^6 km² of permafrost more than a 2°C world. Widespread thawing of permafrost
15 potentially makes a large carbon store (estimated to be twice the size of the atmospheric store, Dolman et al.
16 2010) vulnerable to decomposition, which would lead to further increases in atmospheric carbon dioxide and
17 methane and hence further global warming. This feedback loop between warming and the release of
18 greenhouse gas from thawing tundra represents a potential tipping point. However, the carbon released from
19 thawing permafrost is projected to be restricted to 0.12-0.25 Gt C a⁻¹ to the atmosphere in a 2°C world, and
20 to 0.08-0.16 Gt C a⁻¹ for 1.5°C (Burke et al., 2006). The disparity between the multi-millennial timescales of
21 soil carbon accumulation and potentially rapid decomposition in a warming climate implies that the loss of
22 this carbon to the atmosphere is essentially irreversible (Collins et al., 2013). Additional impacts of thawing
23 tundra include major changes in ecosystems, and regional disruption of human communities and
24 infrastructure (e.g., roads, housing, and transport).

27 3.5.6.4 *Asian Monsoon*

28 It is the pressure gradient between the Indian Ocean and Asian continent that at a fundamental level
29 determines the strength of the Asian monsoon. As land masses warm faster than the oceans, a general
30 strengthening of this gradient, and hence monsoons, may be expected (Lenton et al., 2008). Additional
31 factors such as changes in albedo induced by aerosols and snow-cover change may also affect temperature
32 gradients and consequently pressure gradients and the strength of the monsoon. In fact, it has been estimated
33 that an increase of the landmass albedo to 0.5 would represent a tipping point resulting in the collapse of the
34 monsoon system (Lenton et al., 2008). The overall impacts of the various types of radiative forcing under
35 different emission scenarios are more subtle, with a weakening of the monsoon north of about 25°N in East
36 Asia and a strengthening south of this latitude projected by (Jiang and Tian, 2013) under high and modest
37 emission scenarios. Generally, at the time of composing the SOD there is still *low confidence* in overall
38 projected changes in monsoons because of insufficient agreement between climate models (Seneviratne et
39 al., 2012). Given that scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than
40 those assessed in the studies of Jiang and Tian (2013) there is *low confidence* regarding changes in monsoons
41 at these low global warming levels, as well as regarding the differences between responses at 1.5°C vs. 2°C
42 levels of global warming.

45 3.5.6.5 *West African Monsoon and the Sahel*

46 Earlier work has identified 3°C of global warming as a tipping point leading to a significant strengthening of
47 the West African Monsoon and subsequent wetting (and greening) of the Sahel and Saharah (Lenton et al.,
48 2008). AR5 (Niang et al., 2014) as well as more recent research through the COordinated Downscaling
49 EXperiment for Africa (CORDEX-AFRICA) provide a more uncertain view, however, in terms of the
50 rainfall futures of the Sahel under low mitigation futures. Sylla et al. (2015) project changes in mean
51 precipitation that exhibit a delay of the monsoon season and a decrease in frequency but increase in intensity

1 of very wet events, particularly in the premonsoon and early mature monsoon stages. The premonsoon
2 season is projected to experience the largest changes in daily precipitation statistics, particularly toward an
3 increased risk of drought associated with a decrease in mean precipitation and frequency of wet days and an
4 increased risk of flood associated with very wet events. Even if a wetter Sahel should materialize under 3°C
5 of global warming, it should be noted that there will be significant offsets in the form of strong regional
6 warming and related adverse impacts on crop yield, livestock mortality and human health under such low
7 mitigation futures(Engelbrecht et al., 2015; Sylla et al., 2016; Weber et al.)
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10 3.5.6.6 *Rain forests*

11 Global warming of 3-4°C may represent a tipping point that results in a significant dieback of the Amazon
12 forest, with a key forcing mechanism being stronger El Niño events bringing more frequent droughts to the
13 region (Nobre et al., 2016). Deforestation as well as increased impact of forest fires may independently
14 trigger to a critical threshold in forest cover leading to pronounced dieback, with the deforestation threshold
15 estimated to be 40% (Nobre et al. 2016.) Global warming of 3°C is projected to reduce the extent of tropical
16 rainforest in Central America, with biomass productivity being reduced by more than 50%, and a large
17 replacement of rainforest by savanna and grassland (Lyra et al., 2017).
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20 3.5.6.7 *Boreal forests*

21 Boreal forests are likely to experience higher local warming than the global average (AR5: Collins et al.
22 2013). Northward expansion of the treeline and enhanced carbon storage features in dynamic vegetation
23 models and coupled climate models (Ciais et al., 2013a; Jones et al., 2010). Increased disturbance from fire,
24 pests and heat related mortality may affect the southern boundary of boreal forests(Gauthier et al. 2015).
25 Thawing permafrost will affect local hydrology on small heterogeneous scales, which may increase or
26 decrease soil moisture and waterlogging. Thawing of organic matter may liberate nutrients, which in turn
27 may stimulate enhanced vegetation productivity and carbon storage. A tipping point for significant dieback
28 of the boreal forests is thought to exist at about 3C of global warming (Lucht et al., 2006), but given the
29 complexities of the various forcing mechanisms and feedback processes this is thought to be a highly
30 uncertain estimate.
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33 3.5.6.8 *Heat-waves, unprecedented heat and human health*

34 Increases in ambient temperature are linearly related with hospitalizations and deaths (so there isn't a tipping
35 point per se) once specific thresholds are exceeded. It is plausible that coping strategies will not be in place
36 for many regions, with potentially significant impacts on communities with low adaptive capacity, effectively
37 representing the occurrence of a local/regional tipping point. In fact, if climate change is held below 2°C,
38 taking into consideration urban heat island effects, there could be a substantial increase in the occurrence of
39 deadly heatwaves in cities, with the impacts similar at 1.5°C and 2°C, but substantially larger than under the
40 present climate (Matthews et al., 2017) At +1.5°C, twice as many megacities as present (such as Lagos,
41 Nigeria, and Shanghai, China) are likely to become heat stressed, potentially exposing more than 350 million
42 more people to deadly heat stress by 2050. At +2°C warming, Karachi (Pakistan) and Kolkata (India) could
43 expect annual conditions equivalent to their deadly 2015 heatwaves. These statistics imply a tipping point in
44 the extent and scale of heat-wave impacts. However, these projections do not integrate adaptation to projected
45 warming, for instance, cooling that could be achieved with more reflective roofs and urban surfaces overall
46 (Akbari et al., 2009; Oleson et al., 2010).

3.5.6.9 Agricultural systems: key staple crops

A large number of studies consistently indicate that maize crop yield will be negatively affected under increased global warming, with negative impacts being higher under 2°C of warming than at 1.5°C of warming (e.g., Niang et al. 2014; Schleussner et al. 2016a; Lizumi et al. 2017; Huang et al. 2017). Under 2°C of global warming, losses of 8-14% are projected in global maize production (Bassu et al., 2014). Under more than 2°C of global warming, regional losses are projected to be ~20% if they co-occur with reductions in rainfall (Lana et al., 2017). A World Bank (2013) study for Sub-Saharan Africa indicate that 1.5°C of global warming by 2030 will reduce the present maize cropping areas by 40% making them no longer suitable for current cultivars, with significant negative impacts on suitability for the western Sahel and southern Africa. Increase in warming (2°C) by 2040 would result in further yields loss and damage to maize crops. These changes may be classified as incremental rather than representing a tipping point. Large-scale reductions in maize crop yield including the potential for the collapse of this crop in some regions may exist under 3°C or more of global warming (e.g., Thornton et al. 2011).

3.5.6.10 Agricultural systems: livestock in the tropics and subtropics

The potential impacts of climate change on livestock (Section 3.4.6) and in particular direct impacts through increased heat-stress has been less well studied than impacts on crop yield. A case study of Jamaica reveals that the difference in heat stress for livestock between 1.5°C and 2.0°C is likely exceed the limits for normal thermoregulation and result in persistent heat stress for animals (Lallo et al.). It is plausible that this finding holds for livestock production in both tropical and subtropical regions more generally (see Section 3.4.6).

Table 3.8: Summary of enhanced risks in the exceedance of regional tipping points under different global temperature goals.

tipping point	Warming of 1.5°C or less	Warming of 1.5°C- 2°C	Warming of 2° - 3°C	Warming of more than 3°C
Arctic becomes nearly sea-ice free in September	Arctic summer sea-ice is likely to be maintained. Sea-ice changes reversible under suitable climate restoration	The risk of an ice free Arctic in summer is ~ 50% or higher. Sea-ice changes reversible under suitable climate restoration	Arctic is highly likely to be ice-free in summer.	Arctic is highly likely to be ice-free in summer
Tundra	Decrease in number of growing degree days below 0°C Abrupt increases in tree-cover are unlikely	Further decreases in number of growing degree days below 0°C Abrupt increased in tree cover are unlikely	Abrupt increases in tree-fraction is plausible	Abrupt increases in tree-fraction is plausible
Permafrost	21-37% reduction in permafrost 4 × 106 km ² more permafrost than under 2°C of global warming 0.08-0.16 Gt C a ⁻¹	35-47% reduction in permafrost 0.12-0.25 Gt C a ⁻¹	To be described	To be described

Tipping point	Warming of 1.5°C or less	Warming of 1.5°C-2°C	Warming of 2° - 3°C	Warming of more than 3°C
	released Irreversible loss of stored carbon	released Irreversible loss of stored carbon		
Asian Monsoon	Low confidence in projected changes – more research to be assessed post SOD	Low confidence in projected changes – more research to be assessed post SOD	Low confidence in projected changes – more research to be assessed post SOD	Low confidence in projected changes – more research to be assessed post SOD
West African Monsoon and the Sahel	Uncertain changes, unlikely that a tipping point is reached	Uncertain	Strengthening of monsoon and wetting and greening of Sahel and Saharah (low confidence) Negative associated impacts through increase in extreme temperature events	Strengthening of monsoon and wetting and greening of Sahel and Saharah (low confidence) Negative associated impacts through increase in extreme temperature events
Rainforests	Reduced biomass, deforestation and fire increases pose uncertain risks to forest dieback	Reduced biomass, deforestation and fire increases pose uncertain risk to forest dieback	Potential tipping point leading to pronounced forest dieback	Potential tipping point leading to pronounced forest dieback
Boreal forests	Increased tree mortality at southern boundary of boreal forest	Increased tree mortality at southern boundary of boreal forest	Tipping point for significant dieback of boreal forest (low confidence)	Tipping point for significant dieback of boreal forest (low confidence)
Heat-waves, unprecedented heat and human health	Substantial increase in occurrence of deadly heat-waves More than 350 million more people to deadly heat by 2050 under a midrange population growth scenario	Substantial increase in deadly heat-waves Annual occurrence of heat-waves similar to deadly 2015 heat-waves in India and Pakistan	To be described	To be described
Key staple crops	Global maize crop reductions of about 10%	Larger reductions in maize crop production that under 1.5°C ~ 15%	Drastic reductions in maize crop globally and in Africa, of 20% or more	Potential collapse of maize crop in some regions including southern and East Africa
Livestock in the tropics and subtropics	Increased heat-stress	Onset of persistent heat-stress	Persistent heat-stress likely	Persistent heat-stress likely

1

2 [Placeholder for summary tables on Adaptation based on tables found in annex 3.1.]

[START BOX 3.9 HERE]

Box 3.9: Economic Damage from Climate Change in the United States and the Value of Limiting the Increase in Global Mean Temperature to well below 2°C and 1.5°C in the longer term

Working from the median “no-policy” baseline trajectory in Fawcett et al. (2015, Figure 3.23) brings global emissions to roughly 93 GtCO₂ per year by the end of the century. It is defined by two boundary conditions. Annual global emissions begin around 30 GtCO₂ in 2010, and growing initially at approximately 6% per year. Emissions reach 93 GtCO₂ by 2100 because the rate of growth depreciates by 0.5% per year.

Corresponding transient temperature trajectories can be calculated from a linear relationship between contemporaneous cumulative emissions and transient temperature reported in NRC (2010, page 82): 1.75 °C per 1000 GtC is the median estimate. Uncertainty, here, is driven by the behavior of sinks at higher global temperatures, and by uncertainty about the sensitivity of the climate to external forcing: the 95th percentile temperature for any emissions total is 70% above the temperature associated with median, and the 5th percentile temperature is 40% below the median.

Constrained emissions pathways through 2100 are represented by two trajectories that limit the median estimated increases in transient temperature to 1.5 °C and 2°C above preindustrial levels. They are “ideal” and are comparable in the sense that each of them reduces emissions over time so as to maximize the discounted logarithmic derived utility generated by emissions through. That is to say, they solve two parallel Hotelling-style exhaustible resource problems where cumulative emissions constraints derived from NRC (2010) serve as operating “supply” constraints on total emissions for each of the four temperature targets: 1715 and 2575 GtCO₂, respectively. The Hotelling results with logarithmic utility mean that emissions face exponential downward pressure relative to the initial 6% per year growth at a rate equal to the associated utility discount factor for each target.

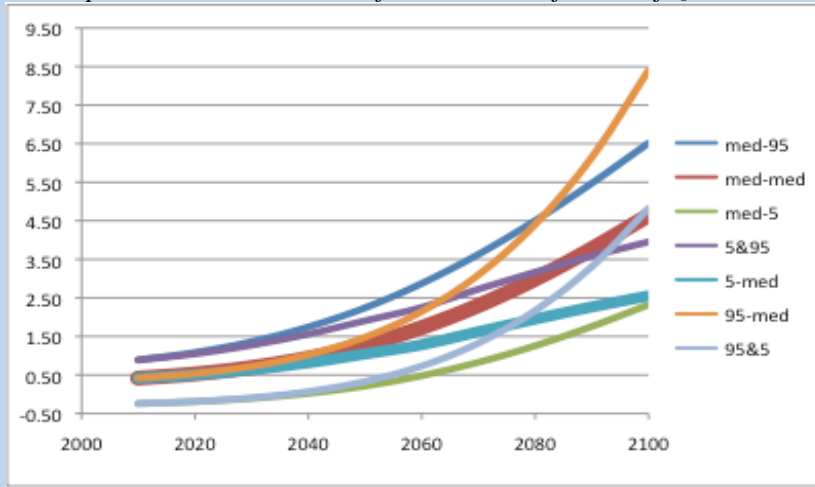
Aggregate economic damages from warming are calibrated in terms of the percentage loss of GDP to the median, 5th percentile, and 95th percentile temperature reaction functions by Hsiang et al. (2017). Panel A of Box 3.9 Figure 1 displays transient trajectories of aggregate economic damages (real GDP) from climate change in decadal increments for the United States through the year 2100 along the “no-policy” baseline described above. Panel B (Box 3.9 Figure 2) shows the avoided damages along a trajectory whose median outcome achieves a 1.5°C temperature limit through 2100. Panel C (Box 3.9 Figure 3) shows the avoided damages along a trajectory whose median outcome achieves a 2.0 °C temperature limit through 2100. Panel D (Box 3.9 Figure 4) compares the avoided damages along a trajectory whose median outcome achieves a 1.5 °C temperature limit through 2100 against a trajectory whose median outcome achieves the higher 2.0 °C temperature limit through 2100; i.e., it reflects the value of extending mitigation efforts to achieve the lower temperature target (with the median trajectory).

The results for the “no-policy” case reveal that economic damages along the “median-median” case (median temperature change and median damages) reach 4.5% of GDP by 2100 surrounded by a range (different combinations of temperature change and damages) between 8.5% and 2.5%. The value of achieving a 1.5 °C temperature limit calibrated in damages avoided along the “median-median” case is nearly 4% by 2100 surrounded by a range of 7.0% and 2.0%. The value of achieving a 2.0°C temperature limit along the “median-median” case is lower as should be expected: 3.5% by 2100 surrounded by a range of 6.5% and 1.8%. The value of achieving a 1.5 °C temperature limit rather than a 2.0 °C is modest; along the “median-median” case, it is around 0.35% by 2100 surrounded a range of 0.20% and 0.65%.

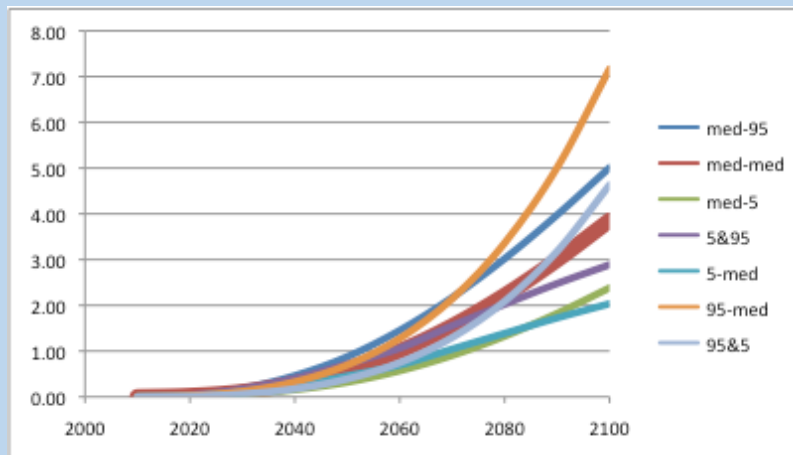
Even though the “no-policy” baseline shows significant damage diversity across temperature and damage trajectories almost immediately, the values of achieving either temperature limit do not diverge significantly until 2040 when their difference tracks between 0.05% and 0.13%. Thereafter, the differences between the

1 two temperature targets do, however, begin to diverge substantially in the second half of the century. This
 2 means that patience will be required while we proceed toward the more aggressive 1.5 °C mitigation
 3 temperature target.
 4

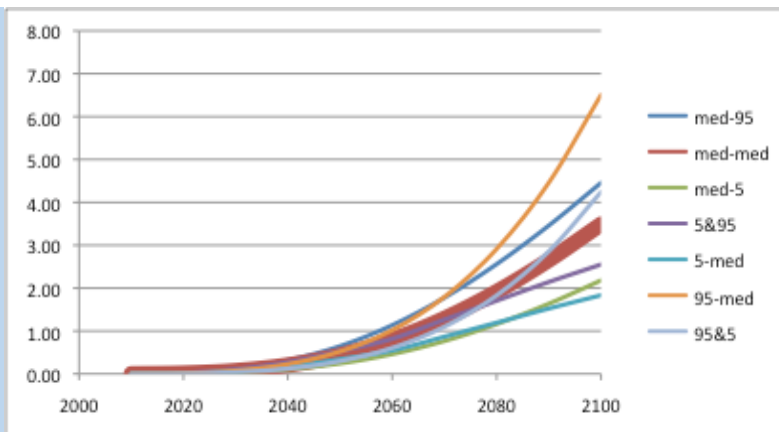
5 *[Placeholder: Figures are placeholders - details to follow – in the final draft.]*



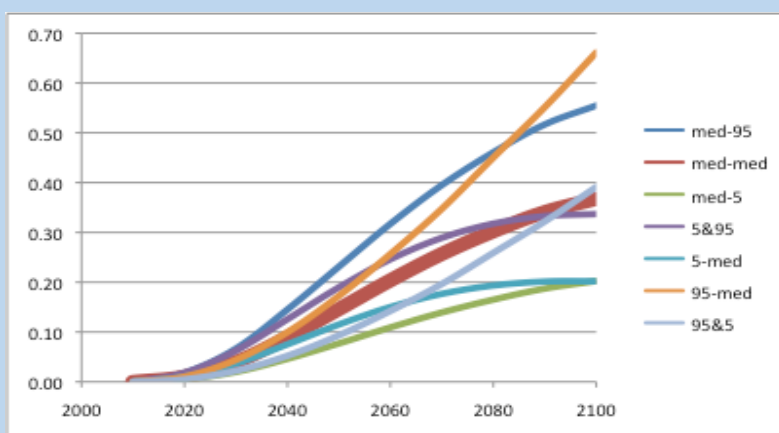
6 **Box 3.9, Figure 1:** Panel A: The Economic Value of Damages along the No-policy Baseline Emissions Trajectories
 7 (difference in percentage of average US GDP loss per year) *
 8
 9



10 **Box 3.9, Figure 2:** The Economic Value of Achieving a 1.5°C Temperature Target Compared to Baseline Economic
 11 Damages (difference in percentage of average US GDP loss per year. *
 12
 13
 14



Box 3.9, Figure 3: Panel C: The Economic Value of Achieving a 2°C Temperature Target Compared to Baseline Economic Damages (difference in percentage of average US GDP loss per year. *



Box 3.9, Figure 4: Panel D: The Economic Value of Achieving a 1.5-degree C Temperature Target Compared to Achieving a 2°C Target(difference in percentage of average US GDP loss per year².

[END BOX 3.9 HERE]

3.6 Implications of different mitigation pathways reaching 1.5°C

3.6.1 Gradual vs overshoot in 1.5°C scenarios

3.6.1.1 Likely pattern of extremes and other changes in climate system

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

²FOOTNOTE Legend for Figure 1: “med-95” signifies the combination of the median emissions trajectory and the 95th percentile damage function; “med-med” signifies the combination of the median emissions trajectory with the median damage function; etc...

3.6.1.2 *Implications for impacts on physical and biophysical systems*

[PLACEHOLDER: Addressing impact thresholds for overshooting levels, based on Section 3.4]

3.6.2 *Non CO₂ implications and projected risks of mitigation pathways*

3.6.2.1 *Land use changes*

3.6.2.1.1 *Land use changes in mitigation scenarios*

Land use changes are an important component of mitigation scenarios (see Cross-Chapter Box on “Land use”). Of the 116 climate change mitigation scenarios that limit global warming to less than 2°C above pre-industrial levels with more than 66% probability, produced by integrated assessment models and reviewed in IPCC AR5, 87% rely on extensive use of negative emission technologies (Smith et al., 2015) in the second half of the 21st century. These are typically Bioenergy with Carbon Capture and Storage (BECCS). In these scenarios, the median rate of sequestration is 3.7 GtC (13.5 GtCO) annually (Wiltshire, 2015) in order to achieve ‘negative emissions’ (Clarke et al., 2014; Fuss et al., 2014). Furthermore, the Paris Agreement aims to ‘achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century’ (UNFCCC/CP/2015/L.9/Rev.1). Negative emission technologies such as BECCS may be required to achieve this. In scenarios more recently developed to be consistent with stabilization at 1.5°C global warming, changes in land use in the form of BECCS, extension of cropland and/or reforestation are a fundamental element (Chapter 2; Guillod et al.; Seneviratne et al.). In the development of these scenarios, however, implications of these land use changes are generally not considered, beside their potential impacts on the carbon cycle. There are, however, substantial impacts that need to be factored in with respect to biodiversity, food security and physical feedbacks to climate.

More recent studies find that scenarios that constrain warming to less than 2°C are consistent with sequestration rates via BECCS at 3.3 GtCyr⁻¹ (Smith et al., 2015). If primary biofuels are used to supply BECCS, to constrain warming to below 2°C, the requirements for land by the end of the century will be extremely large, with estimates reaching up to 18% of the land surface being required (Wiltshire, 2015). Other estimates reach 380-700 Mha/21-64% current arable cropland (Smith et al., 2015); 24-36% arable cropland (Popp et al., 2014); and 508 Mha (Humpenöder et al., 2014). These estimates do not include the potential need to increase the area of land under cultivation to compensate for climate change induced crop yield losses. All these factors would create strong competition for land between biofuel production, food production and biodiversity conservation. Risks to biodiversity conservation and agricultural production are therefore projected to result from mitigation pathways that rely heavily on BECCS sourced from primary biofuels (Smith et al., 2013; Tavoni and Socolow, 2013). In the absence of global forest protection, increasing bioenergy deployment also leads to increases in greenhouse gas emissions from changing land use (Smith et al., 2013, 2015). The resultant projected conversion of natural ecosystems into biofuel cropping (a form of indirect land use change or ‘iLUC’) would result in greenhouse gas emissions from this land use change, as well as increased emissions due to agricultural intensification. This can greatly offset the ‘negative emissions’ benefit of the BECCS itself (Wiltshire, 2015) with estimates ranging from 14-113 GtCO₂ eq cumulatively by 2100 (Popp et al., 2014). Many published estimates of the potential of BECCS do not consider this offset. Those that do include it, however, estimate that the actual potential for BECCS to reduce emissions is greatly reduced once this is taken into account.

A meta-analysis of published estimates of the potential land available to produce primary biofuels, once demand for food has been met, found widely varying estimates (Slade et al., 2014). These estimates depend on future assumptions about population, agricultural intensification and productivity, and changes in diet. Most estimates of the potential land area available for biofuel cropping do not consider the need to set aside

1 land for biodiversity conservation, although some integrated modelling studies simulate the effects of a
2 carbon tax applied to greenhouse gas emissions from land use change as well as from fossil fuel use. In these
3 simulations, forest area remains constant whilst biofuel cropland increases at the expense of agricultural
4 land, which is consistent with the UNFCCC Article 2, which requires that climate change be limited such
5 that ‘ecosystems can adapt naturally’ and that ‘food production is not threatened’).
6

7 In order for ecosystems to adapt to climate change, land use would also need to be carefully managed to
8 allow biodiversity to disperse to areas that become newly climatically suitable (see Section 3.4.1) as well as
9 protecting the areas where the climate remains suitable in the future. This implies a need for a considerable
10 expansion of the protected area network (Warren c et al.). At the same time, adaptation to climate change in
11 the agricultural sector (Rippke et al., 2016) can require transformational as well as new approaches to land
12 use management; whilst in order to meet the rising future food demand of a growing human population,
13 additional land is projected to be needed to be brought into production, unless there are large increases in
14 agricultural productivity (Tilman et al., 2011). Hence, reliance on BECCS using primary biofuels has the
15 potential for large negative consequences for food production and biodiversity conservation (and hence,
16 ecosystem services) (Smith and Torn, 2013). Furthermore, irrigation for bioenergy crops would greatly
17 increase agricultural water withdrawals. One estimate is that BECCS burying 3.3 GtCyr⁻¹ would require an
18 additional 3% of the water currently appropriated to human use (Smith et al., 2015). Another study finds that
19 while the global requirement for water withdrawal for irrigation could double, if such additional withdrawals
20 are prohibited, demand for land (for BECCS) instead increases by 41% (Bonsch et al., 2016).
21

22 The reductions in agricultural yields driven by climate change and/or land management decisions related to
23 negative emission technologies (BECCS and afforestation) are likely to have implications for food security
24 with subsequent economic consequences (e.g., Nelson et al. 2014; Dalin & Rodríguez-Iturbe 2016; Muratori
25 et al. 2016, 2014). In other cases, limitations on the potential of particular mitigation activities may be
26 constrained by resource availability (e.g., Smith et al. 2015). Other aspects of food security in a changing
27 climate are discussed in 3.4.6 and other sections.
28

29 Many of the same issues relating to competition for land surround the potential use of afforestation and
30 reforestation as an alternative negative emission technology to BECCS. Similar rates of sequestration of 3.3
31 GtC/ha require 970 Mha of afforestation and reforestation (Smith et al., 2015). Humpenöder et al. (2014)
32 estimates that afforestation would require 2800 Mha by the end of the century to constrain warming to 2°C.
33 Hence, the amount of land required if mitigation is implemented by afforestation and reforestation is 3 to 5
34 times greater than that required by BECCS. However, not all of this land use is in competition with
35 biodiversity protection. Where reforestation is the restoration of natural ecosystems, this benefits both carbon
36 sequestration and conservation of biodiversity and ecosystem services.
37

38 More recent literature explores scenarios which limit warming to 2°C or below and achieve a balance
39 between sources and sinks of carbon dioxide, using BECCS that relies on secondary (or other) biofuels, or
40 which relies on other options such as forest restoration or changes in diet, or more generally, management of
41 food demand (Bajželj et al., 2014). These scenarios generally avoid, or greatly reduce, the issues of
42 competition for land with food production and with protected area networks for biodiversity conservation
43 (see Cross-Chapter Box 1.1) and provide examples to illustrate how carefully designed mitigation strategies
44 can achieve ‘negative emissions’ without these benefits being offset by emissions from indirect land use
45 change.
46
47

48 3.6.2.1.2 *Biophysical feedbacks on regional climate associated with land use changes*

49 Changes in the biophysical characteristics of the land surface are known to have an impact on local and
50 regional climates through changes in albedo, roughness, evapotranspiration and phenology that can lead to a
51 change in temperature and precipitation. This includes changes in land use through agricultural

1 expansion/intensification (e.g., Mueller et al. 2015) or reforestation/revegetation endeavours (e.g., Feng et al.
2 2016; Sonntag et al. 2016; Bright et al. 2017) and changes in land management (e.g., Luyssaert et al. 2014;
3 Hirsch et al. 2017) that can involve double cropping (e.g., Jeong et al. 2014; B. Mueller et al. 2015; Seifert &
4 Lobell 2015), irrigation (e.g., Sacks et al. 2009; Lobell et al. 2009; Cook et al. 2011; Qian et al. 2013; de
5 Vrese et al. 2016; Pryor et al. 2016; Thiery et al. 2017), no-till farming and conservation agriculture (e.g.,
6 Lobell et al. 2006; Davin et al. 2014), and wood harvest (e.g., Lawrence et al. 2012). Hence, the biophysical
7 impacts of land use changes are an important topic to assess in the context of low-emissions scenarios (e.g.,
8 (van Vuuren et al., 2011), in particular for 1.5°C warming levels (see also Cross-Chapter Box 3.1).

9
10 The magnitude of the biophysical impacts is potentially large for temperatures extreme. Indeed, both changes
11 induced by modifications in moisture availability and irrigation, or by changes in surface albedo, tend to be
12 larger (i.e. stronger cooling) for hot extremes than for mean temperatures (e.g., Seneviratne et al. 2013;
13 Davin et al. 2014; Wilhelm et al. 2015; Hirsch et al. 2017; Thiery et al. 2017). The reasons for reduced
14 moisture availability are related to a strong contribution of moisture deficits to the occurrence of hot
15 extremes in mid-latitude regions (Mueller and Seneviratne, 2012; Seneviratne et al., 2013). In the case of
16 surface albedo, cooling associated with higher albedo (e.g., in the case of no-till farming) is more effective at
17 cooling hot days because of the higher incoming solar radiation for these days (Davin et al., 2014). The
18 overall effect of either irrigation or albedo has been found to be at the most of the order of ca. 1-2°C
19 regionally for temperature extremes. This can be particularly important in the context of low-emissions
20 scenarios because the overall effect is in this case of similar magnitude to the response to the greenhouse gas
21 forcing (Hirsch et al. 2017, see Figure 3.24).

22
23 In addition to the biophysical feedbacks from land use change and land management on climate, there are
24 potential consequences for particular ecosystem services. This includes climate change induced changes in
25 crop yield (e.g., (Asseng et al., 2013, 2015; Butler and Huybers, 2012; Lobell et al., 2014; Schlenker and
26 Roberts, 2009; van der Velde et al., 2012) which may be further exacerbated by competing demands for
27 arable land between reforestation mitigation activities, growing crops for BECCS (see Chapter 2), increasing
28 food production to support larger populations or urban expansion (e.g., see review by Smith et al. 2010). In
29 particular, some land management practices may have further implications for food security where some
30 regions may have increases or decreases in yield when ceasing tillage (Pittelkow et al., 2014).

31
32 It should be noted that the important role of land use change for climate change projections and socio-
33 economic pathways will be addressed in depth in the upcoming IPCC Special Report on Land (REF). In
34 addition, some aspects are treated in more depth in the Cross-Chapter Box 3.1.

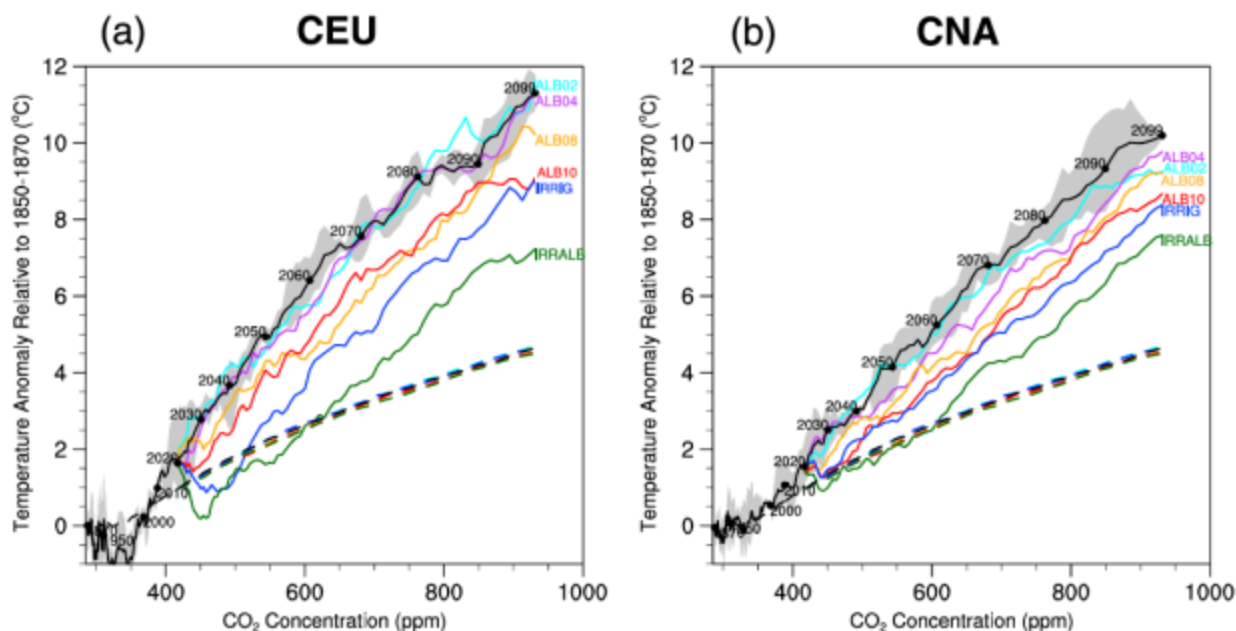


Figure 3.24: Regional temperature scaling with CO₂ concentration (ppm) over 1850 to 2099 for two different SREX regions: Central Europe (CEU) (a) and Central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TX_x) anomaly and dashed lines correspond to the global mean temperature anomaly, where all temperature anomalies are relative to 1850-1870 and units are in °C. The black line in all panels denotes the 3-member control ensemble mean with the grey shaded regions corresponding to the ensemble range. The colored lines correspond to the 3-member ensemble means of the experiments corresponding to albedo +0.02 (cyan), albedo +0.04 (purple), albedo +0.08 (orange), albedo +0.10 (red), irrigation on (blue), and irrigation with albedo +0.10 (green). Adapted from Hirsch et al. (2017).

3.6.2.2 Atmospheric compounds (aerosols and methane)

Anthropogenic driven changes in aerosols cause important modifications to global climate (Bindoff et al., 2013a; Boucher et al., 2013; Sarojini et al., 2016; Wang et al., 2016b; Wu et al., 2013). Projected decreases in cooling aerosols in the next few decades may cause more warming than from greenhouse gases (Kloster et al., 2009; Navarro et al., 2017), especially in the low CO₂ pathways. Because aerosol effects on the energy budget are regional, strong regional changes in precipitation changes from aerosols are likely to occur if aerosols emissions are reduced for air quality or as a co-benefit from switches to sustainable energy sources (Navarro et al., 2017; Wang et al., 2016b). Thus regional impacts, especially on precipitation, are very sensitive to the pathway used to obtain less than 1.5°C warming.

Pathways which rely strongly on reductions in methane versus CO₂ will reduce warming in the short-term because methane is such a strong greenhouse gas, but be warmer in the long term because of the much longer residence time of CO₂ (Myhre et al., 2013a; Pierrehumbert, 2014). In addition, the dominant loss mechanism for methane is atmospheric photooxidation, with this conversion modifying ozone creation and destruction in the troposphere and stratosphere. It therefore modifies the contribution of ozone to radiative forcing, as well as feedbacks onto the oxidation rate of methane itself (Myhre et al., 2013b).

Atmospheric aerosols and gases can also modify the land and ocean uptake of anthropogenic carbon dioxide, but some compounds enhance uptake, while others reduce uptake (Ciais et al., 2013b). While CO₂ emissions tend to encourage greater uptake of carbon by the land and the ocean (Ciais et al., 2013a), methane emissions can enhance (or reduce) ozone pollution, depending on nitrogen oxides, volatile organic compounds, and

1 other organic species concentrations, and ozone tends to reduce land productivity (Myhre et al., 2013b;
2 Wang et al., 2017a). Aside from inhibiting land vegetation productivity, ozone may also alter the CO₂, CH₄
3 and N₂O exchange at the land-atmosphere interface and transform the global soil system from a sink to a
4 source of carbon (Wang et al., 2017a). Aerosols and associated nitrogen-based compounds tend to enhance
5 the uptake of carbon dioxide in land and ocean systems through the deposition of nutrients (Ciais et al.,
6 2013a; Mahowald et al., 2017). Furthermore, aerosols increase the amount of diffuse radiation, which may
7 increase vegetation productivity (Mercado et al., 2009).

8
9 [Placeholder: This section will be slightly expanded for the FGD, in particular on the role of SLFC and
10 aerosols in the 1.5°C scenarios (also in coordination with material from other chapters)].

11 12 13 **3.6.3 Solar Radiation Management**

14
15 Solar Radiation Management (SRM) is discussed in the literature and involves deliberate changes to the
16 albedo of the Earth system in order to reduce the rate of planetary warming. As highlighted in Chapter 1, and
17 consistent with previous IPCC reports (IPCC, 2012b), SRM is not investigated as a mitigation option in
18 Chapter 2. However, we direct the interested reader to the Cross-Chapter Box on SRM and related radiation
19 modification measures (RMMs) in this special report (see Cross-Chapter Box 4.2).

20 21 22 **3.6.4 Beyond the end of the century implications**

23 24 **3.6.4.1 Sea ice**

25 Sea ice is often cited as a tipping point in the climate system (Lenton, 2012). Detailed modelling (Schroeder
26 and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011), however, suggests that Summer sea ice
27 can return within a few years after its rapid removal. Further studies (Armour et al., 2011; Boucher et al.,
28 2012; Ridley et al., 2012) remove sea ice by raising CO₂ concentrations and study subsequent regrowth by
29 lowering CO₂ at the same rate. These studies also suggest changes in Arctic sea ice are neither irreversible
30 nor exhibit bifurcation behavior. It is therefore plausible, however, that the extent of Arctic sea ice may
31 quickly re-equilibrate to end-of-century climate in the event of an overshoot scenario.

32 33 34 **3.6.4.2 Sea level**

35 The impacts of policy decisions related to anthropogenic climate change are likely to have a profound impact
36 on sea level not only for the remainder of this century but for many millennia to come (Clark et al., 2016).
37 On these long timescales, 50 m of sea level rise is potentially possible (Clark et al., 2016). While it is
38 *virtually certain* that sea level will continue to rise well beyond 2100, the amount of rise depends on future
39 cumulative emissions (Church et al., 2013).

40
41 Based on the sensitives summarised by Levermann et al. (2013), the contributions of thermal expansion
42 (0.20 to 0.63 m°C⁻¹) and glaciers (0.21 m°C⁻¹ falling at higher degrees of warming mostly because of the
43 depletion of glacier mass, with a possible total of ~0.6 m) amount to 0.5-1.2 and 0.6-1.7 m, in 1.5 and 2°C
44 warmer worlds respectively. The bulk of sea level rise on greater than centennial timescales is therefore
45 likely to be contributed by the two continental ice sheets of Greenland and Antarctica, whose existence is
46 threatened on multi-millennial timescales.

47
48 For Greenland, where melting from the ice sheet's surface is important, a well-documented instability exists
49 where the surface of a thinning ice sheet encounters progressively warmer air temperatures that further
50 promote melt and thinning. A useful index associated with this instability is the threshold at which mass loss

1 from the ice sheet by surface melt exceeds mass gain by snowfall. Previous estimates (Gregory and
2 Huybrechts, 2006) put this threshold around 1.9 to 5.1°C above preindustrial period. More recent analyses,
3 however, suggest that this threshold sits between 0.8 to 3.2°C (Robinson et al., 2012). The continued decline
4 of the ice sheet after this threshold has been passed is highly dependent on future climate and varies between
5 ~80% loss after 10,000 years to complete loss after as little as 2000 years (contributing ~6 m to sea level).
6

7 The Antarctic ice sheet, in contrast, loses the mass gained by snowfall as outflow and subsequent melt to the
8 ocean (either directly from the underside of floating ice shelves or indirectly by the melt of calved icebergs).
9 The long-term existence of this ice sheet is also affected by a potential instability (the Marine Ice Sheet
10 Instability), which links outflow (or mass loss) from the ice sheet to water depth at the grounding line (the
11 point at which grounded ice starts to float and becomes an ice shelf) so that retreat into deeper water (the
12 bedrock underlying much of Antarctica slopes downwards towards the centre of the ice sheet) leads to
13 further increases in outflow and promotes yet further retreat (Schoof, 2007). More recently, a variant on this
14 mechanism has been postulated in which an ice cliff forms at the grounding line which retreats rapidly
15 through fracture and iceberg calving (DeConto and Pollard, 2016). There is a growing body of evidence
16 (DeConto and Pollard, 2016; Golleger et al., 2015) that large-scale retreat may be avoided in emission
17 scenarios such as RCP2.6 but that higher-emission RCP scenarios could lead to the loss of the West
18 Antarctic ice sheet and sectors in East Antarctica, although the duration (centuries or millennia) and amount
19 of mass loss during such as collapse is highly dependent on model details and no consensus yet exists.
20 Current thinking (Schoof, 2007) suggests that retreat may be irreversible, although a rigorous test has yet to
21 be made.
22
23

24 3.6.4.3 *Permafrost*

25 The slow rate of permafrost thaw introduces a lag between transient permafrost loss and contemporary
26 climate, so that the equilibrium response is likely to be 25 to 38% greater than the transient response
27 simulated in climate models (Slater and Lawrence 2013). The long-term, equilibrium Arctic permafrost loss
28 to global warming is analysed by Chadburn et al. (2017). They use an empirical relation between recent
29 mean annual air temperatures and the area underlain by permafrost coupled to CMIP5 stabilization
30 projections to 2300 for RCPs 2.6 and 4.5. Their estimate of the sensitivity of permafrost to warming is 2.9 to
31 5.0 million km²°C⁻¹ (likely range), which suggests that stabilizing climate at 1.5°C as opposed to 2°C would
32 save roughly 2 million km² (or 13%) of the area presently underlain by permafrost (stabilizing at 73 as
33 opposed to 60% of present-day values).
34
35

36 3.7 Chapter Limitations and Knowledge gaps

37
38 The scientific literature specific to global warming of 1.5°C is only just emerging. This has led to an
39 inconsistency in the amount of information available across the various sections of this report and to the size
40 of knowledge gaps in each section. In particular, the number of available impact studies specific to 1.5°C
41 lags behind other climate projections, due in part to the dependence of the former on the latter. More
42 research and analysis is also needed to clarify projected differences of climate change impacts and
43 consequences for +1.5°C or +2°C global warming. Nonetheless, it is anticipated that as methodologies are
44 refined and more simulations specific to the warming target become available, the amount and scope of the
45 available scientific literature will be greatly expanded.
46

47 The following have been identified as general knowledge gaps in the current scientific literature as they
48 relate to Chapter 3.

- 49 • There is a lack of climate model simulations for low-emission scenarios. Assessments, therefore,
50

1 largely focus on analyses of transient responses at 1.5°C and 2°C. There is also insufficient data to
 2 assess long-term equilibrium stabilization responses
 3
 4

- 5 • It is challenging to detect the relatively small signal between 1.5°C versus 2°C amidst background
 6 noise using robust probabilistic models. This is problematic for physical systems and even more so
 7 for biological phenomena.
 8
- 9 • There is a need for new methods to address uncertainties associated with non-linearities,
 10 innovations, local scales, latent or lagging responses in climate and by extension, associated natural
 11 and human systems.
 12
- 13 • Most projections focus on how climate change could alter the risk associated with a particular
 14 outcome. A region may, however, experience more than one outcome over short time periods (e.g.,
 15 higher temperatures and reduced rainfall resulting in drought, which can affect food- and water-
 16 security). There is need for projections of the aggregate risks for human and natural systems in a
 17 region and their associated uncertainties.
 18
- 19 • Feedbacks of land use/land cover changes for low-emissions scenarios, e.g., in relation to af-
 20 /reforestation, food production, and the expansion of biofuel production, in some cases with carbon
 21 capture and storage (BECCS) and the associated biophysical impacts should be better quantified in
 22 future research and assessments.
 23
- 24 • The impacts of regional effects of changes in aerosol concentrations should be investigated for low-
 25 emissions scenarios.
 26
- 27 • A better understanding is needed of the intersection of climate change with development
 28 pathways. Projecting risks under a range of climate and development pathways would promote
 29 understanding of how development choices could increase or decrease the magnitude and pattern of
 30 risks, and would therefore provide better estimates of the range of uncertainties. In the absence of a
 31 greater understanding, the underlying data are often not being collected, particularly those related to
 32 vulnerability and capacity.
 33

34 Other knowledge gaps emerging from specific sections of the chapter and relating to specific areas are given
 35 in the Table 3.9 below.
 36

37 **Table 3.9:** Some knowledge gaps by area of focus.
 38

Section		Areas for greater understanding and more research:
Section 3.3	Drought	<ul style="list-style-type: none"> • Critical thresholds for droughts between 1.5 and 2°C, remaining large climate model spread and drought-index dependency of projections
	Permafrost	<ul style="list-style-type: none"> • The potentially serious implication of the release of stored carbon as Arctic permafrost thaws for climate stabilization by the end of the century.
	Sea ice	<ul style="list-style-type: none"> • The future of the Antarctic ice sheet in predictions of global sea level. • The linkage between seasonal and year-long sea ice.
	Sea Levels	<ul style="list-style-type: none"> • At local scales, quantifying the impact of changing storminess on the frequency of storm surges demands attention.
	Storms and	<ul style="list-style-type: none"> • Changes in storm intensity and frequency as a function of climate

Section		Areas for greater understanding and more research:
	Hurricanes	change, especially between global warming of 1.5°C and 2°C.
Section 3.4		Areas for greater understanding and more research:
Natural and Human Systems	Freshwater	<ul style="list-style-type: none"> • The combined dynamics of climate and socioeconomic changes in freshwater resources.
	Terrestrial ecosystems	<ul style="list-style-type: none"> • The uncertainty in predicting the response of terrestrial ecosystems to climate which is largely due to the inherent complexity of the systems, and the difficulty in separating climate effects from direct human effects. More complex and more integrated socio-ecosystem models are needed. • A global appraisal of the evolution of the health of the vegetation is needed. More observations are needed to support this: on the field, instrumented sites and remote sensing data. • The fertilization effect. Current projections of carbon storage in vegetation are likely overestimated. • The carbon cycle in the soils at different time scales. • The risk of species maladaptation (e.g., effect of late frosts) when they advance their spring phenology in response to warming. • Predicting the risk associated to extreme events and anticipating their impacts on ecosystems. The effects on ecosystem change are probably equal to or greater than shifts in the mean values of climate variables. • The rate of climate change that can be tracked or adapted to by organisms, and the magnitude of change they can tolerate.
	Ocean systems	<ul style="list-style-type: none"> • The general knowledge about climate change impacts on ocean systems which lags significantly behind our understanding of climate change impacts on terrestrial systems. • The response of deep sea habitats and ecosystems to increasing CO₂ and temperature. • The impact of ocean acidification on the ionic composition of seawater (e.g., through metal ions). • How ocean currents are likely to change with global warming (e.g., changes to thermohaline circulation). • The important but relatively little understood impacts of the steady decline in oxygen to the ocean. • How complex food webs are likely to change in the ocean as warming changes the distribution of marine life. • The interaction between stressors, both climate change and non-climate change, and the potential role of cumulative stress on organisms and ecosystems in the ocean. • How vulnerable populations (tropical coastal communities) can adapt to changing patterns of resource and livelihood opportunities. • The solutions to climate change that also reduce poverty and promote development in coastal societies generally.
	SIDS	<ul style="list-style-type: none"> • Most projections are at too coarse a temporal and spatial scale to adequately inform local decision-making. • There are key research gaps related to food production, tourism and coastal infrastructure, public health, and ecosystem response.

Section		Areas for greater understanding and more research:
	Urban	<ul style="list-style-type: none"> Current UHI projections do not integrate adaptation to projected warming, for instance, cooling that could be achieved with more reflective roofs and urban surfaces overall.
	Tourism	<ul style="list-style-type: none"> There is a lack of integrated sectoral assessments that analyze the full range of potential impacts on tourism.

[START Cross-Chapter Box 3.1 HERE]

Cross-Chapter Box 3.1: Land based negative emissions, in relation to 1.5°C warming

Sabine Fuss, Markku Kanninen, Joeri Rogelj, Sonia Seneviratne, Rachel Warren.

Land use changes are an essential element of low-emissions scenarios, related to 1) decreases of land-use related CO₂ emissions and 2) the implementation of land-based negative emission technologies (NET; alternatively called technologies for Carbon Dioxide Removal (CDR)). These issues will be covered in further detail in the forthcoming IPCC Special Report on Climate Change and Land. The focus of this Box is on issues associated with limiting warming to 1.5C warming.

In 2010, emissions from the agriculture, forestry and land use sector (AFOLU) were close to 10 GtCO₂-eqyr⁻¹, comprising 24.87% of annual greenhouse gas emissions of which land use change contributed about 40% (AR5 WGIII Figure SPM2, Figure 11.2). Reducing emissions from land use change are an important component of low-emissions mitigation pathways (Clarke et al. 2014). Recognition of this has led to the agreement on Reducing Emissions from Deforestation and Degradation (REDD) and its successor REDD+ which includes sustainable management of forests and conservation and enhancement of forest carbon stocks. Although deforestation has slowed its rate, it is still high.

Land-based negative emission/CDR technologies are applied to varying degrees in scenarios produced by integrated assessment models (IAMs) that limit warming to 1.5°C by the end of the century (Van Vuuren et al. (Bertram et al.; Holz et al.; Kriegler et al., 2017; Rogelj et al., 2015). Virtually all scenarios that either limit peak or end-of-century warming to 1.5°C use some level of CDR, be it in the form of bioenergy with carbon capture and storage (BECCS) or afforestation (Chapter 2, Section 2.3).

Both the reduction of land use-related CO₂ emissions and the implementation of land-based CDR technologies may have a large land use footprint when integrated at regional to global scales in scenarios which apply these measure without consideration of other societal objectives (e.g., food production) or potential trade-offs, for instance related to regional biophysical feedbacks of land use (Seneviratne et al., submitted). For example, growing crops for first-generation biofuels (which are derived from food crops like corn or sugar cane) at large scale, could have negative effects on agriculture and ecosystems (Section 3.7.1.2.1), and on sustainable development generally (Section 5.3). Article 2 of the UNFCCC states that “The ultimate objective of this Convention ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner” (UNFCCC, 1992). Hence, any mitigation measures, including CDR measures that demand land for their deployment, should not create risks that could compromise by themselves the very goals of the Article. However, it is possible to design mitigation policies that would minimise these conflicts. For example, CDR portfolios that use secondary biofuels, marginal land, biochar, and reforestation with native trees, as well as land-based NETs can complement other Negative Emissions

1 Technologies/CDR approaches that do show no risk of trade-offs through competition for land such as Direct
2 Air Capture and Storage (DACs) (NETs, Chapter 4.3).

3
4 Although virtually all scenarios that limit either peak or end-of-century warming to 1.5°C use some kind of
5 CDR to some degree, the implications for land can be very diverse (Section 2.3.1, Section 2.4). Scenarios
6 that limit end-of-century warming to below 1.5°C with at least 66% probability show a range of CDR
7 through BECCS by 2050. Scenarios usually use BECCS because it is considered cost-effective in reducing
8 emissions. However, scenario studies have also explored the implications of explicitly limiting the use of
9 BECCS or bioenergy in stringent mitigation scenarios (Bertram et al.; Krey et al., 2014; Strefler et al.; van
10 Vuuren et al.) or even entirely eliminated (Grubler et al.; van Vuuren et al.). Indeed, scenarios that limit end-
11 of-century warming to below 1.5°C are available that use no (Grubler et al.; van Vuuren et al.) or annual
12 amounts of less than 1.5 GtCO₂ yr⁻¹ (Bertram et al.; van Vuuren et al.) – the lower end of the assessed
13 potential range, see Table 1 – in 2050. Without exception, these scenarios all strongly limit demand for
14 energy and resources, and assume healthy diets without excessive meat consumption, amongst other
15 sustainability factors. On the other hand, if no limits to BECCS or few sustainability concerns are
16 considered, scenarios indicate that if energy demand is high and when fossil fuels dominate the baseline
17 energy mix (Kriegler et al., 2017) or when scenarios assumed small emissions reductions by 2030 (Luderer
18 et al.; Roelfsema et al.) projected BECCS contributions can be larger than 7 GtCO₂ yr⁻¹ by 2050. Because
19 scenario design (which is determined by the research question that is explored) determines to a large degree
20 the deployment of BECCS in scenarios, averaging over an arbitrary selection of scenarios does not contain
21 much valuable information. However, under coordinated assumptions that represent a middle-of-the-road
22 socioeconomic future (SSP2) (O'Neill et al., 2017a; Riahi et al., 2017) projected BECCS deployment in
23 2050 varies between four IAM models by an order of magnitude, from 1.3 to 12.8 GtCO₂ yr⁻¹, with a median
24 of about 6.8 GtCO₂ yr⁻¹ (Rogelj et al.). In the same models, but under sustainability assumptions that imply
25 land protection (SSP1; O'Neill et al., 2017), this range is 1.4 to 9.3 GtCO₂ yr⁻¹, with a median of about 4.5
26 GtCO₂ yr⁻¹. For similar reasons, similar variations can be found between land use evolutions in 1.5°C
27 pathways. Virtually all 1.5°C scenarios expand land for energy crop production (Section 2.4), but some do so
28 by less than 200 Mha by 2050 (Bertram et al.; Liu et al.; van Vuuren et al.) while others do so by 500 Mha
29 and more (Rogelj et al.). Again, under the same future middle-of-the-road assumptions (SSP2), projected
30 energy crop expansion by 2050 varies between about 200-700 Mha across models (Rogelj et al.), with a
31 median of 450 Mha. Under more sustainability focussed assumptions (SSP1), this range is 93 to 497 Mha,
32 with a median of 207 Mha (Rogelj et al.). To understand the ultimate trade-offs between CDR and other
33 societal objectives which rely on land (food security, biodiversity, ...) dedicated scenario are needed
34 (Bertram et al.) which explore this question in an integrated fashion.

Footprints of NETS (Sabine, Ch 4, et al) Option	Potentials	Cost	Require d land	Require d water	Impact on nutrients	Impact on albedo	Permanence
	GtCO ₂ y ⁻¹	\$ per tCO ₂	Mha GtCO ₂ ⁻¹	km ³ GtCO ₂ ⁻¹	Mt N, P, K y ⁻¹	No units	No units
BECCS	1.5-5.8	40.4-100.1	31.4-57.9	59.5	Variable	Variable, depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g., no-till farming for crops)	Long-term governance of storage; limits on rates of bioenergy production and carbon sequestration

<i>Afforestation & Reforestation</i>	3.7-6	4.5-25.2	79.3	91.7	0.5	Negative; or reduced GHG benefit where not negative	Saturation of forests; vulnerable to disturbance; post-AR forest management essential
<i>Enhanced Weathering</i>	2.4-5.2	15.1-321.1	2.7	0.4	0	0	Saturation of soil; residence time from months to geological time scale
<i>Biochar</i>	1.7-4.6	117-135	15.6-101.3	0	N:8.2, P:2.7, K:19.1	0.08–0.12	Mean residence times of biochar range between decades to centuries depending on soil type, management, and environmental conditions
<i>Soil carbon sequestration</i>	1.5-4.7	40-80	0	0	N:21.8, P:5.5, K:4.1	0 ¹	Soil sinks saturate and are reversible when the management practice promoting SCS ceases

Cross-Chapter 3.1, Table 1: 2050 potentials ranges for land-based carbon removal options (interquartile literature range, source: (Fuss et al., 2017)), cost (full literature range, source: (Fuss et al., 2017)), required land (based on 2100 estimate for mean potentials by (Smith et al., 2016)), required water (based on 2100 estimate for mean potentials by (Smith et al., 2016)), impact on nutrients (based on 2100 estimate for mean potentials by (Smith, 2016)) and albedo (Smith, 2016; Smith et al., 2016), constraints on permanence and saturation effects (Fuss et al., 2017). Not that other biophysical impacts of land-based CDR options beside albedo (e.g., through changes in evapotranspiration related to irrigation or land cover/use type) are not accounted for in this summary (see text for details).

If this is achieved with no-till farming, then increases of up to 0.1 could occur (Davin et al. 2014)

Table 1 displays the full range of potentials reported in the literature along with their cost and impacts for five land-based CDR options. They are assessed in more detail in Chapter 4, Section 4.3.6. The wide range for some of the options' potentials and costs can be explained by differing assumptions on sustainability conditions, technologies and availability of resources. BECCS for example can make use of first or second generation biofuels, biomass combustion for electricity generation or combinations of both. Similarly, afforestation potentials and costs are contingent on the type of plantations and their subsequent management. Note that recent research (Griscom et al., 2017) looks more closely into conservation, restoration, and improved land management actions that increase carbon storage and/or avoid GHG emissions across global forests, wetlands, grasslands, and agricultural lands. The maximum potential of these actions (when constrained by food and fiber security and biodiversity conservation) is 23.8 Gt CO₂-eq. y⁻¹. As this estimate overlaps with some of the options in Table 1, it is not included. It also includes avoided emissions, while Table 1 is about removals. However, it is important to note that (a) the potential is more than 30% higher than prior estimates, and (b) more than a third of cost-effective CO₂ mitigation needed through 2030 for a >66% chance of holding warming to below 2°C can be met with these options, of which a third can be delivered at or below 10 USD tCO₂-eq.⁻¹ by 2030.

Land use and biophysical feedbacks on climate (albedo, evapotranspiration)

Land use changes do not only affect climate through effects on the carbon cycle, but also through impacts on the energy and water balances (Bonan, 2008; Lawrence et al., 2016; Pitman et al., 2009). This is due to differences in albedo, evapotranspiration and roughness length between land cover, land use, and land management options (e.g., Luyssaert et al. 2014; Davin et al. 2014; Alkama and Cescatti 2016). In this context, while reforestation and afforestation may lead to a cooling through their impacts on the carbon cycle, this effect may be in part counterbalanced by a warming through albedo changes in high-latitudes (Alkama and Cescatti, 2016). Furthermore, potential large-scale implementations of BECCS may require an expansion of crop areas. The prevailing crop management, e.g., inclusion of no-till farming (Davin et al., 2014) or irrigation (Thiery et al., 2017) may substantially affect projected changes in regional climate, in particular temperature extremes (Hirsch et al., 2017). Bar a few exceptions (Jones et al. 2015, Kreidenweis et al. 2016), these biophysical feedbacks of land use management options are not included and hence not considered in present-day Integrated Assessment Models (IAMs) but are relevant for the development of sustainable scenarios optimizing regional climate responses. It has been thus suggested that biophysical feedbacks of land use should be accounted for in the assessment of ecosystem services (Seneviratne et al.).

1 At the moment, Earth-System Models disagree on biophysical climate responses to land cover changes (de
2 Noblet-Ducoudré et al., 2012; Pitman et al., 2009), and also present some systematic biases (Lejeune et al.,
3 2017). Also IAMs present large divergences in simulated changes in land cover and land use for low-emissions
4 scenarios (Popp et al., 2017; Seneviratne et al.). Hence the extent to which the associated biophysical feedbacks
5 could affect projections is still uncertain, but recent results suggest that in some cases, these could be as large
6 regionally for changes in temperature extremes as a modification of global mean temperature from 1.5° to 2°C
7 (Guillod et al.; Hirsch).

9 **Interactions of indirect Land Use Change (iLUC) with adaptation in agriculture and biodiversity sectors**

10 Combining the information in Table 1 concerning the land footprint of BECCS (namely, 31.4-57.9 Mha/ Gt
11 CO₂ sequestered annually) with estimations the contribution of BECCS in scenarios limiting warming to 1.5C
12 (median 6.8 Gt CO₂yr⁻¹, range 1.3-12.8) can provide an estimate of the total potential land footprint projected
13 by these scenarios, providing an estimate of (mean 213-394 Mha, full range 41-741 Mha). The largest
14 uncertainty in these estimates are the amount of BECCS deployed and also the nature of the BECCS, since in
15 some models BECCS is constrained to marginal and abandoned land (Popp et al 2014). This range of estimates
16 is also consistent with several existing examples in the literature (Popp et al. 2014, Humpenoder et al. 2014)
17 which estimate land area requirements for constraining CO₂ concentrations to 450-550 ppm or warming to
18 2C. However, one study argues that sequestration at a rate of 38.4 GtCO₂/year would be consistent with
19 limiting warming to 2C, implying 1.1-1.5Gha of land (Boysen et al 2017). On the other hand, other studies
20 report that limiting warming to 1.5°C can also be achieved without BECCS (Grubler et al. 2017; Holz et al .
21 2017). Mitigation pathways that rely heavily on BECCS sourced from first-generation biofuels or afforestation
22 with non-native trees to constrain warming to 1.5 or 2°C can create competition for land between biofuel
23 production, food production and biodiversity conservation (e.g., Williamson 2016), and risks to biodiversity
24 conservation and agricultural production are projected to result (Tavoni and Socolow 2013, Smith et al 2013)
25 (Section 5.3). This competition for land can cause further conversion of natural ecosystems, for example
26 through deforestation, and this is referred to in the literature as ‘indirect land use change (iLUC)’. Further, in
27 order for the agricultural sector to adapt to climate change, crops might need to be grown in new places, and
28 to help biodiversity adapt to climate change, we need to protect the places that are ‘climate refugia’ for
29 biodiversity and create ‘corridors’ to allow species to track their climate space, which means expanding the
30 protected area network (Price et al submitted). Some areas that are potentially productive for biofuel cropping
31 are also needed for biodiversity protection (Smith et al submitted).

33 **What isn’t in the IAMs**

34 IAMs generally only consider the carbon-cycle effects of land use changes. Biophysical feedbacks (e.g.,
35 through changes in albedo and evapotranspiration) are often not considered, with only few exceptions (Jones
36 et al., 2015; Kreidenweis et al., 2016). However, as highlighted above, they could substantially affect regional
37 climate in some cases to a similar extent as the choice between a 1.5°C and 2°C global warming. IAMs
38 currently consider mainly CDR options that rely on land, notably BECCS, afforestation and other land-
39 management options. Most of these come with risks for trade-offs with other policy goals such as ensuring
40 food security and safeguarding terrestrial ecosystems (Chapter 5.3). Other options to withdraw CO₂ from the
41 atmosphere (e.g., enhanced weathering, (Strefler et al., 2017) can help reducing the pressure on land and
42 augment the mitigation potential of a wider CDR portfolio.

43
44 **Land-based mitigation options and sustainable development.** Many land-based mitigation interventions
45 could help to deliver the SDGs, including sustainable and climate smart land/agricultural management, a shift
46 toward sustainable healthy diets and reduction of food waste. In addition, forestry mitigation options including
47 reducing deforestation, afforestation, and sustainable forest management can provide cost-effective measures
48 and in many cases, create negative emissions. Poorly implemented mitigation interventions could lead to trade-
49 offs and adverse side-effects for some sustainability dimensions. Their appropriate design and implementation
50 that considers local people’s needs, ethics and equity implications, biodiversity and other sustainable
51 development concerns can also provide large synergies with SDGs particularly within rural areas of developing

1 countries.

2
3 **Conclude** When mitigating in an effort to constrain warming to 1.5C, to avoid negative impacts on agriculture,
4 ecosystems and sustainable development, it is essential for mitigation to be designed to minimize the land use
5 footprint.

6
7 **[END BOX Cross-Chapter Box 3.1]**

8
9
10 **[START Cross Chapter Box 3.2 HERE]**

11
12 **Cross-Chapter Box 3.2: 1.5°C warmer worlds**

13 Sonia Seneviratne, Joeri Rogelj, Roland Séférian, Richard Wartenburger, Myles R. Allen, Marcos
14 Bruckeridge, Kristie L. Ebi, Neville Ellis, Ove Hoegh-Guldberg, Richard J. Millar, Antony J. Payne, Petra
15 Tschakert, and Rachel Warren

16
17 **Introduction**

18
19 The Paris Agreement provides climate goals in terms of global mean temperature (1.5°C or 2°C global mean
20 warming above pre-industrial times). However, there are several aspects that remain open regarding what a
21 “1.5°C warmer world” could be like, both in terms of mitigation and adaptation, as well as in terms of
22 projected warming and associated regional climate change, overlaid on anticipated and differential
23 vulnerabilities. **Alternative “1.5°C warmer worlds” resulting from mitigation and adaptation choices,
24 as well as from climate variability (climate noise), can be vastly different** as highlighted in this cross-
25 chapter box. In addition, the spread of models underlying 1.5°C projections also needs to be factored in.

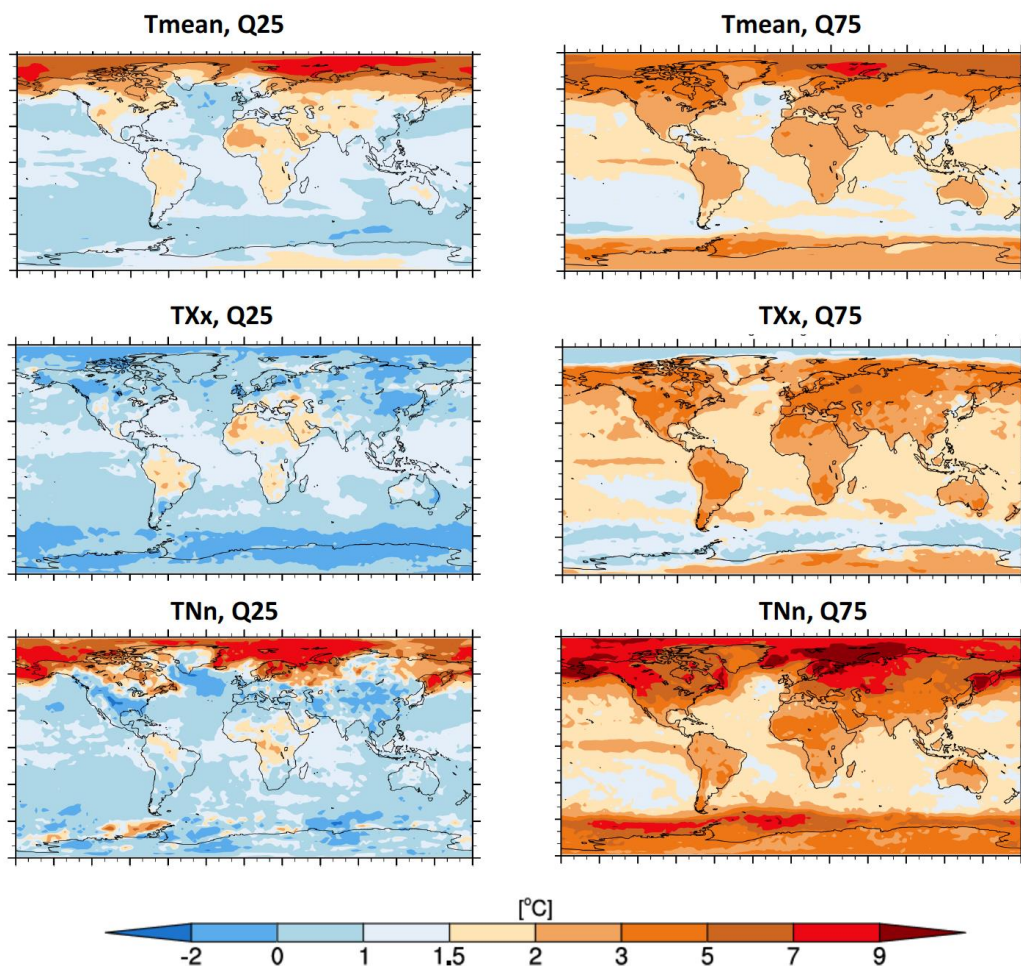
26
27 **Detail**

- 28
29 • **What is a 1.5° global mean warming, how is it measured, and what temperature warming does it
30 imply at single locations and at specific times?** Global mean temperature is a construct: It is the
31 globally averaged temperature of the Earth, which can be derived from point-scale ground observations
32 or computed in climate models (Chapters 1 and 3). Global mean temperature is additionally defined over
33 a given time frame, e.g., averaged over a month, a year, or multiple decades. Because of climate
34 variability, a climate-based global mean temperature typically needs to be defined over several decades
35 (at least 30 years under the definition of the World Meteorological Organization). Hence, whether or
36 when global temperatures reach 1.5°C depends to some extent on the choice of pre-industrial reference
37 period, whether 1.5°C refers to total or human-induced warming, and which variables and coverage are
38 used to define global average temperature change (Chapters 1 and 3). As highlighted in Chapter 1, using
39 the datasets and definitions in AR5, updated, this means that 1.5°C relative to pre-industrial corresponds
40 to 0.88°C (±0.06°C) warmer than the period 1986-2005, or 0.65°C (±0.1°C) warmer than the decade
41 2006-2015, consistent with stated “current level of warming of 0.85°C above pre-industrial levels” in the
42 2013-15 Structured Expert Dialogue. By definition, because the global mean temperature is an average
43 in time and space, there will be locations and time periods in which 1.5°C warming is exceeded, even if
44 the global mean temperature warming is at 1.5°C. In some locations, these anomalies can be particularly
45 large (Cross-Chapter Box 3.2 Figure 1).
- 46
47 • **Many impacts will be different in a world in which temperatures have stabilised at 1.5°C versus a
48 world in which average temperatures have temporarily reached 1.5°C and are continuing to warm.**
49 Land-sea temperature contrast is greater and the intensification of the global hydrological cycle is reduced
50 in a world at 1.5°C that continues to warm versus a world that is approaching equilibrium. Hence impacts

1 when temperatures reach 1.5°C on an overshoot scenario are not fully indicative of impacts after
 2 stabilisation at 1.5°C.

- 3
- 4 • **What is the impact of climate model spread for projected changes in climate at 1.5°C global**
 5 **warming?** The range between single model simulations of projected changes at 1.5°C can be substantial
 6 for regional responses (Chapter 3). For instance, for the warming of cold temperature extremes in a 1.5°C
 7 warmer world, some model simulations project a 3°C warming and others more than 6°C warming in the
 8 Arctic land areas (Box 3.1 Figure 2). For warm temperature extremes in the contiguous United States,
 9 the range of model simulations includes colder temperatures than pre-industrial (-0.3°C) and a warming
 10 of 3.5°C (Cross-Chapter Box 3.2 Figure 2). Some regions display even larger spreads (e.g., 1°C to 6°C
 11 regional warming in hot extremes in Central Europe at 1.5°C warming, Chapter 3). This large spread is
 12 due both to modelling uncertainty and internal climate variability. While the range is large, it also
 13 highlights risks that can be near certainly avoided in a 1.5°C warmer world compared to worlds at higher
 14 levels of warming (e.g., a 8°C warming in cold extremes in the Arctic is not reached at 1.5°C global
 15 warming in the multi-model ensemble, but it could happen at 2°C mean global warming, Cross-Chapter
 16 Box 3.2 Figure 2). Inferred projected ranges of regional responses (mean value, minimum and maximum)
 17 for different mitigation scenarios of Chapter 2 are displayed in Cross Chapter Box 3.2 Table 1.

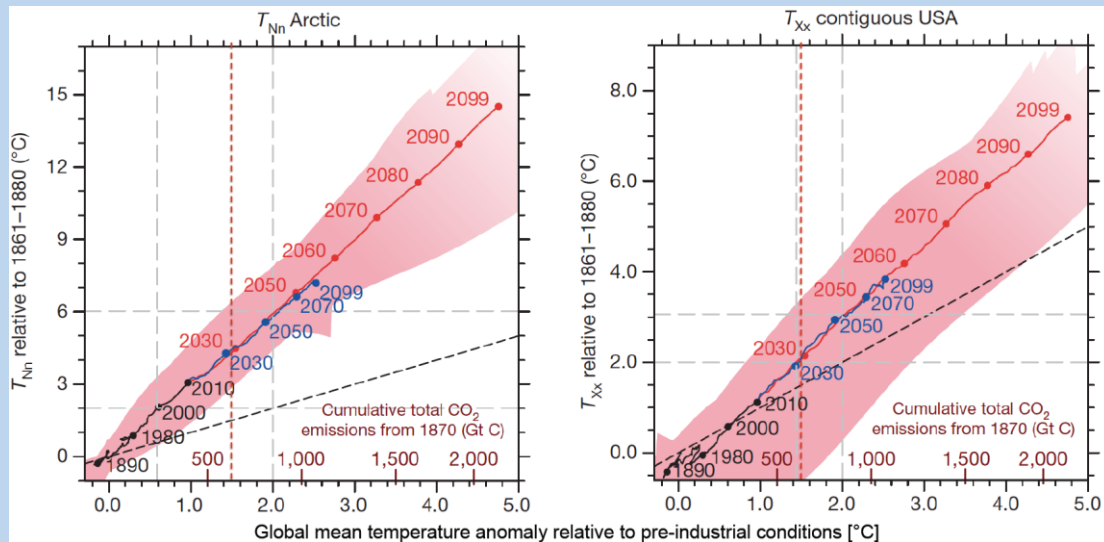
Temperatures with 25% chance of occurring in any 10-year period with
 $\Delta T = 1.5^\circ\text{C}$ (CMIP5 ensemble)



18

Cross-chapter Box 3.2, Figure 1: Stochastic noise and model-based uncertainty of realized climate at 1.5°C.

Temperature with 25% chance of occurrence at any location within 10-year time frames corresponding to $\Delta T_{\text{glob}}=1.5^{\circ}\text{C}$ (based on CMIP5 multi-model ensemble). The plots display at each location the 25th percentile (Q25, left) and 75th percentile (Q75, right) values of mean temperature (T_{mean}), yearly maximum day-time temperature (T_{Xx}), yearly minimum night-time temperature (T_{Nn}), sampled from all time frames with $\Delta T_{\text{glob}}=1.5^{\circ}\text{C}$ in RCP8.5 model simulations of the CMIP5 ensemble. From (Seneviratne et al.).



Cross-Chapter Box 3.2, Figure 2: Spread of projected multi-model changes in minimum annual night-time temperature (T_{Nn}) in the Arctic land (left) and in maximum annual day-time temperature (T_{Xx}) in the contiguous United States as function of mean global warming in climate simulations. The multi-model range (due to model spread and internal climate variability) is indicated in red shading (minimum and maximum value based on climate model simulations). The multi-model mean value is displayed with solid red and blue lines for two different emissions pathways (blue : RCP4.5 ; red : RCP8.5). The dashed red line indicates projections for a 1.5°C warmer world. The dashed black line displays the 1:1 line. [after Seneviratne et al., 2016]

- Impact of emissions pathways with vs without overshoot.** All currently available mitigation pathways projecting less than 1.5°C global warming by 2100 include some probability of overshooting this temperature, i.e. they include some time periods with higher warming than 1.5°C in the course of the coming decades (Chapter 2; Table 2.1). This is inherent to the difficulty of limiting global warming to 1.5°C given that we are already very close to this warming level. The implications of overshooting are very important for impacts, especially if the temperature at peak warming is high, because some impacts may be long-lasting and irreversible in the time frame of the current century, for instance sea ice melting and ecosystem mortality (Chapter 3). The chronology of emission pathways and their implied warming is also important for the more slowly evolving parts of the Earth system, such as those associated with sea level rise. On the other hand, if only very little overshoot is aimed for, the remaining equivalent CO_2 budget available for emissions is very small, which implies that large and immediate global efforts need to be invested in mitigation (Cross-Chapter Box 3.2 Table 1)

- 1 • **Probability of reaching 1.5°C global warming if emissions compatible with 1.5°C pathway are followed.** Emissions pathways in a “projective scenario” (see box on scenarios) compatible with a 1.5°C
2 global warming are determined based on their probability of reaching 1.5°C by 2100 (Chapter 2) given
3 current knowledge of the climate system response. Typically, this probability is set at 66% (i.e. 2/3
4 chances of reaching a 1.5°C global warming or lower). However, this implies that there is a 33%
5 probability that this goal will not be achieved (i.e. exceedance of 1.5°C global warming), even if a 1.5°C
6 pathway is followed, including some possibility of being substantially over this value (generally about
7 10% probability, see Cross Chapter Box 3.2 Table 1.). These alternative outcomes need to be factored in
8 the decision-making process. “Adaptive” mitigation scenarios in which emissions are continually
9 adjusted to achieve a temperature goal are implicit in the Paris global stocktake mechanism, and would
10 transfer the risk of higher-than-expected warming to a risk of faster-than-expected mitigation efforts, but
11 have thus far received less attention in the literature.
12
- 13
- 14 • **The transformation towards a 1.5°C warmer world can be implemented in a variety of ways,** for
15 example by decarbonizing the economy with an emphasis on demand reductions and sustainable
16 lifestyles, or, alternatively, with an emphasis on large-scale technological solutions, amongst many other
17 options (Chapter 2). **Different portfolios of mitigation measures come with distinct synergies and**
18 **trade-offs for other societal objectives.** Integrated solutions and approaches are required to achieve
19 multiple societal **objectives simultaneously.**
20
- 21 • **Risks and opportunities in 1.5°C warmer worlds. The risks to natural, managed, and human**
22 **systems in a 1.5°C warmer world will depend not only on uncertainties in the regional climate**
23 **which results from this level of warming, but also depend very strongly upon the methods that**
24 **humanity has used to limit warming to 1.5°C.** This is particularly the case for natural ecosystems and
25 agriculture (see Cross-Chapter Box 3.1 on Land Use). The risks to human systems will also depend on the
26 magnitude and effectiveness of policies and measures implemented to increase resilience to the risks of
27 climate change, and will depend on development choices over coming decades that will influence
28 underlying vulnerabilities.
29
- 30 • **Aspects not considered or only partly considered in the mitigation scenarios from Chapter 2** include
31 biophysical impacts of land use, water constraints on energy infrastructure, and regional implications of
32 choices of specific scenarios for tropospheric aerosol concentrations or the modulation of concentrations
33 of short-lived greenhouse gases. For comprehensive assessments of the regional implications of
34 mitigation and adaptation measures, such aspects of development pathways would need to be factored in.
35
- 36 • **Could solar radiation management help limit global temperature warming to 1.5°C?** Using SRM
37 could modify the global temperature, but it would create an entirely novel global and regional climate
38 (Cross-Chapter Box on SRM). In case of full deployment, it could substantially reduce tropical
39 precipitation as compared to a world without SRM, while moderate implementations could have less
40 negative impacts (Cross-Chapter Box on SRM). There would be minimal and indirect effects on CO₂
41 concentrations and thus ocean acidification. Depending on the level of implementation, it could also have
42 substantial potential for cross-boundary conflicts because of creating new “winners” and “losers”. Hence,
43 while the global mean temperature might be close to a 1.5°C warming with an SRM implementation, the
44 implications would be very different from those of a 1.5°C global warming reached with early reductions
45 of CO₂ emissions and stabilization of CO₂ concentrations
46
- 47 • **Commonalities of all 1.5°C warmer worlds:** Because the lifetime of CO₂ in the atmosphere is more
48 than 1000 years, the global mean temperature of the Earth responds to the cumulative amount of CO₂
49 emissions. Hence all **1.5°C stabilization scenarios require both net CO₂ emissions and multi-gas CO₂-**
50 **forcing-equivalent emissions to be zero** at some point in time (Chapter 2). This is also the case for
51 stabilization scenarios at higher levels of warming (e.g., at 2°C), the only difference would be the time at

1 which the net CO₂ budget is zero. Hence, **a transition to a decarbonisation of energy use is necessary**
 2 **in all scenarios**. It should be noted that **all scenarios of Chapter 2 include carbon capture and storage**
 3 to achieve the net-zero CO₂ emission budget, but to varying degrees. Because no scenarios explicitly tried
 4 to achieve their target without carbon capture and storage, it is nonetheless an open question whether this
 5 option is absolutely mandatory. CO₂-induced warming by 2100 is determined by the difference between
 6 the total amount of CO₂ generated (which can be reduced by early decarbonisation) and the total amount
 7 permanently stored out of the atmosphere, for example by geological sequestration.

- 8
- 9 • **Storylines of “1.5°C warmer worlds”:** Table 2 display possible storylines based on the scenarios of
 10 Chapter 2 and the impacts of Chapter 3. These storylines are not comprehensive of all possible future
 11 outcomes, but plausible scenarios of 1.5°C warmer worlds with two of them including a stabilization at
 12 1.5°C (Scenarios 1 and 2) and one only achieving a temporary stabilization through SRM before further
 13 warming and a warming stabilization at higher level (Scenario 3).

14 **Conclusions**

- 15
- 16
- 17 • **There is not only one “1.5°C warmer world”.** Important aspects to consider (beside that of global
 18 temperature) are how a 1.5°C global warming stabilization is achieved, including how the policies
 19 influence resilience for human and natural systems, and what are the regional and sub-regional risks. **The**
 20 **time frame to initiate major mitigation measures is essential** in order to reach a 1.5°C (or even a 2°C)
 21 global stabilization of climate warming (Cross-Chapter Box 3.2Table 1).

22 **Cross-Chapter Box 3.2, Table 1:** Different worlds resulting from 1.5°C and 2°C mitigation (prospective) pathways,
 23 including 66% (probable) best-case outcome, and 10% worst-case outcome, based
 24 on Chapter 2 (FOD) scenarios and Chapter 3 assessments of changes in regional
 25 climate. [Placeholder for FGD : Will update the scenarios to Chapter 2 SOD version,
 26 and include ocean impacts (acidification, sea level rise), drought in Amazon
 27 rainforest, one Africa region, as well as a visual display of the data]

		Mitigation pathways (Chapter 2)					
		WB1.5 (well below 1.5°C) with 2/3 “probable best-case outcome” ^a	WB1.5 (well below 1.5°C) with 1/10 “worst-case outcome” ^b	Med1.5 (median 1.5°C) with with 2/3 “probable best-case outcome” ^a	Med1.5 (median 1.5°C) with 1/10 “worst-case outcome” ^b	WB2 (well below 2°C) with 2/3 “probable best-case outcome” ^a	WB2 (well below 2°C) with 1/10 “worst-case outcome” ^b
General characteristics of pathway	Overshoot > 1.5°C in 21 st century ^c	Yes (21/21)	Yes (21/21)	Yes (13/13)	Yes (13/13)	Yes (25/27)	Yes (20/27)
	Overshoot > 2°C in 21 st century	No (0/21)	Yes (17/21)	No (0/13)	Yes (13/13)	No (0/27)	Yes (27/27)
	Carbon capture and storage	Yes (FGD: GtC by when)	Yes (FGD: GtC by when)	Yes (FGD: GtC by when)	Yes (FGD: GtC by when)	Yes (FGD: GtC by when)	Yes (FGD: GtC by when)
	Cumulative CO ₂ emissions up to peak warming (relative to 2016) ^d	640–750	620–720	690–970	670–900	940–1110	850–1080
	Cumulative CO ₂ emissions up to 2100 (relative to 2016) ^d [GtCO ₂]	150–360		250–490		810–1030	
	Global GHG emissions in 2030 ^d [GtCO ₂ y-1]	18–26		26–39		26–38	
	Years of global net zero CO ₂ emissions ^d	2063–2073		2065–2069		2080–2090	
Possi	Global mean	1.7°C	2.05°C	1.78°C	2.14°C	1.9°C (1.85—	2.41°C

		Mitigation pathways (Chapter 2)					
		WB1.5 (well below 1.5°C) with 2/3 “probable best-case outcome” ^{7a}	WB1.5 (well below 1.5°C) with 1/10 “worst-case outcome” ^{7b}	Med1.5 (median 1.5°C) with 2/3 “probable best-case outcome” ^{7a}	Med1.5 (median 1.5°C) with 1/10 “worst-case outcome” ^{7b}	WB2 (well below 2°C) with 2/3 “probable best-case outcome” ^{7a}	WB2 (well below 2°C) with 1/10 “worst-case outcome” ^{7b}
	temperature anomaly at peak warming	(1.65—1.75°C)	(2.02—2.13°C)	(1.75—1.89°C)	(2.11—2.31°C)	1.94°C	(2.31—2.44°C)
	Warming in the Arctic ^c (TNn ^d)	5.02°C (3.03-8.05)	6.11°C (3.86-8.62)	5.23°C (3.32-8.27)	6.37°C (4.27-8.8)	5.59°C (3.56-8.3)	7.17°C (4.42-9.46)
	Warming in the contiguous United States ^e (TXx ^e)	2.45°C (-0.27 - 4.45)	2.95°C (0.54-5.05)	2.55°C (-0.06 - 4.8)	3.12°C (0.61-5.27)	2.71°C (0.16-4.77)	3.55°C (0.9-5.55)
	Warming in Central Brazil ^f (TXx)	2.72°C (1.71-4.21)	3.38°C (2.16-4.91)	2.83°C (1.9 - 4.46)	3.53°C (2.33-5.4)	3.07°C (2-4.58)	3.92°C (2.71-5.68)
	Drying in the Mediterranean region ^e	-1.31 (-5.26 – 1.34)	-1.59 (-6.09-0.96)	-1.42 (-5.54 – 1.15)	- 1.67 (-6.29 – 0.96)	-1.46 (-5.64 – 1.04)	- 1.7 (-5.97 – 0.87)
	Increase in heavy precipitation events ^e in Southern Asia ^e	11.9% (1.76-33)	13.4% (-2.18-47.85)	12.08% (2.95-44.23)	14.78% (-0.29-43.76)	12.44% (0.43-47.11)	17.9% (-0.63-43.12)
Possible climate range in 2100 (regional+global)	Global mean temperature warming by 2100	1.41°C (1.39—1.43°C)	1.81°C (1.79—1.87°C)	1.53°C (1.52—1.6°C)	1.95°C (1.93—2.06°C)	1.84°C (1.76—1.89°C)	2.38°C (2.26—2.43°C)
	Warming in the Arctic ⁱ (TNn)	4.31°C (2.01-6.48)	5.31°C (3.41-8.26)	4.65°C (2.53-7.5)	5.77°C (3.75-8.4)	5.41°C (3.34-8.27)	7.07°C (4.41-9.24)
	Warming in the contiguous United States ⁱ (TXx)	1.98°C (-0.69 - 3.69)	2.61°C (0.03 -4.79)	2.12°C (-0.51 - 3.78)	2.8°C (0.34-4.82)	2.65°C (-0.04 -4.8)	3.44°C (0.66-5.53)
	Warming in Central Brazil ⁱ (TXx)	2.3°C (1.24-3.43)	2.89°C (1.97-4.43)	2.5°C (1.54-3.88)	3.17°C (2.06-4.87)	2.95°C (1.95-4.46)	3.88°C (2.69-5.66)
	Drying in the Mediterranean region ⁱ	-1.09 (-4.22 – 1.43)	-1.45 (-5.6 – 1.19)	- 1.17 (-4.71 - 1.43)	-1.5 (-5.75 -0.9)	-1.44 (-5.56 – 1.15)	- 1.74 (-5.84 – 0.88)
	Increase in heavy precipitation events in Southern Asia ⁱ	9.49% (-4.82 - 25.15)	12.31% (2.11-42.84)	10.34% (-0.34 - 28.5)	12.46% (-1.46-49.32)	12.54% (2.76-44.23)	17.06% (-1.12-43.23)

Cross-Chapter Box 3.2, Table 2: Storylines of possible ‘1.5°C warmer worlds’

The following storylines build upon Table 1 and the assessments of Chapters 1-5. NB: These are only few of possible outcomes, their choice is subjective in nature and only serves illustrative purposes. See Supplementary Information for underlying evidence.

Scenario 1 [one possible storyline among best-case scenarios]:	In 2018, strong participation and support for the Paris agreement and its ambitious goals for reducing CO ₂ emissions by an almost unanimous international community has led to a time frame for net-zero emissions that is compatible with halting the global temperature warming to 1.5°C by 2100. The United States also participated in this effort, through bottom-up contributions from larger cities and larger states.
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<p>Mitigation: Early move to decarbonisation, decarbonisation designed to minimise land footprint, coordination and rapid action of world’s nations towards 1.5°C goal by 2100</p> <p>Internal climate variability: Probable (66%) best-case outcome for global and regional climate responses.</p>	<p>Electric cars became dominant on the market of private vehicles by 2025. Plants for carbon capture and storage were installed in the 2020s. Competition for land between bioenergy cropping, food production and biodiversity conservation was minimised by sourcing bioenergy for carbon capture and storage from agricultural wastes, algae and kelp farms. Agriculture was intensified in countries with coordinated planning associated with a drastic decrease in food wastage. This left many natural ecosystems in fairly good shape although the relocation of species toward higher latitudes and altitudes has resulted in extensive changes in biodiversity within anyone location. Adaptive measures such as the establishment of corridors for the movement of species and parts of ecosystems has become a central practice within conservation management. The movement of species presents new challenges for resource management as novel ecosystems, and pests and disease, increase. Crops were grown on marginal land and no-till agriculture was deployed. Large areas were reforested with native trees. Meat prices were increased to reduce meat consumption.</p> <p>By 2100, global mean temperature is on average 0.5°C warmer than in 2018. There was only a minor temperature overshoot during the century. In mid-latitudes, there are frequent hot summers, and precipitation events and storms tend to be more intense. Coastal communities struggle with the exacerbation of rising seas by stronger storms and inundation, and some have responded by moving, in many cases, with consequences for urban areas, plus the risks of potential conflicts from people moving into areas already occupied. In the Tropics, in particular in mega-cities, there are frequent deadly heatwaves, overlaid on a suite of development challenges and limitations in disaster risk management. Arctic sea ice and glaciers extent have decreased. Reduced Arctic sea ice has opened up new shipping lanes and commercial corridors within the ocean. The Mediterranean area has become drier and irrigation of crops has been expanded, drawing the water table down in many areas. The Amazon has been reasonably well preserved (both through avoided risk of droughts and reduced deforestation) and the forest services are working with the pattern observed at the beginning of the 21st century. While some climate hazards have become more frequent, timely adaptation measures have helped reduce the associated impacts for most, though poor and disadvantaged groups continue to experience high climate risks to their livelihoods and wellbeing. Coral reefs were in part able to recover after extensive dieback in the beginning of the 21st century. The Earth system, while warmer, is still recognizable compared to the 2000s and no major tipping points were reached. Crop yields have remained relatively stable. Aggregate economic damage of climate change impacts are relatively small, although there are some local losses associated with extreme weather events. The quality of life remains similar to that in 2018.</p>
<p>Scenario 2 [one possible storyline among mid-case scenarios]:</p>	<p>The international community continues to support the Paris Agreement and agree in 2018 on reduction targets for CO₂ emissions and time frames for net-zero emissions. However these targets are not ambitious enough to reach a stabilization at 2°C warming, let alone 1.5°C. In the 2020s, internal climate variability leads to higher warming than usual in a reverse development to what happened in the so-called “hiatus” period of the 2000s. Temperatures are regularly above 1.5°C warming although radiative forcing is consistent with a warming of 1.2°C or 1.3°C. Deadly</p>

<p>Mitigation: Delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), stabilization at 1.5°C after overshoot at 2°C</p> <p>Internal climate variability: First, 10% worst-case outcome (2020s), then normal internal climate variability</p>	<p>heatwaves in major cities (Chicago, Kolkata, Beijing, Karachi, Rio de Janeiro), forest fires in California, Southern Europe, and Sydney, and major flooding in Asia, lead to increasing levels of public unrest and political destabilization. An emergency global summit is organized in 2025 to move to much more ambitious climate targets. Costs for rapidly phasing out fossil fuel use and infrastructure, while rapidly expanding renewables to reduce emissions are much higher than in Scenario 1 due to a failure to support economic measures to drive the transition.</p> <p>Temperature peaks at 2°C by the middle of the century, before decreasing again due to intensive implementation of bioenergy plants with carbon capture and storage. Reaching 2°C for several decades eliminates or severely damages key ecosystems such as coral reefs and tropical forests. The elimination of coral reef ecosystems leads to loss of the calcified structures that line coastlines in the tropics, with consequences for coastal communities, which are also facing steadily rising sea levels. The intensive area required for the production of bioenergy combined with increasing water stress sets pressures on food prices, driving elevated rates of food insecurity, hunger and poverty. Crop yields decline significantly in the tropics, leading to prolonged famines in some African countries. Food trumps environment in most countries with the result that natural ecosystems diminish due to climate change but also as a result of land-use change. The ability to implement adaptive action to prevent the loss of ecosystems is frustrated under the circumstances and is consequently minimal. Many natural ecosystems, in particular in the Mediterranean, are lost due to the combined effects of climate change and land use change and extinction rates rise. Massive loss of biodiversity and high levels of extinction take place in the major biomes of the world.</p> <p>By 2100, a global temperature of 1.5°C has been reached and tropical crop yields recover. Several of the remaining natural ecosystems have experienced irreversible damages and there have been many species extinctions. Migration, forced displacement, and loss of identity have been extensive in some countries, reversing some achievements in sustainable development and human security. Aggregate economic impacts of climate change damage are small, but the loss in ecosystem services instead creates large economic losses. The well-being of people has generally decreased since 2018, while the levels of poverty and disadvantage have increased very significantly.</p>
<p>Scenario 3 [one possible storyline among worst-case scenarios]:</p> <p>Mitigation: Uncoordinated action, short-term SRM deployment and 1.5°C global temperature in mid-century, 2100 stabilization at 3°C</p>	<p>Some countries withdraw from the Paris agreement in 2020. In the following years, reduced CO₂ emissions are implemented at local and country scale but efforts are limited and policies fail at local to global levels. Although radiative forcing is increasing, major climate catastrophes do by chance not happen, but there are more frequent heatwaves in several cities and less snow in mountain resorts in the Alps, Rockies and Andes. A 1.5°C warming is reached by 2030, but no major changes in policies occur. Starting with an intense El Niño-La Niña phase in 2038, several catastrophic years take place. An unprecedented drought leads to large impacts on the Amazon rain forest, which has also been affected by deforestation. A hurricane with intense rainfall and associated with high storm surges destroys part of Miami. Some Caribbean Islands cannot recover in time between two hurricane events and populations have to abandon the region. A 2-year drought in the Great plains and a concomitant drought in Eastern Europe and Russia lead to a decline of global crop production and major increases in food prices. Poverty levels increase to a very large scale and risk and incidence of starvation increase very significantly as food</p>

<p>Internal climate variability: First unusual (ca. 10%) best-case scenario, then normal internal climate variability</p>	<p>stores dwindle in most countries.</p> <p>A unilateral decision of SRM deployment is taken by a small coalition of states that are not part of the Paris agreement. The global temperature is momentarily maintained to 1.5°C global warming, but CO₂ emissions and concentrations continue to increase, and the SRM level is thus continuously intensified, with increasingly negative trade-offs. Following monsoon decreases in Asia, which commentators attribute to the SRM deployment, there are major international diplomatic tensions and the SRM program is abandoned. This is followed by a rapid short-term warming to 2°C. Major ecosystems (coral reefs, pristine forests) are destroyed over that period with massive disruption to local livelihoods. After peak oil is reached, countries invest massively in renewable energy and develop technologies for carbon capture and storage.</p> <p>Global mean warming is stabilized at 3°C by 2100, the world as it was in 2018 is no longer recognizable, droughts and water resources stress has rendered agriculture un-viable in some regions and contributed to increases in poverty. Progress on the sustainable development goals has been largely undone and poverty rates have reached a new high. Many countries have experienced massive emigration and immigration. Major conflicts took place. Almost all ecosystems have experienced irreversible impacts, species extinction rates have been high, and biodiversity has strongly decreased, resulting in extensive losses to ecosystem services. Life, for many Indigenous and rural groups, has become untenable in their ancestral lands. Several small island states have given up hope to survive in their places and look to an increasingly fragmented global community for refuge. Aggregate economic damages are substantial owing to the combined effects of climate changes and losses of ecosystem services. The general well-being of people has substantially decreased since 2018.</p>
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[END CROSS-CHAPTER BOX 3.2 HERE]

1 **Frequently Asked Questions**

3 **FAQ 3.1: What would a +1.5°C world look like?**

5 *A world that is warmer by 1.5°C above preindustrial levels will experience stronger impacts of climate*
6 *change than today (at ~1°C warming). This warming will not be uniform across the globe, with some regions*
7 *experiencing far higher warming for periods of time. Land warms faster than the oceans, and will experience*
8 *as much as three times higher warming. Increases in extreme temperature events will occur, including an*
9 *increase in heatwaves, with urban areas being particularly vulnerable, and an increase in the frequency of*
10 *category 4 and 5 tropical cyclones. Fresh water availability will constrain human and ecosystem health and*
11 *industrial development more in a 1.5°C warmer world. This is largely in response to population growth but*
12 *partially as a consequence of climate change. Additionally, reductions in staple crop yield may occur and*
13 *livestock production could be compromised by increasing heat stress. There will be increasing pressure on*
14 *ecosystems, with dieback of rainforests and boreal forests plausible, and with large biome shifts occurring*
15 *within alpine regions.*

17 Knowing what a 1.5°C warmer world would look like, as compared to preindustrial levels, can help societies
18 plan adaptation strategies. Understanding how these impacts can vary, both spatially and over time, can help
19 to know when these actions could be implemented, and what the relative benefits are to acting sooner rather
20 than later.

22 A world that is, on average, 1.5°C warmer than preindustrial levels will experience higher levels of warming
23 over some regions, for given periods of time. Most land areas will experience temperature and extreme
24 temperature anomalies larger than 1.5°C, for some regions as much as three times higher. For example, the
25 Arctic, a highly sensitive region to climate change, is projected to have its coldest nights warm on average by
26 4.5°C. Additionally, some climate models project a mean warming for Central Europe and Central North
27 America's the hottest days of 4.5°C. In cities, where urban heat island effects are superimposed on regional
28 warming, there will be an increase in the occurrence of heatwaves compared to now.

30 Projections of changes in precipitation and heavy precipitation under 1.5°C of warming above preindustrial
31 levels are more uncertain than for temperature and temperature extremes. However, over much of the
32 Northern Hemisphere high latitudes precipitation is likely to increase, whilst much of the subtropics in the
33 Southern Hemisphere may plausibly become drier. A general increase in heavy precipitation events across
34 the globe is plausible, and may occur in association with a general increase in extreme river flood events.
35 The number of tropical cyclones is projected to decrease under 1.5°C of global warming, whilst the most
36 intense (category 4 and 5) cyclones are projected to occur more frequently. The accumulated cyclonic energy
37 is projected to increase globally and consistently so for the North Atlantic, northwestern Pacific and
38 northeastern Pacific Oceans, but with slight decreases projected for the South Pacific, northern Indian and
39 southern Indian Oceans. There are regions that may increasingly experience periods of drought under 1.5°C
40 of warming, including the Mediterranean region (southern Europe, northern Africa, and the near-East),
41 northeastern Brazil and southern Africa. The area of permafrost may decrease significantly under 1.5°C of
42 warming, by as much as 21-37%, with associated decreases in snow cover. Year-round sea-ice is likely to be
43 maintained in a +1.5°C world.

45 Changes over the past 50 years (representing ~0.5°C of global warming of the current state of an
46 approximate +1°C world) have included a steady shift in the biogeographical distribution of species, an
47 increasing frequency of devastating bushfires and decreasing crop yields. Further changes along these lines
48 may be expected. It is important to realize, however, that the assumption of a linear increase in impacts with

1 additional 0.5°C is highly conservative, and that changes in the frequency and intensity of changes are likely
2 to be non-linear.

3
4 About 80% of the world's population already suffers serious threats to its water security as measured by
5 indicators such as water availability, water demand, and pollution. Changes in population will generally have
6 a greater effect on changes in water resource availability under 1.5°C of global warming, but related climate
7 change will contribute to an overall increase in fresh water scarcity.

8
9 Key staple crops such as maize will be under increased pressure under 1.5°C of warming, with a 10%
10 decrease in the global maize crop yield and with losses in the maize cropping areas in Africa being
11 potentially as large as 40%. Livestock production is to be affected negatively as well, mostly through a direct
12 response to increased heat-stress. Ecosystems are to experience increased stress under 1.5°C of warming.
13 Rainforests will plausibly experience biomass loss and increased dieback, with the boreal forests also to
14 experience dieback at their southern boundaries. Alpine regions are to experience severe biome shifts and
15 reduced grassland primary productivity, whilst temperature increases of up to 8°C in Arctic regions will also
16 threaten the natural biodiversity. Shrublands and Fynbos in semi-arid regions are to experience significant
17 losses in areas of suitable climate, in response to rainfall decreases and increases in temperature and fire.
18 Small islands are estimated to lose 70-90% of coral reefs even if global warming can be restricted to 1.5°C.
19 Global warming of 1.5°C will likely increase human heat-related mortality, ozone-related mortality if
20 precursor emissions the same, and is likely increase undernutrition. Generally warmer temperatures are
21 likely to affect the transmission of infectious diseases, with increases and decreases projected depending on
22 disease (e.g., malaria, dengue, West Nile virus, and Lyme disease), region, and degree of temperature
23 change. The magnitude and pattern of future impacts will very likely depend on the extent and effectiveness
24 of additional adaptation and vulnerability reduction.

25
26 *[Placeholder: to include text on how the impact could vary depending on the pathway taken to reaching*
27 *global warming of 1.5°C above preindustrial levels.]*

28
29 *[Figure Suggestion: Summary figure showing main impacts of global warming of 1.5°C, this could feature a*
30 *global map highlighting key regions of change. If possible, show regions where these impacts could change*
31 *if the 1.5°C warming experienced is a stabilised level or if global temperatures are continuing to rise.]*

32
33
34 **FAQ 3.2:** Is a +1.5°C world different to a +2°C world?

35
36 *Understanding the difference between 1.5°C and 2°C of global warming relative to the preindustrial period*
37 *is central to a safe and sustainable future. Before the Paris Agreement was signed in 2015, the world mostly*
38 *focused on holding global warming to 2°C. Yet now, new scientific literature is emerging that highlights*
39 *negative impacts from a 2°C or even lower global warming. There are negative impacts from a global*
40 *warming of 1.5°C but these are less severe than compared to a 2°C increase in global temperatures.*

41 42 **Extreme events**

43 Global warming of 2°C vs 1.5°C is likely to lead to more frequent and more intense hot extremes in most
44 land regions as well as to longer warm spells. Impacts on cities at both 1.5°C and 2.0°C of warming would
45 include a substantial increase in the occurrence of heatwaves compared to the present-day, with temperature
46 related health risks being lower in some but not all cities under 1.5°C of global warming. Several regions are
47 to experience stronger increases in heavy precipitation at 2°C vs 1.5°C of warming, including high-latitude
48 regions (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia),

1 high-altitude regions (Tibetan Plateau) as well as in Eastern Asia and in Eastern North America. In terms of
2 drought, limiting global warming to 1.5°C may substantially reduce the probability of extreme changes in
3 water availability in several regions including the Mediterranean (Southern Europe, northern Africa, and the
4 near-East), in Northeastern Brazil and southern Africa. Constraining global warming to 1.5°C compared to
5 2°C, reduces global water resources stress by an estimated 50% (relative to 1980-2009). In food production
6 systems, limiting warming to 1.5°C above preindustrial levels significantly reduces risks to crop production
7 in Sub-Saharan Africa, West Africa, Southeast Asia, and Central and South America, as compared to 2°C of
8 warming.

9 10 **Ice-regions**

11 Summer-season Arctic sea-ice is likely to persist in a +1.5°C world, the Arctic may retain some summer sea
12 ice but under 2°C (or higher) warming this ice could disappear. Moreover, holding global temperatures to
13 1.5°C could prevent the melting of an estimated 2 million km² of permafrost, but this the release of this
14 thawed carbon is expected to be over many centuries. The world's ice sheets are melting at high rates with
15 significant millennial scale thresholds in both Greenland and Antarctica around 1.5 and 2.0°C. Consequently,
16 a 1.5°C world may also have a significantly reduced probability of a long-term commitment to multi-metre-
17 scale sea level rise. Ocean acidification associated with 1.5°C of warming will be much less damaging than
18 that at 2°C or more. Only 10% of today's coral reefs are likely to survive in a 1.5°C warmer world, and
19 almost no reefs will survive a 2.0°C world.

20 21 **Ecosystems**

22 Constraining warming to 1.5°C versus 2°C is projected to limit biome shifts to high latitudes and altitudes to
23 10% average, as opposed to 25% under 2°C of warming. Habitats at high latitudes will see reduced
24 establishment of woody species in tundra areas, faunal hibernation and migration (high confidence) in a
25 1.5°C versus 2°C world. In a 2°C world, there are higher risks to the extinction of some species but this is
26 reduced in a 1.5°C warmer world. Furthermore, this would reduce risks of other biodiversity factors such as
27 forest fires, storm damage and the geographic spread of invasive species, pests and diseases. The risks of
28 declining ocean productivity, loss of fisheries, and changing ocean chemistry are lower when warming (and
29 corresponding atmospheric greenhouse gas concentrations) is restrained to 1.5°C above pre-industrial levels.

30 31 **Humans**

32 Warming of 2°C poses greater risks to human health than warming of 1.5°C, sometimes with complex
33 regional patterns. Average global temperatures that extend beyond 1.5°C could increase poverty and
34 disadvantage in many populations. By the mid to late of 21st century, climate change is projected to be a
35 poverty multiplier that makes the poor poorer and increases the total number of people in poverty. The risks
36 for dependent coastal communities (which number in the hundreds of millions of people) from reduced
37 income, livelihoods, cultural identity, coastal protection, protection from erosion, and health are lower with
38 1.5°C of global warming compared to 2°C. Keeping global temperature to 1.5°C will still prove challenging
39 for small island developing states (SIDS), which are already facing the threat from climate change at 1°C of
40 warming. At 1.5°C, the accumulated impacts from projected climatic change will be felt across multiple natural
41 and human systems that important to SIDS. These impacts contribute to loss of / change in ecosystems,
42 freshwater resources and associated livelihoods, economic stability, coastal settlements and infrastructure.
43 There are potential benefits to SIDS from avoided risks at 1.5°C versus 2.0°C, especially when coupled with
44 adaptation efforts.

45
46 *[Figure Suggestion: Summary figure showing the main differences between 1.5°C and 2°C global warming*
47 *above pre-industrial levels. Similar to Figure 3.21.]*
48

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