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 Brilli (Italy), Sally Brown (United Kingdom), William Cheung (Canada), Jason Evans (Australia), Hubertus Fisher (Switzerland), Klaus Fraedrich (Germany), Sabine Fuss (Germany), 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), Dann Mitchell (United Kingdom), Dirk Notz (Germany), Lennart Olsson (Sweden), Michael Oppenheimer (United States of America), Shlomit Paz (Israel), Mohammad Feisal Rahman (Bangladesh), Carl-Friedrich Schleussner (Germany), Roland Séférian (France), Jana Sillmann (Germany/Norway), Mouhamadou B. Sylla (Senegal), Petra Tschakert (Australia/Austria), Richard Wartenburger (Germany/Switzerland), Gary Yohe (United States of America), Robert B. Zougmoré (Burkina Faso/Mali)

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

Chapter Scientist: Tania Guillén B. (Germany/Nicaragua)

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Executive summary

Overview: Pathways to 1.5°C warming, "1.5°C warmer worlds"

There are different ways in which a 1.5°C global warming can be realised, with different pathways and related impacts {3.2.1; 3.3; cross-chapter Box 3.12 on "1.5°C warmer worlds"}. This means the impacts of 1.5°C global warming cannot be determined without some associated degree of uncertainty.

The impacts of a 1.5°C warmer world will depend on the pathway by which 1.5ºC is reached. Projected impacts at 1.5°C vary depending on whether global temperature (a) reaches 1.5°C only temporarily (i.e., a transient phase on its way to higher levels of warming); (b) reaches 1.5°C after greenhouse gas concentrations have been stabilised (i.e., without overshoot); (c) reaches 1.5°C after greenhouse gas concentrations have been stabilised but including an overshoot; or (d) arrives at 1.5°C as part of long-term climate equilibrium (i.e., after several millennia) {3.2.1, 3.3}. The differences between a "1.5°C climate" reached via pathways a, b, and c are small for some climate variables (e.g., regional temperature and precipitation 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 warmer worlds"}

A climate characterised by mean global warming of 1.5°C is determined over a climatological period (i.e., typically 20-30 years on average). By definition, a 1.5°C warmer world includes temperatures that are warmer and cooler than 1.5°C across different regions, years and seasons. {3.3.1, 3.3.2, cross-chapter Box 3.12 on "1.5°C warmer worlds"}

Some of these regional and temporal variations are systematic. In particular, terrestrial regions will warm more than oceanic regions over the coming decades (transient climate conditions). Extreme hot days warm more than mean temperatures across mid-latitude continental regions (e.g., Central Europe, Central North America, Southern Africa) and the coldest days of the year warm more than mean temperature in snow and/or ice-covered regions (e.g., in Arctic land regions, snow-cover mountainous regions). {3.3.1, 3.3.2, cross-chapter Box 3.12 on "1.5°C warmer worlds"}

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

Decisions on changes in land use can strongly affect regional climate change through biophysical feedbacks (e.g., changes in land evaporation or surface albedo), potentially affecting regional temperature and precipitation. However, these effects are not considered in the development of the socio-economic pathways in Chapter 2. {3.7.2.1}

Changes in climate at 1.5°C global warming (temperature, precipitation, drought)

At present (year 2017), global warming has reached approximately 1°C compared to pre-industrial levels {Chapter 1, 3.3.1}. Consequently, global mean temperature of 1.5°C corresponds to an additional warming of 0.5°C compared to present. However, impacts can only be partly inferred based on observations because of the presence of non-linear and lag effects for some climate variables (e.g., sea level rise, snow and ice melt) and the fact that the observed record only represents one possible realisation of the climate system. {3.2.1, 3.3.3, cross-chapter Box 3.12 on "1.5° warmer worlds"}

While the impacts of observed warming to date are likely to underestimate the consequences of an additional 0.5°C global warming (as discussed in the preceding paragraph), the effect of half a degree of global warming on temperature and precipitation extremes is already detectable in the observational record {3.3.1}. Similarly, analyses of transient climate projections reveal observable differences between 1.5°C and 2°C global warming in terms of mean temperature and extremes, on a global scale and for most land regions {3.3.1, 3.3.2, 3.3.13}. Such studies also reveal detectable differences between 1.5°C and 2°C global warming precipitation extremes in many land regions {3.3.1, 3.3.3, 3.3.13}. For mean precipitation, meteorological drought (accumulated precipitation deficits), hydrological drought (streamflow deficits), and agricultural drought (soil moisture deficits) there is substantially lower risk in the Mediterranean region at 1.5°C compared to 2°C. {3.3.4}

Given the attributed impacts of past changes in temperatures and the fact that a 1.5°C climate is significantly different from a 2°C climate in terms of temperature extremes on global scale and in many regions {Sections 3.3.1 and 3.3.2}, it can be inferred that the impacts on natural and human systems are substantially reduced by limiting global mean temperature rise to 1.5°C compared to 2°C. Nonetheless, it should be noted that 1.5°C global warming carries a substantial increase in risk to natural and human systems compared to the 1°C warming experienced to date. Hence, warming of 1.5°C can not be considered a "safe" option and requires climate change adaptation if impacts are to be reduced or avoided.

Natural and managed systems

According to the available literature on natural and managed systems, limiting warming to 1.5°C rather than 2°C would carry significant benefits for terrestrial, wetland, coastal, and ocean ecosystems including coral reefs, freshwater systems, and food production systems (i.e., fisheries and aquaculture).

Constraining warming to 1.5°C, compared to 2°C, is projected to halve the climate change related increase in the risk of species extinction, as well as reduce the risks of decline in terrestrial and wetland ecosystem services. A 1.5°C warming limit would roughly constrain the global area of biomes projected to be transformed by climate change to around 10%, compared to around 25% with 2°C of warming. Limiting warming to 1.5°C, compared to 2°C is also projected to reduce climate change induced species range loss, forest fire risk, and the geographic spread of invasive species, pests and diseases. In the Mediterranean, research has identified a possible tipping point between 1.5°C and 2°C warming, above which the biome experiences changes that are unprecedented in the last 10,000 years. In high latitudes, limiting global warming to 1.5°C rather than 2°C would prevent the melting of an estimated 2 million km^2 of permafrost.

Large-scale changes in ocean systems occur as the world warms to 1.5°C above pre-industrial levels. In the transition to 1.5°C, changes to water temperatures will drive some species to relocate and novel ecosystems to appear. Other ecosystems are relatively less able to move, however, and will experience high rates of mortality. A large portion of the coral reefs that exist today will disappear as average global surface temperature reaches 1.5°C above pre-industrial levels, for example. Fisheries and aquaculture will be negatively affected by relocating stocks, and the increased risk of invasive species and disease. Coastal human communities will experience changes to food, income and livelihoods. Nevertheless, there are clear advantages to restraining ocean warming and acidification to levels consistent with a 1.5°C warmer world, compared to 2°C. The risks of declining ocean productivity, distributional shifts and loss in fisheries, and changing ocean chemistry (e.g., acidification, hypoxia) are lower when warming is restrained to 1.5°C above pre-industrial levels. Studies reveal substantial benefits for marine fisheries (a major food source for people) if the 1.5°C global warming target is achieved. Similarly, the risks for dependent coastal communities (which number in the hundreds of millions of people) from reduced income, likelihoods, cultural identity, coastal protection, protection from erosion, and health are much lower with 1.5°C of global warming compared to 2°C.

In freshwater systems, constraining warming to 1.5°C, compared to 2°C, reduces climate-change induced increases in global water resources stress relative to 1980-2009 by an estimated 50%, with particularly large benefits in the Mediterranean. In food production systems, limiting warming to 1.5°C above preindustrial levels significantly reduces risks to crop production in Sub-Saharan Africa, West Africa, SE Asia, and Central and South America, compared to 2°C of warming.

Floods

Regional projected changes in flood risk are consistent with projected patterns in precipitation under a warming scenario of 1.5°C with the largest increases in Asia, the U.S., and Europe.

Health

Warming of 2°C poses greater risks to human health than warming of 1.5°C, often with complex regional patterns. Linear associations between temperature and adverse health outcomes, including heat-related mortality, undernutrition, malaria, dengue, West Nile virus, and Lyme disease, mean that each additional amount of warming affects morbidity and mortality. The magnitude and pattern of future impacts will depend on the extent and effectiveness of additional adaptation and vulnerability reduction, and on mitigation for risks past mid-century.

3.1 Background and framing

The scientific evidence published since the SREX and AR5 on the impacts of 1.5°C global warming on natural and human systems compared to preindustrial times and to stronger warming is reviewed within this chapter. When possible, the focus is on the comparison of a 1.5°C versus 2°C scenarios. The chapter also adopts the risk-framing concept from AR5 as well as definitions of key terms like vulnerability.

The chapter is structured around key themes: from global and regional climate change and hazards (Section 3.3), to impacts on natural and managed ecosystem as well as on humans systems (Sections 3.4 to 3.5) and to avoid impacts and reduced risks (Section 3.6). It also synthesizes the key findings with respect to aggregated avoided impacts and reduced risks at 1.5°C versus stronger warming, and also examines the benefits of achieving 1.5°C, including economic benefits and avoiding of regional tipping points by the achievement of more ambitious global temperature goals and reducing rates of change (Section 3.7). The chapter concludes with key knowledge gaps (Section 3.8). Methods of assessments are summarized in Section 3.2 and conclusions from previous assessments are briefly mentioned in each section.

The geographical scope of the chapter is global, but also with focus on regional changes as well as hot spots. Regional information and hot spots are embedded within the section text or highlighted in chapter Boxes, which are regional (Box 3.3 on 'cold regions', Box 3.4 on SIDS, Box 3.7 on the Mediterranean Basin and the the Middle East, Box 3.8 on Sub-Saharan Africa) or topical (e.g. Box 3.2 on the hydrological cycle, Box 3.5 on tipping points, Box 3.6 on coral reefs in a 1.5°C warmer world, Box 3.9 on cascading and interacting impacts).

This chapter directly draws on Chapters 1 and 2 through the assessment of gradual versus overshooting scenarios and via the definition of potential 1.5°C warmer worlds (cross-chapter Box 3.12). Other interactions with Chapter 2 include the provision of specifics related to the mitigation pathways (e.g. land use changes) and their implications for impacts. The present chapter provides information for the assessment and implementation of adaptation options in Chapter 4, and the context for considering the interactions of climate change with sustainable development in Chapter 5.

3.2 Methods of assessment

3.2.1 Introduction

There are a variety of assessment methods that are used in this chapter given the breadth of fields considered in the chapter, which covers both changes in climate variables, typically addressed in IPCC WG1 reports, and changes in impacts on (natural and managed) ecosystems and humans, which are typically addressed in IPCC WG2 reports. For this reason the underlying data and literature basis for this chapter are broad. For instance, the main relevant prior IPCC material covers two chapters of the IPCC SREX report for physical changes in extremes and the 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 (Hartmann et al. 2013; Bindoff et al. 2013; Collins et al. 2013; Church et al. 2013; Christensen et al. 2013), as well as many chapters of the IPCC WG2 AR5 report with respect to impact assessments associated with climate change (e.g. Jiménez Cisneros et al. 2014; Settele et al. 2014a; Wong et al. 2014; Pörtner et al. 2014a; Porter et al. 2014; Revi et al. 2014; Dasgupta et al. 2014; Cramer et al. 2014; Oppenheimer et al. 2014). Several other chapters of past IPCC reports also provide useful assessments for the present report. In some cases, methods that were applied in the IPCC WG1 and WG2 reports presented differences and needed to be harmonized for the present report. Additionally, the fact that changes in the amount of warming at 1.5°C global was not a focus of past IPCC reports meant that dedicated approaches, in part based on the recent literature, had to be applied that are specific to the present report.

Methods applied for assessing observed and projected changes in climate and weather are presented in Section 3.2.2 and methods applied for assessing observed impacts and projected risks to natural and managed systems and human settlements are described in Section 3.2.3. Background on the IPCC calibrated language applied, in the assessments of this chapter, is provided in Chapter 1 of this report.

3.2.2 Methods for assessing observed and projected climate and weather changes at 1.5°C

Climate models are necessary for the investigation of the response of the climate system to various forcings, to perform climate predictions on seasonal to decadal time scales, and to compute projections of future climate over the coming century. Using these various time frames, global climate models and downscaled output from global climate models (Section 3.2.2.3) are also used as input to impact models to evaluate the risk related to climate change for natural and human systems.

In previous IPCC reports (e.g. IPCC 2007, 2013), climate model simulations were generally used in the context of given 'climate scenarios'. This means that emissions scenarios (Nakicenovic et al. 2000) were used to drive climate models, providing different projections for given emissions pathways. The results were consequently used in a 'storyline' framework, and so presenting the development of climate in the course of the 21st century and beyond if a given emissions' pathway was followed. Results were assessed for different time slices within the model projections, for example 2016-2035 ('near term', which is a bit below a 1.5°C global warming in most scenarios, Kirtman et al. 2013), 2046-65 (mid 21st century, Collins et al. 2013), and 2081-2100 (end of 21st century, Collins et al. 2013). Given that this report focuses on climate change for a given mean global temperature response (1.5°C or 2°C), methods of analysis needed to be developed and/or adapted in order to use existing climate model simulations for this specific purpose.

The following subsections address the following topics. Section 3.2.2.1, addresses the question of how to derive 'climate scenarios' for given global warming limits (e.g. 1.5°C or 2°C warming). Section 3.2.2.2 presents the climate models and associated simulations available to assess these changes in climate at given global temperature limits. Section 3.2.2.3 introduces methods that have been used in previous IPCC reports for the attribution of observed changes in climate and how these can be expanded to assess changes in weather and climate associated with a global warming of 1.5°C or 2°C when no climate simulations are available.

3.2.2.1 Definition of a '1.5°C or 2° C climate projection'

The main challenges of assessing climate changes for a 1.5°C (or 2°C and higher-level) global warming include the followings:

A. Distinguishing a) *transient climate responses* (i.e. 'passing through' 1.5°C or 2°C global warming), b) *short-term stabilization responses* (i.e. late 21st-century output of simulations driven with emissions scenarios stabilizing mean global warming to 1.5°C or 2°C C by 2100), and c) *long-term equilibrium stabilization responses* (i.e. output of simulations at 1.5°C or 2°C once climate equilibrium is reached, i.e. after several millenia). These various responses can be very different for climate variables that respond with some inertia to a given climate forcing. A striking example is sea level rise, for which the projected increases within the 21st century are only slightly dependent on the considered scenario, but which would stabilize at very different levels for a long-term warming of 1.5°C vs 2°C (see Section 3.3.12).

B. The '1.5°C or 2°C emissions scenarios' presented in Chapter 2 are targeted at a *probable* stabilization at around 1.5°C or 2°C global warming by the end of the 21st century. However, when these emissions scenarios are used to drive climate models, the resulting simulations include some that stabilize above these respective thresholds (typically with a probability of 1/3, i.e. 33%, see Chapter 2 and Cross-chapter box 3.12 on '1.5°C warmer worlds'). This is due both to model discrepancies and internal climate variability. For this reason, the climate outcome for any of these scenarios, even those excluding an overshoot (see next point), include some probability of reaching a global climate warming higher than 1.5°C or 2°C. Hence, a comprehensive assessment of '1.5°C or 2°C climate projections' needs to include the consideration of projections stabilizing at higher levels of warming (e.g. up to 2.5-3°C at most, see Chapter 2).

C. Most of the '1.5°C scenarios' and some of the '2°C emissions scenarios' of Chapter 2 include a temperature overshoot during the course of the 21st century. This means that they allow for higher temperatures being reached in the course of the century (typically up to 0.5-1°C higher than the respective target levels at most), before a decline and final stabilization at 1.5°C or 2°C is achieved by 2100. During the overshoot, impacts would therefore correspond to higher transient temperature levels than 1.5°C or 2°C. For this reason, impacts for transient responses at these higher levels are also briefly addressed in Section 3.3. Most importantly, different overshooting scenarios may have very distinct impacts depending on a) the peak temperature at overshooting, b) the length of the overshoot period, c) the associated rate of changes of global temperature over the time period of the overshoot. While some of these issues are briefly addressed in Sections 3.3 and 3.6, and the cross-chapter box 3.11 on '1.5° warmer worlds', the question will need to be addressed more comprehensively as part of the IPCC AR6 report.

D. The meaning of '1.5°C or 2°C' climate was not defined prior to this report, although it is clearly defined relative to the climate associated with the Pre-Industrial climate conditions. This requires an agreement on the exact reference time period (for 0°C warming) and the time frame over which the global warming is assessed (e.g. typically a climatic time period, i.e. 20 or 30 years). As highlighted in Chapter 1, the decision for this report was to define a 1.5°C climate as the climate in which temperatures averaged over a multi-decade timescale are expected to be 1.5°C above the pre-industrial reference period or, 'equivalently in the absence of a substantial secular trend emerging in natural forcing, for which there is no evidence at present', a world in which human-induced warming has reached 1.5°C. The reference pre-industrial period was set over the 30-year period 1850-1879. This definition is used in all assessments of this chapter. This implies that mean temperature of a '1.5°C climate' can be regionally and temporally much higher (e.g. regional annual temperature extremes can display a warming of more than 6°C, see Section 3.3 and cross-chapter box on '1.5°C warmer worlds').

E. Non greenhouse-gas interferences of mitigation pathways can have important impacts on regional climate, for instance biophysical feedbacks from changes in land use and irrigation (e.g. Hirsch et al. 2017; Thiery et al. 2017), or projected changes in short-lived pollutants (e.g. Wang et al. 2017). While these effects are not explicitly integrated in the scenarios from Chapter 2, they may affect projected changes in climate at 1.5°C warming. They are addressed in more detail in Section 3.7.2.

There is at present a lack of climate model simulations for the low-emissions scenarios described in Chapter 2. Therefore, with a few exceptions, the present assessment needs to focus on analyses of transient responses at 1.5°C and 2°C (see point A. above), while short-term stabilization and long-term equilibrium stabilization responses could not be assessed in most cases due to lack of data availability (see also below). This shortfall needs to be addressed as part of the IPCC AR6 in order to provide a comprehensive assessment of changes in climate at 1.5° global climate warming. Note also that in the scenarios considered, unconventional pathways to climate mitigation are not assessed (e.g. solar radiation management). However, a short assessment on this topic is provided in Section 3.7.3 (see also Box 4.13).

The assessment of transient responses in climate at 1.5°C vs 2°C and higher levels of warming (Section 3.3 generally uses the 'time sampling' approach James et al. (2017) which consists of sampling the response at 1.5°C global temperature warming from all available global climate model scenarios for the 21st century (e.g Senevirante et al. 2016). Alternatively, pattern scaling, which is a statistical approach deriving relationships of specific climate responses as a function of global temperature change can also be used and some assessments of this chapter are also based on this method. The disadvantage of pattern scaling, however, is that the relationship may not perfectly emulate the models' response in each location and for each global temperature levels (James et al. 2017). As a third approach, expert judgement can be used to assess probable changes at 1.5°C or 2°C by combining changes that have been attributed for the observed time period (corresponding already to a warming of 1°C, Chapter 1) and known projected changes at 3°C or 4°C (see Section 3.2.2.4). In order to compare effects induced by a 0.5°C difference in global warming, it is also possible in a first approximation to use the historical record as a proxy by comparing two periods which have approximately this difference in warming, (e.g. such as 1991-2010 and 1960-1979, e.g. Schleussner et al. 2017). Using observations, however, does not allow an accounting for possible non-linear changes that would occur above 1°C or 1.5° global warming.

The method to define a 1.5°C or 2°C warming period from transient climate simulations, which builds the basis for the impact assessments within the IMPACT2°C project (Jacob and Solman, 2017) has been described in Vautard et al. (2014).

In a few cases, assessments for short-term stabilization responses could also be assessed using a subset of model simulations that reach a given temperature limit by 2100, but overall model simulations were lacking for such assessments. Nonetheless, some variables (temperature and precipitation extremes) include evidence that suggests that responses after short-term stabilization (i.e. approximately equivalent to the RCP2.6 scenario) are very similar to the transient response of higher-emission scenarios (Seneviratne et al. 2016). This is, however, less the case for mean precipitation (e.g. Pendergrass et al. 2015) for which other aspects of the emissions scenarios appear relevant.

For the assessment of long-term equilibrium stabilization responses, this assessment uses – when available – results from existing simulations (e.g. for sea level rise). Some other results are expected from upcoming projects (e.g. the ‘Half a degree additional warming, prognosis and projected impacts Multimodel Intercomparison Project’ (HappiMIP) (Mitchell et al. 2017)), but at present are not yet available.

3.2.2.2 Climate models and associated simulations available for the present assessment

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

In order to assess the impact and risk of projected climate changes on ecosystems or human systems, typical ESM simulations have a too coarse resolution (100km or more) in many cases. Different approaches can be used to derive higher-resolution information. In some cases, ESMs can be run globally with very-high resolution; however, such simulations are cost-intensive and thus very rare. Another approach is to use Regional Climate Models (RCM) to dynamically downscale the ESM simulations. RCMs are limited-area models with representations of climate processes comparable to those in the atmospheric and land surface components of the global models but with a higher resolution than 100km, generally down to 10-50km (e.g. CORDEX, Giorgi and Gutowski 2015; Jacob et al. 2014a; Cloke et al. 2013; Erfanian et al. 2016; Barlow et al. 2016) and in some cases even higher (convection permitting models, i.e. less than 4km, e.g. Kendon et al. 2014; Ban et al. 2014; Prein et al. 2015). Statistical downscaling is another approach for downscaling information from global climate models to higher resolution. Its underlying principle is to develop statistical relationships that link large-scale atmospheric variables with local / regional climate variables, and to apply them to coarser-resolution models (Salameh et al. 2009; Su et al. 2016). Nonetheless, at the time of writing, we note that there are only very few studies on 1.5°C climate using regional climate models or statistical downscaling.

There are various sources of climate model information available for the present assessment. First, there are global simulations that have been used in previous IPCC assessments and which were computed as part of the World Climate Research Programme (WCRP) Coupled Models Intercomparison Project (CMIP). The IPCC AR4 and SREX reports were mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. We note that the simulations of the CMIP3 and CMIP5 experiments were found to be very similar (e.g. Knutti and Sedláček 2012; Mueller and Seneviratne 2014). In addition to the CMIP3 and CMIP5 experiments, there are results from coordinated regional climate model experiments (CORDEX), which are available for different regions (Giorgi and Gutowski 2015). For instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et al. 2014) for 1.5°C projections will be provided for the SOD. Beside climate models, other models are available to assess changes in regional and global climate system (e.g. models for sea level rise, models for floods, droughts, and freshwater input to oceans, cryosphere/snow models, models for sea ice, as well as models for glaciers and ice sheets. References to be included for SOD). Analyses on impacts of a 1.5°C and 2°C climate using such models include, for example, Schleussner et al. (2016) and upcoming publications from the Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP) Project (Warszawski et al. 2014), which are not yet available at the time of writing, as well as publications from the IMPACT2C project (Jacob and Solman, 2017).

3.2.2.3 Methods for the attribution of observed changes in climate and their relevance for assessing projected changes at 1.5° or 2°C global warming

As highlighted in previous IPCC reports, detection and attribution is an approach which is typically applied to assess impacts of greenhouse gas forcing on observed changes in climate (e.g. Hegerl et al. 2007; Seneviratne et al. 2012; Bindoff et al. 2013). The reader is refered to these past IPCC reports, as well as to the IPCC good practice guidance paper on detection and attribution (Hegerl et al. 2010), for more background on this topic. It is noted that in the IPCC framework, 'attribution' means strictly 'attribution to anthropogenic greenhouse gas forcing'. In some literature reports, in particular related to impacts, 'attribution' is sometimes used in the sense of an observed impact that can be attributed to observed (regional or global) change in climate without considering whether the observed change in climate is itself attributable to anthropogenic greenhouse gas forcing. This definition is not used in this chapter. However, it is noted that in such cases the presence of 'detected' changes can be reported.

Attribution to anthropogenic greenhouse gas forcing is an important field of research for these assessments. Indeed, global climate warming has already reached 1°C compared to pre-industrial conditions (Section 3.3), and thus 'climate at 1.5°C global warming' corresponds to approximately the addition of half a degree warming compared to present-day warming. This means that methods applied in the attribution of climate changes to human influences can be relevant for assessments of changes in climate at 1.5°C warming, especially in cases where no climate model simulations or analyses are available for the conducted assessments. Indeed, impacts at 1.5°C global warming can be assessed in parts from regional and global climate changes that have already been detected and attributed to human influence (e.g. Schleussner et al. 2017). This is because changes that could already be ascribed to anthropogenic greenhouse gas forcing pinpoint to components of the climate system which are most responsive to this forcing, and thus will continue to be under 1.5°C or 2°C global warming. For this reason, when specific projections are missing for 1.5°C global warming, some of the assessments provided in Section 3.3, in particular in Table 3.1, build upon joint assessments of a) changes that were observed and attributed to human influence up to present, so for 1°C global warming and b) projections for higher levels of warming (e.g. 2°C, 3°C or 4°C) to assess the most likely changes at 1.5°C. Such assessments are for transient changes only (see Section 3.2.2.1).

3.2.3 Methods for assessing observed impacts and projected risks to natural and managed systems and human settlements at 1.5°C

Considering that the extent of global warming is still below the thresholds discussed here, there is no observed time series able to provide direct information of 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 and where climate may play only a secondary role.

One approach for assessing impacts on natural and managed systems at 1.5ºC consists of linearly extrapolating the observed impact (under +1°C global warming). This gives a first approximation of trends and relies on the assumption of linear dynamics. While this may be a too coarse 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 paleodata 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 3.1). This, however, remains difficult when the available archives are rare. Several warm periods have been observed in the past, but most were not caused by GHG increase and the warming was often not homogeneous on the globe: e.g. the Medieval period, Mid-Holocene (8000-6000 years BP), or Eemian period (125-1200 year BP). Those periods with high GHG content and which were globally warm are in the far past for which data are sparse: 52-50 Ma BP (Early Eocene) and 3.3-3 Ma BP (Mid-Pliocene) (see AR5 WG1, Chapter 5). A third approach relies on manipulation experiments (Dove et al. 2013a; Bonal et al. 2016), which provide useful information on the causal effect of a few factors (which can be as diverse as climate, GHG, management practices, biological responses) on ecosystems and may provide key insighhts in warming, ocean acidification and their impacts. They do have, however, limits to the degree of complex interactions that can be included.

Impact models coupled to ESM are generally used for the risks associated to projections. Even if the four

RCP scenarios used in the AR5 are not strictly associated to the thresholds of concern, and particularly the difference between the effects of 1.5° and 2°C global warmings, studies on 1.5 and 2°C impact projections have increased in recent times (Schleussner et al. 2016c; Seneviratne et al. 2016; Guiot and Cramer 2016a; Tanaka et al. 2017).

3.2.3.1 Definition of a '1.5°C or 2°C impact projection'

As noted for the assessment of changes in climate at 1.5°C vs other warming levels (Section 3.2.2.2), the comparison of impacts of 1.5°C and 2°C global warming requires specific methodologies. As an example of a methodology applied, Schleussner et al. (2016) calculated the differential effect of 1.5°C and 2°C global warming on water availability and agricultural impacts based on an ensemble of simulations derived under the RCP8.5 scenario, using time slices centred around these specific levels of warming (i.e. the 'time sampling' approach, see Section 3.2.2.1).

Another approach to assess impacts at 1.5°C and 2°C consists of driving an impact model (e.g. ecosystem model or other, see Section 3.2.3.3) with ensemble climate model simulations at different levels of warming (e.g. Guiot & Cramer 2016). As only few such climate simulations were available, that study used a methodology similar to that of Schleussner et al. (2016) to define the appropriate global simulations.

Alternatively, projections of regional changes in climate means or extremes at 1.5° vs 2° (eg. Section 3.3) can be combined with assessments of 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.

It must be noted that a global warming of 2°C is based on a global average of the daily temperature. 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), so the effects on the ecosystems and human systems can be considerably amplified in these areas. It is important to note that the local impacts are assessed on the basis of large local threshold.

3.2.3.2 Detection and attribution methods

As impact studies are based on a two-step approach (ESM coupled to an impact model), the notion of detection and attribution is conceptually different in the climate community and in the impact community. For the first one, it consists of detecting climate change in the climate series and attributing it to human using causal relationships (see Section 3.2.2.3). The separation concerns then two ypes of drivers. For the impact community, detection and attribution differentiates four types of drivers: natural climatic change, anthropogenic climate change, other natural factors and other anthropogenic factors.

Box 3.1: Constraining impacts of a 1.5°C-2°C warmer world using paleoclimate data
[Provisional contents]

1. Can past climate states provide suitable analogues for future warming and its impacts?

2. Impacts and feedbacks connected to past warmer climate
- ice sheets
- sea ice
- ocean circulation
- atmospheric circulation
- marine ecosystems
- ocean acidification and deoxygenation
- terrestrial vegetation and ecosystems
- peatlands
- fire
- greenhouse gas feedbacks

3. Changes in Climate variability and extreme events
- rainfall and storms
- ENSO
- NAO

4. Rates of change and tipping points
- rates of change in climate, greenhouse gases, sea level
- tipping points in the Greenland Ice Sheet, Antarctic Ice Sheet, ocean circulation, marine ecosystems, land ecosystems

5. Constraining climate sensitivity from past warm periods

3.3 Global and regional climate changes and associated hazards: Observed changes (including paleo); attributed changes; projected risks; avoided risks at 1.5°C

This section provides the assessment of changes in climate at 1.5°C *vs.* other levels of global warming. Section 3.3.1 provides an overview on global changes in climate, with a focus on global patterns of temperature and precipitation. Sections 3.3.2-3.3.11 provide assessments for specific aspects of the climate system, including regional assessments for temperature (3.3.2) and precipitation (3.3.3) means and extremes. A global synthesis is provided in Section 3.3.12 together with a table summarizing the main assessments of this overall section. Section 3.3.13 provides a highlight of key climate-based risks and hot spots of changes in physical climate associated with a global warming exceeding 1.5°C.

The present assessment builds upon assessments from the IPCC SREX report Chapter 3 (Seneviratne et al. 2012) and the IPCC AR5 WG1 report (Stocker et al. 2013; Hartmann et al. 2013; Bindoff et al. 2013; Collins et al. 2013; Christensen et al. 2013), as well as on more recent literature related to projections of climate at 1.5°C and 2°C (e.g. Schleussner et al. 2016a; Seneviratne et al. 2016; Wartenburger et al.; Vautard et al. 2014; Déqué et al. 2016; Zaman et al. 2016; Maule et al. 2016). More details on the applied methods of assessment are provided in Section 3.2. The main analyses of projections are based on transient evaluations of climate at 1.5°C *vs.* 2°C global warming based on global climate model simulations driven with the RCP8.5 scenario (see Section 3.2.2). As discussed in Section 3.2.2, for temperature and precipitation extremes, these evaluations are approximately consistent for scenarios stabilizing close to 1.5°C or 2°C global warming (RCP 2.6), however they may differ for other quantities (e.g. mean precipitation).

[More details from ISIMIP, HAPPI-MIP, IMPACT2C and other ongoing activities will be included in the releated sub-sections from 3.3 for the Second Order Draft.]

3.3.1 Global changes in climate

3.3.1.1 Observed and attributed changes

Warming of the Global Mean Surface Temperature (GMST) compared to pre-industrial levels has at the time of writing this report (2017) reached approximately 1°C (Chapter 1). At the time of writing of the AR5 WG1 report (i.e. for time frames up to 2012, Stocker et al. 2013), Hartmann et al. (2013) assessed that the globally averaged combined land and ocean surface temperature data as calculated by a linear trend, showed a warming of 0.85 [0.65 to 1.06]°C, over the period 1880–2012, when multiple independently produced datasets existed, and about 0.72 [0.49 to 0.89]°C over the period 1951–2012. Hence most of the global warming has occurred since 1950 and it has continued substantially in recent years. These values are for global mean warming, however, regional trends can be much more varied (Figure 3.1). With a few exceptions, most land regions display stronger trends in the global mean average, and by 2012, with a warming of about 0.85°C (see above), some land regions already displayed warming higher than 1.5°C (Figure 3.1). Hence, as highlighted in further subsections, it is important to take into account that a 1.5°C or 2°C warming implies much larger regional warming on land.

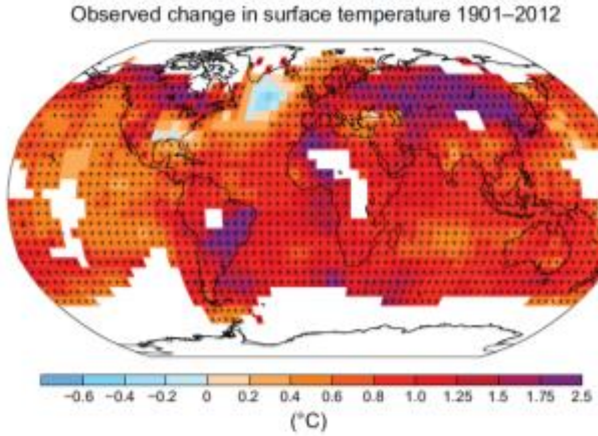


Figure 3.1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset. Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. From Stocker et al. (2013)

An area in which substantial new literature has become available since the AR5 is the apparent reduction in the global mean surface temperature trend (GMST) observed during 1998-2012, compared to the long term trend during 1951-2012 (Stocker et al. 2013; Karl et al. 2015; Lewandowsky et al. 2016; Medhaug et al. 2017). We note as discussed in Medhaug et al. (2017) that 2015 and 2016 were the two warmest years on record (based on GMST), demonstrating that the warming trend at the Earth's surface has continued apace. Nonetheless, the related literature is relevant for the assessment of changes in climate at 1.5°C global warming, since this event illustrates the possibility that the global temperature response may be decoupled from the radiative forcing over short time periods. While this may be associated with cooler global temperatures as during the recent so-called, but erroneously labelled, 'hiatus' period, this implies that there could also be time periods where GMST is temporarily higher than 1.5°C even if the radiative forcing is consistent with an average global warming of 1.5°C in long-term.

Recent publications have indicated that the apparent slowdown in global surface temperature rise during 1998-2012 was overestimated at the time of the AR5 due to issues with data corrections, in particular to coverage (Cowtan and Way 2014; Karl et al. 2015; see Annex 3.1 Figure S3.2). In addition, there is evidence that the slower pace of surface warming was due, in part, to lower surface heating of the oceans accompanied by higher rates of heating at depth. Thus, it can be concluded that the period in question did not reflect, to any extent, a slowdown in the overall heating of the Earth's climate system (Yang et al. 2016). There is substantial evidence supporting this latter assessment, including the continued meltdown of the Arctic sea ice (Stocker et al. 2013), the unabated increase in global sea level (Stocker et al. 2013), and continued strong warming of hot extremes over land (Seneviratne et al. 2014) during this time period. For this reason, GMST is not the most accurate measure to assess the impact of greenhouse gas forcing on the Earth's climate system in a transient climate context which has important relevance for the definition of a '1.5°C climate' (see cross-chapter Box 3.12 on a 1.5°C warmer world).

A large fraction of the detected global warming has been attributed to anthropogenic forcing (Bindoff et al. 2013). The AR5 (Bindoff et al. 2013) assessed that it is *virtually certain* that human influence has warmed the global climate system and that it is *extremely likely* that human activities caused more than half of the observed increase in GMST from 1951 to 2010 (see Annex 3.1 Figure S3.1). The AR5 (Bindoff et al. 2013) assessed that greenhouse gases contributed a global mean surface warming *likely* to be between 0.5°C and 1.3°C over the period 1951–2010, with the contributions from other anthropogenic forcings *likely* to lie between – 0.6°C and 0.1°C, from natural forcings *likely* to be between – 0.1°C and 0.1°C, and from internal variability *likely* to be between –0.1°C and 0.1°C. Regarding observed global changes in temperature extremes, the IPCC SREX report assessed that since 1950 it is *very likely* that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale, that is, for land areas with sufficient data (Seneviratne et al. 2012).

With respect to specific changes associated with a global warming of 0.5°C, as highlighted in Section 3.2, the observational record can be used to assessed past changes associated with a global warming of this magnitude, this assessment being then considered as an analogue for the difference between a scenario at 1.5°C and at 2°C global warming. This approach has its limitation, since it does not account for non-linearity in responses, including possible regional or global tipping points (see Box 3.5 on tipping points). Nonetheless, it can provide some first assessment of aspects of the climate system that have been identified as being sensitive to a global warming change of this magnitude. Schleussner et al. (2017) have recently performed an analysis using this approach. They assess observed changes in extreme indices for the 1991-2010 versus the 1960-1979 period, which corresponds to just about 0.5°C GMST difference in the observed record (based on the GISTEMP dataset, Hansen et al. 2010). This particular study found that substantial changes due to 0.5°C warming were apparent for indices related to hot and cold extremes, as well as for the Warm Spell Duration Indicator (WSDI). Some results are displayed in Figure 3.2. For observational datasets (HadEX2 and GHCNDEX, Donat et al. 2013a,b) show that one quarter of the land has experienced an intensification of hot extremes (TXx) by more than 1°C and a reduction of the intensity of cold extremes by at least 2.5°C (TNn). Half of the global land mass has experienced changes in WSDI of more than 6 days and the emergence of extremes outside the range of natural variability is particularly pronounced for this duration-based indicator (Figure 3.2). Results for TXx based on reanalysis products are similar to the 20CR product, but even more pronounced for the ERA reanalysis. As noted by Schleussner et al. (2017), however, results based on reanalyses products need to be considered with caution. Hence the observational record does suggest that an additional 0.5°C rise in global warming has noticeable global impacts on temperature extremes.

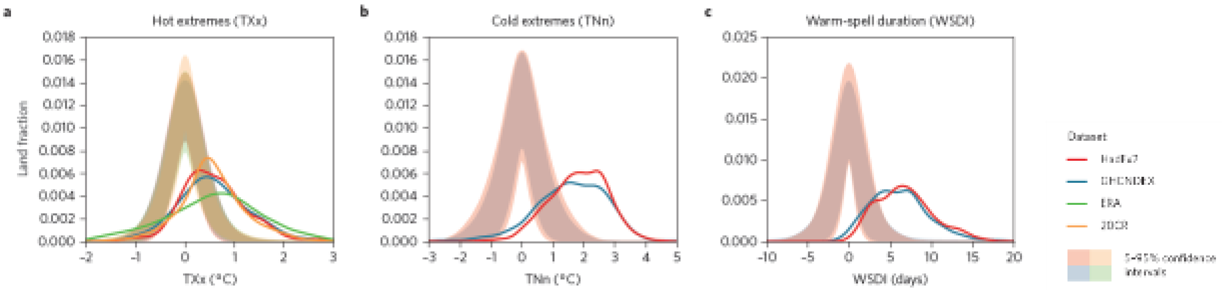


Figure 3.2: Differences in extreme temperature event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. For TXx, the analysis includes also reanalysis data from ERA and 20CR over the global land area. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years. (based on Schleussner et al. (2017))

Observed global changes in the water cycle, including precipitation, are more uncertain than observed changes in temperature (Hartmann et al. 2013; Stocker et al. 2013). The AR5 assessed that it is very likely that global near surface and tropospheric air specific humidity have increased since the 1970s (Hartmann et al. 2013). However, AR5 also highlighted that during recent years the near surface moistening over land has abated (*medium confidence*), and that as a result, there have been fairly widespread decreases in relative humidity near the surface over the land in recent years (Hartmann et al. 2013). With respect to precipitation, some regional precipitation trends appear to be robust (Stocker et al. 2013), but when virtually all the land area is filled in using a reconstruction method, the resulting time series of global mean land precipitation shows little change since 1900. Hartmann et al. (2013) highlight that confidence in precipitation change averaged over global land areas since 1901 is low for years prior to 1951 and medium afterwards. However, for averages over the mid-latitude land areas of the Northern Hemisphere, Hartmann et al. (2013) assessed that precipitation has likely increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudinal zones area-averaged long-term positive or negative trends have low confidence due to data quality, data completeness or disagreement amongst available estimates (Hartmann et al. 2013). For heavy precipitation, the AR5 assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al. 2013).

Regarding specific analyses on global observed changes in precipitation indicative of responses to a global warming of 0.5°C, Schleussner et al. (2017) have also provided analyses for precipitation extremes (Figure 3.3), similar to those previously discussed for temperature extremes (Figure 3.2). While the changes are more moderate than for temperature extremes (Figure 3.2), robust increases in observed precipitation extremes can also be identified for annual maximum 1-day precipitation (RX1day) and consecutive 5-day precipitation (RX5day). The analysis also reveals that a quarter of the land mass has experienced an increase of at least 9% for extreme precipitation (RX5day).

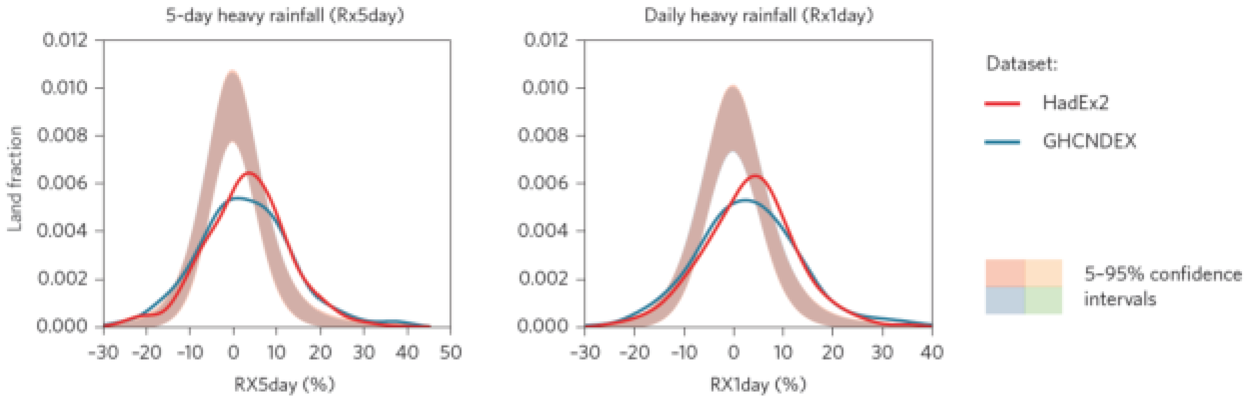


Figure 3.3: Differences in extreme precipitation event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years. (based on Schleussner et al. (2017))

3.3.1.2 Projected changes at 1.5ºC

Figure 3.4 includes maps of projected changes in local mean temperature warming at 1.5°C *vs.* 2°C global mean warming. Similar analyses are provided for temperature extremes (changes in the maximum temperature of the local hottest day of the year, TXx, and in the minimum temperature of the local coldest day of the year, TNn) in Figure 3.5. The responses for both analyses are derived from transient simulations of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) for the RCP8.5 scenario, similarly as in Seneviratne et al. (2016). As highlighted in Section 3.2.2, the results are similar for other emissions scenarios, and for 1.5°C in particular with responses of simulations for the RCP2.6 scenario, which stabilize below / at around 2°C (Seneviratne et al. 2016; Wartenburger et al.; see also Annex 3.1 Figure S3.3).

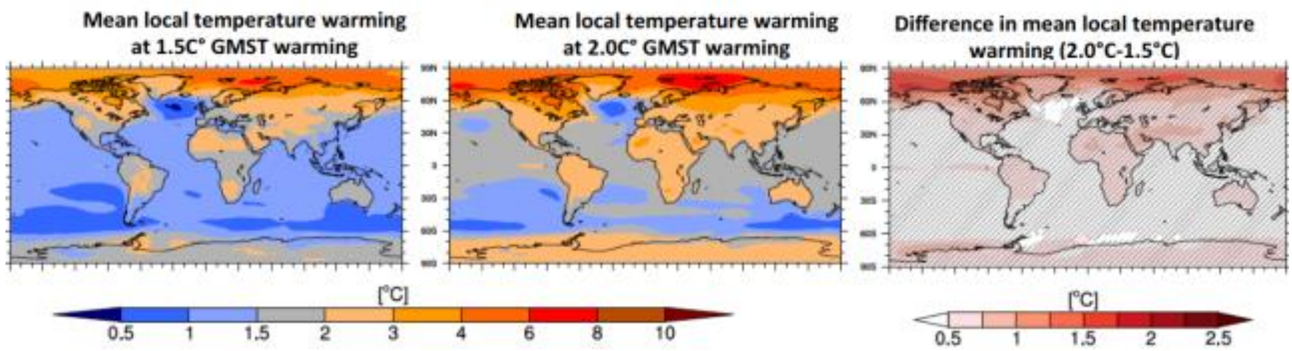


Figure 3.4: Projected local mean temperature warming at 1.5°C global warming (left), 2.0°C global warming (middle), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. (2016)). Note that the warming at 1.5°C GMST warming is similar for RCP2.6 simulations (see also Annex 3.1 Figure S3.3).

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

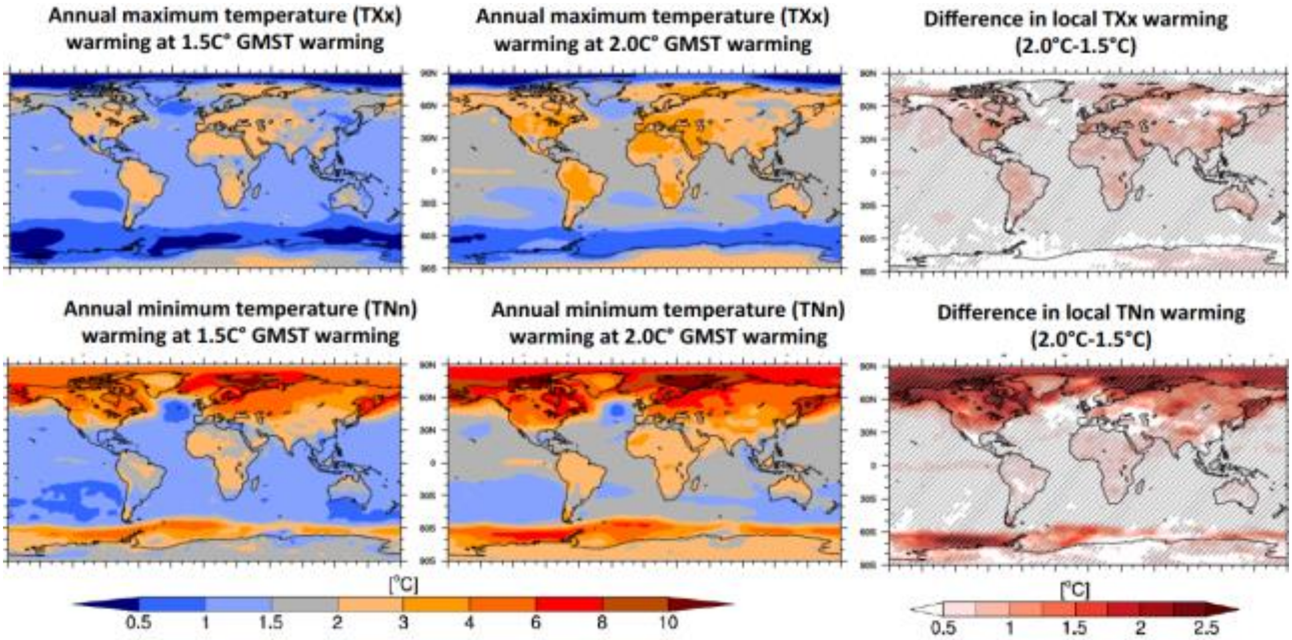


Figure 3.5: Projected local warming of extreme temperatures (top: Annual maximum daytime temperature, TXx; bottom: Annual minimum nighttime temperature, TNn) warming at 1.5°C global warming (left), 2.0°C global warming (middle), and difference (right; hatching highlights areas in which 2/3 of the models 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). Note that the warming at 1.5°C GMST warming is similar for RCP2.6 simulations (see also Annex 3.1 Figure S3.4).

Figure 3.6 displays the projected changes in mean precipitation and heavy precipitation (5-day maximum precipitation, Rx5day) at 1.5°C , 2°C and their difference, using the same approach as for Figures 3.4 and 3.5 (see also Methods, Section 3.2.2). Compared to changes in temperature, changes in precipitation are not globally uniform and projections are more uncertain. However, some regions display substantial changes in mean precipitation between 1.5°C vs. 2°C global warming, in particular decreases in the Mediterranean area, including Southern Europe, the Arabian Peninsula and Egypt. There are also changes towards increased heavy precipitation in some regions, as highlighted in Section 3.3.3. The differences are generally small between 1.5°C and 2°C global warming (Figure 3.6). Some regions display substantial increases, for instance in Southern Asia, but generally in less than 2/3 of the models (Figure 3.6).

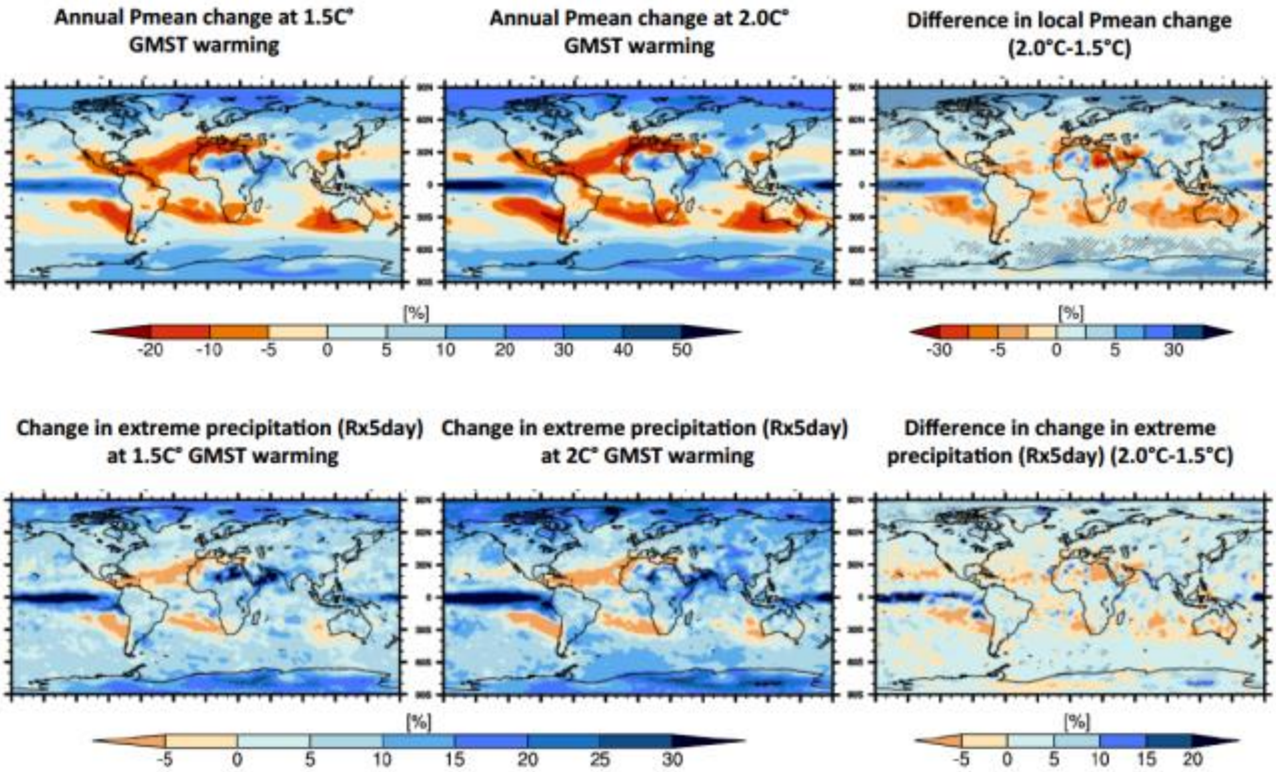


Figure 3.6: Projected changes of mean (top) and extreme (5-day maximum precipitation) precipitation at 1.5°C global warming (left), 2.0°C global warming (middle), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Assessed from transient response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

Analyses have also been performed 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 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 in Figure 3.6.

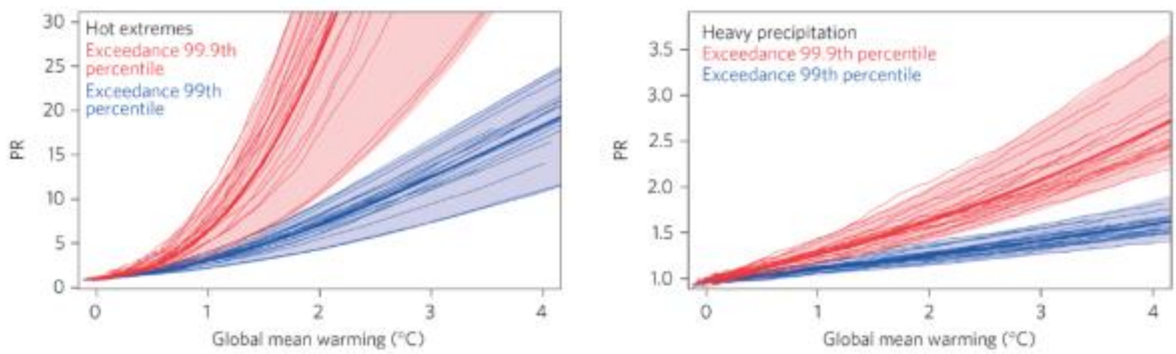


Figure 3.7: Probability ratio of exceeding the (blue) 99th and (red) 99.9th percentile of pre-industrial daily temperature (left) and precipitation (right) at a given warming level relative to pre-industrial conditions averaged across land (from Fischer and Knutti (2015)).

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, including urban climate

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. In particular, Cowtan and Way (2014) recently 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). 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 availability of data is sufficient and the attribution chapter of the AR5 (Bindoff et al. 2013) assessed that over every continental region, except Antarctica, it is *likely* that anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century. Further, it assessed that it is *likely* that there has been an anthropogenic contribution to the very substantial Arctic warming since the 1960s. Bindoff et al. (2013) also assessed that the anthropogenic influence has *likely* contributed to temperature change in many sub-continental regions.

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), so consistent with detected global changes (Section 3.3.1.1). It also assessed 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 or 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 are currently not available on regional scale from the literature, unlike global assessments (Schleussner et al. 2017), although preliminary results suggest that a 0.5°C global warming can also be identified for temperature extremes in a few large regions (Europe, Asia, Russia, North America; see supplementary material of (Schleussner et al. 2017).

An area of particular concern is related to possible changes in extreme heat events in cities (e.g. Section 3.5.2. and cross-chapter Box 4.14 on cities). The climate in cities differs from surrounding regions due to the structures present and intensive human activity that occurs there. This is often referred to as the urban heat island (UHI) effect. Generally, cities are warmer in summer; and at night, than nearby rural areas, though this warming depends on many factors including the density of buildings, the geographical setting of the city, time of day, and season. In general, it has been found that the UHI effect is larger when there is: low wind speed; low cloud cover; large populations or city sizes; (Arnfield 2003). Multiple mechanisms have been cited for causing the UHI (Rizwan et al. 2008; Zhao et al. 2014).

Studies have been conducted to estimate the UHI intensity in many cities (Mirzaei and Haghighat 2010). Using satellite data to examine the annual average surface UHI intensity in the 32 largest cities in China, Zhou et al. (2014) found large variability with values ranging from 0.01 to 1.87°C in daytime. In the USA, Imhoff et al. (2010) found an average annual surface UHI intensity across the 38 largest cities of 2.9°C, except for cities in arid and semi-arid climates where the cities were found to be cooler than their surrounding rural areas. Peng et al. (2012) used similar satellite data to examine the surface UHI across 419 global big cities. They estimate an annual average UHI intensity of 1.3°C, with some cities reaching as high as 7°C during daytime in summer, and a few cities surrounded by desert having negative surface UHI intensity. Tropical cities generally have UHI intensities that are lower than comparable temperate cities

(Roth 2007). It should be noted that while the annual mean urban heat island intensity is a few degrees, the urban environment can enhance heat waves by more than the average UHI intensity (Li and Bou-Zeid 2013).

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

A further increase of 0.5°C or 1°C will likely have detectable effects on temperature means and/or extremes in some regions because changes in mean and extreme temperatures have already been detected for several years (e.g. IPCC SREX assessment, Seneviratne et al. (2012) at global and also continental scale (Sections 3.3.1.1 and 3.3.2.1), and so for a global warming of less than 1°C (Chapter 1). More detailed regional assessments can also be performed based on climate projections as presented hereafter.

We note that upcoming publications on regional climate simulations and impact assessments from an extension of the IMPACT2C (Jacob and Solman, 2017) project as well as from the ISIMIP and HAPPI-MIP projects etc. will provide additional data basis for assessment of this chapter.

This section provides an assessment of differences in projections at 1.5°C *vs.* 2°C global warming using the empirical scaling approach presented in Section 3.2 (building upon Seneviratne et al. 2016). Figure 3.8 displays the IPCC SREX regions (see Section 3.2. for an overview) changes in temperature hot extremes (annual maximum daytime temperature, TXx) as a function of global mean temperature warming. The plot insets display the full range of CMIP5 simulations (orange range for RCP8.5 simulations, blue range for RCP2.6 simulations) as well as the mean response for both simulation ensembles (orange and blue lines, respectively). As highlighted in previous publications (Seneviratne et al. 2016; Wartenburger et al. *in review*), the mean climate model response of changes in the absolute temperature of extremes is found to be approximately linear and independent of the considered emission scenario. This implies that the transient response (inferred from the RCP8.5 simulations) is close to the equilibrium response (corresponding to the RCP2.6 simulations).

Figure 3.8: Projected changes in annual maximum daytime temperature (TXx as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger et al. *in review*).

There is a stronger warming of the regional land-based hot extremes compared to the mean global temperature warming in most land regions (also discussed in Seneviratne et al. 2016). The regions displaying the stronger contrast are Central North America, Eastern North America, Central Europe, Southern Europe/Mediterranean, Western Asia, Central Asia, and Southern Africa. As highlighted in Vogel et al. (2017), the location of these regions can be related to their climate regimes, which are associated with strong soil moisture-temperature coupling (related to a transitional soil moisture regime Koster et al. 2004; Seneviratne et al. 2010). Due to enhance drying in these regions (see Section 3.3.5), evaporative cooling is decreased, leading to a regional added warming compared to the global temperature response. In general, these regions also show the largest spread in temperature extremes response, likely related to the impact of the soil moisture-temperature coupling for the overall response. This spread is due to both intermodel variations in the representation of drying trends (Orlowsky and Seneviratne 2013; Greve and Seneviratne 2015) and to differences in soil moisture-temperature coupling in climate models (Seneviratne et al. 2013; Stegehuis et al. 2013; Sippel et al. 2016), whereby also feedbacks with clouds and surface radiation are relevant (Cheruy et al. 2014). Furthermore, in some regions also internal climate variability can explain the spread in projections (Deser et al. 2012). Regions with the most striking spread in projections of hot extremes include Central Europe, with projected regional TXx warming at 1.5°C ranging from 1°C to 5°C warming, and Central North America, which displays projected changes at 1.5°C global warming ranging from no warming to 4°C warming (Figure 3.8).

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

Figure 3.9 displays similar analyses as Figure 3.7 but for the annual minimum nighttime temperatures, TNn. The mean response of these cold extremes displays less discrepancy with the global levels of warming (often close to the 1:1 line in many regions), however, there is a clear amplified warming in regions with snow and ice cover. This is expected given the Arctic warming amplification (Serreze and Barry 2011), which is to a large part due to snow-albedo-temperature feedbacks (Hall and Qu 2006). In some regions and for some model simulations, the warming of TNn at 1.5°C global warming can reach up to 8°C regionally (e.g. Northern Europe, Figure 3.7) and thus be much larger than the global temperature warming.

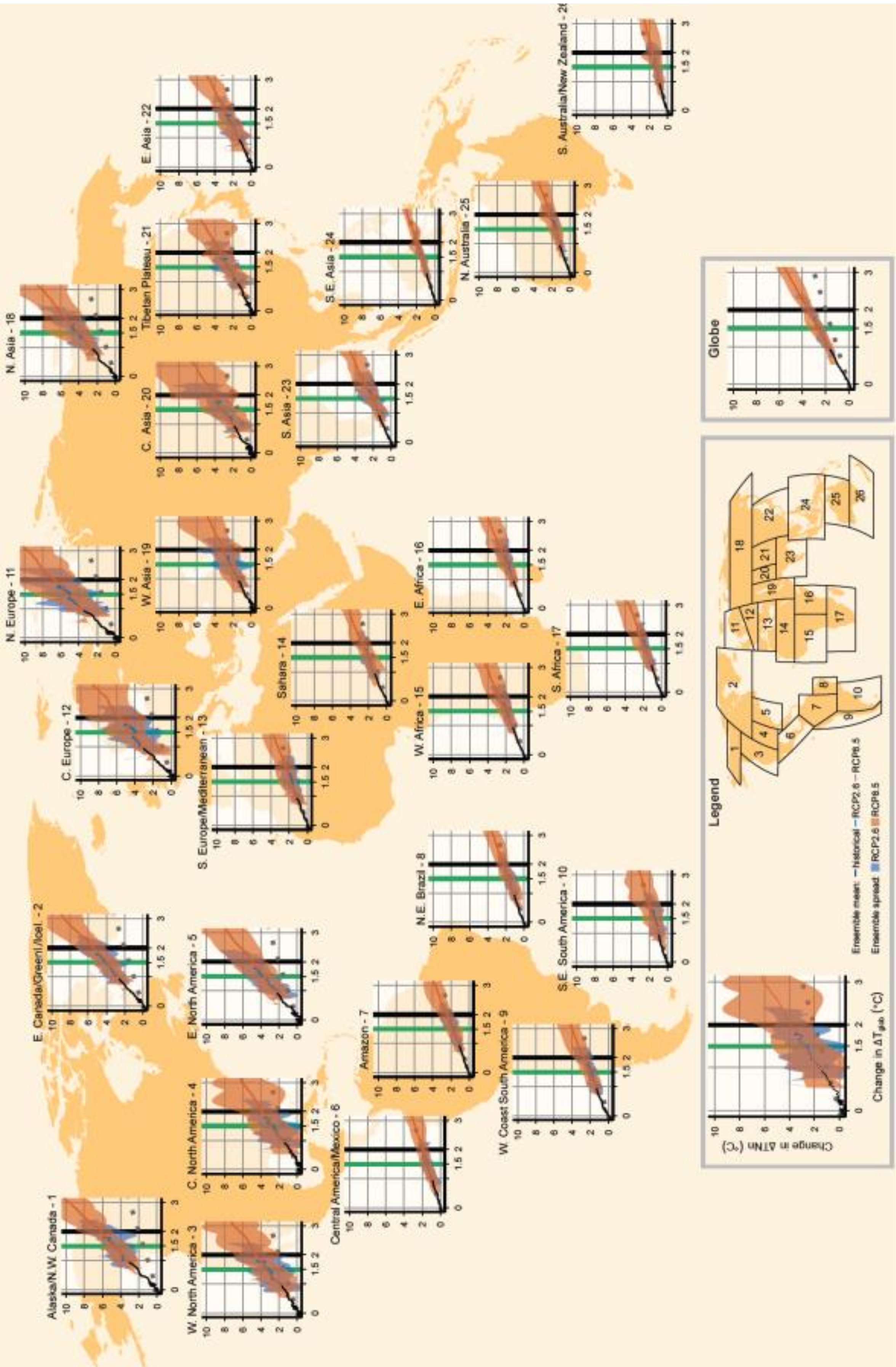


Figure 3.9: Projected changes in annual minimum nighttime temperature (TNn) as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger et al. *in review*).

Figure 3.10 additionally displays maps of changes in the number of hot days (NHD) and number of frost days (NFD) at 1.5°C and 2°C global mean surface temperature warming. These analyses reveal clear patterns of changes between the two warming levels. For the number of hot days, the largest differences are found in the tropics due to the lower interannual temperature variability (Mahlstein et al. 2011), and despite the tendency for higher absolute changes in hot extremes (Figure 3.8). These analyses are consistent with other recent assessments. Coumou and Robinson (2013) find that under a 1.5°C warming, already 20% of the global land area, centered in low latitude regions, is projected to experience highly unusual monthly temperatures during boreal summers, which nearly doubles a 2°C warming. In addition, Russo et al. (2016) identified that under a 2°C warming, heat waves that are unusual under present climate conditions are projected to occur on a regular basis.

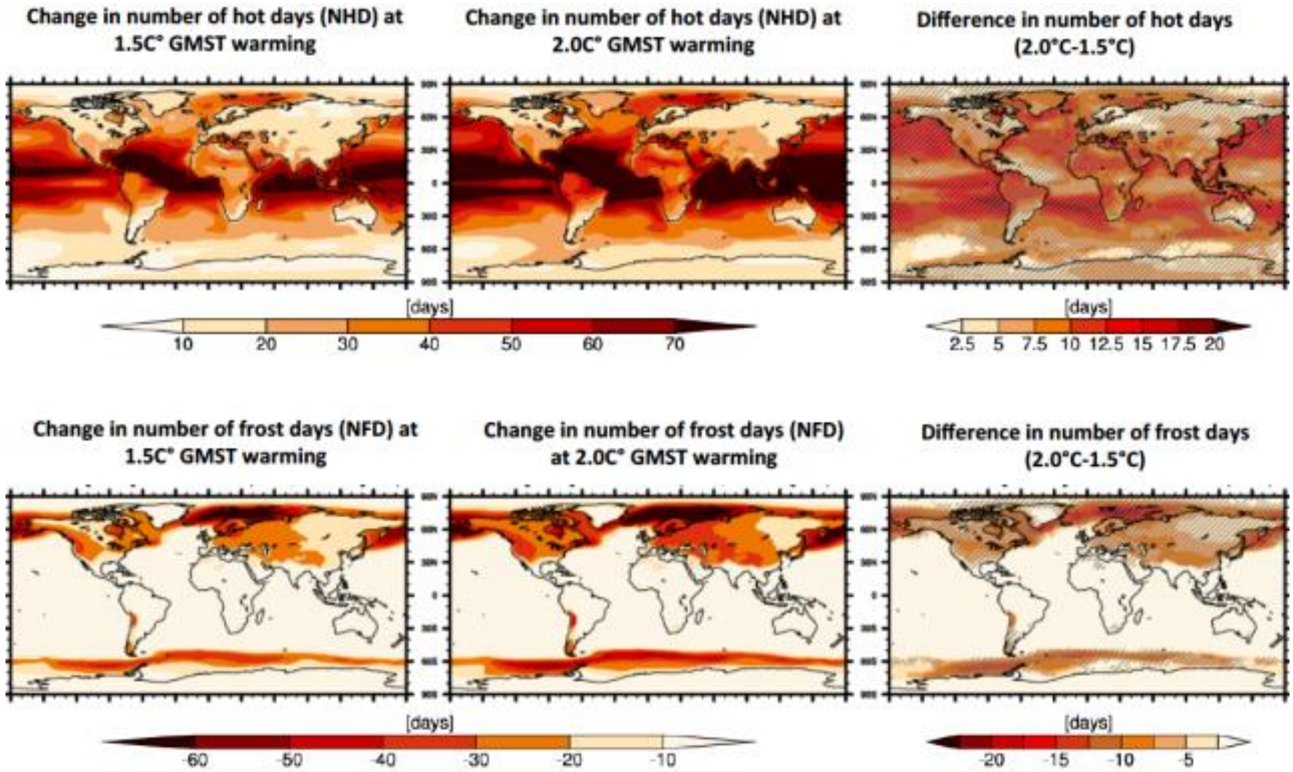


Figure 3.10: Projected changes in number of hot days (10% warmest days, top) and in number of frost days (days with T<0°C, bottom) at 1.5°C (left) and 2°C (right) GMST warming, and their difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Adapted from Wartenburger et al. *in review*).

Vautard et al. (2014) found for a global 2°C warming that most of Europe will experience higher warming than the global average with strong distributional patterns across Europe. For instance, a North–South (West–East) warming gradient is found for summer (winter) along with a general increase and summer extreme temperatures. More results for 1.5°C will be included in the SOD.

Regarding projection of changes in temperature in cities, few studies have been conducted into the combined effect of UHI and global warming. McCarthy et al. (2010) run a global climate model at 300km resolution, and find that UHI intensity could increase by as much as 30% but on average decreased by 6% for a doubling of CO_2. These simulations do not account for many of the differences between cities and demonstrate substantial errors in many locations. A small number of studies have used km-scale regional climate models to investigate this for selected cities (Conlon et al. 2016; Grossman-Clarke et al. 2017; Kusaka et al. 2016; Georgescu et al. 2012; Argüeso et al. 2014). In general, these studies find that the UHI remains in a future warmer climate with increases in UHI intensity occurring due to increases in population and city size. The impact on humans depends on humidity as well as temperature changes. The first studies to look explicitly at these effects (Argüeso et al. 2015; Suzuki-Parker et al. 2015) suggest the possibility that future global warming and urban expansion could lead to more extremes in heat stress conditions.

Matthews et al. (2017) did a recent study assessing specifically projected changes in the occurrence of deadly heatwaves in cities at 1.5°C, 2°C and higher levels of global warming, based on global climate model simulations, and integrating the effects of UHI as well as of relative humidity on human heat stress. They identify that even if global warming is held below 2°C, there would already be a substantial increase in the occurrence of deadly heatwaves in cities, and that the impacts would be similar at 1.5°C and 2°C, but substantially larger than under present climate. They assess in particular that with only 1.5°C of global warming, twice as many megacities (such as Lagos, Nigeria, and Shanghai, China) could become heat stressed compared to present, exposing more than 350 million more people to deadly heat by 2050 under a midrange population growth scenario. Matthews et al. (2017) also highlight that at 2°C warming, Karachi (Pakistan) and Kolkata (India) could expect conditions equivalent to their deadly 2015 heatwaves every year. While it already highlights substantial risks of deadly heat in cities at 1.5°C global warming, this study suggests that the changes at 1.5°C and 2°C global warming would still be substantially less than if higher levels of global warming were reached (2.7°C or 4°C). It should be noted, nonetheless, that such projections do not integrate adaptation to projected warming, for instance cooling that could be achieved with more reflective roofs and urban surfaces overall (Oleson et al. 2010; Akbari et al. 2009).

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 a consideration of changes in monsoon precipitation. 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

The AR5 (Bindoff et al. 2013) assessed that when considering just land regions with sufficient observations, the largest signal of differences in mean precipitation between models with and without anthropogenic forcings is in the high latitudes of the Northern Hemisphere, where increases in precipitation are a robust feature of climate model simulations.

For heavy precipitation, the AR5 assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al. 2013). The SREX 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, but it 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 IPCC SREX (Seneviratne et al. 2012) 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).

For monsoons, the SREX assessed that there is *low confidence* in trends because of insufficient evidence (Seneviratne et al. 2012). There are a few new available assessments (Singh et al. 2014), which show that using precipitations observations (1951-2011) of the South Asian summer monsoon there have been significant decreases in peak-season precipitation over the core-monsoon region and significant increases in daily-scale precipitation variability. However, there is not sufficient evidence to revise the SREX assessment of *low confidence* in overall observed trends in monsoons.

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

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

Regarding changes in heavy precipitation, Figure 3.11 displays projected changes in the 5-day maximum precipitation (Rx5day) as function of global temperature warming, using a similar approach as in Figures 3.8 and 3.9. This analysis shows that projected changes in heavy precipitation are more uncertain than for temperature extremes. However, the mean response of the model simulations is generally robust and linear (see also Fischer et al. 2014; Seneviratne et al. 2016). As highlighted in Seneviratne et al. (2016), this response is also found to be mostly independent of the considered emissions scenario (e.g. RCP2.6 vs. RCP8.5 in Figure 3.9). This appears to be a specific feature of heavy precipitation, possibly due to a stronger coupling with temperature, as the scaling of projections of mean precipitation changes with global warming shows some scenario dependency (Pendergrass et al. 2015). An analysis by Wartenburger et al. (*in review)* suggests that for Eastern Asia, there are substantial differences in heavy precipitation at 1.5°C vs. 2°C. Vautard et al. (2014) find a robust increase in heavy precipitation everywhere and in all seasons, except Southern Europe in summer, with amplitudes in the range 0–20%.

Projected changes in monsoons at 1.5°C and 2°C compared to present have not been assessed in the literature so far. At the time of the IPCC SREX report, the assessment was that there was *low confidence* in overall projected changes in monsoons (for high-emissions scenarios) because of insufficient agreement between climate models (Seneviratne et al. 2012). There are a few publications that provide more recent evaluations on projections of changes in monsoons for high-emissions scenarios. Jiang and Tian (2013), who compared the results of 31 and 29 reliable climate models under the SRES A1B scenario or the RCP4.5 scenario, respectively, found little projected changes in the East Asian winter monsoon as a whole relative to the reference period (1980-1999). Regionally, they found a weakening north of about 25°N in East Asia and a strengthening south of this latitude, which resulted from atmospheric circulation changes over the western North Pacific and Northeast Asia owing to the weakening and northward shift of the Aleutian Low, and from decreased northwest-southeast thermal and sea level pressure differences across Northeast Asia. In summer, Jiang and Tian (2013) found a projected slight strengthening of monsoon in East China over the 21st century as a consequence of an increased land-sea thermal contrast between the East Asian continent and the adjacent western North Pacific and South China Sea. Using six CMIP5 model simulations of the RCP8.5 high-emission scenario, Jones and Carvalho (2013) found a 30% increase in the amplitude of the South American Monsoon System (SAMS) from the current level by 2045-50. They also found an ensemble mean decrease of 14 days in the onset and 17-day increase in the demise date of the SAMS by 2045-50. The most consistent CMIP5 projections analysed confirmed the increase in the total monsoon precipitation over southern Brazil, Uruguay, and northern Argentina. Given that scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the studies of Jiang and Tian (2013) and Jones and Carvalho (2013), there is *low confidence* regarding changes in monsoons at these low global warming levels, as well as regarding differences in responses at 1.5°C vs. 2°C.

Figure 3.11: Projected changes in annual 5-day maximum precipitation (Rx5day) as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger et al., *in review*).

3.3.4 Drought and dryness

3.3.4.1 Observed and attributed changes

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

Because of the uncertainty in the detection of observed changes in droughts over the whole historical record (i.e. for close to 1°C warming, see above), the level of confidence in the attribution of changes in regional drought is generaly expected to be *low*, and at most *medium* for global assessments. For this reason, observed trends can generally not be used to infer possible changes in dryness associated with a further 0.5°C or 1°C warming. However, it should be noted that a recent publication using both an observational and a climate model-based assessment assessed that human emissions have substantially increased the probability of drought years in the Mediterranean region (Gudmundsson and Seneviratne 2016).

3.3.4.2 Projected changes in drought and dryness at 1.5°C vs. 2°C

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

Some submitted and published literature is now available on the evaluation differences in drought and dryness occurrence at 1.5°C and 2°C global warming for a) precipitation-evapotranspiration (P-E, i.e. as a general measure of water availability; Greve et al. 2017; Wartenburger et al. 2017), b) soil moisture anomalies (Lehner et al. 2017; Wartenburger et al.), c) consecutive dry days (Schleussner et al. 2016c; Wartenburger et al.), d) the 12-month Standardized Precipitation Index (Wartenburger et al., *in review*) e) the Palmer-Drought Severity Index (Lehner et al. 2017), f) annual mean runoff (Schleussner et al. 2016c), see also next section). These analyses are overall consistent, despite the known sensitivity of drought assessment on chosen drought indices (see above).

Figure 3.12 from (Greve et al. 2017), derives the sensitivity of regional changes in precipitation minus evapotranspiration to global temperature changes. The analysed simulations span the full range of available emissions scenarios and the sensitivities are derived using a modified pattern scaling approach. The applied approach assumes linear dependencies on global temperature changes while thoroughly addressing associated uncertainties via resampling methods. Northern high latitude regions display robust responses towards increased wetness, while subtropical regions display a tendency towards drying but with a large range of responses. Even though both internal variability and the scenario choice play an important role in the overall spread of the simulations, the uncertainty stemming from the climate model choice usually accounts for about half of the total uncertainty in most regions (Greve et al. 2017). An assessment of the implications of limiting global mean temperature warming to values below (i) 1.5°C or (ii) 2°C show that opting for the 1.5°C target might just slightly influence the mean response, but could substantially reduce the risk of experiencing extreme changes in regional water availability (Greve et al. 2017).

The analysis for the mean response is also qualitatively consistent with results from (Wartenburger et al., *in review*), which use an empirical scaling rather than pattern scaling for a range of drought and dryness indices, as well as with a recent assessment of Lehner et al. (2017), which considers changes in droughts assessed from the soil moisture changes and from the Palmer-Drought Severity Index. We note that these two further publications do not provide a specific assessment for changes in tails of the drought and dryness distribution. The conclusions of Lehner et al. (2017) are that a) risks of consecutive drought years shows little change in the US Southwest and Central Plains, but robust increases in Europe and the Mediterranean, and that b) limiting warming to 1.5°C may have benefits for future drought risk, but such benefits are regional, and in some cases highly uncertain.

Overall all available analyses project 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. *in review*; Figure 3.12). The fact that this is a region that is also already displaying substantial drying in the observational record (Seneviratne et al. 2012; Sheffield et al. 2012; Greve et al. 2014; Gudmundsson and Seneviratne 2016) provides additional evidence supporting this tendency, suggesting that it is a hot spot of dryness change above 1.5°C. A regional analysis of significant differences in different dryness indices between 1.5°C and 2°C provided in Section 3.3.1.13 (from Wartenburger et al., *in review*)) additionally highlights southern Africa as a possible further hot spot of change towards increased drying.

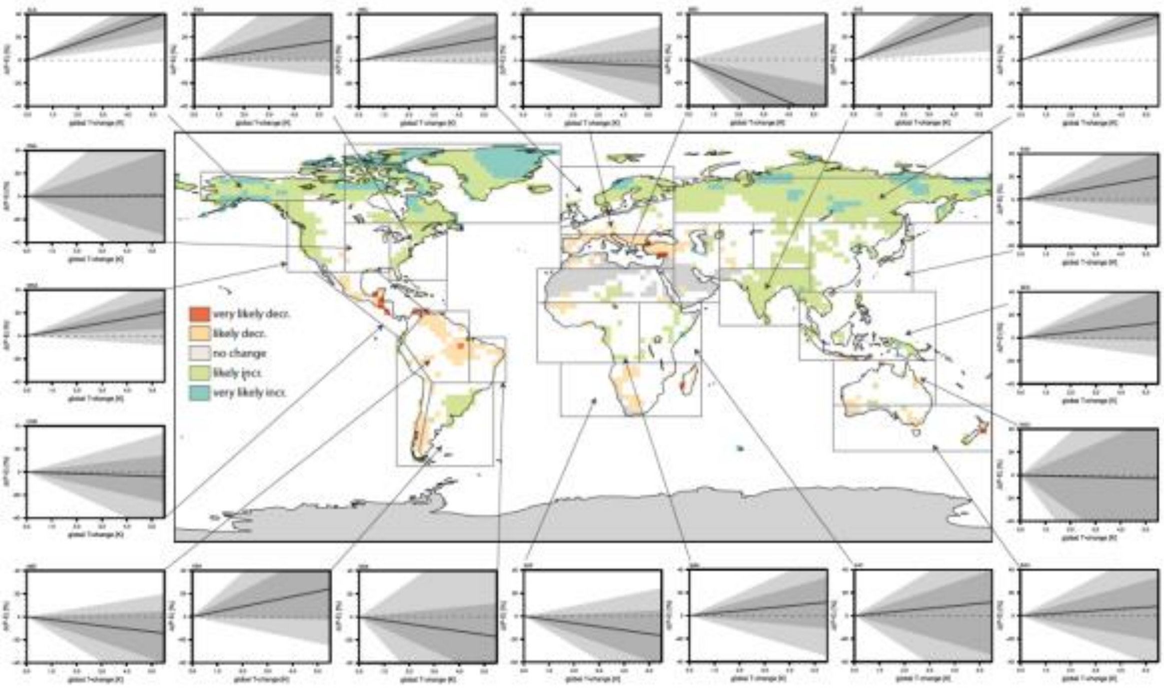


Figure 3.12: Conceptual summary of the likelihood of increases/decreases in P-E considering all climate models and all scenarios. Panel plots show the uncertainty distribution of the sensitivity of P-E to global temperature change as a function of global mean temperature change averaged for each SREX regions outlined in the map (from Greve *submitted*).

3.3.5 Runoff and flooding

AR5 concluded that there is low *confidence low* for an increasing trend in global river discharge during the 20th century and that there is *limited evidence* and *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale (Hartmann et al. 2013). Additionally, it also concluded that increasing trends in extreme precipitation and discharge in some catchments implies with *medium confidence* greater risks of flooding at regional scale (IPCC 2014a).

There has been progress since AR5 in identifying historical and future changes in streamflow and continental runoff. Dai (2016) using available streamflow data shows that long-term (1948–2012) flow trends are statistically significant only for 27.5% of the 200 world’s major rivers with negative trends outnumbering the positive ones. However, while streamflow trends are mostly statistically insignificant, these trends are consistent with observed regional precipitation changes. From 1950 to 2012 precipitation and runoff have increased over southeastern South America, central and northern Australia, the central and northeast United

States, central and northern Europe, and most of Russia and decreased over most of Africa, East and South Asia, eastern coastal Australia, southeastern and northwestern United States, western and eastern Canada, and in some regions of Brazil. A large part of these regional trends probably has resulted from internal multidecadal and multiyear climate variations, especially the Pacific decadal variability (PDV), the Atlantic multidecadal oscillation (AMO) and the El Niño-Southern Oscillation (ENSO) although the effect of anthropogenic GHG and aerosols are likely also important (Hidalgo et al. 2009; Gu and Adler 2013, 2015; Luo et al. 2016). Alkama et al. (2013) shows an increase in runoff over South Asia, northern Europe, northern Asia and North America, and a decrease over southern Europe under the RCP 8.5 emission scenario with no significant change over Central America. Additionally over South America and Africa, there is no consensus in the sign of change. Koirala et al. (2014) shows increases in projected high flows in northern high latitudes of Eurasia and North America, Asia, and eastern Africa and decreases in mean and low flows in Europe, Middle East, southwestern United States and Central America under the RCP8.5 scenario with similar spatial distribution and lower magnitude of projected changes under the RCP4.5 scenario.

Among human activities that influence the hydrological cycle are land-use/land-cover changes and water withdrawal for irrigation, which can have a big impact on runoff at basin scale although there is less agreement over its influence on global mean runoff (e.g. Gerten et al. 2008; Sterling et al. 2012; Betts et al. 2015). Some studies suggest that increases in global runoff resulting from changes in land-cover or land-use (predominantly deforestation) are counterbalanced by decreases from irrigation (Gerten et al. 2008; Sterling et al. 2012).

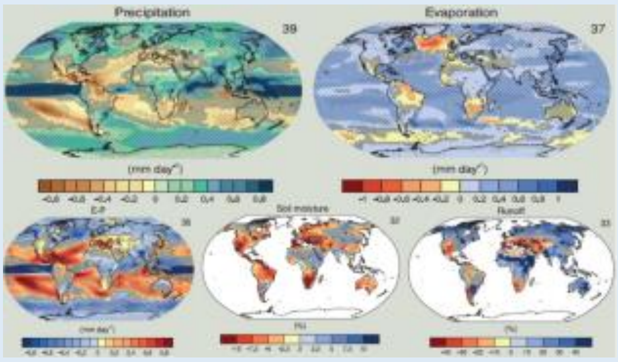
Most recent analyses of trends and projections in flooding and extreme runoff are limited to basin or country scales (Camilloni et al. 2013; Alfieri et al. 2015; Huang et al. 2015b; Mallakpour and Villarini 2015; Aich et al. 2016; Stevens et al. 2016) with few at global or continental scales (Hirabayashi et al. 2013; Dankers et al. 2014; Asadieh et al. 2016; Dai 2016; Alfieri et al. 2017). In some regions such as the La Plata basin in South America (Camilloni et al. 2013), the Elbe basin and rivers flowing from the Alps in Germany (Huang et al. 2015) and the Niger basin in West Africa (Aich et al. 2016) projected flood changes are associated to increases in magnitude and/or in frequency consistent with the projected patterns in precipitation. In Europe, flood peaks with return periods above 100 years are projected to double in frequency during the next three decades (Alfieri et al. 2015). Under a high-concentration scenario, large increase in flood frequency in Southeast Asia, Peninsular India, eastern Africa and the northern half of the Andes are also expected (Hirabayashi et al. 2013). At global scale, Alfieri et al. (2017) estimate at least a doubling of flood risk compared to 1976–2005 under a warming scenario of 1.5°C with the largest increases in Asia, U.S., and Europe. In contrast, changes are statistically not significant in Africa and the northern half of the Andes are also expected (Hirabayashi et al. 2013).

A few publications specifically assess changes in runoff at 1.5°C global warming. At global scale, Alfieri et al. (2017) estimate at least a doubling of flood risk compared to 1976–2005 under a warming scenario of 1.5°C with the largest increases in Asia, U.S., and Europe (in particular in Northern and Eastern Europe). In contrast, changes are statistically not significant in Africa and Oceania for all considered warming levels between 1.5°C and 4°. Schleussner et al. (2016c) also provide analyses of projections of changes in mean annual runoff at 1.5°C and 2°C, which display a decrease in water availability in subtropical regions and in particular the Mediterranean (see also Section 3.3.4), as well as increases in much of the high northern latitudes, as well as in parts of India, East Africa and parts of the Sahel.

[More regional details from IMPACT2C, ISIMIP and Happi-MIP etc to be included in the Second Order Draft.]

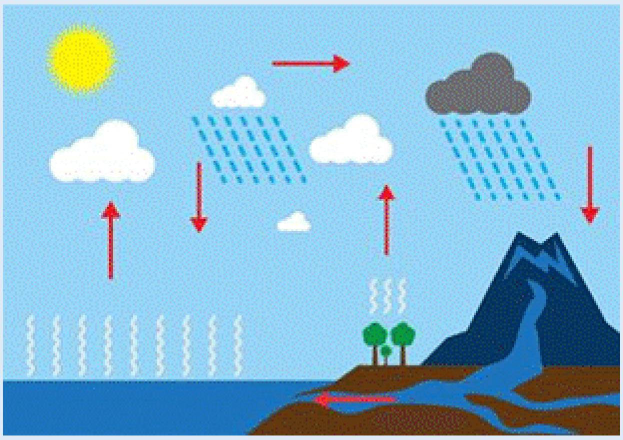
Box 3.2: Variables that should be discussed:

- Precipitation
- Evaporation
- Evaporation minus Precipitation
- Soil moisture
- Runoff
- Groundwater



Box 3.2, Figure 1: Precipitation and evaporation *[Will include a Figure like this from AR5 in the chapter for a 1.5°C world]*

- Summary of projected impacts and risks (i.e. exposure to floods, change in global scale irrigation water demand) and adaptation options



Box 3.2, Figure 2: Water cycle *[Suggested Figure: projected changes in each component for a 1.5°C world]*

3.3.6 Snow and permafrost

In AR5, Collins et al. (2013) assessed a weak decrease in the extent of seasonal snow cover (SCE, in the Northern Hemisphere spring, March-April mean) for RCP2.6 of 7 ± 4% (one standard deviation range) in the last two decades of the century compared to the 1986-2005 reference period. They were only able to attach *medium confidence* to this statement because of the considerable scatter between CMIP5 model projections and the strong simplifications inherent in incorporating snow processes within global climate models. For context, the equivalent decrease for RCP7.5 was 25 ± 8 %. These reductions are related to both precipitation and temperature changes, which also lead to a shortening of the duration of seasonal snow cover. This interaction is complex in a warming world with more precipitation falling as rain as opposed to snow and more snowmelt countered by projected increases in snowfall in winter months over the northern high latitudes. No literature could be found relating explicitly to a 1.5°C warming scenarios, however new material relating to snow cover is expected to arise from the HAPPI project (Mitchell et al. 2017).

It is *virtually certain* (Collins et al. 2013) that projected warming in the northern high latitudes combined with changes in snow cover will lead to shrinking near-surface permafrost. For RCP2.6, Collins et al. (2013) assigned *medium confidence* to their assessment because of the simplified representation of soil physics in climate models. For RCP2.6, they quote Slater and Lawrence's (2013) finding of a reduction in the area of near-surface permafrost of 37 ± 11 % for the last two decades of the century compared to the 1986-2005 reference period (compared to 81 ± 12 % for RCP8.5). There is also an indication that permafrost decline halts around the middle of the century for RCP2.6, while continuing in other RCP scenarios. These results are based on the surface frost index method applied to CMIP5 model output. The same methodology was employed by Guo and Wang (2016), who find similar results but differentiate between fractional permafrost loss in high-latitude and high-altitude areas (the latter are slightly more susceptible to loss) and regionally (the United States and China are more susceptible than Russia and Canada).

Widespread thawing of permafrost potentially makes a large carbon store (estimated to be twice the size of the atmospheric store, Dolman et al. 2010) vulnerable to decomposition, which would lead to increases in atmospheric carbon dioxide and methane concentrations. The modelling literature at the time of the AR5 was not sufficiently developed to quantify the effect of these process other than to say, with *low confidence* (Collins et al. 2013), that permafrost may become a net emitter by the end of the century. The assessment was unable to determine whether the resultant changes to the climate system would be irreversible (see 3.6.4), however the disparity between the multi-millennial timescales of soil carbon accumulation and potentially rapid decomposition in a warming climate implies that the loss of this carbon itself can be thought of as an irreversible loss.

3.3.7 Storms, tropical cyclones and wind

There is increasing evidence that the number of very intense tropical cyclones have increased in recent decades across most ocean basins, with associated deceases in the overall number of tropical cyclones (Elsner et al. 2008; Holland and Bruyère 2014). This trend holds in particular over the North Atlantic, North Indian and South Indian Ocean basins (e.g. Singh et al. 2000; Singh 2010; Kossin et al. 2013; Holland and Bruyère 2014), and is largely based on the observational record of the satellite era (the last two to three decades), since the tropical cyclone observational record is extremely heterogeneous before this period (e.g. Walsh et al. 2016b). Coupled global climate model (CGCM) projections of the changing attributes of tropical cyclones under climate change are consistently indicative of increases in the global number of very intense tropical cyclones (e.g. Christensen et al. 2013). Model projections are also indicative of general decreases of tropical cyclone frequencies under climate change, although more uncertainties are associated with such projections at the ocean basin scale (e.g. Knutson et al. 2010; Sugi and Yoshimura 2012; Christensen et al. 2013).

A general theory explaining these findings, and thereby strengthening confidence in the projections, has recently been proposed, and states that under global warming the tropical ocean is warmer and associated with above normal pressure in the middle to high troposphere, which suppresses the general formation of tropical cyclones, leading to greater intensities associated with the systems that do develop (Kang and Elsner 2015). This increase in tropical cyclone intensity at the expense of frequency occurs in the presence of an increase in moisture in the lower atmosphere (and therefore an increase in the convective instability of the atmosphere) associated with a warmer ocean (Kang and Elsner 2015). However, it should be noted that significant uncertainties surround the model projections in terms of the quantitative changes in the number of very intense tropical cyclones and decreases in the overall number of cyclones, globally and even more so at regional (specific ocean basin) scales. Even when comparing to present-day climate the projections for the end of the 21st century under well-developed climate change signals and several degrees of global warming reflect large uncertainties in quantitative changes (e.g. Christensen et al. 2013; Tory et al. 2013). This suggests that it may be a tall order for current climate models to defensibly distinguish between the changes in tropical cyclone attributes under 1.5°C *vs.* 2°C of global warming, globally and even more so at regional scales, and indeed there is currently a complete lack of studies exploring this question.

Wind change assessments are usually motivated by a need to understand changes in the sector for which they are relevant such as agriculture (McVicar et al. 2008; Vautard et al. 2010); wind energy (Pryor and

Barthelmie 2010; Troccoli et al. 2012) wave climate (Hemer et al. 2013; Hemer and Trenham 2016 and Young et al. 2011 for assessing changes in ocean waves). Extreme wind hazard is most meaningfully assessed in terms of the specific meteorological storms (e.g. Walsh et al. 2016) whereby factors such as changes in the region over which the storms occur (e.g. Kossin et al. 2014), changes in frequency and intensity of the storms, and how they are influenced by modes of natural variability are relevant considerations.

Studies examining projections in winds have found increases in 10 m mean and 99th percentile winds in high latitude ocean regions particularly in winter in CMIP3 models (McInnes et al. 2011). This in turn influences wave climate projections with robust increases in waves projected in the southern ocean in CMIP3 models (Hemer et al. 2013). While projected changes in mean winds are generally small, there is the potential for large changes in wind characteristics (including for example directions or extremes) at the boundaries of major circulation features that are projected to undergo future shifts in location. For example O'Grady et al. (2015) find changes in predominant wind direction in CMIP 5 models during summer in southeastern Australia with potential consequences for longshore sediment transport due to the projected poleward movement of the subtropical ridge in southeastern Australia. The southward expansion of the region affected by tropical cyclones (e.g. Kossin et al. 2014) may change the likelihoods of extreme winds if tropical cyclone regions of occurrence expand towards the poles.

Over the oceans, Zheng et al. (2016) confirmed that the global oceanic sea-surface wind speeds increased at a significant overall rate of 3.35 cm s^{-1} yr^{-1} for the period 1988–2011 and that only a few regions exhibited decreasing wind speeds without significant variation over this period. The increasing wind speeds were more noticeable over the Pacific low-latitude region than over region of higher latitude. Wind speeds trends over the western Atlantic were stronger than those over the eastern Atlantic, while the south Indian Ocean winds were stronger than that those over the north Indian Ocean. This is confirmed by Ma et al. (2016) who showed that the surface wind speed has not decreased in the averaged tropical oceans. Liu et al. (2016) used twenty years (1996–2015) of satellite observations to study the climatology and trends of oceanic winds and waves in the Arctic Ocean in the summer season (August–September). The Atlantic-side seas, exposed to the open ocean, host more energetic waves than those on the Pacific side. Waves in the Chukchi Sea, Beaufort Sea (near the northern Alaska), and Laptev Sea have been significantly increasing at a rate of 0.1–0.3 m $decade^{-1}$. The trend of waves in the Greenland and Barents Seas, on the contrary, is weak and not statistically significant. In the Barents and Kara Seas, winds and waves initially increased between 1996 and 2006 and later decreased. Large-scale atmospheric circulations such as the Arctic Oscillation and Arctic dipole anomaly have a clear impact on the variation of winds and waves in the Atlantic sector. Studies addressing the difference between 1.5ºC and 2.0 ºC scenarios don't exist.

3.3.8 Ocean circulation and temperature (including upwelling)

The temperature of the upper layers of the ocean (0-700 m) has been increasing at a rate just behind that of the warming trend for the planet. The surface of three ocean basins have been warming over the period 1950-2016 (by 0.11°C, 0.07°C, and 0.05°C per decade for the Indian, Atlantic and Pacific oceans respectively; Hoegh-Guldberg et al. 2014, AR5 Chapter 30), with the greatest changes occurring at the highest latitudes.

Isotherms (lines of equal temperature) are traveling to higher latitudes at rates of up to 40 km per year (Burrows et al. 2014; García Molinos et al. 2015). Long-term patterns of variability make detecting signals due to climate change complex, although the recent acceleration of changes to the temperature of the surface layers of the ocean has made the climate signal more distinct (AR5 WGII Ch30). Increasing climate extremes in the ocean are associated with the general rise in global average surface temperature as well as more intense patterns of climate variability (e.g. climate change intensification of ENSO). Increased heat in the upper layers of the ocean is also driving more intense storms and greater rates of inundation, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas.

Increasing land-sea temperature gradients, as induced by higher rates of continental warming compared to the surrounding oceans under climate change, have the potential to strengthen upwelling systems associated with the eastern boundary currents (Benguela, Canary, Humboldt and Californian Currents) (Bakun 1990). The most authoritative studies of observed trends are indicative of a general strengthening of longshore winds (Sydeman et al. 2014), but are unclear in terms of trends detected in the upwelling currents themselves (Lluch-Cota et al. 2014). However, the weight of evidence from CGCM projections of future climate change indicates the general strengthening of the Benguela, Canary and Humboldt up-welling systems under enhanced anthropogenic forcing (Wang et al. 2015). This strengthening is projected to be stronger at higher latitudes. In fact, evidence from regional climate modelling is supportive of an increase in long-shore winds at higher latitudes, but at lower latitudes long-shore winds may decrease as a consequence of the poleward displacement of the subtropical highs under climate change (Christensen et al. 2017; Engelbrecht et al. 2009). Key to analysis of the relative impact of 1.5°C and 2°C of global warming on upwelling systems, may be the analysis of changing land-temperature gradients for different temperature goals. Such an analysis can be performed for the large ensembles of CMIP5 CGCMs, and can be supplemented by more detailed parameterisations derived from high-resolution regional climate modelling studies.

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

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

3.3.9 Sea ice

Collins et al. (2013) report that the CMIP5 multi-model average for fractional Arctic sea ice loss under RCP2.6 is 8% for February and 43% for September (2081-2100 compared to a reference of 1986-2005). For context, the equivalent figures for RCP8.5 are 34 and 94%, respectively. They have *medium confidence* in these values as projections of the real world because of errors in the modelled present-day extent and the large spread in model response.

Further analysis (e.g. Massonnet et al. 2012) suggests a strong positive relationship between metrics such as the September extent over recent decades and predicted time taken for the Arctic to become nearly ice free in September. Given these biases in the CMIP5 ensemble, recalibration based on the simulation of recent ice conditions has been suggested. Studies based on this approach predict faster ice loss than the full CMIP5 ensemble would suggest. The subset of CMIP5 models averages a fractional loss of September extent of 56% for RCP2.6 (compared to 43% noted above). In common with many preceeding studies, Mahlstein and Knutti (2012) identify a strong linear relationship between September sea ice extent and global mean temperature in observations and climate model output. They use this approach to relate the threshold for a nearly ice free Arctic in September to mean global surface warming. Their estimate of ~2°C relative to the present day (or ~3°C relative to preindustrial) is consistent with Collins et al. (2013) range of 1.6 to 2.1°C relative to the present day (or ~2.6 to 3.1°C relative to preindustrial), although uncertainty is still substantial. More recently, Screen and Williamson (2017) revisit this style of approach in the context of the Paris Agreement using CMIP5 results. On the basis of a statistical analysis of climate model output for RCP4.5 and RCP8.5, they estimate that a nearly ice-free Arctic in September has a vanishingly small probability (less than 1:100,000) while global mean temperature change remains below 1.5 °C (here relative to preindustrial), however for warming above 2.0°C (again relative to preindustrial) this probability rises to 43%. Rosenblum and Eisenman (2016) interpret the offset of ~ 1°C between the earlier literature (based on CMIP3) and this more recent work in terms of volcanic forcing, which caused simulated cooling between the 1980s and 1990s that was fully incorporated in CMIP5 models but only included in about half of the CMIP3 models. Notz and Stroeve (2016) derive a relation based on observations between September extent and cumulative CO_2 emissions to estimate that Septembers would become nearly ice-free with a further 1000 Gt of emissions. In common with Mahlstein and Knutti (2012), they also note that observations suggest that sea-ice loss is more sensitive to forcing (CO_2 in this case) than models would suggest.

Collins et al. (2013) discuss the loss of Artic 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; Sedlacek 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.

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

Box 3.3: Cold Regions

[Currently there is a connection to the Artic text in this chapter and eventually an overlap with the Arctic case study from Chapter 4. This will be reconciled for the second order draft. The Box has 2 major themes, which are Arctic and Antarctic (1) and high altitude subsyystems (2). First ideas to be included are included here.]

1) Arctic:

Sea ice

Sea ice extent in the Arctic is a critical quantity that has undergone major cahnges in the last 30–40 years. Research suggests that a summer ice-free Arctic is virtually certain to be avoided if the 1.5°C target of the Paris Agreement is met; the 2°C target may be insufficient to prevent an ice-free Arctic (Screen and Williamson 2017).

Temperature extremes

Recently, global temperature targets have been translated into regional and impact related climate targets (Seneviratne et al. 2016). The results suggest that coldest night-time temperatures in the Arctic will increase by about 5.5°C for the 2°C global warming target; this increase will be reduced to 4.4°C for a 1.5°C global warming target.

Permafrost

Thawing permafrost has the potential of unlocking vasts amount of CO_2 and methane as well as putting infrastructures at risk. While warming of 2°C would see permafrost-covered land shrink by more than 40%, compared to the period 1960–1990, stabilising at 1.5°C would reduce the loss to about 30% (Chadburn et al. 2017).

Land ice and sea level rise

Information about 1.5°C warming impacts on Antarctica

2) Affected high altitude subsystems:

Glaciers, permafrost, lakes (endorheic), vegetation, for Andes, Alps, Tibetan Plateau, etc…

- Temperature (stand alone):

Degree days (+ growing season length) as a measure of net radiation affecting:
=> ice sheets plus surface runoff and consequences
=> glacier melt plus runoff and glacier lakes,
=> permafrost melt
=> vegetation change
=> montains versus plateau topographic environments

Impact-1 (hazards): land slide, natural dams of glacier-lake
Impact-2 (farming): change in pasture and farming habits

- Temperature rise plus precipitation (enhanced/reduced; summer/winter)

=> cloud feedback example:
more rain and clouds (and runoff) - less solar - less net-radiation/pot. evaporation - larger lakes

- Temperature rise plus snow depth and duration:

affecting albedo and sfc water/energy balance and storage

- Temperature rise plus near surface winds:

affecting evaporation, diurnal circulations (mountain-valley winds and jets)

- Temperature rise plus surface energy and water balance:

Relevance of water storage, drainage *vs.* surface runoff

3.3.10 Sea level

Projected Global Mean Sea Level (GMSL) rise is the sum of contributions from ocean heat uptake and thermal expansion; glacier and ice-sheet mass loss; and anthropogenic intervention in water storage on land. There is high confidence that sea level has been rising from the late 19th to early 20th centuries, and that low rates of rise characterized the previous two millennia (Church et al. 2013). It is very likely that GMSL has risen by 0.17 and 0.21 m from 1901 to 2010, and that the rate has roughly doubled during the last decade of this period and between 1920 and 1950 (Church et al. 2013).

It is *virtually certain* that GMSL will continue to rise beyond 2100 (Church et al. 2013). This is true for all emission scenarios including RCP2.6 so that it is probable that even strong reductions in GHG emissions will not halt this process, however it may result in a slowing of the rate of GMSL rise by the end of the century. The effect of this slowing is that the year in which a particular height above present-day seal level is inundated, it is shifted further into the future. Two contributors to GMSLR projections (ice sheet outflow and terrestrial water storage) were reported in the AR5 without scenario dependence because, at that time, there was insufficient scientific basis to quantify these differences. Clearly, scenario dependence is crucial in assessing the effects of strong reductions in GHG emissions on GMSLR. AR5 is therefore an insufficient basis for assessing ice-sheet outflow and terrestrial water storage, and more recent projections will need to be assessed.

Ocean heat uptake and thermal expansion is the dominant component in the AR5 assessment of (Church et al. 2013) and contributes 0.10 to 0.18 m of 0.26 to 0.55 m total GMSL rise in scenario RCP2.6 (likely ranges, 2081-2100 relative to 1986-2005). Ocean heat uptake is the integral over time of surface heat flux, the amount of consequent thermal expansion is therefore dependent not only on the cumulative total of GHG emissions but also on the pathway of emissions. In this way, reducing emissions earlier rather than later in the century more effectively mitigates GMSL rise by thermal expansion (Zickfeld et al. 2012; Bouttes et al. 2013).

In common with most other contributors to GMSL rise, ocean heat uptake and thermal expansion continue centuries to millennia beyond the stabilization of GHG and radiative forcing (Schewe et al. 2011). In RCP2.6, for instance, the rate of GMSLR peaks at ~2030 but only falls to half this value by the end of the century. There is some potential for nonlinear behaviour in the response of ocean heat uptake to global surface warming associated with changes in ocean circulation and deep water formation.

Mass loss from mountain glaciers and ice caps is projected to account for a likely range of 0.04 to 0.16 m GMSL rise in the AR5 assessment for RCP2.6 (from a total of 0.26 to 0.55 m 2081-2100 relative to 1986-2005, Church et al. 2013). The rate at which mass is lost is projected to be fairly constant through time despite changes in global surface warming, which may represent a balance between increased warming towards the end of the century the depletion of low-elevation ice.

Glaciers have a similar integral relation to global surface warming as ocean heat uptake, and glacier contribution to GMSL is similarly unlikely to stabilize by the end of the century even under strongly reduced GHG emissions. Projections suggest that, under RCP2.6, between 45% and 85% of current ice volume will survive to the end of the century (Clark et al. 2015). Mass loss from marine-terminating glaciers by ice berg calving is not well represented by models and may introduce nonlinearity into the response of glaciers to climate change. Projections of glacier mass losses relating to 1.5° C climate are likely to be forthcoming from the HAPPIMIP project (Mitchell et al. 2017).

The Greenland ice sheet can contribute to GMSL rise in two main ways. These are by increases in the outflow of ice (typically by the calving of ice bergs and the melt at the termini of marine outlet glaciers) and by increases in surface melt. While projections of the latter are routinely made, process-based modelling of the former is in its infancy and AR5 projections were unable to differentiate between emission scenarios. Subsequently, Fuerst et al. (2015) were able to make projections based on emission scenario using an ice-flow model forced by the regional climate model MAR (considered by Church et al. 2013 to be the 'most realistic' such model). Fuerst et al. (2015) obtain an RCP2.6 likely range of 0.02 to 0.06 m by the end of the century (relative to 2000). This is somewhat smaller than the RCP2.6 projection made by Church et al. (2013) (0.04 to 0.10 m) probably reflecting an over estimate of the scenario-independent contribution from outflow ('rapid dynamics').

Various feedbacks between the Greenland ice sheet and the wider climate system (most notably those related to the dependence of ice melt on albedo and surface elevation) make irreversible loss of the ice sheet a possibility. Two definitions have been proposed for the threshold at which this loss is initiated. The first is based on the surface temperature at which net Surface Mass Balance (SMB, the difference between mass loss, mostly melt and subsequent runoff, and gain, mostly snowfall) first becomes negative for the current ice-sheet geometry. Church et al. (2013) assess this threshold to be 2°C or above (relative to pre-industrial). A second definition is based on the evolution of a dynamical model of the ice sheet when forced in an ensemble of prescribed warmings. Robinson et al. (2012) find a very likely range for this threshold of 0.8 to 3.2°C. In both cases, the timescale for eventual loss of the ice sheet can be tens of millennia and assumes constant surface temperature forcing during this period. Where temperature to cool subsequently, the ice sheet may regrow although the amount of cooling required is likely to be highly dependent on the duration and rate of the previous retreat.

Published process-model projections are now available for the contribution of the Antarctic ice sheet to GMSL rise over the remainder of the century, which are based on models that could potentially allow Marine Ice Sheet Instability (MISI, the continued retreat an ice sheet resting on bedrock below sea level once triggered by external warming of the surrounding ocean and/or atmosphere) so that the separate assessment of MISI used by Church et al. (2013) may no longer be necessary.

The three main papers to provide projections can be divided into two groups. DeConto and Pollard (2016) and Golledge et al. (2015) both suggest that RCP2.6 is the only RCP scenario leading to millennial-scale contributions to sea level of below 1 m, and DeConto and Pollard (2016) indicate a contribution to GMSL rise of 0 to 0.22 m by the end of the century. Cornford et al. (2015) compared SRES scenarios A1B and E1 (emissions stabilized at 500 ppm CO_2 by 2050). They obtained the counter-intuitive result of a higher contribution to sea level from E1 than A1B of ~0.02 m by the end of the century. This arises because ocean warming in both A1B and E1 is similar and generates similar increases in outflow, however increases in snow fall caused by atmospheric warming (e.g., Frieler et al. 2015) are greater in A1B which compensates the increased outflow and leads to a reduced contribution to GMSL rise. The difference between these two sets of projections can most likely be attributed to both the numerical treatment of grounding-line migration (e.g., Durand and Pattyn 2015) and the detailed forcing employed (Cornford et al. 2015) used results from regional atmosphere and ocean modelling, including Hellmer et al. (2012). DeConto and Pollard (2016) introduce a new mechanism by which ice can be lost rapidly from Antarctica (cliff collapse), however the amount of surface warming required to initiate this process seems very unlikely for reduced emission scenarios, such as RCP2.6. Levermann et al. (2014) develop response functions for the ice sheet based on the idealised SEARISE inter-comparison (Bindschadler et al. 2013) and obtain an end-of-century projection of

0.02 to 0.14 m for RCP2.6. Both the long-term committed future of Antarctica and its end-of-century GMSL contribution are complex and require detailed process-based modelling, however a threshold in this contribution may be present close to scenario RC2.6.

There is potential for the methodology used by Church et al. (2013) to derive GMSL rise projections, to be used in the present special report with updated process-based projections for the individual contributors based on RCP2.6 and using recent literature published after AR5, in particular for the Greenland and Antarctic ice sheets.

Church et al. (2013) indicate that it is very likely that sea level will have a strong regional pattern through the 21st century and beyond, however it is also very likely that over about 95% of the world's ocean will experience sea level rise and that about 70% of global coastlines will experience sea level rise within 20% of the global mean. While Church et al. (2013) are primarily concerned with RCPs 4.5 and 8.5, it seems probable that these statements also apply to RCP2.6 and scenarios in which emissions are strongly reduced. It is also very likely that there will be an increase in extreme sea levels by 2100 in some regions because of increased mean sea level (*high confidence*) and storms (*low confidence*). Assuming that the former is the main driver of extreme sea levels, a technique based on a network of the tide gauges covering most of the world (Hunter 2012) could be used to assess differences in return period associated with emissions scenarios close to RCP2.6, as it was for RCP4.5 in Church et al. (2013).

Box 3.4: Small Developing States (SIDS)

1. **The climate related risks for SIDS**
    a. Climate change risk profiles for SIDS are not uniform. Climate impacts vary and are dependent on the magnitude, frequency and extent of an event, the bio-physical nature of the island and its social, economic and political setting (AR5).
    b. Noting from literature how the key climate related risks for SIDS change for 1.5 vs 2 degree warming or higher. Distinguishing between results for Caribbean, Indian Ocean and Pacific Ocean small island regions.
        i. Temperature trends and heat extremes.
        ii. Rainfall and rainfall extremes. If possible capture variations within the small island regions e.g. among the more dispersed Pacific islands where equatorial regions are likely to get wetter, whereas the sub-tropical high pressure belts will likely get drier under higher levels of warming (AR5).
        iii. Sea level rise.
        iv. Tropical cyclones.

2. **Changes in impacts on natural & human systems important for SIDS. Focus only on impacts at 1.5 versus 2°C or higher warming where the literature allows. Identifying also where the literature does not enable distinctions. Potentially a table. Emphasis on:**
    a. Freshwater resources. Freshwater supplies present challenges due to the topography and geology of small islands as well as water storage capacities. There is limited freshwater on many small islands and potential changes in its availability and quality linked to climate change will have adverse impacts on the economies of the SIDS.
    b. Terrestrial ecosystems. Climate change, interacting with other drivers, is undermining the ecosystems of SIDS. The economies of many SIDS are dependent on these ecosystems. Are there differences at 1.5 vs 2 for (for example) ecosystem and species shifts, declines in range and the invasion of exotic and pest species. These impacts are generally magnified on small islands due to limited areas, isolation and high levels of endemic species.
    c. Coastal erosion and marine ecosystems. Many SIDS are dependent on their coastal resources for livelihoods and wellbeing, productivity and economic survival and coastal protection. What will be the impact on coral reefs, mangroves, wetlands, and seagrass for 1.5 vs 2 or higher?

d. Food production and livelihoods. Potential impacts on coastal fisheries due to (i) direct effects and (ii) effects of increased coral reef bleaching, beyond degradation due to overfishing and pollution. Are there also potential positive impacts, for example, projected positive changes in tuna fisheries and freshwater aquaculture in the Pacific (AR5).
e. Tourism. Tourism is a major weather and climate-sensitive sector on many small islands. There are potential direct impact on environmental resources that serve as major tourism attractions or on coastal infrastructure, as well as indirect impact via resource degradation (e.g. beach erosion, coral bleaching) which negatively impact the attractiveness of the destination.
f. Infrastructure, settlements and 'coastal squeeze'. The majority of human communities and infrastructure in SIDS are located in coastal zones, with limited island relocation opportunities, especially on atoll islands. Populations, infrastructure, agricultural areas and fresh groundwater supplies are all vulnerable to extreme tides, wave and surge events and sea level rise (AR5).
g. Public health. SIDS suffer from climate sensitive health problems, including morbidity and mortality from extreme weather events and certain vector, food and water-borne diseases. Extreme weather and climate events have both short and long term effects on human health. Transboundary processes also already have a negative impact on small islands.

3. Updated Key risks

Noting that some keys risks were identified in AR5. Using information from above to update 'Key Risk' table from AR5 consistent with what is being done in other sections of Chapter 3. Noting that the lack of long term data for determining baseline conditions is a constraint. Reiterating that context-specific conditions are important consideration when considering risks for each small island state.

3.3.11 Ocean chemistry

The ocean is a dominant and fundamentally important component of the climate system. The properties of the ocean are influenced by the composition of the atmosphere, temperature and the degree of mixing of the water column. In addition, the composition of the ocean is also influenced by inundation as well as surface evaporation, ice, and activities of organisms and ecosystems (Stocker et al. 2013). Despite these many influences, ocean chemistry has been relatively stable for millions of years (Honisch et al. 2012).

Many recent changes in ocean chemistry can be attributed to human activities. Around 30% of CO_2 emitted by human activities, for example, has been absorbed by the ocean where it combines with water to produce a dilute acid which disassociates and drives 'ocean acidification' (Cao et al. 2007; Stocker et al. 2013). These changes have resulted in a sustained decrease in ocean pH by 0.1 pH units since the Preindustrial Period, as well as the concentration of key ions such as protons, carbonate and bicarbonate ions. Total acidity and bicarbonate ion concentrations have increased by approximately 26%, while carbonate concentrations have decreased by a similar amount (Cao and Caldeira 2008; Stocker et al. 2013).

Rates of change in ocean chemistry are already higher than that seen in the last 65 million years, if not the last 300 million years (e.g. ocean acidification; Honisch et al. 2012). These rates of change are unprecedented: The current rate and magnitude of ocean acidification are at least 10 times faster than any event within the last 65 Ma (high confidence; Ridgwell and Schmidt 2010) or even 300 Ma of Earth history (medium confidence; Honisch et al. 2012 and Pörtner et al. 2014b). Periods of high atmospheric concentrations of CO_2 in the paleo-record have been accompanied by a reduction in calcifying ecosystems such as coral reefs (e.g. (PETM, 55.3 Ma; Veron 2008; Pörtner et al. 2014). The time taken to reverse ocean acidification by continental weathering processes takes tens of thousands of years (Honisch et al. 2012) and hence consideration must be given to the irreversibility of the emerging risks associated with changes to ocean chemistry.

Changes attributed to ocean acidification also vary regionally with the greatest changes occurring where temperatures are lowest (e.g. polar regions, increasing CO_2 solubility), or where CO_2 rich water is brought to the surface by upwelling. Acidification can also be influenced by effluents from natural or disturbed coastal land use, and other non-climate factors such as the atmospheric deposition of acidic materials may not be directly attributable to climate change, yet amplify the effects of ocean acidification due to increased atmospheric CO_2 (Bates and Peters 2007; Duarte et al. 2013).

Ocean acidification also influences other aspects of the ionic composition of seawater by changing the organic and inorganic speciation of trace metals, with increases in the predicted free ion concentrations such as Al by 20-fold by end of century. These changes are of concern given the importance of these ions to biological systems yet have not been comprehensively explored (Stockdale et al. 2016). Other aspects of ocean chemistry have been changing. Oxygen concentrations vary regionally, and are highest in the Polar regions, and lowest in eastern basins of the Atlantic and Pacific oceans, and in the northern Indian Ocean. Increasing temperatures in the upper layers of the ocean has led to a decrease in the solubility of gases such as oxygen with concentrations declining at the rate of 2% since 1960 (Schmidtko et al. 2017). Changes in ocean mixing together with increased metabolic rates in the deep ocean has increased the frequency of areas ('dead zones') where oxygen has fallen to levels that are unable to sustain oxygenic life (Altieri and Gedan 2015) with risks being projected for a broader regional impact including the tropics (Altieri et al. 2017). Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e. evaporation and inundation; Hoegh-Guldberg et al., 2014). Some regions (e.g. northern oceans and Arctic regions) have decreased salinity (i.e. due to melting glaciers and ice sheets) while others are increasing in salinity due to higher sea surface temperatures (Durack et al. 2012).

Numerous risks from rapid changes to ocean chemistry to biological systems have been identified (Kroeker et al. 2013; Gattuso et al. 2015a; Albright et al. 2016; Dove et al. 2013b; Pörtner et al. 2014b). A comprehensive meta-analysis (Kroeker et al. 2013) synthesized the results and conclusions of 228 studies and revealed risks to the survival, calcification, growth, development, and abundance of a broad range of taxonomic groups (i.e. from algae to fish) with considerable evidence of predictable trait-based sensitivities. Organisms with shells and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a broad number of organisms, although there were examples of taxa that did not show the sensitivity. Risks were enhanced when taxa were exposed to elevated CO_2 and sea temperature. Given the broad and multiple risks, and the many potentially complex interactions, evidence and a full understanding of the risks of changing ocean chemistry at an early stage.

3.3.12 Global synthesis

3.3.12.1 Summary on global changes in key climate variables and climate extremes

Table 3.1 below provides a summary of detected, attributed, and projected changes at 1.5°C and 2°C global warming for several climate variables, including climate extremes. The underlying data basis is the IPCC SREX report Chapter 3 (Seneviratne et al. 2012), several chapters of the AR5 WG1 report (Hartmann et al. 2013; Bindoff et al. 2013; Collins et al. 2013), and new evidence in publications since AR5 (including analyses displayed in this Chapter). The projections are assessed both based on transient simulations (i.e. passing through 1.5°C or 2°C, including overshoot) and based on projected changes at equilibrium (based on the HappiMIP experiment (Mitchell et al. (2017). More details on the applied methods are provided in Section 3.2.

Table 3.1: Summary on global changes in key climate variables and climate extremes: Detected observed changes, attributed observed changes, and projected changes at 1.5°C and 2°C global warming, including both transient changes and changes at equilibrium. Assessments are provided qualitatively (top half of cell) and if available also quantitatively (bottom half of cell). Symbols for references are: S12 (Seneviratne et al. 2012), H13 (Hartmann et al. 2013), B13 (Bindoff et al. 2013), and C13 (Collins et al. 2013).

	Detected observed changes	**Attributed observed changes**	**Projected transient changes until 2100 (passing through)**		**Projected changes at equilibrium**	
			1.5°C	**2°C (transient or overshoot)**	**1.5°**	**2°**
Mean temperature	**Globally**: ***Virtually certain*** increase [B13]; **Regionally**: ***Very likely*** increase in most regions [REFS?] **Globally**: ~1° global surface warming [REFS?]; **Regionally**: Higher detected warming than 1°C in many regions [REFS?]	**Globally**: ***Virtually certain*** human influence on increase [B13] **Regionally**: ***Very likely*** human influence on increase in most regions [REFS?] **Globally**: ***Likely*** 0.5-1.3°C warming over 1951-2010 time period [B13] **Regionally**: ?[REFS?]	**Globally**: ***Virtually certain*** increase [assessment based on observed and attributed changes] **Regionally**: ***Very likely*** increase in most regions [assessment based on observed and attributed changes] **Globally**: 1.5°C **Regionally: *Very likely*** higher warming than 1.5°C in most land regions (on average between 1.5°C-3°C depending on region) [Fig. 3.4]	**Globally**: ***Virtually certain*** increase [assessment based on observed and attributed changes] **Regionally**: ***Very likely*** increase in most regions [assessment based on observed and attributed changes, and C13 for CMIP5 projections] **Globally**: 2°C **Regionally: *Very likely*** higher warming than 2° on land (on average between to 2-4° depending on region) [Fig. 3.4]	Not yet available (Happi-MIP experiments)	Not yet available (Happi-MIP experiments)
Mean precipitation	**Globally**: ***Low confidence*** in global trends in mean precipitation [H13] ***Low confidence*** in trends in monsoons because of insufficient evidence. [S12]	**Globally:** No attribution on global scale [REF?] ***Low confidence*** in human influence on trends in monsoons due to insufficient evidence. [S12]	TO BE ASSESSED, probably ***Low confidence***	TO BE ASSESSED, probably ***Low confidence***	Not yet available	Not yet available
Temperature extremes (hot and cold extremes)	**Globally: *Very likely*** increase in number of warm days/nights and decrease in number of cold days/nights (S12, H13) **Regionally**: See section 3.3.2	**Globally: *Very likely*** anthropogenic influence on trends in warm/cold days/nights at the global scale. [B13] **Regionally**: No attribution of trends at a regional scale with a few exceptions. [S12, B13]	**Globally: *Very likely*** further increase in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes [Sections 3.3.1 and 3.3.2, Figs 3.2, 3.5, 3.7, 3.8, 3.9 and 3.10] **Regionally**: ***Likely*** increase in most land regions [Figs. 3.5, 3.8, 3.9, and 3.10 Section 3.3.2 ; **magnitude of change:** ***Likely*** higher warming than 1.5°C in most land regions (on average between 2°C-6°C depending on region and considered extreme index) Figs. 3.5, 3.8 and 3.9; Sections 3.3.1 and 3.3.2] **Globally**: - **Regionally: *Likely*** higher warming than 1.5°C in most land regions (on average between 2°C-6°C depending on region and considered extreme index) [Fig. 3.3.2; Section 3.3.2]	**Globally: *Virtually certain*** further increase in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes [assessment based on S12 and C13 for CMIP5 projections] **Regionally**: ***Very likely*** increase in most land regions Figs. 3.5, 3.8, 3.9, and 3.10; Section 3.3.2]**; magnitude of change:** **Regionally: *Likely*** higher warming than 2°C in most land regions (on average between 3°-8° depending on region and considered extreme index) [Figs. 3.5, 3.8 and 3.9; Sections 3.3.1 and 3.3.2]	Not yet available	Not yet available

	Detected observed changes	Attributed observed changes	Projected transient changes until 2100 (passing through)		Projected changes at equilibrium	
			1.5°C	2°C (transient or over-shoot)	1.5°	2°
Heavy precipitation	**Globally**: *Likely* more regions with increase than regions with decreases (S12)	**Globally**: *Medium confidence* that human influences have contributed to intensification of extreme precipitation at the global scale (S12)	**Globally:** *Medium confidence* in further increase in more regions than in regions with decrease (based on attributed changes, Sections 3.3.1 and 3.3.3, and Figs. 3.3, 3.6, 3.7 and 3.11]	**Globally:** *Medium confidence* in further increase in more regions than in regions with decrease [Figs 3.6 and 3.11]	Not yet availab le	Not yet availab le
Runoff and flooding	**Globally:** *Low confidence* at the global scale regarding even the sign of observed changes in frequency or magnitude of floods [S12] *High confidence* in trend toward earlier occurrence of spring peak river flows in snowmelt- and glacier-fed rivers. [S12]	**Globally:** *Low confidence* that anthropogenic warming has affected the magnitude or frequency of floods at a global scale. *Medium confidence to high confidence* in anthropogenic influence on changes in some components of the water cycle (precipitation, snowmelt) affecting floods.	**Globally:** *Low confidence* in global projections of changes in flood magnitude and frequency because of insufficient evidence. [based on observed and attributed changes, and S12 for RCP8.5 projections] *Medium confidence* (based on physical reasoning) that projected increases in heavy precipitation would contribute to rain-generated local flooding in some catchments or regions [based on S12]	**Globally:** *Low confidence* in global projections of changes in flood magnitude and frequency because of insufficient evidence. [based on observed and attributed changes, and S12 for RCP8.5 projections] *Medium confidence* (based on physical reasoning) that projected increases in heavy precipitation would contribute to rain-generated local flooding in some catchments or regions [based on S12]	Not yet availab le	Not yet availab le
Droughts and dryness	**Globally:** *Medium confidence* that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but opposite trends also exist [S12]. No support for increasing drying in dry regions and increasing wetting in wet regions, except in high latitudes (Greve et al. 2014)	**Globally:** *Medium confidence* that anthropogenic influence has contributed to some observed changes in drought patterns. *Low confidence* in attribution of changes in drought at the level of single regions due to inconsistent or insufficient evidence. [S12]	**Globally:** *Medium confidence* that some trends patterns could be enhanced, in particular in the Mediterranean region and Southern Africa [assessment based on observed trends, and published literature (Section 3.3.4), and Figure 3.12]	**Globally:** *Medium confidence* that some trends patterns could be enhanced, in particular in the Mediterranean region and Southern Africa [assessment based on observed trends, and published literature (Section 3.3.4), and Fig. 3.12]	Not yet availab le	Not yet availab le
Snow, glaciers and permafrost	*Likely* increased thawing of permafrost with *likely* resultant physical impacts. [S12] -- NEED ASSESSMENT FOR SNOW	*Likely* anthropogenic influence on thawing of permafrost [S12] -- NEED ASSESSMENT FOR SNOW	*Likely* increased thawing of permafrost with *likely* resultant physical impacts. [based on assessment for observed changes] - NEED ASSESSMENT FOR SNOW	*Likely* increased thawing of permafrost with *likely* resultant physical impacts. [based on assessment for observed changes] - NEED ASSESSMENT FOR SNOW	Not availab le	Not availab le

	Detected observed changes	Attributed observed changes	Projected transient changes until 2100 (passing through)		Projected changes at equilibrium	
			1.5°C	2°C (transient or over-shoot)	1.5°	2°
Storms, tropical cyclones, and wind	**Globally:** *Likely* poleward shift in *extratropical cyclones*. [S12] *Low confidence* that any observed long-term (i.e., 40 years or more) increases in *tropical cyclone* activity are robust, after accounting for past changes in observing capabilities. **Regionally:** *Low confidence* in regional changes in intensity of *extratropical cyclones*. [S12]	**Globally:** *Medium confidence* in an anthropogenic influence on poleward shift. [S12] *Low confidence* in attribution of any detectable changes in tropical cyclone activity to human influences (due to uncertainties in historical tropical cyclones record, incomplete understanding of physical mechanisms, and degree of tropical cyclone variability). [S12]	**Globally:** *Medium confidence* in projected poleward shift of mid-latitude storm tracks. [based on assessment for observed changes] *Low confidence* in changes in tropical cyclones [based on observed and attributed changes]	**Globally:** *Medium confidence* in projected poleward shift of mid-latitude storm tracks. [based on assessment for observed changes] *Low confidence* in changes in tropical cyclones [based on observed and attributed changes]	Not yet availab le	Not yet availab le
Ocean circulation and temperature (e.g., upwelling)	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	Not availab le	Not availab le
Sea ice	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	Not availab le	Not availab le
Sea level (mean & extremes)	**Globally**: [[ASSESSMENT FOR MEAN SEA LEVEL?]] *Likely* increase in extreme coastal high water worldwide related to increases in mean sea level in the late 20th century. [S12]	**Globally:** [[ASSESSMENT FOR MEAN SEA LEVEL?]] *Likely* anthropogenic influence on extreme coastal high water worldwide via mean sea level contributions [S12]	**Globally:** [[ASSESSMENT FOR MEAN SEA LEVEL?]] *Likely* increase in extreme coastal high water worldwide via mean sea level contributions [based on observed and attributed changes]	**Globally:** [[ASSESSMENT FOR MEAN SEA LEVEL?]] *Likely* increase in extreme coastal high water worldwide via mean sea level contributions [based on observed and attributed changes]	Not yet availab le	Not yet availab le
Ocean chemistry	Very high confidence in decrease in pH, oxygen and carbonate, while similar confidence increase in bicarbonate and protons	Almost certain decrease in oxygen content due to warming trends.. Charges in carbonate chemistry almost certainly driven by increasing carbon dioxide content (high confidence)	Progress changes in risk. Risk increases with increase in ocean temperature and carbon dioxide content.	High confidence in impacts being higher with higher temperature and carbon dioxide.	Not availab le	Not availab le

Box 3.5: Tipping points at 1.5°C and higher levels of warming

The prospect of passing climate tipping points was considered as a 'reason for concern' in the IPCC WG2 report (IPCC 2014; Oppenheimer et al. 2014) (and has been put forward by some authors as a motivation for limiting global warming to as low a temperature as possible (Lenton et al., 2008; Smith et al., 2009). A tipping point occurs when a small change in forcing (e.g. global temperature) leads to a qualitative change in the future state of a sub-system of the global climate system (Lenton et al., 2008). The resulting change may unfold rapidly or slowly and may be in some cases difficult to reverse, depending on the climate sub-system involved (Lenton et al., 2008).

As discussed in the IPCC SREX report, possible future occurrence of low-probability, high-impact scenarios associated with the crossing of poorly understood climate thresholds cannot be excluded, given the transient and complex nature of the climate system (Seneviratne et al. 2012). However, literature is still sparse on the assessment of tipping points and their robustness, especially with a focus on 1.5°C vs higher levels of warming, and we thus assign only *low confidence* in the following assessments. This reflects the fact that tipping points involve complex interactions and are difficult to validate. In addition, evidence is often limited to single models or observational evidence (see hereafter). Nonetheless, an assessment that we have *low confidence* should not be interpreted as meaning that no change is expected in this extreme or climate element (see Seneviratne et al. 2012).

Existing studies have identified – through literature review (Lenton et al., 2008), expert elicitation (Kriegler et al., 2009; Lenton et al., 2008), and scanning of the CMIP5 model database (Drijfhout et al., 2015) - several potential climate tipping points that could be passed under different levels of global warming. The corresponding sub-system changes (and timescales) range from fast loss of sea-ice (years-decades) or land snow (decades), collapse of ocean convection (years-decades), abrupt vegetation changes (decades), reorganization of ocean circulation (decades-centuries), to loss of ice sheets (centuries-millennia).
Here we focus on which climate tipping points existing literature suggests could be passed or avoided by limiting warming to 1.5°C or 2°C. Existing assessments agree that the likelihood of passing tipping points increases with global temperature. However, whilst expert elicitation results suggest a roughly linear increase in the likelihood of passing specific tipping points with global temperature (Kriegler et al., 2009; Lontzek et al., 2015), a recent analysis of CMIP5 model projections suggests a clustering of abrupt changes in the interval of 1.5-2°C warming (Drijfhout et al., 2015). Abrupt changes predicted at low levels of global warming involve sea-ice, land ice/snow and high-latitude ocean circulation (deep convection) (Drijfhout et al., 2015), consistent with observations that the polar regions are particularly sensitive to global warming and proposals that they have several potentially easily-triggered tipping points (Lenton, 2012; Lenton et al., 2008). In this context, it should be noted that not only the mean global warming is relevant for the assessment of tipping points, but also the time point at which this warming is realized (e.g. within the 21st century or after several millennia, see also section 3.2). This is particularly important for tipping points associated with sea ice and sea level rise. We next discuss specific classes of tipping point that have been proposed to be relevant at low levels of warming.

Sea-ice: Arctic summer sea-ice cover has been declining non-linearly over the last ~30 years, due to both warming and atmospheric circulation changes (Ding et al., 2017). During boreal winter/austral summer 2016-7 the global sea-ice extent dropped ~2M km^2 below previous years indicating unprecedented Antarctic summer sea-ice loss. Abrupt sea-ice declines are forecast in some models under future forcing, with their occurrence increasing from 2 model simulations with this feature at <1.5°C to 5 at <2°C (Drijfhout et al., 2015). Across a wider range of models (regardless of whether the ice loss is abrupt) the likelihood of an ice-free Arctic (defined as September sea-ice extent <1 million km^2) increases from exceptionally unlikely (<1 in 100,000 chance) under 1.5°C warming to 39% (about as likely as not) under 2°C warming (Screen and Williamson, 2017). Impacts that have been proposed to result from crossing of sea-ice tipping points range from amplification of regional warming and possible changes in mid-latitude weather patterns to major ecological shifts (Bhatt et al., 2014; Vihma, 2014).

Land-ice/snow: Abrupt declines in snow volume on the Tibetan plateau are forecast in some model projections, increasing in occurrence from 1 model simulation at <1.5°C to 3 at <2°C (Drijfhout et al., 2015). Potential remote impacts may include intensification of Eurasian heatwaves (Wu et al., 2016) and weakening of the East Asian summer monsoon (Xiao and Duan, 2016). It is unclear whether permafrost thawing represents a tipping point because it is predicted to respond quasi-linearly to temperature change. Regardless, the extent of permafrost loss is expected to increase from 4.8 (2.6-6.8) M km^2 at 1.5°C to 6.6 (4.4-8.6) M km^2 at 2°C (Chadburn et al., 2017). Impacts include amplification of global warming from CH_4 and CO_2 release, ecological changes, and regional disruption of transport and infrastructure.

Ocean circulation: Deep convection in the Labrador Sea region has already switched on and off in the observation record and is projected to collapse in some models (Drijfhout et al., 2015). Impacts include sea-ice expansion, cooling of the N. Atlantic region, southward shift of the ITCZ (Drijfhout et al., 2015) and increases in sea-level along the E. side of N. America (Yin et al., 2009). A full collapse of the Atlantic meridional overturning circulation (AMOC) is predicted in one model at low warming (Drijfhout et al., 2015), with correspondingly greater impacts. The occurrence of these abrupt changes in ocean circulation increases from 4 model simulations displaying this shift at <1.5°C to 9 at <2°C (Drijfhout et al., 2015). Furthermore, the AMOC may be systematically biased too stable in current models (Liu et al., 2017), meaning that the likelihood of collapse at low levels of warming may have been underestimated. Nonetheless, given the only *limited evidence* (single-model result), we assess that there is *low confidence* at present regarding the existence of a possible AMOC-related tipping point between 1.5°C and 2°C.

Ice sheets: Already at ~1°C global warming, observations suggest that parts of the West Antarctic Ice Sheet (WAIS) and the Greenland Ice Sheet (GIS) are in retreat,. Paleo-climatic interpretations can be used to assess the longer-term Global Mean Sea Level (GMSL) commitment at ~1°C warming, with the ~1°C globally warmer Eemian (last interglacial period, MIS 5e) having had peak 6-9 m GMSL rise, of which 5-8 m was from polar ice sheets (Dutton et al., 2015). Models estimate a ~2 (0.6-3.5) m Eemian contribution from the GIS, implying ~4.5 (1.5-7.4) m from Antarctica.

At 1.5°C, 2°C, or greater warming recent models suggest the GIS, WAIS, and parts of the East Antarctic ice sheet (EAIS) could become vulnerable to irreversible loss. The entire GIS could be under threat at >1.5°C warming, ultimately contributing up to ~7 m to GMSL over multi-millennial timescales (IPCC, 2013; Knutti et al., 2016; Robinson et al., 2012). Similarly, there are indications that both WAIS and EAIS may exhibit threshold behavior between RCP2.6 and higher scenarios. For the higher scenarios, Golledge et al. (2015) obtain near-equilibrium contributions to sea level of up to 9 m after 3000 years and de Conto and Pollard (2016) 12 to 14 m after 500 years, dependent on model physics. Both studies suggest equilibrium contributions of less than a metre for RCP2.6.

Biomes: Abrupt terrestrial biomes shifts are predicted in some models, but only at >2°C warming (Drijfhout et al., 2015; Lenton et al., 2008). These shifts include greening of the Sahel, Amazon dieback, expansion of the boreal forest into the tundra at its northern edge, and dieback of the boreal forest at its southern boundary. We note that all of these projections are extremely uncertain and generally based on single-model studies. For this reason, the *confidence* in the existence of these thresholds, and the global warming levels at which they might occur, is assessed as present to be *low*. Almost complete degradation of tropical coral reefs has been assessed to possibly occur at ~2°C warming (Schleussner et al., 2016), but it is unclear at present if this development could be fully irreversible (See Section 3.3.)

In summary, existing studies have proposed that limiting global warming to 2°C could significantly reduce the risk of passing some damaging tipping points, especially terrestrial biome loss, but there is *low confidence* in these assessments. It has also been suggested that major tipping point risks remain at higher values than 2°C global warming, notably from irreversible ice sheet loss, as well as Arctic sea-ice loss and collapse of Labrador Sea convection. Restricting global warming to 1.5°C may significantly reduces these high-latitude tipping point risks, but we may still be committed even at present 1°C warming to irreversible ice-sheet loss and multi-millennial multi-metre sea-level rise. While we assess that present literature does not allow to assign more than *low confidence* in the identification of the potentially most critical climate tipping points and of the global warming levels at which they are most likely to be triggered, they need to be considered as the associated risk cannot be excluded at present, and could be major if realized.

3.3.13 Identified hotspots based on regional climate changes and associated hazards

3.3.13.1 Hot spots for temperature, precipitation, and droughts

Figures 3.15, 3.16, 3.17 include an objective identification of 'hot spots' / key risks in temperature, precipitation and drought indices subdivided by regions, based on the submitted article of (Wartenburger et al., *in review*). The considered regions follow the classification of the IPCC SREX report (IPCC 2012), (Seneviratne et al. 2012; see Fig. 3.18) and also include the global land. The figures display red shading for all instances in which a significant difference is found between regional responses at 1.5°C *vs.* 2°C.

Based on these analyses, the following can be stated. Significant changes in responses are found for most temperature indices (Fig. 3.15), with the exception of i) diurnal temperature range (DTR) in most regions, of ii) ice days (ID), frost days (FD), and growing season length (GSL) in mostly warm regions, and iii) of the minimum yearly value of the maximum daily temperature (TXn) in very few regions. For precipitation (Figure 3.16) significant differences are found for the global land for all indices related to precipitation extremes, but not for the mean precipitation. Hot spots for changes in heavy precipitation between 1.5°C and 2°C global warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including China and Japan) and in Eastern North America. Results are less consistent for other regions.

For measures related to changes in dryness and drought (Figure 3.17), significant tendencies towards enhanced drying are found in the Mediterranean region and Southern Africa (for both the consecutive number of dry days and soil moisture anomalies). There is also a significant change towards an increase in the cumulative number of dry days in Northeastern Brazil. Identified significant changes in other regions are related to decreases in dryness (e.g. in high-latitude and high-altitude regions displaying mean increases in precipitation, see Figure 3.16 and previous paragraph).

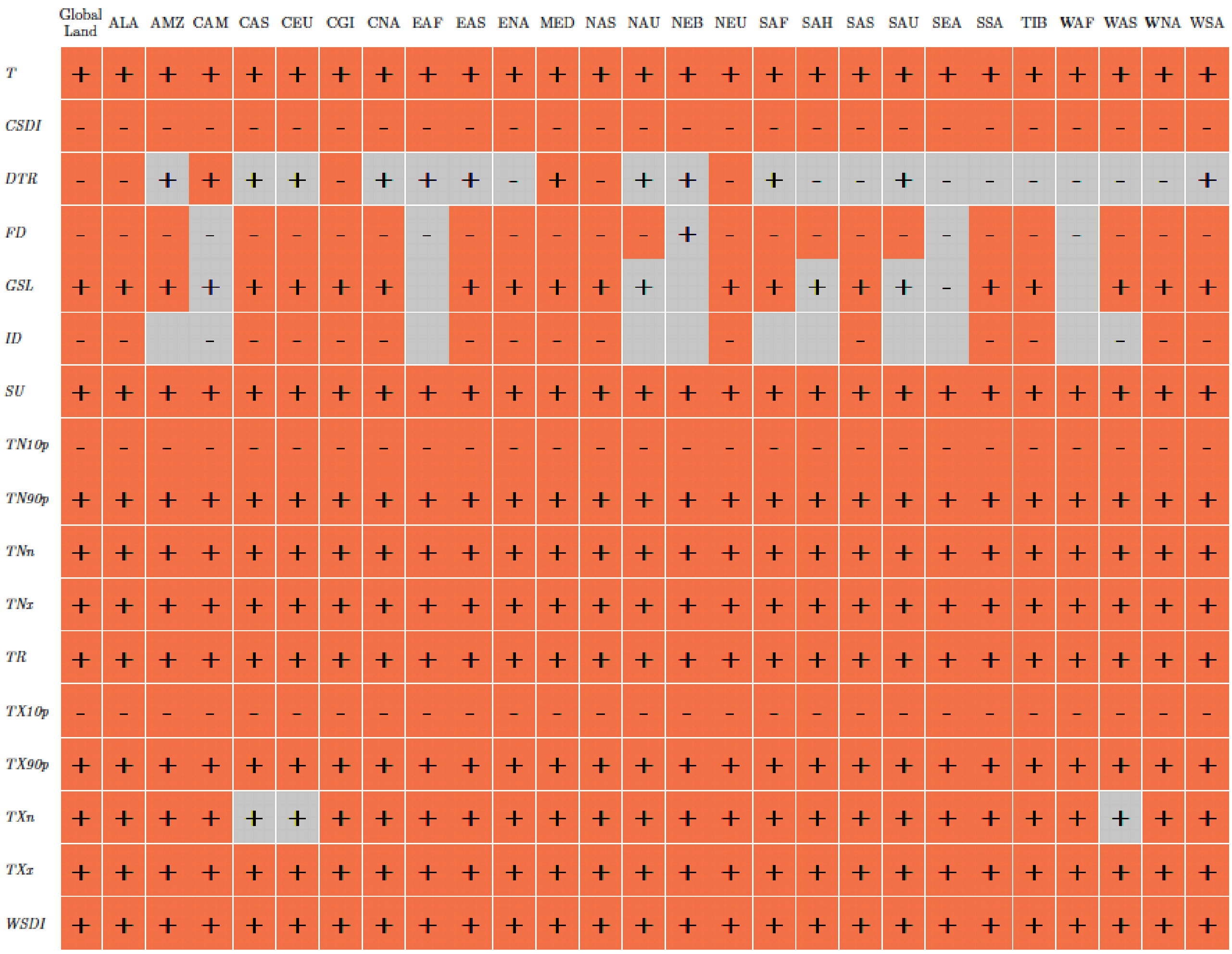


Figure 3.13: Significance of differences of regional mean temperature and range of temperature indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: T: mean temperature; CSDI: Cold Spell Duration Index; DTR: Diurnal Temperature Range; FD: Frost Days; GSL: Growing Season Length; ID: Ice Days; SU: Summer Days; TN10P: Proportion of days with minimum temperature (TN) below 10th percentile of TN; TN90p: Proportion of days with TN higher than 90th percentile TN; TNn: minimum yearly value of TN; TNx: maximum yearly value of TN; TR: Tropical Nights; TX10p: Proportion of days with maximum Temperature (TX) lower than 10th percentile of TX; TX90p: Proportion of days with TX higher than 90th percentile of TX; TXn: minimum yearly value of TX; TXx: maximum yearly value of TX; WSDI: Warm Spell Duration Index. Columns indicate analysed regions and global land (see Figure 3.18 for definition). 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., *in review*).

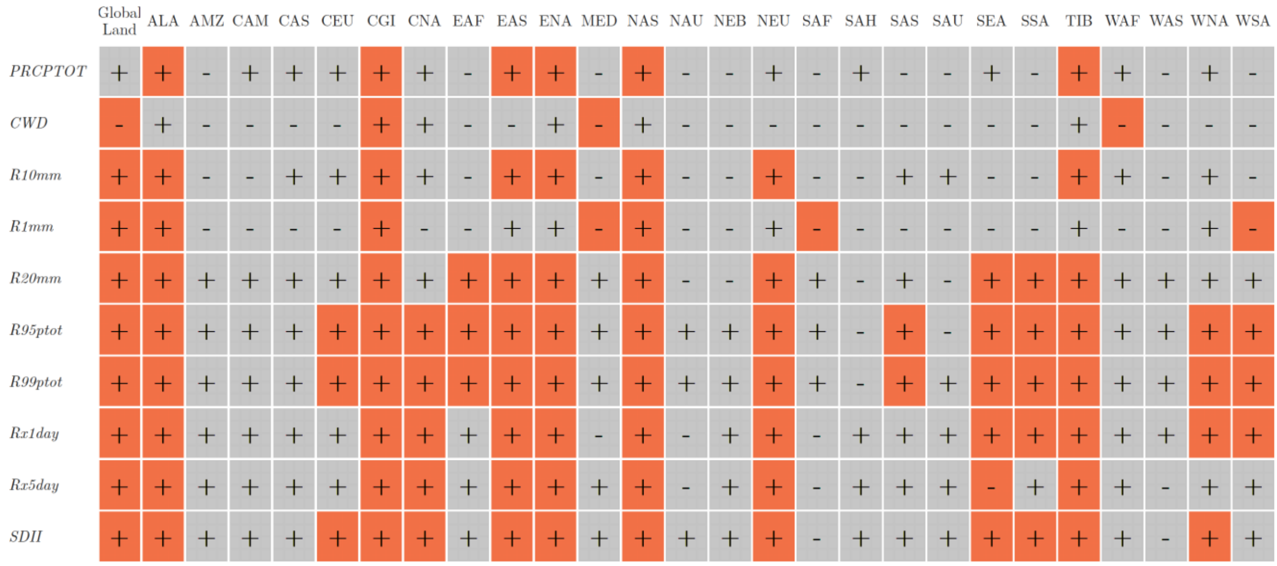


Figure 3.14: Significance of differences of regional mean precipitation and range of precipitation indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: PRCPTOT: mean precipitation; CWD: Consecutive Wet Days; R10mm: Number of days with precipitation > 10mm; R1mm: Number of days with precipitation>1mm; R20mm: Number of days with precipitation >20mm; R95ptot: Proportion of rain falling as 95th percentile or higher; R99ptot: Proportion of rain falling as 99th percentile or higher; RX1day: Intensity of maximum yearly 1-day precipitation; RX5day: Intensity of maximum yearly 5-day precipitation; SDII: Simple Daily Intensity Index. Columns indicate analysed regions and global land (see Figure 3.18 for definition). 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., *in review*).

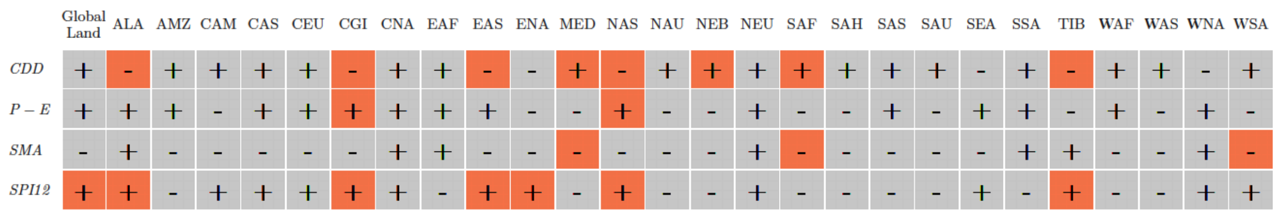


Figure 3.15: Significance of differences of regional drought and dryness indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: CDD: Consecutive Dry Days; P-E: Precipitation minus Evaporation; SMA: Soil Moisture Anomalies; SPI12: 12-month SPI. Columns indicate regions and global land (see Figure 3.18 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., *in review*).

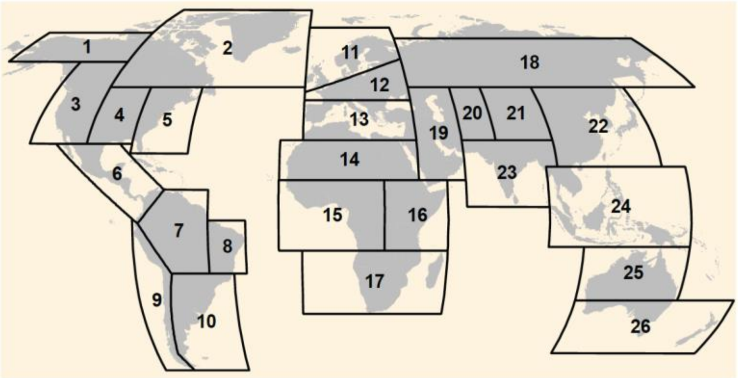


Figure 3.16: Regional domains defined in the IPCC SREX (IPCC 2012; Seneviratne et al. 2012) and AR5 (IPCC 2013) (IPCC 2013; http://www.ipcc-data.org/guidelines/pages/ar5_regions.html) report. 1: Alaska/NW Canada (ALA); 2: Eastern Canada/Greenland/Iceland (CGI); 3: Western North America (WNA); 4: Central North America (CAN); 5: Eastern North America (ENA); 6: Central America / Mexico (CAM); 7: Amazon (AMZ); 8: North East Brazil (NEB); 9: West Coast South America (WSA); 10: Southeastern South America (SSA); 11: Northern Europe (NEU); 12: Central Europe (CEU); 13: Southern Europe/Mediterranean region (MED); 14: Sahara (SAH); 15: Western Africa (WAF); 16: Eastern Africa (EAF); 17: Southern Africa (SAF); 18: Northern Asia (NAS); 19: Western Asia (WAS); 20: Central Asia (CAS); 21: Tibetan Plateau (TIB); 22: Eastern Asia (EAS); 23: Southern Asia (SAS); 24: Southeast Asia (SEA); 25: Northern Australia (NAU); 26: Southern Australia (SAU).

[To be completed with information from Happi-MIP, ISIMIP etc. for the Second Order Draft.]

3.4 Observed impacts and projected risks in natural and managed ecosystems

The natural and managed ecosystems assessed in the Working Group II contribution to the IPCC AR5 were freshwater resources; terrestrial and inland water systems (in this report now called terrestrial and wetland ecosystems), coastal systems and low-lying areas, ocean systems, and food security and food production systems. In this report the onserved and projected risks to these ecosystems are respectively assessed in Sections 3.4.1 – 3.4.5. Natural and managed ecosystems are embedded within the reasons for concern / key vulnerabilities assessed within the context of Article 2 of the UNFCCC (Cramer et al. 2014) and included the following key risks which pertain to the systems covered in this section:

- Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise;
- Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings;
- Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic; and
- Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.

3.4.1 Terrestrial and wetland ecosystems

3.4.1.1 Observed impacts

Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their projection into the future relies on three general approaches: inference from analogous situations in the past or in the present; manipulative experimentation, deliberately altering one of a few factors at a time; and models with a mechanistic or statistical basis (Rosenzweig and Neofotis 2013). The literature assessed in the

AR5 typically focused on describing and quantifying linkages between weather and climate patterns and outcomes, with limited detection and attribution studies (Cramer et al. 2014). The observed changes described in this section contribute to the loss of ecosystem services (e.g. access to safe water) that are supported by biodiversity (Cramer et al. 2014) and hence contribute to the risks assessed in Section 3.5. The observed impacts may be attributed to climatic change, which can be anthropogenic or not.

The vulnerability of ecosystems to climate change is determined by the sensitivity of ecosystem processes to the particular elements of climate undergoing change and the degree to which the system can maintain its structure, composition, and function in the presence of such change, either by tolerating or adapting to it. The absence of observed changes does not preclude confident projections of future change for three reasons: climate change projected for the 21st century substantially exceeds the changes experienced over the past century for 2°C+ global warming scenarios; ecosystem responses to climate change may be nonlinear; and change may be apparent only after considerable time lags (AR5 WGII Chapter 4).

3.4.1.1.1 Changes in phenology

AR5 suggests spring advancement of -2.8 ± 0.35 days per decade for most of the North Hemisphere ecosystems. This is confirmed for 72% of the species by (Parmesan and Hanley 2015) but they highlight that the response is often more complex and need community-level experiments. It is confirmed for some regions (Wu et al. 2016; Dugarsuren and Lin 2016; Crabbe et al. 2016; Xu et al. 2015) but not everywhere (Zhang et al. 2016; Liu et al. 2016). For animals, although a number of non-climatic factors influence phenology, warming has contributed to the overall spring advancement observed in the NH (high agreement and medium evidence, AR5 Section 4.3.2.1.2, p292). Seddon et al. (2016) quantitatively measured ecologically sensitive regions with recent amplified responses to climate variability for the Arctic tundra, parts of the boreal forest, the tropical rainforest, alpine regions, steppe and prairie regions of central Asia and North and South America, the Caatinga deciduous forest in eastern South America, and eastern areas of Australia. 63% of vegetation in Central Asia during the period 1982–2012 was found to be significantly affected by precipitation change ($p < 0.05$) while 32% vegetation was affected by air temperature ($p < 0.05$) (Zhang et al. 2016b).

During 1985 - 2012, timing of phenological spring (represented by the timing of bud expansion of *Ulmus pumila*), summer (represented by the timing of 50% of full flowering of *Syringa reticulate*) and autumn (represented by the timing of fruit maturity of *Lonicera maackii*) in Harbin, Heilongjiang Province have been advanced by 7 days, 6 days and 19 days respectively, while timing of phenological winter (represented by the timing of end of leaf fall of *Juglans mandshurica*) has been delayed by 2 days. Compared to the original calendar, the average dates of phenophases have been advanced by 3 to 11 days in spring, summer and autumn, but delayed by 3 days in winter (Xu et al. 2015).

3.4.1.1.2 Changes in species range, abundance and extinction

AR5 Chapter 4 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. Average range shifts across taxa and regions were approximately 17 km poleward and 11 m up in altitude per decade. Changes in temperature are already emerging as a driver of changes in species richness, with one meta-analysis of the 245 studies reported in the literature finding that 3.6% of 327 reported changes in richness were attributed to temperature change (Murphy and Romanuk 2014). It is noted that this meta-analysis excluded studies which accounted for past changes in precipitation or other climatic variables in addition to temperature change, indicating that the fraction attributable to climate change reported here has been likely to be underestimated. More significantly, Wiens (2016) meta-analysis of 27 studies of observed local extinctions in a total of 976 found that 47% of local extinctions reported across the globe could be attributed to climate change, especially in tropical regions, and in freshwater habitats, with a greater proportion of local extinctions noted for animals. Evidence is accruing which attributes changes in abundance to changes in climate. A study of 501 mammal, bird, aphid, butterfly and moth taxa in the UK found that since the 1970s, changes in climate had significantly affected the abundance of 15.8% of species, and 48% of the population declines in moths and 63% of the population increases in winged aphids could be attributed to climate change (Martay et al. 2016),while 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. Their conservation status is: 42 near threatened, 78 vulnerable, 44 endangered and 34 critically endangered (due to a combination of potential changes in climate and other factors). Taylor and Kumar (2016) confirm how sensitive many of these species are to climate change in an extensive meta-analysis of literature relating to these 305 species. Pecl et al. (2017) summarize at the global level the consequences of the species redistribution for economic development, livelihoods, food security, human health and culture (see Figure 3.19 from Pecl et al. (2017)). 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.

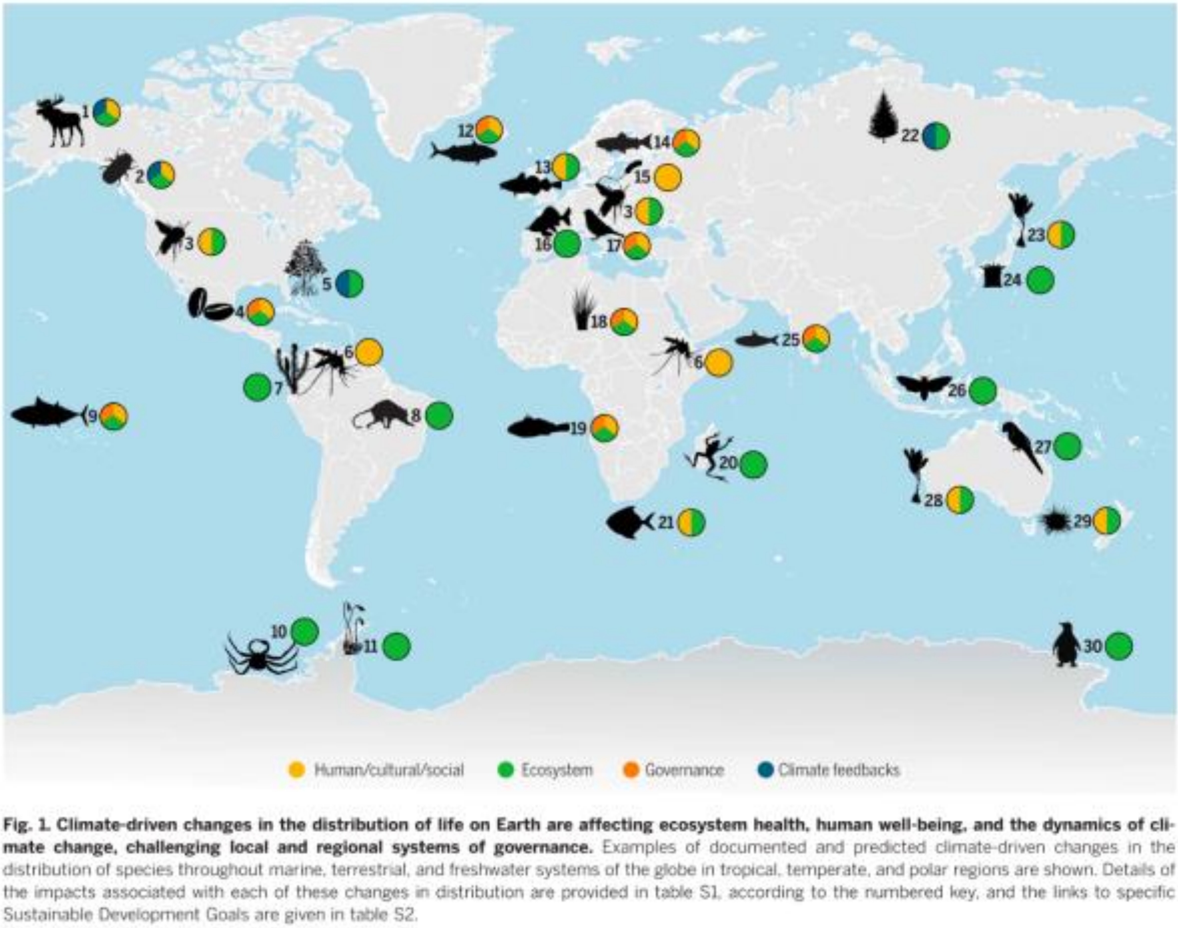


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Figure 3.17: Climate-driven changes in the distribution of life on Earth are affecting ecosistems health, human well-being and the dynamics of climate change. *[May develop a Figure based on Pecl et al. (2017)]*.

3.4.1.1.3 Changes in ecosystem function, biomass and carbon stocks

According to AR5-Chap4, there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era. There is *low confidence* in attribution of these trends to climate change. Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution. Spring warming has largely stimulated ecosystem productivity at latitudes between 30°N and 90°N, but suppressed productivity in other regions (Xia et al. 2014). From a meta-analysis covering all ecosystems, Slot and Kitajima (2015) found that leaf respiration of most terrestrial plants can acclimate to gradual warming, potentially reducing the magnitude of the positive feedback between climate and the carbon cycle in a warming world. A green effect due to fertilization is often observed in the tropics (Murray-Tortarolo et al. 2016; Zhu et al. 2016) and in China [LAI increase of 0.0070 yr^{-1}, between 0035 yr^{-1} to 0.0127 yr^{-1}] (Piao et al. 2015). Tropical forest mainly threatened (by deforestation and fragmentation) as a consequence of recent industrial exploitation and human population growth is now also threatened by climatic change and many species are harmed by habitat loss, warming and emerging pathogens (Laurance 2015). All the dangers often operate in concert, amplifying their impacts.

WGII AR5 concluded that deforestation has slowed over the last decade, including in the tropical regions, and that biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*), but are vulnerable to loss to the atmosphere as a result of rising temperature, drought, and fire projected in the 21st century. In the tropical regions, Anderegg et al. (2015) show that the total ecosystem respiration, at the global scale, has decreased in response to increase of nighttime temperature (1 Pg C / year /°C, p=0.02). Munoz-Rojas et al. (2016) demonstrated increased rates of soil respiration in semi-arid ecosystems in burnt areas versus unburnt ones. From 1901 to 2010, Fisher et al. (2013) assess from nine land surface models that the African rain forest was an increased sink of carbon but with also an increasing uncertainty. Boreal forest productivity has increased as a result of warming (*medium confidence*) during the 1980s but many areas have experienced productivity decline (*high confidence*) because of drying air (which can lead to increased fire frequency and intensity) and lack of adaptation. There is now additional evidence for attribution of increased forest fire in North America to anthopogenic climate change during 1984-2015, via the mechanism of increasing fuel aridity almost doubling the western US forest fire area compared to what would have been expected in the absence of climate change (Abatzoglou and Williams 2016). Grassland carbon storage in China has shown an increasing trend, with the average annual growth rate of 9.62 Tg C yr^{-1} during 1961 - 2013, and temperature was the main determinant factor, explaining about 72.3% of its variation (Zhang et al. 2016a).

Yang et al. (2015) showed a reduction of the carbon sink of global terrestrial ecosystems by 0.57 PgC/yr in ecosystems with high carbon storage, such as peatlands and tropical forests. Forest must be seen as prime regulators within the water, energy and carbon cycles and so a powerful adaptation tool (Ellison et al. 2017). Another mitigation tool is the soil compartment. Lal (2014) highlights the promise of soil C sequestration on the basis of the magnitude of net biome productivity (3 Pg C/year), and the hypothesis that some of this productivity can be retained in the soil to offset emissions and also enhance the resilience of soil and agroecosystems to climate change. Decomposition rates and porewater DOC concentrations significantly increased under elevated temperature conditions; however, the quality of this carbon was variable, showing signs of both increased lability and recalcitrance (Dieleman et al. 2016).

3.4.1.1.4 Regional and Ecosystem-Specific Risks

According to AR5 WGII Chapter 4, the High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century, with an increased vegetation productivity in both North America and northern Eurasia. There is *medium confidence* that rapid change in the Arctic is affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number. The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation. This is confirmed by recent literature (Bring et al. 2016; Yang et al. 2016; Jiang et al. 2016; DeBeer et al. 2016). Both of these processes facilitate conditions for woody species establishment in tundra areas. In the arctic ecosystems, (Mortensen et al. 2014) indicate that among the 114 abiotic, performance and phenological variables related to several tens of taxa, 32 showed a positive trend and 51 a negative trend, the most negative concerning the plants, arthropods, predators, zooplankton. Cooper (2014) show that the main causes of Arctic terrestrial ecosystem disruption are delays in winter onset and mild winters. Long-term absence of snow reduces vascular plant cover in the understorey by 92%, reduces fine root biomass by 39% (Blume-Werry et al. 2016).

According to AR5 WGII Chapter 4, in many places around the world the savanna boundary is moving into former grasslands on elevation gradients and tree cover and biomass has increased over the past century. It has been attributed to changes in land management, rising CO_2, climate variability and change (often in combination). Rangelands are highly responsive to changes in water balance. For the Mediterranean species, it has been observed shift in phenology, range contraction, health decline because of precipitation decrease and temperature increase. The area percentage of actual grassland net primary productivity (NPP) change on Tibet Plateau caused by climate change strongly declined over the last 30 years, but the percentage change resulting from human activities doubled in the same periods (Chen et al. 2014). Guan et al. (2014) found that the rainy season length has strong nonlinear impacts on tree fractional cover of dry forests and savannas. Xu et al. (2015) estimated the annual herbaceous desert of China had a high resilience to temperature variations. In semi-arid biomes of the SW USA, recent drought conditions had a strong negative impact on vegetation production (Barnes et al. 2016).

According to AR5 WGII Chapter 4, freshwater ecosystems are considered to be among the most threatened on the planet. Although peatlands cover only about 3% of the land surface, they hold one-third of the world's soil carbon stock (400 to 600 Pg). They are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning. Wetland salinization, a widespread threat to the structure and ecological functioning of inland and coastal wetlands, is currently occurring at an unprecedented rate and geographic scale (Herbert et al. 2015). The ecosystem water conservation of the alpine ecosystem of the Source Region of the Yellow River has a slightly decreasing trend of -1.15 mm/year during the period of 1981-2010 (Yunhe et al. 2016). Tropical fish Geophagus brasiliensis introduced in southwestern Australia river from South America has a growth rate higher than most of the native fish species (Beatty et al. 2013). Xu et al. (2016) estimated that the wetland vegetation of China had a high resilience to climate change.

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

3.4.1.2.1 Biome Shifts

Using an ensemble of seven Dynamic Vegetation Models driven by projected climates from 21 alternative Global Circulation Models, Warszawski et al. (2013) show that approximately 25% more biome shifts are projected to occur under 2ºC warming than under 1.5°C warming (Figure 3.20). Figure 3.20 maps the level of global warming at which biome shifts become significant regionally, and indicates that areas where biome shifts would be avoided by constraining warming to 1.5°C as compared with 2°C are located in the Arctic, Tibet, Himalayas, South Africa and Australia. The proportion of biome shifts is projected to (approximately) further double for warming of 3°C. This is consistent with an earlier study which projected 1.6ºC warming would induce a 10% transformation of global ecosystems (47% wooded tundra, 23% cool conifer forest, 21% scrubland, 15% grassland/steppe, 14% savannah, 13% tundra and 12% temperate deciduous forest, with ecosystems variously losing 2–47% of their extent).

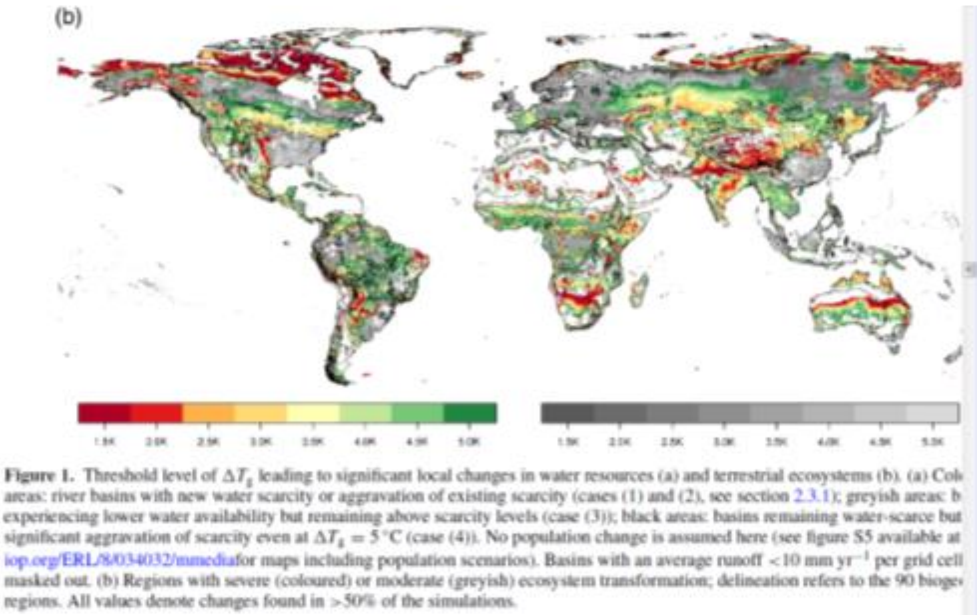


Figure 3.18: Threshold level of 1Tg leading to significant local changes in water resources (a) and terrestrial ecosystems (b). (a) Coloured areas: river basins with new water scarcity or aggravation of existing scarcity (cases (1) and (2), see section 2.3.1); greyish areas: basins experiencing lower water availability but remaining above scarcity levels (case (3); black areas: basins remaining water-scarce but without significant aggravation of scarcity even at 1Tg = 5 ◦C (case (4)). No population change is assumed here (see also Annex 3.1 Figure S5. iop.org/ERL/8/034032/mmediafor maps including population scenarios). Basins with an average runoff 50% of the simulations. Source: (Gerten et al. 2013)

3.4.1.2.2 Changes in species range, abundance and extinction

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, AR5-WGII-Ch4) 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 species using 21 alternative projected climates derived from GCM output, and projected that with 4°C warming, and realistic dispersal rates, 34+/-7% of the animals, and 57+/-6% of the plants, would lose 50% or more of their climatic range by the 2080s. In comparison, with 2°C warming these projected losses were reduced by 60% if warming were constrained to 2°C. Information relating to 1.5°C warming has now been estimated from this earlier study, indicating that with 1.5°C warming, and realistic dispersal rates, the losses are projected to be reduced by approximately 80% (79-82%) compared to those at 4°C warming) and 50% (range 46-56%) compared to those at 2°C warming. Hence at 1.5°C, 7+/-2% animals and 10+/-2% plants are projected to lose 50% or more of their climatic range (Smith et al.).

3.4.1.2.3 Changes in ecosystem function, biomass and carbon stocks

AR5 assessed that there remains large uncertainty in the land carbon cycle behavior in the future (Ciais et al. 2013), with most, but not all, CMIP5 models simulating continued terrestrial carbon uptake under all four RCP scenarios (Jones and Carvalho 2013). Disagreement between models outweighs differences between scenarios even up to 2100 (Hewitt et al. 2016; Lovenduski and Bonan 2017). Increased CO_2 will drive further increases in land carbon sink (Ciais et al., 2015; Schimel et al., 2015) which could persist for centuries (Pugh et al. 2016). Climate change may accelerate plant uptake (Gang et al. 2015), but also decomposition processes (Todd-Brown et al. 2014; Koven et al. 2015; Crowther et al. 2016). Ahlstrom et al. (2012) found a net loss of carbon in extra-tropics and largest spread across model results in the tropics. The net effect of climate is to reduce the carbon sink expected under CO_2 increase alone (AR5). Friend et al., (2014) found substantial uptake of vegetation carbon under future scenarios when considering the effects of both climate change and elevated CO_2.

There is few published literature examining modelled land carbon changes specifically under 1.5°C warming, but here existing CMIP5 models and published data are used to draw some conclusions. For systems with significant inertia, such as vegetation or soil carbon stores, changes in carbon storage will depend on the rate of change of forcing and so are dependent on the choice of scenario. Therefore, the focus is on GPP – the rate of photosynthetic carbon uptake – by the models, rather than by changes in their carbon store, as this will be less dependent on legacy effects of the choice of scenario. We draw on the 1% per year idealized simulations with coupled carbon cycle models for a number of reasons. Firstly, simulations exist with a range of models, and two simulations have been run which allow for the explicit separation of the role of CO_2 and the role of climate on the carbon cycle. Secondly, there are no confounding effects of land-use. Land-use forcing is a significant driver of changes in land carbon storage but is not simply linked with global temperature change (Ciais et al. 2013), and so analysis of model results from future scenarios that include both climate change and land-use change effects are difficult to interpret in terms of the role of these drivers individually (Hewitt et al., 2016).

Results show (Figure 3.21) different responses to climate change in different regions. The models show a consistent response of increased GPP in temperate latitudes of approximately 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 temperate forests, however Ahlstrom et al (2012) show this could be offset or reversed by increases in decomposition. CMIP5 models also project an increase in high-latitude productivity, but in the tropics, there is marked disagreement between models even over the sign of response, and sufficiently weak signal to noise to allow confident assessment of the future changes. Two models with increased tropical productivity also show lower high latitude gains. These are the two CMIP5 models which include treatment of terrestrial nitrogen cycling, highlighting the important role of nutrient limitations on future terrestrial carbon uptake. Globally, GPP increases or remains approximately unchanged in most models.

The role of nitrogen, and other nutrient, limitation will strongly modulate terrestrial carbon cycle response to both CO_2 and climate (Zaehle et al. 2015; Weider et al. 2015). AR5 assessed high confidence in thawing of permafrost thaw but low confidence in the amount of carbon that may be released. Observational constraints suggest stabilisation at 1.5°C would save approximately 2 million km^2 of permafrost compared with stabilisation at 2°C (Chadburn et al. 2017), but the timescale for release of thawed carbon as CO_2 or CH_4 is likely to be many centuries (Burke et al. 2017).

There is no clear evidence of strong non-linearities or thresholds between 1.5°C and 2°C, so impacts on terrestrial carbon storage will be greater at 2°C than at 1.5°C. If global CO_2 concentrations and temperatures stabilise, or peak and decline, then both land and ocean carbon sinks will also decline, and may even reverse (Jones et al. 2016; Cao and Caldeira 2010).

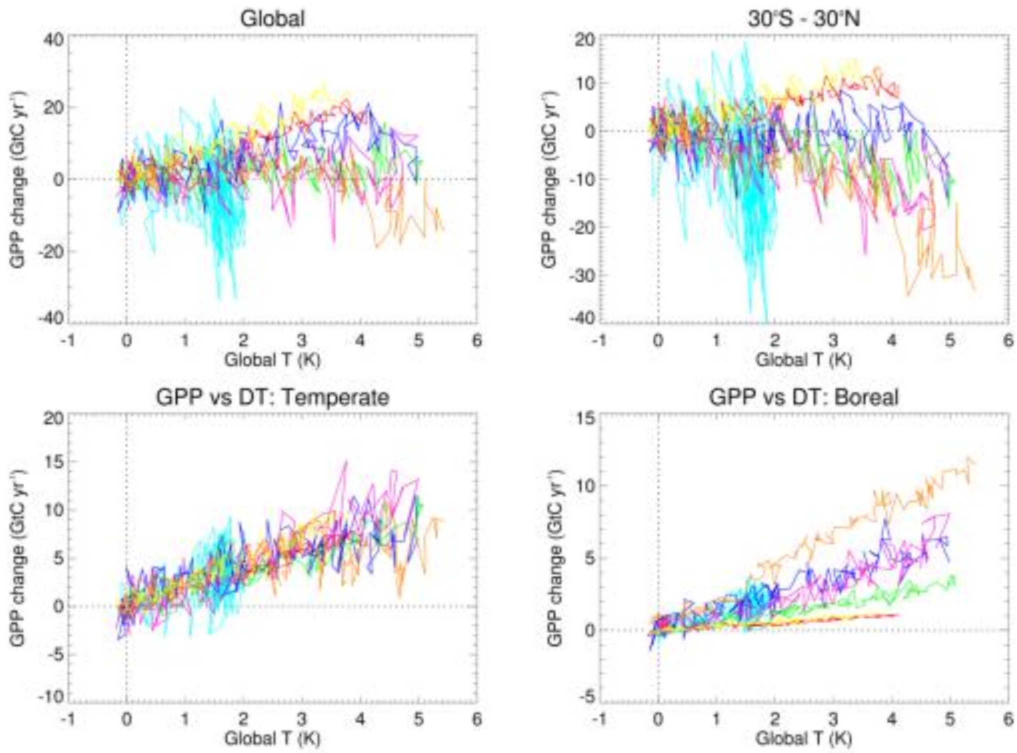


Figure 3.19: The response of terrestrial productivity (GPP) to climate change, globally (top right) and for three latitudinal regions: 30S-30N; 30-60N and 60-90N. Data was used from the the CMIP5 model archive (http://cmip-pcmdi.llnl.gov/cmip5/). Seven Earth System Models used: NorESM-ME (yellow); CESM (red); IPSL-CM5-LR (dark blue); GFDL (pale blue); MPI-ESM (pink); HadGEM2-ES (orange); CanESM2 (green). Results are differences in GPP from model simulations with ('1pctCO_2') and without ('esmfixclim1') the effects of climate change. Data is plotted against global mean temperature increase above pre-industrial from simulations with 1% per year increase in CO_2 ('1pctCO_2').

Sui and Zhou (2013) found that the regional temperate grasslands in China acted as a small carbon sink at 11.25 g C m^{-2} year^{-1} in the study area of 64.96 million hectares with a high inter-annual variability ranging from -124 to 122.7 g C m^{-2} year^{-1} during the period of 1951-2007. The sink of temperate grasslands will be reduced if the climate gets warmer and drier during this century since the increasing net primary production does not keep up with the increase of heterotrophic respiration.

AR5 also highlighted projected increases in the intensity of storms, wildfires and pest outbreaks (Settele et al. 2014b), which can potentially lead to forest dieback. This would contribute to a decrease in the terrestrial carbon sink. The increased amount of evidence that anthropogenic climate change has already caused significant increases in fire area in N America (see 3.4.1), is in line with projected fire risks. Fire risks are projected to increase further at 1.5ºC warming relative to the present day: in one study, projections on the basis of the CMIP3 ensemble of climate models (SRES A2 scenario) indicated with high 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 ºC; as compared with over 61.9% of the global land area in 2070-2099, corresponding to a warming of approximately 3.5ºC (Figure 10.5 panel A, Meehl et al. 2007), which indicates an ensemble average projection of 0.7 ºC or 3ºC above 1980-1999, which is itself 0.5ºC above pre-industrial) (Figure 10.5 panel A, Meehl et al. 2007). Romero-Lankao et al. (2014) (Box 26-1) also indicated significantly lower wildfire risks in North America for near term warming (2030-2040, which may be considered a proxy for 1.5ºC) than at 2ºC.

3.4.1.2.4 Regional and Ecosystem-Specific Risks

The AR5 identified a 'high risk the large magnitudes and high rates of change will result within this century in abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the Amazon and the Arctic' (Settele et al. 2014a).

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

Amazon

Amazon tropical forest has been shown to be close to its climatic threshold (Hutyra et al., 2005; Good et al., 2011), but this threshold may move under elevated CO_2 (Good et al., 2011). Future changes in rainfall, especially dry season length, will determine response of Amazon forest (Sombroek, 2001; Good et al., 2013). The forest may be especially vulnerable to combined pressure from multiple stressors: namely changes in climate and continued anthropogenic disturbance (Borma et al., 2013; Nobre et al., 2016). Modelling (Huntingford et al. 2013) and observational constraints (Cox et al., 2013) suggest large scale forest dieback less likely than suggested under early coupled modelling studies (Cox et al, 2000; Jones et al., 2009). Nobre et al., (2016) estimate climate threshold of 4C and a deforestation threshold of 40%.

Arctic

Forest and Woodlands

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

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

Dryland ecosystems: Savannas, shrublands, grasslands, deserts

Mediterranean-type ecosystems were identified as being particularly sensitive to climate change in both Fischlin et al. (2007) and Settele et al. (2014), being vulnerable to drought and increased fire frequency. Recent studies using independent complementary approaches now show that there is a regional-scale tipping point in the Mediterranean between 1.5 ºC and 2ºC warming (Schleussner et al. 2016c; Guiot and Cramer 2016a). Using a large ensemble of climate and hydrological model projections the former identifies that at 1.5ºC warming, median water availability is projected to decline by 9% relative to the period 1986-2005 (by which time warming of 0.6ºC above pre-industrial levels had occurred, see IPCC (2013) in comparison to 17% at 2ºC, whilst the length of dry spells increases by 7% under 1.5ºC warming compared to 11% under 2°C warming. The latter finds that only 1.5ºC warming constrains the region's climate to lie within Holocene climate variability – whilst 2ºC warming results in transformation of 12-15% of the Mediterranean biome area. 4ºC warming is projected to transform Southern Spain into a desert.

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

Lü et al. (2016) pointed out that warming and changing precipitation had significant interactive effects, different from the accumulation of single-factor effects, on functional traits of Stipa species. The correlation and sensitivity of different plant functional traits to temperature and precipitation differed. Precipitation is the key factor determining the growth and changes in plant functional traits in Stipa species, and that temperature mainly influences the quantitative fluctuations of the changes in functional traits.

Rivers, lakes, wetlands, peatlands:
Settele et al. (2014) find that rising water temperatures are projected to lead to shifts in freshwater species distributions and worsen water quality.

Some of these ecosystems respond non-linearly to changes in temperature, for example it has been found that the wetland function of the Prairie Pothole region in North America is projected to decline beyond a local warming of 2-3ºC above present (a 1ºC local warming, corresponding to a 0.6ºC global warming). If the ratio of local to global warming remains similar for these small levels of warming, this would indicate a global temperature threshold of 1.2-1.8ºC warming. Hence constraining global warming to approximately 1.5ºC warming would maintain the functioning of the prairie pothole ecosystem in terms of their productivity and biodiversity (Johnson et al. 2016).

Table 3.2: Key risks and related observed impacts, adaptation options and avoided risks at 1.5ºC as compared to 2ºC for terrestrial and wetland ecosystems (links to AR5 and new literature – see following table for merged risk, adaptation and avoided risk table.).

Table XX | Key risks for terrestrial and freshwater ecosystems from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). For the near term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.

Climate-related drivers of impacts				Level of risk & potential for adaptation
Warming trend	Extreme temperature	Drying trend	Precipitation	Potential for additional adaptation to reduce risk Risk level with **high** adaptation Risk level with **current** adaptation

Key risks to terrestrial and wetland ecosystems

Updated key risk	Adaptation options	Avoided risks	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased risk of species extinction: a large fraction of the species assessed is at increased risk of extinction due to climate change, often in interaction with other threats. Risks are especially high for species with low dispersal rates, occupying flat landscapes, where the projected climate velocity is high, and for species in isolated habitats such as mountaintops, islands, or small protected areas. Cascading effects through interactions between species, especially those vulnerable to phenological changes, amplify risk (AR5, *high confidence*). Average species range shifts across taxa and regions were approximately 17 km poleward and 11 m up in altitude per decade (AR5). Wiens (2016) reported that 47% of the 976 found could be attributed to climatic change, especially in tropical regions and freshwater habitats. Taylor and Kumar (2016) confirm how sensitive many of these species are to climate change in an extensive meta-analysis of literature relating to 305 species; even if greenhouse gas emissions stopped today, the effort for human systems to adapt to the most crucial effects of climate- driven species redistribution need to be massive (Pecl et al., 2017).	Adaptation options that lower climate-change related extinction risks include: increasing protected area networks, especially to protect climate change refugia (Warren et al submitted); reducing concomitant stresses such as land use change, over-exploitation, and pollution; assisted dispersal; and in a few limited cases, ex-situ conservation.	Studies based on analysis of traits, and studies based on range loss both indicate that at at 2-3ºC warming a.p.i. 20-30% of species studied are at increased risk of extinction (AR4). Although 50% range loss does not imply extinction per se, it is a good indicator increased extinction risks and of the general levels of climatic stress on species. Studies of the numbers of species projected to lose half their climatic range suggests that increases in extinction risks would be halved at 1.5 relative to 2ºC. Risks are higher levels of warming are even greater. For example Warren et al., 2013 project that for 80,000 species under 4ºC warming 34+/-7% of the animals, and 57+/-6% of the plants, would lose 50% or more of their climatic range, whereas under 2ºC warming these losses are reduced by 60% to a level of 15+/-3% animals and 19+/-3% plants. Under 1.5ºC warming the losses are reduced by 80% relative to 4ºC warming and 53% relative to 2ºC warming. Hence at 1.5ºC warming 7+/-2% animals and 10+/-2% plants are projected to lose 50% or more of their climatic range (Smith et al submitted).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Reduction in terrestrial carbon sink: terrestrial and freshwater ecosystems have sequestered about a quarter of the carbon dioxide (CO_2) emitted to the atmosphere by human activities in the past three decades *(high confidence)*. Tcarbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere, resulting from increased fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures (AR5, *medium confidence*). Yang et al. (2015) showed a reduction of the carbon sink of global terrestrial ecosystems by 0.57 PgC/yr in peatlands and tropical forests; increased forest fires in N. America due to anthropogenic climate change (Abatzoglou and Williams, 2016).	Improving land use management, e.g. to reduce deforestation and increase soil and agrosystem productivity (Lal, 2014). Improving land use management, e.g. to reduce deforestation and increase soil and agrosystem productivity (Lal, 2014).	Increased CO_2 will drive further increases in land carbon sink (Schimel et al., 2015) which could persist for centuries (Pugh et al., 2016). There is no clear evidence of strong non-linearities or thresholds between 1.5 and 2.0°C, so (avoided) impacts are expected to scale with global temperature. If global CO_2 concentrations and temperatures stabilise, or peak and decline, then both land and ocean carbon sinks will also decline, and may even reverse (Cao and Caldeira, 2010; Jones et al., 2016). A limitation of tropical nighttime temperature could avoid a strong vulnerability of the carbon sink in the tropical biosphere (Anderegg et al., 2015).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Amazon tipping point: moist Amazon forests could change abruptly to less-carbon-dense, drought- and fire-adapted ecosystems (*low confidence*, AR5). Amazon tropical forest has been shown to be close to its climatic threshold (Hutyra et al., 2005; Good et al., 2011), but this threshold may move under elevated CO_2 (Good et al., 2011). Modelling (Huntingford et al, 2013) and observational constraints (Cox et al., 2013) suggest large scale forest dieback *less likely* than suggested under early coupled modelling studies (Cox et al, 2000; Jones et al., 2009).	Improving land use management, reduce deforestation and fires.	Nobre et al., (2016) estimate climate threshold of 4.0°C and deforestation threshold of 40%. Staying below 4.0°C avoids threshold on forest resilience.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Tree mortality and forest loss attributed to climate change *(high confidence)*. Projected impacts on forests include increases in the intensity of storms, wildfires and pest outbreaks, potentially leading to forest dieback (AR5, *low confidence*). Laurance (2015) highlights that tropical forest mainly treathened until now by industrial exploitation and human population growth is now also treathened by climatic change and many species are harmed by emerging pathogens.		Romero-Lankao et al. 2014 (AR5 Box 26-1) indicate significantly lower wildfire risks in North America for 1.5ºC warming compared to 2.0ºC warming. One study projects fire frequency would increase over 37.8% of global land areas (Moritz et al. 2012) under 1.2ºC warming as compared with over 61.9% of the global land area for 3.5ºC warming.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high

Continued next page →

Table XX | Continued

Key risks to terrestrial and wetland ecosystems (continued)					
Updated key risk	**Adaptation options**	**Avoided risks**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Mediterranean ecosystems: it has been observed shift in phenology, range contraction, health decline because of precipitation decrease and temperature increase.		At 1.5°C warming, median water availability is projected to decline by 9% relative to the period 1986-2005 in comparison to 17% at 2°C. Tipping point for the Mediterranean ecosystems between 1.5 and 2°C warming (Schleussner et al. 2016); unprecedented changes since 10,000 years from +2.0°C global warmin (Guiot and Cramer, 2016); 4.0°C warming is projected to transform Southern Spain into a desert (Guiot & Cramer, 2016; Barredo et al 2016).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Boreal forest tipping point (AR5: increase in pests and fires in boreal forests, *medium confidence*).		Northward expansion of the treeline and enhanced carbon storage is seen in dynamic vegetation models and coupled climate models (Jones et al., 2010; Ciais et al., 2013). Increased disturbance from fire, pests and heat related mortality may affect the southern boundary of the boreal forest (Gauthier et al., 2015, and references therein). Thawing permafrost will affect local hydrology.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Transformation of Arctic ecosystems: risk of disruption of ecosystem functioning due to warming. Warming has already been linked to observations of: permafrost degradation, woody species establishing in tundra, loss of Arctic sea ice, disruption of some population cycles, and decline of polar bear (AR5II-CHAP4). Further confirmed by Bring et al. 2016; Yang et al. 2016; Jiang et al. 2016 DeBeer et al. 2016)		Examples include: 47% loss of wooded tundra with 1.6°C warming, compared with 68% at 3.6°C. Observational constraints suggest limiting global warming to 1.5°C would save approximately 2 million km^2 of permafrost compared to the case of 2.0°C warming (Chadburn et al. 2017).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Transformation of global ecosystems: most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (high confidence) Seddon et al. (2016) quantitatively measured ecologically sensitive regions with recent amplified responses to climate variability in the Arctic tundra, parts of the boreal forest belt, the tropical rainforest, alpine.	As for increases is species extinction risk.	About 10% by area of global ecosystems are projected to transform for a warming of 1.6°C. The area affected is projected to increase by 25% under 2.0°C warming, and then to double between 2 and 3.0°C warming (Warszawski et al., 2013) . Regional impacts (at temperatures to be determined) include: half of naturally vegetated land surface in China could be under moderate or severe risk at the end of the 21st century including the Tibetan Plateau (Yin et al., 2016). Substantial shifts in bioclimatic conditions can also be expected throughout the transboundary Kailash Sacred Landscape (KSL) of China, India and Nepal by the year 2050. Over 76% of the total area may shift to a different stratum, 55 % to a different bioclimatic zone, and 36.6% to a different ecoregion (Zomer et al. 2014).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Spread of pests and diseases: changes in climate affect the distributions of pests and diseases and can introduce them to new areas.		Constraining warming to 1.5°C would significantly reduce the risk associated with the spread of invasive species. Examples include those that can be agricultural pests or cause disease in animals (examples from Australia include Queensland fruit fly, chytridiomycosis in frogs, Box 25.4, Reisinger et al. 2014) as well as pine beetle (which causes tree mortality and exacerbates fire risk).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Risk of loss of ecosystem functioning and services.		All of the above key risks threaten to reduce ecosystem functioning and services. Hence it can be seen that 1.5°C warming is projected to preserve more of today's ecosystem functions and services than 2.0°C warming. Higher levels of warming would result in greater losses of ecosystem services.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high

[Modified text to be integrated into Table 3.2 (these headings should be reflected in all of the merged tables of this style (directly above)]

Key risk and related observed impacts	Adaptation options	Avoided risks
KEY RISKS TO TERRESTRIAL AND WETLAND ECOSYSTEMS		
Increased risk of species extinction: a large fraction of the species assessed is at increased risk of extinction due to climate change, often in interaction with other threats. Risks are especially high for species with low dispersal rates, occupying flat landscapes, where the projected climate velocity is high, and for species in isolated habitats such as mountaintops, islands, or small protected areas. Cascading effects through interactions between species, especially those vulnerable to phenological changes, amplify risk (AR5, high confidence). Average species range shifts across taxa and regions were approximately 17 km poleward and 11 m up in altitude per decade (AR5) Wiens (2016) reported that 47% of the 976 found could be attributed to climatic change, especially in tropical regions and freshwater habitats. Taylor and Kumar (2016) confirm how sensitive many of these species are to climate change in an extensive meta-analysis of literature relating to 305 species; even if greenhouse gas emissions stopped today, the effort for human systems to adapt to the most crucial effects of climate-driven species redistribution need to be massive (Pecl et al, 2017)	Adaptation options that lower climate-change related extinction risks include: increasing protected area networks, especially to protect climate change refugia (Warren et al.); reducing concomitant stresses such as land use change, over-exploitation, and pollution; assisted dispersal; and in a few limited cases, ex-situ conservation.	Studies based on analysis of traits, and studies based on range loss both indicate that at at 2-3ºC warming a.p.i. 20-30% of species studied are at increased risk of extinction (AR4). Although 50% range loss does not imply extinction per se, it is a good indicator increased extinction risks and of the general levels of climatic stress on species. Studies of the numbers of species projected to lose half their climatic range suggests that increases in extinction risks would be halved at 1.5 relative to 2ºC. Risks are higher levels of warming are even greater. For example (Warren et al. (2013) project that for 80,000 species under 4ºC warming 34+/-7% of the animals, and 57+/-6% of the plants, would lose 50% or more of their climatic range, whereas under 2ºC warming these losses are reduced by 60% to a level of 15+/-3% animals and 19+/-3% plants. Under 1.5ºC warming the losses are reduced by 80% relative to 4ºC warming and 53% relative to 2ºC warming. Hence at 1.5ºC warming 7+/-2% animals and 10+/-2% plants are projected to lose 50% or more of their climatic range (Smith et al.)
Reduction in terrestrial carbon sink: Terrestrial and freshwater ecosystems have sequestered about a quarter of the carbon dioxide (CO_2) emitted to the atmosphere by human activities in the past 3 decades (high confidence). Tcarbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere, resulting from increased fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures (AR5, medium confidence). Yang et al. (2015a) showed a reduction of the carbon	Improving land use management, e.g. to reduce deforestation and increase soil and agrosystem productivity (Lal 2014)	Increased CO_2 will drive further increases in land carbon sink (Schimel et al., 2015) which could persist for centuries (Pugh et al., 2016). There is no clear evidence of strong non-linearities or thresholds between 1.5 and 2 degrees, so (avoided) impacts are expected to scale with global temperature. If global CO_2 concentrations and temperatures stabilise, or peak and decline, then both land and ocean carbon sinks will also decline, and may even reverse (Cao and Caldeira, 2010; Jones et al. 2016) A limitation of tropical nighttime temperature could avoid a strong vulnerability of the carbon sink in the tropical biosphere (Anderegg et al. 2015)

Key risk and related observed impacts	Adaptation options	Avoided risks
sink of global terrestrial ecosystems by 0.57 PgC/yr in peatlands and tropical forests; increased forest fires in N. America due to anthropogenic climate change (Abatzoglou and Williams 2016).		
Amazon tipping point. Moist Amazon forests could change abruptly to less-carbon-dense, drought- and fire-adapted ecosystems (low confidence, AR5). Amazon tropical forest has been shown to be close to its climatic threshold (Hutyra et al., 2005; Good et al., 2011), but this threshold may move under elevated CO_2 (Good et al., 2011). Modelling (Huntingford et al., 2013) and observational constraints (Cox et al., 2013) suggest large scale forest dieback less likely than suggested under early coupled modelling studies (Cox et al, 2000; Jones et al., 2009).	Improving land use management, reduce deforestation and fires	Nobre et al.(2016) estimate climate threshold of 4°C and deforestation threshold of 40%. Staying below 4C avoids threshold on forest resilience.
Tree mortality and forest loss attributed to CC (high confidence). Projected impacts on forests include increases in the intensity of storms, wildfires and pest outbreaks, potentially leading to forest dieback (AR5, low. Confidence). Laurance (2015)highlights that tropical forest mainly treathened until now by industrial exploitation and human population growth is now also treathened by climatic change and many species are harmed by emerging pathogens.	More effective management of fire, pests and pathogens.	Romero-Lankao et al. (2014, AR5 Box 26-1) indicate significantly lower wildfire risks in North America for 1.5ºC warming compared to 2ºC warming. One study projects fire frequency would increase over 37.8% of global land areas (Moritz et al. 2012)under 1.2 ºC warming as compared with over 61.9% of the global land area for 3.5ºC warming.
Mediterranean ecosystems: it has been observed shift in phenology, range contraction, health decline because of precipitation decrease and temperature increase.		At 1.5ºC warming, median water availability is projected to decline by 9% relative to the period 1986-2005 in comparison to 17% at 2ºC Tipping point for the Mediterranean ecosystems between 1.5 and 2ºC warming (Schleussner et al. 2016c); unprecedented changes since 10,000 years from +2°C global warmin (Guiot and Cramer 2016a); 4 ºC warming is projected to transform Southern Spain into a desert (Guiot and Cramer 2016a; Barredo et al. 2016)..

Key risk and related observed impacts	Adaptation options	Avoided risks
Boreal forest tipping point (AR5: increase in pests and fires in boreal forests, medium confidence)		Northward expansion of the treeline and enhanced carbon storage is seen in dynamic vegetation models and coupled climate models (Jones et al., 2010; Ciais et al. 2013) Increased disturbance from fire, pests and heat related mortality may affect the southern boundary of the boreal forest (Gauthier et al., 2015, and references therein). Thawing permafrost will affect local hydrology.
Transformation of Arctic ecosystems: Risk of disruption of ecosystem functioning due to warming. Warming has already been linked to observations of: permafrost degradation, woody species establishing in tundra, loss of Arctic sea ice, disruption of some population cycles, and decline of polar bear. (AR5II-CHAP4) Further confirmed by Bring et al. 2016; Yang et al. 2016; DeBeer et al. 2016b; Jiang et al. 2016		Examples include: 47% loss of wooded tundra with 1.6C warming, compared with 68% at 3.6C. Observational constraints suggest limiting global warming to 1.5 degrees would save approximately 2 million km^2 of permafrost compared to the case of 2°C warming (Chadburn et al. 2017).
Transformation of global ecosystems: Most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (high confidence) Seddon et al. (2016) quantitatively measured ecologically sensitive regions with recent amplified responses to climate variability in the Arctic tundra, parts of the boreal forest belt, the tropical rainforest, alpine	As for increases is species extinction risk.	About 10% by area of global ecosystems are projected to transform for a warming of 1.6C. The area affected is projected to increase by 25% under 2°C warming, and then to double between 2 and 3C warming (Warszawski et al, 2013) Regional impacts (at temperatures to be determined) include: Half of naturally vegetated land surface in China could be under moderate or severe risk at the end of the 21st century including the Tibetan Plateau (Yin et al. 2016). Substantial shifts in bioclimatic conditions can also be expected throughout the transboundary Kailash Sacred Landscape (KSL) of China, India and Nepal by the year 2050. Over 76% of the total area may shift to a different stratum, 55 % to a different bioclimatic zone, and 36.6 % to a different ecoregion (Zomer et al. 2014).
Spread of pests and diseases: changes in climate affect the distributions of pests and diseases and can introduce them to new areas.		Constraining warming to 1.5°C would significantly reduce the risk associated with the spread of invasive species. Examples include those that can be agricultural pests or cause disease in animals (examples from Australia include Queensland fruit fly, chytridiomycosis in frogs, Box 25.4, Reisinger et al.), as well as pine beetle (which causes tree mortality and exacerbates fire risk).

Key risk and related observed impacts	Adaptation options	Avoided risks
Risk of loss of ecosystem functioning and services.		All of the above key risks threaten to reduce ecosystem functioning and services. Hence it can be seen that 1.5°C warming is projected to preserve more of today's ecosystem functions and services than 2°C warming. Higher levels of warming would result in greater losses of ecosystem services.

3.4.2 Coastal and low lying areas (inc. small islands)

3.4.2.1 Observed impacts and adaptation

Sea-levels will not stop rising with temperature stabilisation at 1.5°C or 2°C leading to salinisation, flooding and erosion, meaning that over multi-centennial timescales, adaptation, built on bespoke local practices, remains essential.

Observations of sea-level rise are likely (and are) to be felt first through slow onset events in salinisation of ground waters leading to land degradation, mixing in estuaries and wetlands. Risks for biological and human systems in coastal and low-lying areas will escalate through siumultaneous changes to the intensity of storms, rapid sea level rise, and increasing vulnerability as protective ecosystems such coral reefs and mangrove forests are disrupted by changing conditions. Stabilization of ocean temperature (and planetary temperatures generally) will lead to conditions that will enable biological systems to 'catch up' with environmental conditions through the re-assortment of organisms and ecosystems to areas of the world most optimal in terms of their biology and ecology.

Studies do not specifically address causes of change to anthropogenic temperature or sea-level rise. Observation evidence has been suggested on land degradation due to salt water intrusion in Kiribati and Tuvalu (Wairiu 2017). In the Delaware Estuary, US, upward trends of streamflow adjusted salinity (measured since the 1900s) have been detected (Ross et al. 2015), accounting for the effects of streamflow and seasonal variations. Through modelling it is suggested that sea-level rise may be the cause of increased salinity. Saltmarshes in Connecticut and New York measured from 1900 to 2012, have accreted with sea-level rise, but lost marsh surface relative to tidal datums, leading to increased marsh flooding and further accretion (Hill and Anisfeld 2015). This stimulated marsh carbon storage, and aided climate change mitigation. Le Cozannet et al. (2014) reviewed recent impacts of sea-level rise on shoreline changes, focusing on methodologies employed. They found no general conclusions of the impacts of sea-level rise at a global scale, without taking account the characteristics of each site. There is high confidence that adaptation is happening now due to multiple drivers of change, particularly in environments, which are rapidly changing. Retreat and migration are increasing being considered in management response.

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

Due to the commitment to sea-level rise, there is no clear impact-temperature function relationship. Uncertainties in sea-level rise, largely due to ice melt mean added uncertainty for impacts. Crucially, at 1.5°C, the legacy of sea-level rise is critical, having a significant effect on impacts, in the latter half of the 21st century and beyond (Hinkel et al. 2014). Most published articles relate to sea-level rise, rather than temperature. There are few articles published with impacts at 1.5°C or 2°C. There is high confidence that adaptation has a great ability to reduce impacts (Hinkel et al. 2014; Wong et al. 2014), particularly in small island states (Wong et al. 2014).

Migration of small islands subject to sea-level rise (within the bounds of 1.5°C and 2°C) nationally and internationally remains a reality with land purchases or arrangements made with other nations (Kelman 2015; Constable 2017; Yamamoto and Esteban 2017). Adaptation in small islands needs to combine scientific knowledge, historical responses and traditional cultures, but there is evidence that solutions that fit mainland areas, cannot be applied to small islands (Nunn et al. 2017). To cope with and adapt to hazards, there is a need to retain traditional knowledge (Weir et al. 2017) and skills (Warrick et al. 2017). Small islands are often hampered by lack of information (e.g. from climate models) or finance, and there is a need to spread aid more effectively (Weber 2017) and understand how and where it is being spent (Betzold 2015).

In delta regions, salinity is a key issue affecting water security, mixed with changes of land use and wider processes of development. Increasing temperature (up to 5°C is likely to reduce yield and soil health (Hossain et al. 2015). Increased river salinity and saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C (Zaman et al. 2016). Yang et al. (2015b) found that on the Snohomish River estuary, Washington, USA future climate scenarios (A1B 1.6°C and B1 2°C in the 2040s) had a greater effect on salinity intrusion than future land use/land cover change, resulting in a shift in the salinity intrusion upstream in low conditions, and further downstream in low conditions.

Globally millions of people may be at risk from sea-level rise (Hinkel et al. 2014; Hauer et al. 2016), particularly if there is no further adaptation. By 2030, if sea-levels rise by 0.3m by 2030, 400 million people could be living in 23 coastal megacities, 370 million in Asia, Africa and South America. Subsidence will enhance those exposed (Jevrejeva et al. 2016). Jevrejeva et al. (2016) report with 2°C of warming, more than 70% of global coastlines will experience sea-level rise greater than 0.2 m. With 4°C of warming, 80% of coastlines could experience 0.6 m of sea-level rise (by 2083 under RCP8.5). The highest sea-levels are projected for small island nations in low to mid latitude Pacific islands and India Ocean islands. The amplification of flooding, for high and/or low frequency events (Buchanan et al. 2017) and different forcing factors, including waves (Arns et al. 2017; Vitousek et al. 2017; Storlazzi et al. 2015) is also cause for concern even with sea-level rise associated with a rise in temperatures of 2°C, or within the next few decades.

Adaptation pathways (Little and Lin 2016; Barnett et al. 2016; Smith et al. 2013; Buurman and Babovic 2016; Rosenzweig and Solecki 2014; Ranger et al. 2013) help broaden possibilities of adaptation, but is not widespread practice in coastal zones. Since AR5, there remains a lack of long-term strategic planning examples in the literature or practice. Globally, adaptation must consider dual threats and solutions, including subsidence (which may be greater than the effects of sea-level rise at 1.5°C and 2°C), earthquakes and other hazards (Jamero et al. 2016; Yamamoto and Esteban 2017; Brown et al. 2014).

Coastal wetland ecosystems are also at risk from sea level rise and salinisation. Historically many mangroves world-wide have been able to cope with sea-level rise (Woodroffe 1990),of up to 8-9 cmof rise over one hundred years (Ellison and Stoddart 1991), by migrating landward or seaward (Erwin 2009) or through trapping sediment. Ellison and Stoddart (1991) suggest that mangroves may be able to cope with up to 12 cm of sea-level rise over a one hundred year timeframe provided the sufficient sediment exists. When rate of Holocene sea-level rise have been greater than this, mangrove systems have collapsed (Ellison and Stoddart 1991). Salinisation may lead to shifts to more salt-tolerant plants (Blasco et al. 1996).

The projections given only take account of sea-level rise and subsidence, but not any additional sediment gain from river deposition, which could reduce the rate of loss. Sediment can also be deposited to form new land, including that in mangrove environments. Overall in the Bangladeshi part of the Ganges-Brahmaputra-Meghna delta recent data since the 1980s indicates there has been a slight net gain of land (Brammer 2014; Sarwar and Woodroffe 2013), whereas in the Sundarbans mangroves, a net loss has been reported (Shearman et al. 2013). Temporally, Rahman et al. (2011) also found that between 1973 and 1989 the shoreline accreted in the Sundarbans at a rate of 10 km2/yr, but from 1989 until 2010, the area declined at 4 km2/yr.

Table 3.3: Key risks and related observed impacts, adaptation options and avoided risks at 1.5ºC as compared to 2ºC for coastal and low-lying areas (including small islands) (links to AR5 and new literature). To be integrated with Table 30-3 from IPCC AR5 (see example below).

Key risks coastal and low lying systems					
Updated key risk	**Adaptation options**	**Avoided risks**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Impact: High exposure of people, economic activity, and infrastructure in low-lying coastal zones, Small Island Developing States (SIDS), and other small islands to sea level rise and coastal flooding including storm surges.		With 2.0°C of warming, more than 70% of global coastlines will experience sea-level rise greater than 0.2m. With 4°C of warming, 80% of coastlines could experience 0.6m of sea-level rise. The highest sea-levels are projected for small island nations in low to mid latitude Pacific islands and India Ocean islands (Jevrejeva et al. 2016). It is anticipated that additional results will become available by the time of the SOD. In particular, AR5 methods will be used to determine the contribution of steric effects, glacier and ice sheet mass loss to Global Mean Sea Level Rise, and regionalization of this signal. Potentially, the impact of this sea level rise on the return period of extreme sea levels might also be assessed using standard techniques. Whether the confidence associated with these techniques would allow a meaningful assessment of the differences between 1.5 and 2.0°C is currently unclear, although avoided risks for higher levels of warming could be assessed.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Salinity intrusion: Wetland salinization is currently occurring at an unprecedented rate and geographic scale (Herbert et al. 2015).		Decreased salinity intrusion in the Snohomish river estuary: constraining warming to 2.0°C compared to 1.6°C avoided an increase of 2% in mean annual flows, and a decrease of 6% in median annual flows. Yang et al. (2015).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Loss of wetland ecosystems and associated ecosystem services.				Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Loss of dryland ecosystems and associated ecosystem services.				Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Observations: saltwater intrusion into freshwater and groundwater: land degradation due to salt water intrusion in Kiribati (loss of pandanus trees) and Tuvalu (swamp taro pit gardens) (Wairiu 2017; Webb 2007).	None described.	None described.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Observations: increased salinisation of streamflow measured since the 1950s in the Delaware Estuary, US. Ross et al. (2015).	None described.	None described.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high
Observations: saltmarshes in Connecticut and New York measured from 1900 to 2012, have accreted with sea-level rise, but lost marsh surface relative to tidal datums, leading to increased marsh flooding and further accretion.	Autonomous adaptation of the marsh environments. As flooding increased, organic matter accumulated and selectively accelerated mineral deposition. Increased carbon storage as accretion accelerates.	None described.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low Medium Very high

3.4.3 *Ocean systems*

Around 71% of the Earth's surface is covered by an ocean that is a critical component of the Earth’s climate system. Not only does the ocean play a dominant role in maintaining stable global temperatures, climates and the atmospheric gas content, but the ocean is home to a vast number of organisms and ecosystems which provide ecosystem goods and services worth $(US) 2.4 Trillion each year (Hoegh-Guldberg et al. 2015). Many of the most disadvantaged communities depend on the ocean for food and income, with inequities projected to increase as coastal and ocean resources experience increasing risks from climate change and human activities in general (Halpern et al. 2015).

Due to the difficulty of accessing the ocean, knowledge about the ocean and its ecosystems lags that of terrestrial ecosystems, especially when it comes to the impacts of increasing atmospheric greenhouse gas concentrations on ocean habitats, ecosystems and human users. Knowledge of basic ocean systems, as well as projected risks and challenges, have increased significantly since AR5 which the focus on the ocean and its systems increased significantly over previous reports (Hoegh-Guldberg et al. 2014; Pörtner et al. 2014a; IPCC 2013). The world's largest habitat, the deep sea, remains one of the least understood on the planet, however, despite the growing evidence that current changes in the deep ocean may encase significant risks of irreversible change within the Earth's climate system. Understanding the components, processes, and tipping points, as well as how humans are changing this vast part of the earth is likely to become increasingly important.

Regionally, the ocean can be separated into a number of global regions which range from up-welling regions, semi-enclosed seas, coastal boundary systems, sub-tropical gyres, polar and the deep seas (Hoegh-Guldberg et al. 2014). A range of ocean systems operate within these ocean regions, and mediate the response of these complex regions to environmental changes that include both natural and human driven change. Much of the background to these ocean systems and potential changes are outlined in the working group II report as part of IPCC AR5, particularly (Rhein et al. 2013; Hoegh-Guldberg et al. 2014; Pörtner et al. 2014a).

In the context of understanding the response of ocean systems to further increases in global average surface temperature of 1.5ºC and 2ºC, there are examples of high levels of attribution of changes to climate change, and not. The full set of projected key risks, avoided risks at 1.5ºC and adaptation options has been laid out in Table 3.4 which is an update and modification of Table 3.3, based on AR5 (Hoegh-Guldberg et al. 2014). The companion table, Table 3.4, is from the same volume and synthesises the attributed changes, adaptation options, and frameworks required for decision making on the world's ocean regions. Rather than attempt to describe every aspect of the observed impacts, adaptation options and, avoided risks at 1.5ºC, we have summarised this information here in Table 3.4 and briefly highlight the key messages in the accompanying text.

3.4.3.1 Observed impacts and adaptation options

3.4.3.1.1 Net Primary Productivity, fisheries and distributional shifts

There are numerous observations of impacts of climate change on ocean systems, which are various degrees of confidence in terms of attribution. Changes in the productivity of ocean systems associated with the redistribution and loss of NPP can be attributed to climate change in some regions (e.g. slowing of equatorial up-welling) with low to medium confidence (Row 1, Table 3.4). Similar levels of confidence can be assigned to increasing the fish catch associated northern latitude sites where ice retreat is stimulating primary productivity through greater light levels and nutrients from mixing.

These changes add to other drivers of primary as well as fisheries productivity such as changes to where isotherms are located as the ocean warms (Row 2, Table 3.4). Organisms from phytoplankton to sharks are moving to higher latitudes as ocean waters warm (rates greater than 10 km/year), with implications for biodiversity, food webs, and ecosystem structure such as decreased equatorial biodiversity and increased biodiversity at higher latitudes (Burrows et al. 2011; Poloczanska et al. 2013; Hoegh-Guldberg et al. 2014). Some fixed organisms (e.g. corals and seaweeds) that are restricted to correspondingly low rates of re-distribution tend to experience high rates of mortality by not being able to move (see Box: Coral ecosystems). Forecasting where fish stocks are likely to be, due to both natural variability (e.g. ENSO, PDO) and climate drivers will be important to adaptation strategies in which fishing infrastructure is relocated, downsized or expanded according to observed trends. Given the speed of changes, fishing infrastructure might necessarily be flexible to meet the rapid changes in ocean conditions. Non-industrial fishing communities might also need assistance as fish stocks in some regions change (e.g. the Equator; Cheung et al. 2010; Fernandes et al. 2013; Weatherdon et al. 2016; Cheung et al. 2013). In this case, alternative livelihoods and other forms of assistance to shift fishers from changing fishing opportunities would be needed.

3.4.3.1.2 Hypoxia and ocean acidification

Warming and stratification of the ocean are leading to reduced oxygen concentrations in ocean water generally, with increasing observations of impacts. This is exacerbated by coastal pollution which is leading to greater input of organic carbon into deep ocean, and along with increased temperatures is resulting in higher metabolic rates and hence further decreasing oxygen concentrations (Row 3 Table 3.4). Combination of climate change and coastal pollution is increasing the number of hypoxic areas which are increasingly off-limits to oxygenic lifeforms. Mass mortalities of commercially important organisms has placed increasing pressure on fisheries.

As a result of ocean acidification (Row 4, Table 3.4), surface ocean waters have undergone decrease of around 0.1 pH units (i.e. a 30% increase in proton) and key ions such as carbonate have decreased by a similar amount since the Pre-Industrial Period. There is now a substantial literature on the physiological and behavioural impacts of marine organisms and ecosystems (see section on ocean chemistry above) including declining photosynthesis, calcification, and growth, together with increases in de-calcification, respiration and other metabolic processes. While there is an expanding literature on how changes to ocean chemistry such as acidification influence organisms and ultimately ecosystems, there are few unambiguous examples of the impacts of ocean acidification on organisms in the field. As discussed previously, ocean acidification reduces the ability of organisms to recover from disturbances, tending to work synergistically with ocean warming. Adaptation options include reducing local sources of coastal acidification (e.g. coastal pollution and bacterial substrates) so as to decrease the metabolic demand on water column oxygen levels. Adaptation options in this particular case are likely to involve interventions in coastal and catchment management (i.e. efforts to reduce pollution).

3.4.3.1.3 Framework organisms and ecosystems

Many ecosystems include species that play a disproportionately important role in creating and maintaining the physical structure (framework) of ecosystems. In doing so, these organisms play a crucial role in providing habitat to very large numbers of organisms. These organisms are central components of ocean systems and their loss is likely to be serious for biodiversity, ecosystem function, and a range of ecosystem services that many humans depend on (Row 5, Table 3.4). Prominent examples include coral reefs, mangroves, seagrass, and kelp forests, all of which are facing pressure from local human activities and varying degrees of impacts from climate change (Hoegh-Guldberg et al. 2014; Pörtner et al. 2014a). As will other organisms, framework building organisms are sensitive to changes in the conditions that surround them. Changes can influence physiological processes such as respiration, photosynthesis, gas exchange, and calcification, with the rate of these processes increasing with temperature until a threshold level is attained, at which time rates of physiological processes tend to decline rapidly (Pörtner et al. 2014a). These responses to temperature can also drive significant changes in organisms and ecosystems that include changes to community composition, food webs and ecosystem dynamics (Hoegh-Guldberg et al. 2014; Pörtner et al. 2014a).

The thresholds play an important role in the response of rebuilding corals. Increases in sea temperatures that exceed 0.9°C above the long-term summer maximum for a region trigger the disintegration of the all-important symbiosis that corals have with dinoflagellate protists from genus *Symbiodinium*. If temperatures remain elevated for weeks or even months, impacts of mass coral bleaching and mortality grow in size (Heron et al. 2016) until almost complete mass-mortalities begin to occur (Hughes et al. 2017). As outlined elsewhere (Chapter box: Coral reefs), the loss of living corals has a substantial impact on biodiversity, coastal protection and fisheries productivity (Graham 2014; Rogers et al. 2014). Coral cover decreasing below 10% is associated with net erosion of the carbonate structures that represent coral reefs (Perry et al. 2013). While coral reefs represent a particularly clear example of how impacts on systems that create ecological frameworks can be large, other framework organisms such as mangroves and seagrass have other challenges such as sea level rise (Alongi 2008).

Impacts of sea level rise and other factors such as strengthening storms are affecting coastal areas through inundation and habitat loss (Row 6, Table 3.4). While some ecosystems (e.g. mangroves sea grasses) may be able to move shoreward as sea levels increase, coastal development often curtailment these opportunities for adapting to sea level rise and climate change in general. Options for responding to these challenges include reducing the impact of other stresses such as those arising from tourism, fishing, distracting development and unsustainable aquaculture/agriculture. In some cases, restoration of coastal habitats and ecosystems can be a cost-effective way of responding to changes arising from rising sea levels, intensifying storms coastal inundation of saline conditions.

Adaptation options for preserving frame-work building organisms such as corals involve reducing non-climate related stressors such as pollution, overfishing and physical destruction of these systems. In addition, there has been increasing interest in concentrating efforts on locations where organisms may be more climate robust than others or less exposed to climate change (van Hooidonk et al. 2013; Bongaerts et al. 2010). In this case, this could involve areas of cooler conditions due to upwelling, deep water communities that experience less extreme conditions and impacts, or variable conditions that lead to more resilient organisms. Given the potential value of these organisms for surviving climate change, efforts for preventing their loss to non-climate stresses are important (Fine et al. 2013; Cacciapaglia and van Woesik 2015; Chollett et al. 2013; van Hooidonk et al. 2013; Bongaerts et al. 2010; Chollett et al. 2014), see also (Pim Bongaerts et al. 2017; Chollett et al. 2017).

3.4.3.1.4 Fisheries

Fisheries are affected by a range of climate related factors (Rows 8-13, Table 3.4). As a result, impacts produce a number of effects on fisheries such as the decreased production of global shellfish fisheries as a result of ocean acidification (high confidence), global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes (medium confidence), and the movement of valuable stock such as tuna away from countries currently enjoying the revenue and benefits (high confidence). In addition, the loss of coral reef structures has also reduced the habitat and hence availability of reef fish important for small scale fisheries across the world's tropical regions, with growing risks for coastal communities, especially in the tropical regions where other options to fisheries protein are limited. See further discussion of fisheries in food production systems.

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

3.4.3.2.1 Gradual increase in avoidable risks

Understanding the avoided risks associated with restricting global warming to 1.5°C above the Industrial Period is important for understanding the benefits of restricting climate change to these levels. Some factors (e.g. primary productivity, ocean acidification, and distribution shifts) tend to show continuous changes that make estimates of the difference between today, 1.5°C, and 2°C and above a simple linear extension of what has been happening so far. In these cases, for example, an increase of 0.5°C would be accompanied by a proportional increase in the loss of primary productivity or extent to which species are moved towards higher latitudes. With a further 0.5°C increase, productivity (NPP) of equatorial regions would decline further and temporary increases in NPP in high latitude sites would continue. Likewise, distributional shifts in biodiversity, particularly fish and invertebrate species, would continue to change as temperature increased in the upper layers of the ocean. Ocean acidification would continue to disrupt organisms and ecosystem processes, with the erosion of the 3D structure of coral reefs continuing and interacting with intensifying storms and increased activities of bioeroders. Impacts of hypoxia would impact many valuable fisheries, with increasing loss to be accounted for in terms of costs and availability to industries such as fishing, tourism and aquaculture (Cheung et al. 2010; Weatherdon et al. 2016). Avoiding increases beyond 1.5ºC are expected to have significant cost savings accompanying them as the decreases at 2ºC and above are avoided (Cheung et al. 2016).

3.4.3.2.2 Abrupt changes in avoided risks

In other cases, changes are likely to be less continuous and gradual. For example, mass coral bleaching events and the impacts of intensifying storms are likely to be more abrupt in their impacts as recently demonstrated the Great Barrier Reef in 2016 and 2017. In these cases, reefs might be intact for several decades but destroyed in a single period of months due to elevated sea temperatures. Models reveal that increases in sea temperature will see an average increase in the frequency by which mass coral bleaching and mortality events occur. Under an average increase in global sea temperatures of 1.5°C , mass coral bleaching and mortality events are likely to impact coral reefs 2-4 times per decade, which will drive average coral cover on these various downward over time. However, reaching 2ºC will triple the frequency of mass coral bleaching (i.e. 2-4 bleaching events per decade under 1.5ºC versus 10 events per decade under 2ºC; (Hoegh-Guldberg et al. 2014) causing greater loss of coral and associated species and services. Restricting overall warming to 1.5ºC will prevent the total loss of coral reefs, with remaining coral reefs benefiting from an increasingly stable set of ocean conditions by mid-to-late century.

3.4.3.2.3 Impacts on fisheries and livelihoods

Given the importance of fisheries to humanity, it is worth noting the benefits of staying close to 1.5ºC. Impacts on marine fish stocks and fisheries will most likely be less under 1.5-2°C when compared to higher warming scenarios. Sensitivity to the 1.5-2°C relative to other warming scenarios differ between regions, with fish stocks and fisheries being highly sensitivity in tropical and polar systems. Direct benefits of achieving the 1.5°C global warming target can be substantial (Cheung et al. 2016) from increases in fisheries revenues and contribution to protein and micronutrients availability particularly to the most vulnerable coastal communities (tropical developing countries and SIDS).

Table 3.4: Key risks & related observed impacts, adaptation options and avoided risks at 1.5ºC as compared to 2ºC for ocean ecosystems and marine fisheries (links to AR5 and new literature).

Table 30-3 | Key risks to ocean and coastal issues from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer term era of climate options (here, for 2080–2100), for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Climate-related drivers of impacts: Warming trend; Extreme temperature; Extreme precipitation; Precipitation; Damaging cyclone; Sea level; Ocean acidification; Hypoxia

Level of risk & potential for adaptation: Potential for additional adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Key risks to ocean ecosystems

Updated key risk	Adaptation options	Avoided risks	Climatic drivers	Timeframe	Risk & potential for adaptation
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity (NPP) s, plus reduced up-welling in equatorial *(medium confidence)*. Some EBUE upwelling have increased e.g. California, Benguela, and Humboldt upwelling systems. Increased productivity may increase respiration and lead to an increased risk of anoxia at depth. [AR5 6.5.1, 6.3.4, Box CC-PP]. New Literature: Kwiatkowski et al. 2017; Weatherdon et al. 2016; Sydeman et al. 2014; Cheung et al. 2016.	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and over harvesting. Responses to the impact of these changes on fisheries is discussed below.	Clear differences between 1.5°C versus 2.0°C likely to exist at regional scales. Remaining at 1.5°C would reduce the reduction of NPP in tropical regions (stabilise up-welling as compared to continual decreases expected at 2.0°C of higher) but may increase in NPP temporarily at high latitudes with implications for fisheries productivity and food availability (see below). Increased NPP in some systems can lead to decreases in oxygen and, in cases, increased anoxia at depth - e.g. in some EBUE *(low confidence)*.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Distributional shift in fish and invertebrate species as temperatures change leading to increased risks of reduced fisheries catch potential at low latitudes, e.g., in EUS, CBS, and STG regions *(high confidence)*. Climate-driven species redistribution at regional to global scales increases risks to ecosystem functioning, human well-being, and the dynamics of climate change itself. [AR5 6.3.1, Box CC-MB] New Literature: Brown et al. 2016; Poloczanska et al. 2016; Pecl et al. 2017; García Molinos et al. 2017; García Molinos et al. 2015; Weatherdon et al. 2016; Cheung et al. 2016.	Adaptation options involve the relocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential as well as deploying flexible management that can react to variability and change. Further options include improving fish resilience to thermal stress by reducing other stressors such as eutrophication, the expansion of sustainable aquaculture, and development of alternative livelihoods in some regions.	Achieving an increase in average global temperature of 1.5°C will reduce the rate of warming and hence will significantly slowdown (and eventually stabilise) the movement of organisms towards higher latitudes and warming regions. This will reduce impacts on fisheries from mobile fish stocks, reduce the incidence of disease, and of invasive species, benefiting fisheries, aquaculture and coastal communities as compared to conditions under 2.0°C or more *(medium evidence, high certainty)*.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
High mortalities and loss of habitat for larger fauna including commercial species due to hypoxia expansion and effects *(high confidence)*. [AR5 6.3.3, 30.5.3.2, 30.5.4.1-2] New Literature: Altieri and Gedan 2014; Bakun et al. 2015; Bijma et al. 2013; Carstensen et al. 2014; Di Lorenzo 2015; Payne et al. 2016.	Options involve relocation of industrial fishing activities as a consequence of the hypoxia-induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Special fisheries may benefit (e.g. Humboldt squid). Reducing the amount of organic carbon running off of coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.	Exceeding 1.5°C will increase the extent to which ocean water columns are stratified and by which systems such as the equatorial upwelling are reduced. Keeping well below 2.0°C will maintain mixing of the water (i.e less column stratification) and will reduce the risks of ocean anoxia, especially if non-climate factors such as eutrophication are brought under control.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high
Ocean acidification (together with temperature) reduce reproduction, growth and survival of calcifiers e.g. invertebrates (pteropods, shellfish, sea urchins), reef building corals, calcareous red algae among others *(high confidence)*. [AR5 5.3.3.5, 6.1.1, 6.3.2, 6.4.1.1, 30.3.2.2, Box CC-OA] New Literature: Mackenzie et al. 2014; Meynecke et al. 2015; Lemasson et al. 2017; Haigh et al. 2015; Barton et al. 2015.	In case of coral reefs, reducing non-climate stresses, mainly pollution and limiting pressures from tourism, fishing and physical impacts can help build ecological resilience. Evidence for differential resistance and evolutionary adaptation of some species exists; however, rates are slow relative to the current unprecedented rates of increase in CO_2 and temperatures.	The broad and insidious effects of ocean acidification are proportional to atmospheric CO_2 content, hence keeping concentrations of CO_2 lower than 450 ppm (i.e. associated with 1.5°C) will result in a proportional decrease in risk to a range of systems. Commercial oysters will have greater survival at the CO_2 equivalent of 1.5°C versus 2.0°C, with associated industries remaining viable for longer. Coral reefs will have a more positive carbonate balance and hence will be able to retain their carbonate structures for longer, thereby reducing the risks from increasingly unprotected coastal areas and decreases in fish habitat (i.e. important for reef fisheries and coastal livelihoods).		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	Very low – Medium – Very high

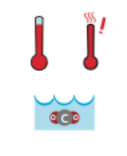
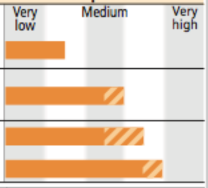
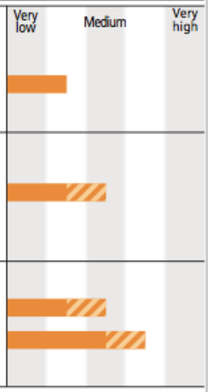
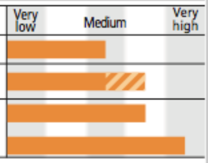
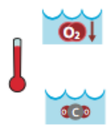
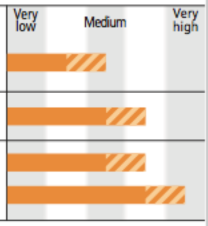
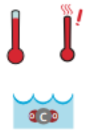
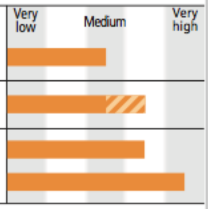
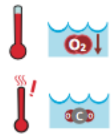
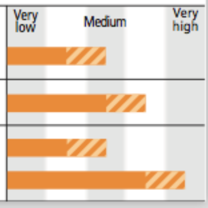
Continued next page →

Key risks to ocean ecosystems (continued)

Updated key risk	Adaptation options	Avoided risks		Timeframe	Risk & potential for adaptation
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in CBS, SES, and STG regions *(high confidence)*. [AR5 5.4.2.4, 6.4.2, 30.3.1.1, 30.3.2.2, 30.5.2,30.5.3, 30.5.4, 30.5.6, Box CC-CR] New Literature: Bozec et al. 2014; Freiler et al. 2013; Spalding and Brown 2015; Palumbi et al. 2014; Graham et al. 2015.	Adaptation options includes reducing pollution, and limiting pressures on corals from activities such as tourism, fishing and unsustainable coastal development. Affected nations should also plan for the increased numbers of people who will suffer reduced livelihoods by helping people move to alternative livelihoods such as sustainable aquaculture.	Reaching 2.0°C will triple the frequency of mass coral bleaching (i.e. 2-4 bleaching events per decade under 1.5°C versus 10 events per decade under 2.0°C (Hoegh-Guldberg et al. 2014) causing greater loss of coral and associated species and services. Restricting overall warming to 1.5°C will prevent the total loss of coral reefs which is likely to occur at global temperatures of 2.0°C or more.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in CBS and STG subregions *(medium to high confidence)*. [AR5 5.5.2, 5.5.4, 30.5.6.1.3, 30.6.2.2, Box CC-CR] New Literature: Ferrario et al. 2014.	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients. Increased mangrove, coral reef, and seagrass protection and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat.	Restraining warming to 1.5°C is *likely* to drive lower numbers of intense storms than expected at 2.0°C above the preindustrial. Combined with higher sea levels, inundation and storm damage will be significantly higher at 2.0°C as compared to 1.5°C *(medium confidence)*.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high
Marine biodiversity loss at high rate of climate change. (medium confidence) [AR5 6.3.1-3, 6.4.1.2-3, Table 30.4, Box CC-MB] New Literature: Cheung et al. 2009; García Molinos et al. 2015; Brown et al. 2016.	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution, over harvesting and physical damage from coastal development, tourism and fishing, as well as adopting spatial planning to allow for protection, and movement of populations and communities in some cases.	Maintaining average global surface temperature to 1.5°C will reduce the rate at which biodiversity is likely to be lost. In additional advantage of aiming for 1.5°C is that global conditions have a good chance of stabilising by mid-to-late century, which will reduce even further the loss of biodiversity. Higher planetary temperatures (2.0°C and above) will see temperature thresholds for most if not all organisms being exceeded - leading to relocation or mortality.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	Very low / Medium / Very high

Continued next page →

Table 30-3 (continued)

Key risks to fisheries					
Updated key risk	**Adaptation options**	**Avoided risks**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Decreased production of global shellfish fisheries *(high confidence)*. [AR5 6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2.1, Box CC-OA] New Literature: Handisyde et al. 2016; Ahmed et al. 2017; Clements and Chopin 2017; Weatherdon et al. 2016; Ekstrom et al. 2015; Rodrigues et al. 2015; Lee 2016.	Protecting reproductive stages and brood stock from periods of high ocean acidification (and chemical buffering) can reduce impacts (as would selecting stock with high tolerance to OA). Effective shift to alternative livelihoods, changes in food consumption patterns, and adjustment of (global) markets.	Limiting atmospheric CO_2 concentrations associated with 1.5°C will reduce the impact of ocean acidification on early stages of shellfish. Stabilisation of atmospheric levels of CO_2 will also increase the use of resistant cultivars for aquaculture (i.e. relatively more resistant to ocean acidification).		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes *(medium confidence)*. [AR5 6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2] New Literature: Lehodey et al. 2017; Matear et al. 2015; Graham 2014.	Adaptation options are limited but could involve the relocation of industrial fishing effort in response to regional decreases (low latitude), or to the expansion of aquaculture and other food production systems. Affected countries could use forecasting (e.g. PDO, ENSO) to guide fisheries to target periods of up-welling and high productivity while reducing fishing through periods of strong El Nino events (which may be increasing as a result of climate change). Increasing coastal poverty at low latitudes likely to increase as fisheries have to target smaller fishes – partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrialized fishing efforts.	Clear differences between 1.5°C versus 2.0°C likely to exist at regional scales in fisheries productivity. Remaining at 1.5°C would reduce the extent of the reduction of NPP in tropical regions (stabilise up-welling as compared to continual decreases expected at 2.0°C of higher) with implications for fisheries productivity and food availability (see below). Increased NPP in some systems is *likely* lead to decreases in oxygen and, in cases, increased anoxia at depth - e.g. in some EBUE *(low confidence)*.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific tuna fisheries *(high confidence)*. [AR5 6.3.1, 6.4.3, Table 30.4] New Literature: Lehodey et al. 2017; Matear et al. 2015; Graham 2014.	International fisheries agreements and instruments, such as the tuna commissions, may have allow continued access to catch as populations re-locate under warming, plus ensuring sustainability of fisheries yields.	Avoided risks at 1.5°C versus 2.0°C or higher include smaller relocation distances and eventually stabilised redistribution of pelagic fisheries (e.g. Tuna)		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Variability of small pelagic fishes in EBUEs is becoming more extreme at interannual to multidecadal scales, making industry and management decisions more uncertain *(medium confidence)*. [AR5 6.3.2, 6.3.3, 30.5.2, 30.5.5, Box CC-UP] New Literature: Barange et al. 2014; Hollowed et al. 2013.	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity increases resilience of the fisheries.	These differences will be smaller at 1.5°C persons to decrease healthy for higher.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction *(high confidence)*. [AR5 6.4.1, 30.5.3-4, 30.5.6, Box CC-CR] New Literature: Speers et al. 2016; Bell et al. 2013.	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).	Decrease in catch and species diversity in tropical reef fisheries likely to be lower at 1.5°C versus 2.0°C.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Current spatial management units, especially the marine protected areas (MPAs), may fail in the future due to shifts in species distributions and community structure *(high confidence)*. [AR5 6.3.1, 6.4.2.1, 30.5.1, Box CC-MB] New Literature: Burrows et al. 2014; García Molinos et al. 2017; Poloczanska et al. 2016.	Continuous revision and shifts of MPA borders and of MPA goals and performance.	Challenges of moving spatial planning are reduced at 1.5°C versus 2.0°C or higher, given smaller amounts of change and eventual stabilisation of ocean conditions.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	

Box 3.6: Coral reefs in a 1.5ºC warmer world

Coral reefs are found along tropical and subtropical regions of the world where they provide habitat for over a million species and underpin the livelihoods of an estimated 500 million people through the support of small-scale fisheries, livelihoods, and income from industries such as fisheries and tourism (Burke et al. 2011). Many of these mostly coastal people do not have significant alternatives and hence are vulnerable to changes to this resource base (Cinner et al. 2016; Barbier 2015).

The success of reef-building corals is the result of a symbiosis between simple animals (corals) and tiny plants like organisms belonging to the genius *Symbiodinium*. The symbiosis depends on mutualistic relationship whereby *Symbiodinium* traps the energy of the sun and provides food for the animal host, while at the same time being given access to inorganic nutrients such as ammonium and phosphate (Hoegh-Guldberg 1999). As a result of the efficiencies of this relationship, reef-building corals have flourished in the otherwise nutrient poor waters of tropical and subtropical coastlines, persisting over hundreds of millions of years (Veron 2008; Pörtner et al. 2014a)

Despite their importance, the abundance of coral reefs is decreasing due to local (non-climate) factors such as pollution, overfishing and unsustainable coastal development. As a result of these combined impacts, at least 50% of coral reefs have been lost over the past 30 years with an increasing signature from increasing sea temperature (De'ath et al. 2012). Thermal stress beyond 1ºC above the long-term summer maxima for an area causes the breakdown of the symbiosis with Symbiodinium to disintegrate resulting in coral bleaching. As a result, corals tend starve, get diseased, out-competed, and, in many cases, will die *en masse*. As corals disappear, so do fish and other dependent species, directly impacting fisheries and other coastal livelihoods, plus an array of important ecosystem services with humans (Graham et al. 2015; Graham 2014).

The link between sea temperature and mass coral bleaching has been established through decades of laboratory and field research (Hoegh-Guldberg et al. 2014), with the relationship between temperature and mass bleaching and mortality being so reliable that satellites measuring sea temperature anomalies can predict when and where mass coral bleaching and mortality is going to occur (Hedley et al. 2016; Heron et al. 2016). Attribution of mass coral bleaching and mortality to climate change has been assessed as having very high confidence in the detection of the impacts and high confidence in the attribution to climate change (Box 18-3, (Cramer et al. 2014).

The impacts of rising sea temperature are also exacerbated by ocean acidification (see section of Ocean Chemistry) which reduces the ability of corals and other calcifiers (e.g. foraminifera, macroalgae, molluscs) to produce their skeletons and shells, and grow and reproduce (Gattuso et al. 2015b; Pörtner et al. 2014a; Hoegh-Guldberg et al. 2014). In terms of coral reefs, ocean acidification reduces the ability of coral reefs to recover, and leads to greater activity by decalcified organisms (Dove et al. 2013b; Fang et al. 2013, 2014; Reyes-Nivia et al. 2014; Kline et al. 2012; Reyes-Nivia et al. 2013). As this coral bleaching and mortality increases, the ability for coral reefs to recover slows, leading to a reduced capacity to recover after impacts such as storms, or thermal stress and mortality, and ultimately to an even more rapid loss of coral dominated ecosystems (Kennedy et al. 2013b). Paleontological studies confirm the sensitivity of coral reefs to changes in atmospheric CO_2, with carbonate coral reefs disappearing for long periods of time when CO_2 levels were high (Veron 2008; Pörtner et al. 2014a)..

The extraordinarily warm conditions of the past three years have confirmed these projected risks to coral reefs from ocean warming with a multi-year global event which saw the unprecedented loss of 50% of the corals from the world's largest coral, the Great Barrier Reef (Hughes et al. 2017). In the same two-year period, in which projected but yet to be seen back-to-back mass coral bleaching and mortality events occurred, similar mass coral mortality was seen in the Caribbean Sea, and Pacific and Indian oceans. Early predictions (Hoegh-Guldberg 1999) have essentially become reality (Hughes et al. 2017) supporting subsequent with modelling work (Frieler et al. 2012; van Hooidonk et al. 2016; Hoegh-Guldberg et al. 2014) that strongly projects that mass coral bleaching events will continue to increase in frequency and intensity, with catastrophic outcomes for coral reefs globally in all but the most restrained RCPs (i.e. RCP 1.9 and RCP 2.6).

The close relationship between mass coral bleaching and mortality and temperature anomalies enables the projected risks at 1.5ºC to be calculated. Projections indicate that coral bleaching events will become annual events by mid-century for most regions under RCP 4.5 and higher emission scenarios (Hoegh-Guldberg et al. 2014, see Figure 30-10). Mass coral bleaching events are likely to occur 2-4 times per decade under RCP2.6, except in the case of the Caribbean, Gulf of Mexico and Eastern Pacific where mass bleaching events become annual occurrences by mid-to-late century.

Differences between rates of heating suggest the possibility of temporary climate refuges (Caldeira 2013; Keppel and Kavousi 2015; Cacciapaglia and van Woesik 2015)(van Hooidonk et al. 2013), which may provide an important role in terms of the regeneration coral reefs once the climate has been stabilised (Paris Agreement). Similar proposals have been made for the potential role of deep water (30 to 150 m) or mesophotic coral reefs (Holstein et al. 2016)(Bongaerts et al. 2010) although the ability of these ecosystems to repopulate damaged shallow water areas may be limited to a particular subset of corals (Bongaerts et al. 2017).

This analysis highlights the avoided risk of achieving RCP2.6 or lower (1.5ºC), as compared to the accumulating risks at RCP4.5 (~2ºC) or higher. The avoided risk is embodied in the reduced incidence (i.e. 2-4 bleaching events per decade versus 10 events per decade). The avoided risks are even clearer when one looks at the projected risks of mass mortality events like those that affected the Great Barrier Reef and many other coral reef ecosystems in the past two decades. This case, mass mortality events are absent in the case of RCP 2.6, and occur at most every decade in the case of RCP 4.5. Scenarios higher than RCP 4.5 see a rapid increase in the risk of mass mortality events from 1-4 per decade and 5-10 per decade, for RCP 6.0 and RCP 8.5 respectively. Given that coral reefs take a minimum of 10 to 15 years to replace coral killed during impacts such as mass coral bleaching and mortality events (Baker et al. 2008), scenarios projecting more than one mass mortality events per decade (e.g. RCP 6.0 and 8.5) are projected to eliminate coral dominated ecosystems (Hoegh-Guldberg *et al.*, 2014).

While the avoided risks of 2ºC are clear, restraining further increases in average global temperature to 1.5°C will still result in projected risk of losing 90% of rebuilding corals (van Hooidonk and Huber 2012; Frieler et al. 2012; van Hooidonk et al. 2016). However, assuming that the Paris Agreement and climate stabilisation is achieved by mid-century, protecting the remaining coral reefs (10%) from non-climate stressors will be important in terms of regenerating coral reefs mid-to-late century. In this regard, restraining warming to 1.5°C is critical for maintaining significant coral reef biodiversity within the world's oceans. Losing 90% of today's coral reefs will decrease resources and increase poverty levels across the world's tropical coastlines. Anticipating these challenges to food availability and income will become increasingly important, as will be the need to reduce other non-climate stresses on these essential resources.

3.4.4 Freshwater Resources (quantity and quality)

3.4.4.1 Observed impacts and adaptation

Detection and attribution to freshwater resources including quantity and quality must be interpreted with caution because of confounding factors such as land use changes, water demand, and urbanization (Cisneros et al. 2014).

3.4.4.1.1 Water availability including stream flow

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (robust evidence, high agreement) and has increased winter flows because more winter precipitation falls as rain instead of snow. There is robust evidence of earlier breakup of river ice in Arctic rivers. Streamflow is lower in summer, decrease in snow storage has exacerbated summer dryness (Cisneros et al. 2014).

Progresses since the AR5 in observed physical changes on streamflow and continental runoff are consistent with precipitation trends identified in Section 3.3.5. Even though, observed impacts on streamflow have been detected and attributed to anthropogenic climate change, observed changes on water availability have been dominantly affected by socioeconomic changes. The number of studies on detection and attribution of observed changes in streamflow by climate and anthropogenic changes have been increasing since AR5. In the studies, multiple drivers such as land use change, urbanization, reservoir control, water consumption and the significant natural variability of hydrological variables are considered and have reveal that anthropogenic climate change and human activity have both significantly influenced the status of water resources (Wu *et al.*, 2016). For example, anthropogenic influence had a far greater contribution (>56.6%) to the streamflow variability than that by climate change (<43.4%) in the Liao River Basin, one of the largest basins in northeast China (Zhang et al., 2017). In Huxi and Taihu Zone, Hangjiahu Zone, Huangpujiang Zone, and Wuyang Zone in the Taihu Lake Basin Tai located in the core region of the Yangtze River Delta, China, human activities contributed to 76~79%, 83~84%, 84~92%, and 95~97%, of the runoff variation, respectively (Peng et al., 2016). In Agula watershed in northern Ethiopia, climate variability and human activities (e.g., proper watershed management practices and associated changes in land use/land cover among other factors) contributed to 22% and 78 %, of changes in mean annual streamflow, respectively (Fenta et al., 2017). Population under water scarcity has increased by nearly 16 times since the 1900s although total population increased only 4-fold over the same period (Kummu et al., 2016). Per capita water consumption only shows a slight and irregular increase over the past century, while the expansion of water scarcity is predominantly explained by the effects of spatial distribution of population growth relative to water resources (Kummu *et al.*, 2016).

3.4.4.1.2 Extreme hydrological events (floods and droughts)

There is *low confidence*, due to limited evidence, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale and very few studies have considered variations over time in hydrological (streamflow) drought, largely because there are few long records from catchments without direct human interventions (Cisneros et al. 2014).

Since AR5, the number of studies based on long-term observed data has been limited. For example, Flood vulnerability has been greatly affected by spatiotemporal changes in populations and assets and changed over time and space depending on local socioeconomic development conditions, including flood protection measures, topography and hydro-climatic conditions (Tanoue et al., 2016). Long-term analysis in flood vulnerability between 1960 and 2013 showed decreasing trends in global mortality rates and global loss rates, and inverse relationships were found between flood vulnerability and GDP per capita (Tanoue *et al.*, 2016).

Human-induced climate change contributed to 3-year drought in Syria since the beginning in the winter of 2006/2007 (Kelley *et al.*, 2015).

3.4.4.1.3 Groundwater

Both detection of changes in groundwater systems and attribution of those changes to climatic changes are rare owing to a lack of appropriate observation wells and a small number of studies (Cisneros et al. 2014).

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

3.4.4.1.4 Water quality

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 (Cisneros et al. 2014).

Regional studies that have been conducted since AR5 demonstrate the water temperature increase and water quality degradation by climate change. For example, the mean yearly temperature of fluvial waters over the period 1961–2010 in the Central European Plain showed a positive trend, ranging from 0.17 to 0.27°C (10 years)-1, and its fastest rise in spring reached from 0.08 to 0.43°C (10 years)-1. The increase in water temperature correlated strongly with rising air temperature (Marszelewski and Pius, 2016).

3.4.4.1.5 Soil erosion and sediment load

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, Cisneros et al. 2014).

Climate change impacts on soil erosion have been observed over the world, and many studies suggest that the rainfall is the most direct influencing factor (Li and Fang, 2016). For example, in eight large Chinese rivers from 1991-2007, every 1% change in precipitation has led to a 2% change in sediment loads (Lu et al., 2013).

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

3.4.4.2.1 Water availability including stream flow

Climate change is projected to reduce renewable surface water resource significantly in most dry subtropical regions (robust evidence, high agreement), in contrast, water resources are projected to increase at high latitudes (Cisneros et al. 2014).

Reduction of water resource availabilities under 2ºC global mean temperature (GMT) rises compared to pre-industrial conditions is projected to be greater than 1.5ºC GMT rise, however socioeconomic condition might be greater than variation between GMT rises.

At the global scale, projected runoff changes are consistent with the findings on precipitation changes summarized in Section 3.3.3 and differences are most prominent in the Mediterranean region where the median reduction in runoff almost doubles from about 9% (likely range: 4.5–15.5 %) at 1.5ºC to 17% (8–28 %) at 2ºC (Schleussner et al. 2016). A considerable difference between the impacts on mean runoff and low runoff and less discernible difference between the impacts on mean annual maximum runoff at 1.5ºC and 2°C warming are projected on European water resources (Donnelly et al. 2017).

Mean global warming levels of 1.5ºC, 2ºC, 2.5ºC, 3ºC, 3.5ºC, 4ºC, 4.5ºC, 5ºC (MAGICC6 with 19 GCMs using a pattern-scaling) are projected to expose an additional 4%, 8%, 9%, 10%, 11%, 12%, 12.5%, and 13% of the world population to new or aggravated water scarcity, respectively, with >50% confidence (Gerten *et* al. 2013). Under global warming of 1.7°C in 2021–2040, 2.7°C in 2043–2071, and 3.7°C in 2061–2086 (transition of RCP 8.5), the multi-model medians with eleven GHMs by five GCMs project reduction in water resources, by at least one of the two criteria (experience a discharge reduction >20% and >1σ), about 8%, 14%, and 17% of the global population, respectively (Schewe et al. 2014). Under the SSP2 population scenario using 31-y averages associated with the different warming levels, the percentage of people living in countries below 500 m^3 per capita (1,000 m^3 per capita) is projected to rise to 6% (13%) at 1.7°C, 9% (21%) at 2.7°C, and 12% (24%) at 3.7°C of global warming, according to the multi-model medians with eleven GHMs by five GCMs (Schewe et al. 2014). GMT increase of around 1.5ºC (transition of RCP2.6 in 2050, SSP1-5, 19 GCMs) would reduce exposure to increased ensemble mean of water scarcity by 184–270 million people compared to impacts under the around 2 ºC (transition of RCP4.5 in 2050, SSP1-5, 19 GCMs), however variation between socioeconomic differences is greater than variation between GMT rises (Arnell and Lloyd-Hughes 2014).

At the regional scale, many regions especially in Europe, Australia and southern Africa are projected to be substantially affected in terms of water at 1.5ºC above the Pre-Industrial period (Gerten et al., 2013). Ensembles project clear increases in the magnitude of maximum flows under 1ºC, 2ºC and 3ºC for the Upper Amazon, Ganges, and Lena, and decreases in the magnitude of minimum flows under 2ºC and 3°C for the Rhine, and Tagus, which are consistent with projected changes in Q5 and Q95 (Gosling et al., 2017). For several small island developing states (SIDS), particularly across the Caribbean region, a substantial fraction (~25%) of the large overall freshwater stress projected under 2°C at 2030 can be avoided by limiting global warming to 1.5°C (Karnauskas et al.). From 0.8-2.3ºC rises of GMT, seasonal changes in discharge for the River Mitano under HadCM3 have a negligible influence on mean annual river discharge (<1% change from the discharge for the 1961-1990 baseline period) (Kingston and Taylor, 2010).

Increase of water demand under 2.0ºC GMT rises is projected to be similar to 1.5ºC GMT rise. Twenty-five (five GHMs by five GCMs) ensemble projections under 2.2ºC (2.7ºC) (transition GMT rise of RCP2.6 and

RCP4.5 in 2035–2065) show India, China, Pakistan, USA and global irrigation water demand increases by around -1.7% (-1.5%), 10.3% (13.3%), -0.6% (1.6%), -2.4% (2.4%) and 8.6% (9.4%), respectively (Wada et al., 2013). Under GMT rises of 1.5ºC (transition of RCP2.6 by GFDL-ESM2M in 2011–2040), 1.6ºC (RCP2.6 by GFDL-ESM2M in 2071–2100, transition of RCP4.5 by GFDL-ESM2M in 2011-2040, transition of RCP8.5 by GFDL-ESM2M in 2011-2040), 1.9ºC (transition of RCP4.5 by MIROC-ESM-CHEM in 2011–2040), and 2.1ºC (transition of RCP2.6 by MIROC-ESM-CHEM in 2011–2040, transition of RCP4.5 by HadGEM2-ES in 2011–2040, transition of RCP8.5 by MIROC-ESM-CHEM in 2011–2040), and 4.0ºC (transition of RCP4.5 by MIROC-ESM-CHEM in 2071–2100), the projected ranges of changes in global irrigation water withdrawal with human configuration fixing non-meteorological variables at circa 2000 are 1.8%, 1.1–2.3%, 1.4%, 0.6–2.0%, and 2.8% respectively (Hanasaki et al., 2013).

The effectiveness of water use efficiency measures as adaptation to climate change is largely determined by the potential of modern information technology to achieve more efficient water resource use and management as well as human responses and choices in the uptake of measures (O'Connell, 2017). Other important element of climate change adaptation on water resources is the governance structure, and specifically the manner in which institutional design propositions support adaptation processes at different levels (Huntjens *et al.*, 2012).

3.4.4.2.2 Extreme hydrological events (floods and droughts)

Global flood risk will increase in the future partly due to climate change (limited evidence, *medium agreement*), however projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods (Cisneros et al. 2014).

Global Mean Temperature (GMT) increase of 1.5ºC would reduce exposure to increased flooding compared to impacts under the 2ºC, however socioeconomic condition might be greater than variation between GMT rises. An ensemble of indicator changes in freshwater-related hazards due to climate change projects statistically significant differences between 1.5°C and 2°C GMT rise taking into account the uncertainty due to both GCMs and GHMs (Döll et al.).

GMT rises of around 1.5ºC (transition of RCP2.6 in 2050, SSP1-5, 19 GCMs) would reduce exposure to increased flooding by 26–34 million compared to impacts under the around 2ºC (transition of RCP4.5 in 2050, SSP1-5, 19 GCMs), however variation between socioeconomic differences is greater than variation between GMT rises (Arnell and Lloyd-Hughes, 2014). Impacts of global warming of 1.5ºC and 2ºC (transition, seven GCMs) are projected 100% and 170% increase in population affected and 120% and 170% increase in damage (Alfieri *et al.*, 2016). A significant increase in potential flood fatality (+5.7%) is projected without any adaptation if GMT increases by 1.5°C to 2.0°C, whereas an increase in potential economic loss (+0.9%) is not significant (Kinoshita et al.). Under 1.5°C and 2°C warming (transition of RCP8.5, 5GCMs, 10GHMs), global direct flood damage could increase by 63% and 80% and human losses by 73% and 98%, resulting in a welfare loss of 0.27% and 0.34%, respectively (Dottori et al.).

The global monthly population exposed to extreme drought by around 1.5°C (2021-2040 under RCP8.5) and around 2.0°C (2041-2060 under RCP8.5) warming is projected to be 114.3 and 190.4 million people (Smirnov *et al.*, 2016).

Changes in flood risk are unevenly distributed, with the largest increases in Asia, U.S., and Europe, in contrast, changes are statistically not significant in most countries in Africa and Oceania (Alfieri et al., 2016). Significant differences of river floods in Europe between 1.5°C and 2ºC, and 2°C and 3 ºC GMT rises project almost 33% and about 70 %, respectively (Thober et al.). A multimodel ensemble of 45 hydrological simulations (three RCPs, five GCMs, three hydrological models) projects the changes in low flows project significant for about half of the European rivers between 1.5 and 2°C global warming, and about 80% of the rivers between 1.5°C and 3°C, respectively (Andreas et al.). The difference of projected river discharge (three hydrological models and five GCMs) between global warming of 2ºC (transient, RCP4.5 during 2040–2059) and 1.5 ºC (transient, RCP2.6 during 2020–2039) is positive for almost all the time scales (1.4%, 3.5%, 4.5%, 2.1%, 2.4% respectively for annual, spring, summer, 90% percentile and 10% percentile discharges) which suggests that the increment of 0.5ºC could lead to more flood events in the in the Upper Yangtze River Basin (Chen *et al.*, 2017). In the Haihe River Basin in China, population exposure to droughts in the 1.5°C warming level is projected to be reduced by 30.4% relative to the 1986–2005 period, but increase by 74.8% in the 2.0°C warming level (Sun *et al.*, 2017).

The differences in projected global economic damages with and without adaptation of flood protection show that adaptation measures have the potential to greatly reduce present and future flood damage, and the costs are often lower than the benefits (Winsemius *et al.*, 2016).

3.4.4.2.3 Groundwater

Climate change is projected to reduce groundwater resources significantly in most dry subtropical regions (robust evidence, high agreement) (AR5 WGII Chapter 3).

Climate change under 1.5 ºC GMT rise is projected to reduce groundwater resources significantly in some regions. For a GMT rise of 1.5ºC (transition of RCP 8.5), an ensemble mean (five GCMs) of around 1.6% (range 1.0-2.2%) of global land area is projected to suffer from an extreme decrease of renewable groundwater resources of more than 70%, while the affected areas increase to 2.0% (range 1.1-2.6%), 3.0% (range 1.5-5.3%), and 3.4% (1.9–4.8%) for a GMT rise of 2ºC, 3ºC, and 4ºC, respectively (transition of RCP8.5) (Portmann et al., 2013). In a groundwater-dependent irrigated region in Northwest Bangladesh, the average groundwater level during the major irrigation period (January-April) decreased by 0.15–2.01 m because of an increase in temperature of around 1.6–5.6°C, which increased irrigation costs by 0.05–0.54 thousand BDT ha^{-1} (Salem et al., 2017).

3.4.4.2.4 Water quality

Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (medium evidence, *high agreement*) (AR5 WGII Chapter 3).

Degradation of water quality under 1.5ºC and 2.0ºC GMT rises is projected to be similar.
For example, the daily probability of exceeding the chloride standard for drinking water and the maximum duration of the exceedance in Lake IJsselmeer (Andijk) slightly increase to the same degree for GMT rises of 1.5ºC and 2.5ºC (Bonte and Zwolsman, 2010).

GMT rises of around 2ºC (transition of RCP4.5 in 2050-2055, 4 GCMs), mean monthly DO concentrations project to decrease mean monthly DO concentrations and nutrient concentrations around 1.5ºC GMT rise (transition of RCP2.6 in 2050-2055, 4 GCMs) in the upper Qu’Appelle River (Hosseini et al., 2017).

3.4.4.2.5 Soil erosion and sediment load

Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (medium evidence, high agreement) (AR5-WGII Chapter 3).

Published papers in respect of climate change impacts on soil erosion have been increasing since 2000 over the world (Li and Fang, 2016). Average annual sediment loads is projected to be similar under 1.5ºC and 2.0ºC GMT rises (Cousino et al., 2015).

Table 3.5: Key risks and related observed impacts, adaptation options and avoided risks at 1.5ºC as compared to 2ºC for freshwater systems (links to AR5 and new literature). To be integrated with Table 30-3 from IPCC AR5 (see example below).

Climate-related drivers of impacts			Level of risk & potential for adaptation
Warming trend	Drying trend	Extreme precipitation	Potential for additional adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Key risks to ocean ecosystems

Updated key risk	Adaptation options	Avoided risks	Climatic drivers	Timeframe	Risk & potential for adaptation
Flood risks are associated with climate change and increase with increasing greenhouse gas emissions (robust evidence, high agreement) [WGII AR5 Table 3-4]. However there still remains limited evidence that anthropogenic climate change has affected the frequency and magnitude of floods at global scale.	Development, improvement, maintenance and upgrades of facilities such as flood control structure, levees, and sewerage. Promoting urban and rural development for disaster risk reduction, enhancing preparedness for evacuations, emergency operations, and continuity of business activities.	By 2100, the number of people exposed annually to a 20th century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6) [WGII AR5 Table 3-4]. In line with these findings, GMT rises of 1.5°C are projected to significantly reduce global exposure to increased flooding compared to impacts under 2.0°C (robust evidence, high agreement) resulting in reduced flood-related economic damages and mortality risks. Regionally, significant differences exist for reduced flood projections in Europe and in a number of river basins including the Yangtze river basin in China. However, it should be noted that changes in socioeconomic conditions might have a stronger influence than the additional half a degree warming (Doll et al., Thober et al., Chen et al. 2017, Arnell & Lloyd-Hughes 2014, Alfieri et al. 2016, Kinoshita et al. Dottori et al.).		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions *(robust evidence, high agreement)* [WGII AR5 3.4, 3.5]. Changes in water availability have been attributed in part to anthropogenic climate change in some regions although the primary driver of changes in water availability is socioeconomic change.	Reductions in water availability exacerbate competition for water between agriculture, ecosystems, settlements, industry and energy production, affecting regional water supplies, energy, and food security.	Reduction of water resource availability is projected to be higher under 2.0°C warming than under 1.5°C warming *(robust evidence, high agreement)*. Additional increases in persons exposed to water stress since 1986-2009 could double at 2.0°C compared to 1.5°C *(medium confidence)*. Differences are strongest in the Mediterranean where median reduction in runoff is projected to double between 1.5°C and 2.0°C. For several small island developing states (SIDS), particularly across the Caribbean region, a substantial fraction (~25%) of the large overall freshwater stress projected under 2.0°C at 2030 can be avoided by limiting global warming to 1.5°C. However, changes in socioeconomic conditions might have a stronger influence than the additional half a degree warming (Schleussner et al. 2016, Gerten et al. 2013, Hanasaki et al. 2013, Arnell & Lloyd-Hughes 2014, Karnauskas et al.).		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Changes in meltwater yields from stored glacier ice [AR5 3.4.3]	Meltwater yields from stored glacier ice are projected to increase in many regions during the next decades and decrease thereafter. Also, continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments. These changes create an adaptation challenge.	Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century. Changes beyond the committed change are expected due to continued warming….		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high

3.4.5 Food security and food production systems (including fisheries)

3.4.5.1 Observed impacts and adaptation

For food security and food production systems quantifying the observed impacts of climate change is an extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate. Implementing specific strategies can partly alleviate the impacts of climate change on these systems, whilst the degree of compensation is mainly dependent on geographical area and crop (Rose et al. 2016).

3.4.5.1.1 Crop production

Impact studies on agricultural crops were focused on several components that contribute to food productions (crop suitability and yield, CO_2 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, however, changes on crop production. These impacts are evident in many areas of the world ranging from Asia (Sun et al. 2015; He and Zhou 2016; Chen et al. 2014b); to America (Cho and McCarl 2017) and Europe and are particularly important for typical local crops that are cultivated in specific climate conditions (e.g. Mediterranean crops like olive and grapevine, Moriondo et al. 2013a,b).

Several studies have estimated impacts of observed mean climate changes on crop yields over the past half century. Based on these studies, observed changes in climate seem to have negatively affected the production capacities of crops like wheat and maize (Lobell et al. 2011); whilst the effects on rice and soybean yields have been smaller. Warming has produced positive effects on crop production in some high-latitude (Jaggard et al. 2007; Chen et al. 2014b; Supit et al. 2010; Gregory and Marshall 2012; Sun et al. 2015; He and Zhou 2016). In some instances, climate change has led to the possibility of more than one harvest per year (Sun et al. 2015; Chen et al. 2014a). Abebe et al. (2016) suggested a maize grain yield increase at elevated CO_2 by 45.7% and 0.5% at +1.5°C and +3.0°C respectively compared to ambient conditions. Singh et al. (2013) observed a potato yield increase of 11% at elevated CO_2 (i.e. 550 ppm) and +1°C but a yield decrease of 13.7 %when a further increase in CO_2 has been associated to a rise in temperature of +3°C.

Crop productions are strongly affected by increases in extreme events, but the quantification of these changes is more difficult. There is evidence that changes in the frequency of extreme events have affected cropping systems (e.g. changes in rainfall extremes, Rosenzweig et al. (2014); increases in hot nights, Welch et al. 2010, Okada et al. 2011; extremely high daytime temperature, Schlenker and Roberts 2009, Jiao et al. 2016; drought, Jiao et al. 2016 Lesk et al. 2016; heat stress, Deryng et al. 2014; chilling damage Jiao et al. 2016).

In addition to these, it is necessary to taken into account the effects of changes in atmospheric composition (i.e. CO_2 and O_3 concentration). The increase of atmospheric CO_2 has played an important role in yields by enhancing radiation and water use efficiencies. The rise in tropospheric O_3 has produced losses of yields of about 5-10% (Van Dingenen et al. 2009).

Finally, the impacts on the occurrence, distribution and intensity of pest and disease on crop yields have been investigated. The results showed a general increase in pest and disease attacks related to higher winter temperatures that allowed pests to survive. Jiao et al. (2014) observed that climate warming and agricultural pests and diseases produced decrease in grain yield for winter wheat, maize and double cropping paddy rice in China.

3.4.5.1.2 Livestock production

The impacts of climate change on livestock production have been considerably less studied than the previous food systems noted. Attention has largely been dedicated to ruminal diseases (e.g. blue-tongue virus Guis et al. 2012) or zoonotic diseases. In both cases, climate change has facilitated the recent and rapid spread of the virus or ticks.

3.4.5.1.3 Fisheries Production

The detection and attribution of observed climate change impacts are different when inland and marine fisheries are considered. Marine fishery is very sensitive to warming trends in water temperature. Several studies indicated that in Northern and Southern Oceans the observed increases in sea temperatures produced poleward migrations of marine species (Cheung et al. 2010, 2013; Last et al. 2011). These changes have particularly negative implications for coastal fisheries in tropical developing countries (Cheung et al. 2013). Studies, dedicated to fishery in coral reef ecosystems, show that declines in coral reef cover, due to overfishing and rising ocean temperatures, have led to the decreased abundance of the majority of fish species associated with coral reefs (Graham et al. 2009, 2011; Wilson et al. 2006; Wilson et al. 2010).

Less information is available on the impact of climate change fishery resources in freshwater systems and aquaculture. The studies conducted on these have not always produced consistent interpretations on the causes of the reduction of fish yields (e.g. increasing temperature, changes in fishery practices) (Ndebele-Murisa et al. 2011; Marshall 2012; Dawson et al. 2016).

3.4.5.1.4 Food security

The impacts of observed climate change on food production are evident as reported in the above sections, but to quantify that these imply some effects on food security is rather difficult. Thus, there are few studies reporting clear links between climate change and food security. Among these Lobell et al. (2011) estimated that prices of traded food commodities increase due to the role of temperature and rainfall trends on food supply (+19%), but, was lower when increased CO_2 was considered (+6%).

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

3.4.5.2.1 Crop Production

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

There are few studies since AR5 focused on the impacts on cropping systems for scenarios where global mean temperatures increase within 1.5°C. (Schleussner et al. 2016c) project that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and C&S America. Ricke et al. (2015) highlight how globally, cropland stability declines rapidly between 1 and 3ºC warming. Similarly, Bassu et al. (2014) suggested that an increase of air temperature negatively influence the modeled maize yield response of -0.5 Mg ha^{-1} per°C and even a conservative target of 2°C global mean warming would lead to losses of 8-14% in global maize production. Challinor et al. (2014), using multi-model ensemble projections, indicated high vulnerability of wheat and maize production in tropical regions, whilst Niang et al. (2014), using the near term (2030-2040) as a proxy for 1.5ºC warming, projected a significant lower risks to crop productivity in Africa compared to 2ºC warming. Abebe et al. (2016) suggested a maize grain yield increase at elevated CO_2 by 45.7% and 0.5% at +1.5°C and +3.0°C respectively compared to ambient conditions. Singh et al. (2013) observed a potato yield increase of 11% at elevated CO_2 (i.e. 550 ppm) and +1°C but a yield decrease of 13.7 %when there is further increase in CO_2 associated with a rise in temperature of +3°C.

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 infurther yields losses and damages to the main African crops (i.e. maize, sorghum, wheat, millet, groundnut, cassava). For South East Asia a 2°C warming by 2040 results in a one third decline in per capita crop production (Nelson et al. 2010) associated with a genral crop yield decreases. Schleussner et al. (2016) highlighted an increase of rice and soy yields at 1.5°C and 2°C warming in the tropics compared to present-day yields as result of the positive effect of CO_2-fertilization. Schmitz et al. (2014) using a inter-comparison of global agro-economic models with harmonized drivers of population, GDP, and biophysical yields for different socioeconomic and climate scenarios, projected an increase of cropland of 10–25% by 2050 especially for sub-Saharan Africa and South America.

3.4.5.2.2 Livestock Production

Climate change impacts on livestock will include effects on forage and feed, direct impacts of changes in temperature and water availability on animals, and indirect effects via livestock diseases.

Warming is expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al. 2010; Hatfield et al. 2011; Izaurralde et al. 2011). Simulations for grasslands (Graux et al. 2013) and sown pastures (Perring et al. 2010) also project negative impacts on forage quality.

High temperatures tended to reduce animal feeding and growth rates (André et al. 2011; Renaudeau et al. 2011). The impacts of a changing climate on dairy cow production showed that, in some regions, milk yields will be reduced and mortality increased because of heat stress throughout the current century.

The possibility of supplying water for an increasing livestock population will be affected by climate change in many places. For example, Masike and Urich (2008) project that warming will cause an annual increase in cattle water demand.

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

3.4.5.2.3 Fisheries Production

Expected changes in the intensity, frequency, and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification, and changes in precipitation with associated changes in groundwater and river flows are expected to determine significant changes across a wide range of aquatic ecosystem types and regions with consequences for fisheries and aquaculture in many places (FAO 2009; Hollowed et al. 2013; King et al. 2015)**.**At the global scale, projections suggested that climate change could lead to increase in fisheries yield in high-latitude regions, but a decrease in the tropics (Cheung et al. 2010). According to World Bank (2013), an increase of 2°C by 2040 could lead significant reduction in available protein from fisheries in sub-Saharan Africa and a decrease in maximum catch potential around the Philippines and Vietnam. See also section 3.4.3 above (Fisheries in Ocean systems section)

Risks for fisheries and aquaculture are likely to rise steadily as atmospheric CO_2 concentrations increase (e.g. risks for fisheries and aquaculture, Alin et al. 2014, Feely et al. 2016; coastal protection provided by coral reefs; plankton communities within coastal and oceanic food webs, Mathis et al. 2015, Bednaršek et al. 2017). Risks become much greater as atmospheric CO_2 increase beyond 450 ppm (equivalent to 1.5ºC), with a significant reduction in the impacts likely to ecosystems and human systems if concentrations of CO_2 are kept lower than this (Kroeker et al. 2013; Gattuso et al. 2015a). Risks associated with declining oxygen have not been comprehensively assessed although the rapid rise of 'dead zones' should be a point of major concern for fisheries in some regions (e.g. USA).

Other projected risks include risks are large in the case of ecosystems characterized by high rates of calcium carbonate deposition (e.g., coral reefs, some plankton communities) which are sensitive to decreases in the saturation states of calcium carbonate (i.e. aragonite and calcite), leading to a reduced (and eventually negative) ratio of calcification to de-calcification (Kennedy et al. 2013a; Dove et al. 2013b). Long-term changes in the structure of marine environments have resulted in the 'flattening' of coral ecosystems (Alvarez-Filip et al. 2009) with projected risks for reef fish productivity, coastal protection and other ecosystem services for humans (Rogers et al. 2014; Grandcourt and Cesar 2003; Saarikoski et al. 2015; Graham 2014; Graham et al. 2007; Tseng et al. 2015). In many locations, the carbonate balance is low or negative (Kennedy et al. 2013a) indicating the net erosion of carbonate coral reefs.

Understanding the risks of further increases in atmospheric CO_2 depend on whether future increases are sudden (e.g. involving tipping points) or gradual. Changes to the carbonate chemistry of seawater is expected to decrease the ability of calcifying organisms to produce shells and skeletons, slowing the recovery of these organisms from impacts such storms and heating events. The projected risk in this case is likely to increase steadily, with corals and other calcifying organisms becoming increasingly brittle in the face of other factors such as tropical storms that may be intensifying. Similarly, decreasing levels of oxygen are likely to increase the risk of increasing numbers of catastrophic low oxygen mortality events.

Given the steadily increasing nature of risks associated with changing ocean chemistry, avoided risks between 1.5°C and 2°C include (1) a reduced loss of carbonate coral reef structures and therefore greater retention of coastal protection for key ecosystems and coastal human communities, (2) reduced numbers of 'dead zones' and hence retention of otherwise lost habitat for organisms and fisheries, (3) lower levels of disruption to key organisms and ecosystem processes and the retention of ecosystem resilience, and (4) reduced level of risk of from 'wild card' impacts that arise from the large number of currently unexplored interactions and changes (e.g. interactions between ocean acidification, biology and effects on solubility trace metals).

3.4.5.2.4 Food security

The overall impact of climate change on food security is considerably more complex and greater than impacts on agricultural productivity. Several components of food security will be affected by climate change, ranging from food access, utilization and availability due to water, sanitation, and energy availability to food insecurity and price due to the frequency and severity of climate extremes.

Global temperature increases of about 4°C or more, combined with increasing food demand, would pose large risks to food security globally and regionally, and risks to food security are generally greater in low latitude areas (Rosenzweig et al. 2013; Rosenzweig and Hillel 2015).

von Lampe et al. (2014) indicated an average annual rates of changes of real global producer prices for agricultural products between −0.4% and +0.7% between 2005 and 2050, whilst (Nelson et al. 2014a) argued as differences in the price effects of climate change are accompanied by differences in land use change. Also, Nelson et al. (2014a)) using ensemble global economic models reported, on average, higher prices for almost all commodities in all regions, with lower yields and reduced consumption depending on the climate stresses used. Lotze-Campen et al. (2014) by comparing five agro-economic models suggested that the overall impacts of high demand for second-generation bioenergy on global food prices are rather modest (+5% on average) and that agricultural price effects will be mainly affected by the direct climate impacts on crop yields (+25% on average for 2050 using RCP8.5).

In countries where agriculture is the major source of livelihood (e.g. West Africans coutries) several studies pointed out that in addition to climate change, there are existing inefficiencies in agriculture. It appears that climate change will unequivocally hurt agriculture and that right now there is room for improvements in yield with the proper investments (Muller 2011; Roudier et al. 2011; Neumann et al. 2010). There is also a need for appropriate awareness raising to inform mostly illiterate farmers about how to efficiently use technologies as well as to ensure that they are aware of their rights and are able to negotiate for benefits. Also, a good understanding of various agricultural subsectors and their respective current adaptation strategies; policy developments and institutional settings may foster the adoption of sustainable agricultural systems that effectively mainstream climate change in the region (Zougmoré et al. 2016).

Table 3.6: Key risks and related observed impacts, adaptation options and avoided risks at 1.5ºC as compared to 2ºC for food security and food production systems (links to AR5 and new literature). To be integrated with Table 7-3 from IPCC AR5 (see copy below).

Climate-related drivers of impacts						Level of risk & potential for adaptation
Warming trend	Extreme temperature	Drying trend	Extreme precipitation	Carbon dioxide fertilization	Ocean acidification	Potential for additional adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Key risks food security and food production systems

Updated key risk	Adaptation options	Avoided risks	Climatic drivers	Timeframe	Risk & potential for adaptation (Very low – Medium – Very high)
Reductions in mean crop yields due to climate change and increases in climate variability, leading to risks of food security and malnutrition, and risks to incomes and livelihoods. Reductions in crop yields have been observed especially for wheat and maize in low latitude regions, whilst increases have been observed in high latitude regions.	Changing planting and harvesting dates, Crop switching, high efficiency irrigation, (subject to water availability), N fertiliser, expanding/moving cropland to new areas and abandoning other areas, mixed farming, weather-index insurance schemes.	AR5: Impact studies for major cereals showed that yields of maize and wheat begin to decline with 1°C to 2°C of local warming (corresponding to smaller values of global warming) in the tropics. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with local warming of 3°C to 5°C (corresponding to smaller values of global warming). However, all crops showed negative yield impacts for 3°C of local warming (corresponding to a smaller value of global warming) without adaptation (Porter et al., 2014) and at low latitudes under nitrogen stress conditions (Rosenzweig et al., 2014). Since AR5, a variety of studies using different approaches (simulation of crop yields, crop suitability, and studies of agricultural pests and diseases) all indicate higher crop yields and productivity for 1.5°C warming compared to 2.0°C warming. These studies include some which project that the crop yields under 1.5°C warming will be greater than today's in some regions. Areas benefiting from constraining warming to 1.5°C (as compared with 2.0°C) in these studies include Africa (both Sub-Saharan and West Africa), SE Asia, and Central & South America (Porter et al. 2014, Rosenzweig at el 2014, Schleussner et al. 2016, Ricke et al. 2016, Bassu et al. 2014, Challinor et al., 2014, Niang et al., 2016, World Bank 2013).	Warming trend, Drying trend, Extreme temperature, Extreme precipitation, Carbon dioxide fertilization, Ocean acidification	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Risks to livestock: mortality risks due to reduced quantity/quality of feed, heat stress and water stress, and increased prevalence and intensity of livestock disease, potentially leading to loss of livelihoods (Thornton et al 2009, Mario et al 2015)	Changing grazing management systems, improved feeding, Weather-index insurance, transformation of farming systems, dietary shifts, food processing and storage, changing livestock breeds, change from grazing systems to mixed systems, increases in industrial systems, changes in food processing and storage, diversification of production systems (Thornton and Herrero 2014)	Awaiting literature		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	

Box 3.7: Mediterranean Basin and the Middle East droughts

Over several millennia, human society and the natural environment have co-evolved in the Mediterranean Basin, laying the ground for very diverse and culturally rich communities. Even if the technology level may protect them in some way from climatic hazards, the consequences of climatic changes for inhabitants of the Mediterranean continue to depend on the interplay of an array of societal and environmental factors (Holmgren et al. 2016). Previous IPCC assessments and recent publications have shown that the Mediterranean region (including both the northern and southern part of the Mediterranean basin) is projected to be particularly affected by regional changes in climate under increased warming, including consistent climate model projections of increased drying and strong regional warming (Seneviratne et al. 2012; Collins et al. 2013; Christensen et al. 2013; Greve and Seneviratne 2015; see also Section 3.3). These changes are also expected already at lower levels of warming (Section 3.3.4) and consistent with detected changes under the present level of warming (Greve et al. 2014, Section 3.3.4). Analyses show that risks of drying in the Mediterranean region can be substantially reduced if global warming is limited to 1.5°C compared to 2°C or higher levels of warming (Guiot and Cramer 2016a; see also Section 3.3.4).

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

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

The Syrian up-rising, which began in March 2011 is the outcome of complex but interrelated factors (Gleick and Heberger 2014; Kelley et al. 2015).. While the main target of the multi-sided armed conflict has been a political regime change, the uprising was also triggered by a set of social, economic, religious and political factors leading to a disintegration of the country with a growing rural-urban divide, rising unemployment, and growing poverty (De Châtel 2014). The climate hypothesis has been fiercely contested and although causality cannot to be found in such a simple direct relationship, it cannot be denied that drought played a significant role in triggering the crisis, as this drought was the longest and the most intense in the last 900 years (Cook et al. 2016).

The Syrian example is but one in a long series of collapses or declines of civilizations in the Middle East which coincided with severe droughts, for example the end of the Bronze Age some 3200 years ago (Kaniewski et al. 2015a). The spiral of decline into which the flourishing Eastern Mediterranean civilizations were plunged 3200 years ago, and the ensuing chaos, remains a persistent riddle in Near Eastern history. Most of the coastal cities of Eastern Mediterranean were destroyed, burned, and often left unoccupied thereafter, putting an end to the elaborate network of international trade that had ensured prosperity in the Aegean and the eastern Mediterranean. The rural settlements that emerged mainly persisted through adapted agro-pastoral activities and limited long-distance trade (Kaniewski et al. 2015b). Drought may have hastened the fall of the Old World by sparking famine, invasions and conflicts, leading to the political, economic and cultural chaos referred to as the ‘Late Bronze Age crisis’.

The 21st century drought and the Holocene droughts are climatically different. Trigo et al. (2010) have shown that the two-fold precipitation deficit in 1998-2002 and in 2007-2009 period lead to two long period with a 10m-decrease on the water level of Lake Tharthar, the largest lake in Iraq located between the Tigris and Euphrate. Impact on wheat and barley production was maximum in Iraq and Syria. Kelley et al. (2015) showed that the precipitation deficit was strongly amplified by the high evapotranspiration due to high temperatures, while the Holocene droughts were only due to lack of precipitation during a long period (several centuries). These leads to the conclusion that future precipitation deficits amplified by high temperature are of high risk for the Mediterranean natural and managed ecosystems.

3.5 Observed impacts and projected risks in human systems

3.5.1 Introduction

The human systems assessed in the AR5 WGII report were urban areas; rural areas; key economic sectors and services; human health; human security; and livelihoods and poverty. Observed and projected risks to these systems are respectively assessed in Sections 3.5.2 – 3.5.7. Human systems are embedded within the reasons for concern / key vulnerabilities assessed within the context of Article 2 of the UNFCCC (Cramer et al. 2014) and included:

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

The literature assessed in the AR5 typically focused on describing and quantifying linkages between weather and climate patterns and outcomes, with limited detection and attribution studies (Cramer et al. 2014). The observed changes in human systems described in this section should be taken within the context of section 3.4 because the risks of climate change to human systems are increased by the loss of ecosystem services (e.g. access to safe water) that are supported by biodiversity (Cramer et al. 2014). For all human systems, climate is one of many drivers of adverse outcomes, with patterns of demographic change, socioeconomic development, trade and tourism, and other factors also important. In addition, incomplete understanding of interactions among adverse outcomes across sectors and regions, and insufficient data, limits exploration of the full range of observed changes in human systems that could be attributed to climate change.

3.5.2 Urban areas

3.5.2.1 Observed impacts

AR5 (Cramer et al. 2014) did not assess what climate-related impacts in urban areas could be attributed to climate change. Urbanization, development patterns, geography, and other factors can generate systemic risks that exceed the capacities of cities to prepare for and manage the risks of climate variability and change in, for example, low-lying coastal zones (Revi et al. 2014; Birkmann et al. 2014; Rosenzweig et al. 2015; Morton et al. 2014). Extreme weather and climate events, such as inland and coastal flooding and drought, temperature extremes, reductions in air quality affect populations living in urban areas by increasing the risks of injuries, illnesses, and deaths, and by disrupting livelihoods and incomes. These can be compounded by geo-hydrological hazards, such as landslides and saltwater intrusion. Weather and climate variability also can affect water quality and quantity; functioning of critical infrastructure; and urban ecosystems, biodiversity, and ecosystem services. The coupled systems within cities can lead to novel, interacting hazards. The effects of weather and climate variability on rural and peri-urban agriculture, ecosystem services, and other sources of resources (e.g. firewood) affect cities through urban-rural interactions.

3.5.2.2 Projected risks at 1.5ºC versus 2ºC and adaptive capacity

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

Existing climate models are better at projecting implications of varying levels of GHG forcings on the physical systems than assessing differential risks that are associated with achieving a specific temperature target of 1.5ºC or 2ºC (James et al. 2017). These methodological challenges in parsing differential risks at 1.5 versus 2 degrees are amplified—when combined by varying assumptions in socio-economic pathways (Kamei et al. 2016; Jiang and Neill 2017; Krey et al. 2012) - once scaled down for urban areas. New methods may be necessary to address uncertainties associated with non-linearities, innovations, local scales, latent or lagging responses in climate (James et al. 2017), and by extension, associated natural and human systems.

Assessment of key climate change risks at 1.5°C versus 2°C warming (Schleussner et al. 2015) has implications for urban areas (Figure 3.21). Direct risks are due to heat related extreme events, variability in water supply, and sea-level rise. Indirect risks may be due to variability in agricultural yields and loss of coral reefs. For extreme heat events, an incremental 0.5 degrees of global-average warming implies a robust shift from the upper-bounds of observed natural variability to a new global climate regime (Schleussner et al. 2015). This has differential implications for the urban poor and non-poor. Adverse impacts of such extreme heat events are salient in tropical coastal areas of Africa, South America, and South East Asia (Schleussner et al. 2015) - where large slum and other vulnerable urban populations reside. Heat induced regional variance in median water supply has implications for Mediterranean cities. Mediterranean water stress increased from 9% to 17% in a 1.5 versus 2°C warming world. Likewise, regional dry spells expand from 7% to 11%. Sea-level rise is expected to be lower for 1.5°C versus 2°C lowering risks for coastal metropolitan agglomerations.

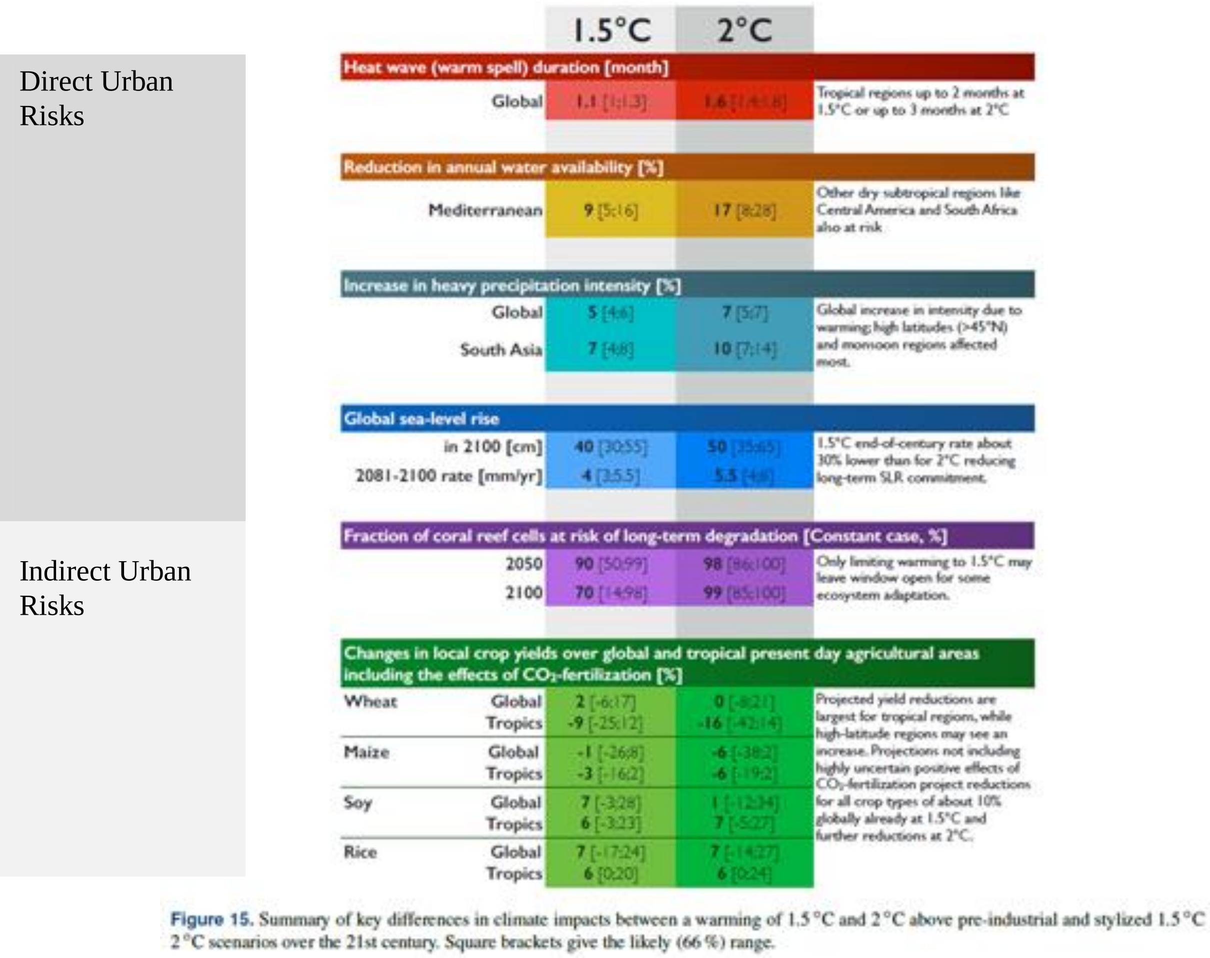


Figure 3.20: Summary of key differences in climate impacts between a warning of 1.5ºC and 2ºC above pre-industrial and stylized 1.5ºC 2ºC scenarios over the 21st century. Square brackets give the live (66%) range. Source: (Schleussner et al. 2015)

There is growing evidence that cities are likely to experience greater heat stress than the regional warming under 1.5°C and 2°C scenarios because of urban heat island effects. Projection of near surface temperature in Israeli cities due to urbanization are expected to exceed 3°C in several urban jurisdictions (Kaplan et al. 2017). Land-use changes due to urbanization in eastern China are altering the regional land-sea temperature difference and may be a contributing factor to changes in the East Asian Subtropical Monsoon (Yu et al. 2016). Incremental warming of 0.5°C above 1.5°C are expected to increase extreme 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 and Zhai). Urban morphology, water, and vegetation are factors affecting the differential warming between urban and rural areas in the United States and suggest managing albedo as a mechanism to adapt (Zhao et al. 2014; Li et al. 2016a).

3.5.3 Key economic sectors and services

Climate change will affect energy systems, tourism, and the water sector through direct impacts on operations (e.g. sea level rise) and through impacts on supply and demand, with the risks varying significantly across geographic region, season, and time. Projected risks also depend on assumptions with respect to population growth, the rate and pattern of urbanization, and investments in infrastructure. Cramer et al. (2014) (AR5) concluded that in low-income countries, higher annual temperatures and higher temperatures averaged over 15-year periods result in substantially lower per capita income and lower economic growth. Portions of the energy sector are sensitive to higher temperatures (e.g. increasing demand for cooling and decreasing demand for heating), and many energy technologies are sensitive to weather and climate. Tourism is sensitive to weather and climate, particularly winter sports, beach resorts, and nature resorts. Overall, the impacts of climate change will be small relative to other drivers of economic sectors and services.

Table S3.3 in Annex 3.1 provides a further summary of the knowledge to date.

3.5.3.1 Energy systems

3.5.3.1.1 Observed impacts

The operations of energy systems can be affected by ambient temperature (e.g. demand for air conditioning, and impacts on operational requirements of power plants), water runoff (e.g. hydropower), and other weather conditions (e.g. solar power) (Arent et al. 2014). Arent et al. (2014) summarized the weather variables affecting energy technologies (thermal and nuclear power plants, hydropower, solar energy, wind power), their possible impacts, and adaptation options.

3.5.3.1.2 Projected risks at 1.5°C vs. 2°C

Arent et al. (2014) concluded that climate change will likely increase the demand for energy in most regions. At the same time, increasing temperature will decrease the thermal efficiency of fossil, nuclear, biomass, and solar power generation technologies. Most impacts will be related to increased temperatures. In warm regions, demand for and use of air conditioning is expected to increase (Arent et al. 2014). Projecting risks is complex because of uncertainties in climate projections, and because of the interactions of climate change with population growth and other factors. For example, in Ethiopia, capital expenditures through 2050 may either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario (Block and Strzepek 2012). In the Zambezi river basin, hydropower may fall by 10% by 2030, and by 35% by 2050 under the driest scenario (Strzepek et al. 2012). Impacts on energy systems can affect gross domestic product (GDP).

Limited publications since the AR5 focuseon climate change impacts on energy systems. Globally, gross hydropower potential is projected to increase (+2.4% under RCP2.6; +6.3% under RCP8.5) with the most growth in central Africa, Asia, India, and northern high latitudes (van Vliet et al. 2016). At minimum and maximum increases in temperature of 1.5°C and 2°C, the overall stream flow in Florida, USA is expected to increase by an average of 21% with pronounced seasonal variations, resulting in increases in power generation in the winter (72%) and autumn (15%) and decreases in summer (-14%) (Chilkoti et al. 2017). Changes were greater at the higher projected temperature. In a reference scenario with global mean temperatures rising by 1.7°C from 2005 to 2050, U.S. electricity demand in 2050 is 1.6 to 6.5 % higher than a control scenario with constant temperatures (McFarland et al. 2015). In Europe, no major differences in large-scale wind energetic resources, inter-annual or intra-annual variability are projected for 2016-2035 (Carvalho et al. 2017). However, in 2046-2100, wind energy density is projected to decrease in Eastern Europe and increase in Baltic regions (-30% vs. +30%). Intra-annual variability is expected to increase in Northern Europe and decrease in Southern Europe. Decreased electricity generation of -15% is projected for Brazil starting in 2040, declining to -28% later in the century (de Queiroz et al. 2016).

3.5.3.2 Tourism

3.5.3.2.1 Observed impacts

Arent et al. (2014) concluded that weather and climate are important factors demand for tourism and recreation services, and the tourist sector is susceptible to extreme weather.

3.5.3.2.2 Projected risks at 1.5 vs 2.0°C

Although there is limited research on the projected risks of 1.5°C *vs.* 2°C temperature increase, the magnitude and patterns of projected impacts are temperature-dependent, indicating that risks will be greater with higher temperature increases. A 2°C global temperature increase is projected to impact summer and winter European tourism (Grillakis et al. 2016; Damm et al. 2016) and annual park visits in Ontario, Canada (Hewer et al. 2016). Mediterranean areas such as the southern Iberian Peninsula are projected to have reduced climate favorability from June to August due to increases in daytime temperature. Austria and Italy are most at risk of losing winter overnight stays related to skiing. In Portugal, increasing temperatures are projected to decrease inbound tourism arrivals between 2.5% and 5.2%, reducing the Portuguese GDP between 0.19% and 0.40% (Pintassilgo et al. 2016). In Italy and Tunisia, there could be climate-induced tourism revenue gains, especially during spring and autumn, as well as revenue losses in the summer months due to increased heat stress (Köberl et al. 2016). Additionally, climate change could impact tourism by reducing the number of climate comfort days; such is the expected case in Iran (Yazdanpanah et al. 2016a).

3.5.3.3 Transportation

3.5.3.3.1 Observed impacts

Road, air, rail, and pipeline transportation are susceptible to weather and climate, including increases in precipitation and temperature; extreme weather events (flooding); sea level rise; and incidence of freeze-thaw cycles (Arent et al. 2014). Much of the published research on the risks of climate change for the transportation sector has been qualitative. Risks depend on the location of the infrastructure (climatic zone); three major zones and vulnerabilities:

- Freezing/frost zone: Permafrost, freeze-thaw cycles, precipitation, flooding, sea level rise, and storms (coastal);
- Temperate zone: Precipitation intensity, flooding, maximum daily precipitation, sea level rise, and storms (coastal); and
- Tropical zone: Precipitation intensity, flooding, maximum daily precipitation, sea level rise, and storms (coastal)

3.5.3.3.2 Projected risks at 1.5°C vs 2.0°C

Limited new research since the AR5 supports that increases in global temperatures will impact the transportation sector. Increased temperatures are projected to impact weight restrictions for aircraft takeoff, which may lead to increased costs for airlines (Coffel et al. 2017). Large-scale commercial shipping in the North Sea Route (NSR) will not be possible until 2030 for bulk shipping and 2050 for container shipping under RCP 8.5, but more shipping is expected to contribute to a mean temperature rise of 0.05% (Yumashev et al. 2017). Climatic losses are projected to offset 33% of the total economic gains from NSR under RCP8.5, with the biggest losses projected to occur in Africa and India.

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

3.5.3.4 Water

3.5.3.4.1 Observed impacts

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

3.5.3.4.2 Projected risks at 1.5°C vs 2°C

The cost of flooding is expected to increase due to climate change in low-, middle- and high-income countries, with greater risks at higher warming levels. Continental U.S. mean annual flood damages are projected to increase by US$5 billion and US$12 billion in 2050 and 2100, respectively (Wobus et al. 2014). Low flows are projected to decrease for the Rhine river catchment from −11% at 2°C to −23% at 3°C (Gosling et al. 2017). Conversely, the Lena river catchment is projected to experience increases in high flow volumes of +17% at 2°C to +26% at 3°C. At 1.5°C global temperature increase, increases in runoff are projected to affect the Scandinavian mountains and decreases in runoff are projected to affect Portugal (Donnelly et al. 2017). At 2°C, all of Norway, Sweden, and northern Poland are projected to experience increases in runoff, while the Iberian, Balkan, and parts of the French coasts are projected to face decreases. In the UK, climate change could increase the annual cost of flooding almost 15-fold by 2080 under high emissions scenarios (ABI 2005). By 2050, Bangladesh could face incremental costs of flood protection (against sea and river floods) of US$2.6 billion initial costs and US$54 million annual recurring costs (Dasgupta et al. 2010). Floods and droughts are projected to cost Kenya about 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka et al. 2005).

3.5.4 Human health

3.5.4.1 Observed impacts from AR5

Climate change is adversely affecting human health by increasing exposure and vulnerability to climate-related stresses (Cramer et al. 2014). 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 impacts: 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).

Further, 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 vulnerability of individuals to a range of diseases (high confidence).

While noting 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, with medium confidence. Further, there is increasing evidence that high ambient carbon dioxide (CO_2) 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 evidence is lacking of associated changes in the distribution of Lyme disease.

3.5.4.2 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 include heatwaves; Lyme disease in Canada; and *Vibrio* emergence in northern Europe provided evidence using multi-step attribution that climate change is adversely affecting human health (Ebi et al. 2017; Mitchell 2016; Mitchell et al. 2016). Changes in 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 what would have occurred without climate change, adjusting for urbanization and the urban heat island effect (Astrom et al. 2013).

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

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

3.5.4.3 Projected risk at 1.5°C and 2°C

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

- Greater risks of injuries, diseases, and death due to more intense heatwaves and fires (very high confidence);
- Increased risk of undernutrition resulting from diminished food production in poor regions (high confidence);
- Consequences for health of lost work capacity and reduced labor productivity (high confidence);
- Increased risks of food- and waterborne diseases (very high confidence) and vectorborne diseases (medium confidence);
- 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).

Tables S3.4, S3.5 and S3.6 in Annex 3.1 summarize the projected risks to human health from studies of temperature-related mortality, vectorborne diseases, and undernutrition assessed in and since the AR5.

Temperature-related mortality: Projected heat-related mortality and projected hazardous heat conditions increase with the degree of temperature change (Hales et al. 2014; Dong et al. 2015; Wang et al. 2015; Vardoulakis et al. 2014; Hanna et al. 2011; Guo et al. 2016; Doyon et al. 2008; Benmarhnia et al. 2014; Voorhees et al. 2011; Schwartz et al. 2015; Wang et al. 2016b; Anderson et al. 2016; Jackson et al. 2010; Wu et al. 2014; Kingsley et al. 2016; Petkova et al. 2013, 2017; Marsha et al. 2016; Astrom et al. 2013; Hajat et al. 2014; Huynen and Martens 2015; Martinez et al. 2016; Honda et al. 2014; Li et al. 2016b, 2015; Garland et al. 2015; Mora et al. 2017; Oleson et al. 2015); under the assumption of a linear relationship between high ambient temperature and mortality (e.g. Gasparrini et al. 2015; Hales et al. 2014), the magnitude of the health impacts of 2.0°C are greater than 1.5°C, with the extent varying by region, presumably because of average temperatures (e.g. risks are higher in regions with cooler average temperatures), population vulnerability, the built environment, access to air conditioning, population acclimatization and other factors. Taking into account that very high ambient temperatures are associated with non-linear increases in mortality in some regions (Rocklöv and Ebi 2012), would result in greater projected heat-related mortality of 2.0°C than 1.5°C. Populations at highest risk include older adults, children, women, those with chronic diseases, and people taking certain medications. Increases in heat-related mortality generally are projected to outweigh any reductions in cold-related mortality with warmer winters (Hajat et al. 2014; Huang et al. 2012; Huynen and Martens 2015; Schwartz et al. 2015; Vardoulakis et al. 2014; Oleson et al. 2015)

Evidence suggests recent adaptation reduced the impacts of heatwaves (Astrom et al. 2013; Arbuthnott et al. 2016; de' Donato et al. 2015; Sheridan and Dixon 2016). Assumptions of additional adaptation reduce the projected magnitude of risks under different warming scenarios (Anderson et al. 2016; Hales et al. 2014; Huynen and Martens 2015; Li et al. 2016b; Petkova et al. 2017).

Occupational health: The conclusion of Smith et al. (2014) that safe work activity and worker productivity during the hottest months of the year would be increasingly compromised with additional climate change was supported by recent publications (Kjellstrom et al. 2013; Sheffield et al. 2013). In Nicaragua by 2050, the percent of days with high heat stress was projected to increase from 10% to 15% by 2050 when outdoor afternoon wet bulb globe temperatures could increase 3°C (Sheffield et al. 2013). In South East Asia by 2050, wet bulb globe temperatures as high as 34-35°C are projected, with associated loss of productivity (Kjellstrom et al. 2013). Worldwide by 2050, environmental heat stress was projected to reduce labor capacity by 20% in hot months from a 10% reduction today from recent climate change, assuming no change in worker behavior or workplace conditions (Dunne et al. 2013).

Other studies, instead of projecting worker productivity, projected other measures of the future risks higher temperatures. Worldwide projections of the costs of preventing workplace heat-related illnesses through worker breaks suggest that GDP losses in 2100 could range from 2.6-4.0%, with higher costs under scenarios of higher greenhouse gas emissions and SSP3 (Takakura et al. 2017). Because the relationship between the costs of heat-related illness prevention and temperature is approximately linear, the different in economic loss between the 1.5°C and 2°C goal in 2100 is projected to be approximately 0.3% global GDP. In China, taking into account population growth and employment structure, high temperature subsidies for employees working on extremely hot days are projected to increase from 38.6 billion yuan/year in 1979-2005 to 250 billion yuan/yr in the 2030s and 1,000 billion yuan/yr in 2011 (Zhao et al. 2016), with higher costs under RCP8.5 than under RCPs 4.5 and 2.6.

Undernutrition: Publications since the AR5 support the conclusions that climate change will negatively affect childhood undernutrition, particularly stunting, through reduced food availability, and will negatively affect undernutrition-related childhood mortality and disability-adjusted lives lost (DALYs), with the largest risks in Asia and Africa (Ishida et al. 2014; Hasegawa et al. 2016; Springmann et al. 2016) (Table 3.6 in Annex 3.1). Climate change is projected to constrain trends in increasing food security, such that the avoided number of childhood deaths will be smaller (Springmann et al. 2016). Climate change-related changes in dietary and weight-related risk factors will increase mortality due to global reductions in food availability, fruit and vegetable consumption, and red meat consumption (Springmann et al. 2016). The projected health risks are greater at 2° *vs.* 1.5°C warming. For example, under SSP3 in 2100, the projected global mean per-capita food intake is 2950-2960 kcal/person/day at 1.5°C and 2930-2960 kcal/person/day at 2°C. The projected global undernourished population is 530-550 million at 1.5°C and 540-590 million at 2°C (Hasegawa et al. 2016) .

Further, climate change is reducing the protein and micronutrient content of major cereal crops, which is expected to further affect food security (Myers et al. 2017). Socioeconomic conditions are the primary driver of vulnerability.

Malaria: Recent projections of the potential impacts of climate change on malaria globally and for China, Asia, Africa, and South America (supplementary materials), confirm the conclusions reached in the AR5 (Smith et al. 2014) that weather and climate are among the drivers of the geographic range, intensity of transmission, and seasonality of malaria, and that the influences of temperature and precipitation are nonlinear (Caminade et al. 2014; Song et al. 2016b; Tompkins and Caporaso 2016; Khormi and Kumar 2016; Kwak et al. 2014; Zorello Laporta et al. 2015). Most projections suggest the burden of malaria could increase with climate change because of a greater geographic range of the *Anopheles* vector, longer season, and/or increase in the number of people at risk, with larger burdens with greater amounts of warming, with complex regional patterns. Some regions are projected to become too hot and/or dry for the *Anopheles* mosquito, such as in northern China and parts of south and southeast Asia (Khormi and Kumar 2016; Tompkins and Caporaso 2016).

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

West Nile Virus: Projections in North America and Europe suggest a latitudinal and altitudinal expansion of regions climatically suitable for West Nile Virus transmission, particularly along the current edges of its transmission areas, and extension of the transmission season, with the magnitude and pattern of changes varying by location and degree of warming (Harrigan et al. 2014; Brown et al. 2015; Morin and Comrie

2013; Chen et al. 2013; Semenza et al. 2016).

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

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

3.5.5 Migration and conflict

3.5.5.1 Observed Impacts

The discussion of human security in the AR5 WGII focusses on five issues of economic and livelihoods, culture, migration and mobility, armed conflics, and state integrity and geopolitical rivalry (Adger et al. 2014). Each of the paragraphs below summarises the findings for each issue.

3.5.5.1.1 Livelihoods and poverty

Olsson et al. (2014) concluded that climate-related hazards can interact with and exacerbate other factors that affect livelihoods, particularly people living in poverty. Poor people are poor for different reasons, so are not uniformly affected and not all vulnerable people are poor. The impacts of climate-related hazards are felt through losses in food, water, and household security, and through a loss of sense of place. Changes in weather patterns can alter rural livelihoods, with consequences for development, including poverty traps. The general high vulnerability of marginalized and disadvantaged groups means climate-related hazards can worsen poverty and inequalities, creating new vulnerabilities and opportunities.

3.5.5.1.2 Human security

Cramer et al. (2014) assessed the literature on the connection between climate change and human security, focusing on conflict and involuntary migration. Each is multi-causal, with multiple drivers and embedded social processes. Overall, evidence of a climate change signal was limited, with more evidence of impacts of climate change on the places where indigenous people live and on traditional ecological knowledge.

3.5.5.1.3 Human mobility

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

Since the AR5, there are increasing propositions which try to link climate change and migrations and conflicts (e.g. Christiansen 2016; Selby 2014; Theisen et al. 2013; Buhaug et al. 2014). The linkages between climate and security encompass risks of conflicts, national security concerns, critical national infrastructure, geo-political rivalries and threats to human security (Gemenne et al. 2014). Although it is still difficult to substantiate and single out climate change as a key determinant of conflict and indeed still remain controversial (Schäfer et al. 2016; Buhaug 2015; Salehyan 2014). Some studies even warn against deterministic positivist approach toward linking extreme wheather or climate change directly with human security issues in general (Selby 2014; Raleigh et al. 2014). A study by Gleditsch and Nordås (2014) suggested that the IPCC through its previous Assessment Reports are found to express unclear and sometimes conflicting messages on the relationships between climate change with human security in general.

3.5.5.1.4 Conflict

For the collapse of civilizations and large-scale climate disruptions, such as severe or prolonged drought, Cramer et al. (2014) concluded the detection of a climate change effect and an assessment of the importance of its role could only be made with low confidence because of the limits of understanding and data. Research on the relationship between interannual climate variability (not climate change) and civil conflict at that time generally focused on Africa. Although statistical relationships were identified in some studies, the results were challenged in others on technical and substantive grounds. Therefore, Cramer et al. (2014) concluded neither the detection of an effect of climate change on civil conflict nor an assessment of the magnitude of any such effect could be made with a degree of confidence.

Hsiang and Burke (2014) did a first major review of past studies on the association between violent conflict and socio-political stability associated with changes in climate variables. They find some causal associations at different level from local to global and also at different time scales from hour to millennium, all in historical or modern period (Hsiang and Burke, 2014). Schleussner et al. (2016) tried to establish the relationships between armed-conflict risks and climate-related disasters in ethnically fractionalized countries. They indicated that there is no clear signal that environmental disasters directly trigger armed conflicts. They however found that globally, between 1980-2010, there is a 9 % coincidence rate regarding armed-conflict outbreak and disaster occurrence such as heat waves or droughts, with 23% of conflict occur in ethnically highly fractionalized countries robustly coinciding with climatic calamities such as those in North and Central Africa and Central Asia. Another study by Kim (2016) which discusses the relationships between economic shocks and coups of different rainfall and temperature variations of 148 countries between 1960 and 2005 find that a decrease in GDP per capita growth rates, induced by short-run weather shocks, significantly increases the probability of a coup attempt.

Studies are being conducted to determine the relationships between water scarcity, drought and conflict at different part of the world, both at the regional or national level. Kallis and Zografos (2014) reviewed the relationships between hydro-climatic change, conflict and security, by which they are influenced through water scarcity and violent conflict. They categorized the findings into trans-boundary basins and water wars; climate, water and armed conflict; vulnerability and disasters; and political ecology. They hence proposed four different causal routes to understand their relationships. First, (geo) political-economic factors cause war or violence, and in turn lead to people become vulnerability to hazard which in turn undermine their security. Second, hydro-climatic and or man-made hazard cause conflict which serves to change weak institutions and or reduce vulnerability, and hence enhance security. Third, strong institutions reduce violent conflict and improve human and social security, and last, mal-adaptation causes conflict and undermines security (Kallis and Zografos, 2014).

Africa

A mapping of climate security vulnerability in Africa done up to the sub-national level suggested that the Horn of Africa, South Sudam, Coastal Madagascar and Mozambique, northern Nigeria and southern Mali, Sierra Leone and Guinea are the most vulnerable areas (Busby et al. 2014). Another study of the link between climate change and violent conflict in East Africa (Kenya and Uganda) suggested that high exposure, high vulnerability and high general risk of violent conflict onset are the three main components determining the risk of conflict. They find that cohesive social structure which provide means for conflict resolution matters in place line Liotoktok in Kenya as is local political and economic development (Ide et al. 2014). A study by Buhaug et al. (2015) to determine climate variability, food production shocks and conflict in Sub-Saharan Africa by examining 50 years of statistical data suggests that while there is a robust link between changes in weather pattern and food production, there is weak and often inconsistent connection between food production and violent conflict. Buhaug et al. (2015) proposed the linkages are that adverse weather cause agricultural loss which could lead to loss of state revenues which in turn lead to Coup d’etat and civil conflict. It can also lead to food price shock, which can lead further to urban unrest. It can further cause hunger and livelihood loss, which in turn lead to mal-distribution or aid corruption, which in turn to urban unrest. Lastly hunger can trigger migration which can in-turn lead to non-state conflict. (Okpara et al. 2015) conducted study on Lake Chad review different phases from dry-small to Mega phases between 1960 – 2010 which experienced drastic reduction on water level from 1960 to 1985 and slightly increased after, to the trend in violence and fatalities in the Lake Chad region. The study finds a sixtyfold increase in the trend of violence and fatalities between 1997 – 2014 periods. They further show that fishermen around Lake Chad are more vulnerable to climate-related losses but better off in terms of response capacities compared to the farmers and pastoralists in the area. The pastoralists are reported more aggression due to water shortage and the farmers suffer the most (Okpara et al. 2017).

The Mediterranean

Schleussner et al. (2016) reiterates the importance of the Mediterranean region as a hot-spot for water availability and dry spells increases between 1.5ºC and 2ºC.A study by Gleick (2014) on water, drought, climate change and conflict in Syria provides a compelling discussion on how water and climatic conditions have directly influenced deterioration of Syrian's economic conditions, and over time, and complicated with complex religious and ethnic diversity has escalated the violence and conflict in Syria today. Kelley et al. (2015) found that during the 2007-2012 drought, the conflict in Syria is 2 to 3 times more likely.

South Asia

A study conducted across Asia suggested that there is little evidence that climate variability is linked to civil violence (Wischnath and Buhaug 2014a). Water conflicts between upper and lower riparian are most prominent in South Asia which create inter and intra-state conflicts. Inter-state hydro-politics is among the top agenda in South Asia (Hassan et al. 2017). Furthermore in South Asia, agricultural sectors were predicted to be adversely affected by the climate changed-induced productivity changes leading to a food shortage by 2030 (Bandara and Cai 2014). Wischnath and Buhaug (2014b) examined food production and conflict severity in India they find that a food production loss is associated with more severe civil violence and hence food insecurity is the intermediate link between climate and conflict. They then proposed three complimentary processes by which lower food production can escalate existing conflicts through lower opportunity cost for rebelling, increased opportunities for recruitment and also widespread social grievances.

3.5.5.1.5 Migration

Brzoska and Fröhlich (2016) proposed different patterns by which migration is considered as a response to global environmental change, by which people with high vulnerability and low resilience and adaptive capacity migrate in three forms of displacement/resettlement, forced migration, and labour migration, while people with low vulnerability but high resilience and adaptive capacity can also migrate in form of labour migration (circular or voluntary).

In Malawi, Suckall et al. (2017) show that climate change is likely to increase barriers to migration from rural to urban areas since climate stresses and shocks erodes migration aspirations and capabilities The government of Viet Nam has migration as one of the policies to reduce the impacts of climate change, through encouraging migration of rural populations to industrial areas with labor needs (Collins et al. 2017). The originating areas received remittances while the destination areas got affected through increase in size and quality of the urban labor force (Collins et al. 2017). In Indonesia, a study to determine the effects of variations in temperature and precipitation along with sudden natural disasters to infer their relative influence on migration shows that the effect is likely permanent and relatively longer distance (Bohra-Mishra et al. 2014). They also found that the turning value for migration is at average of 25 degree C, which means that any increase in temperature below 25 reduces outmigration and above it increases outmigration (Bohra-Mishra et al. 2014).

3.5.5.2 Projected risks at 1.5°C and 2°C and adaptive capacity

In the AR5, risks to livelihoods and poverty are expected to worsen with additional climate change because of the interactions of weather and change with non-climate stressors and entrenched structural inequities to shape vulnerabilities (Olsson et al. 2014). The extent to which climate change could slow economic growth and poverty reduction, further erode food security, and create new poverty traps would affect the number and distribution of poor individuals and communities between now and 2100. Most severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia. Climate change is expected to exacerbate multi-dimensional poverty in most low- and middle-income countries, including high mountain states, countries at risk of sea level rise, and countries with indigenous populations.

The warming of the Arctic has opened new possibilities for faster and expanded cruise industry in the region. The cruise industry in Arctic Canada has grown 115% between 2005 and 2015 (Dawson et al. 2014). While the current trade and marine regulations have been able to manage the increased flow, it is expected that the need to manage the sector in the future will be more complex which call for complex multi-jurisdictional regulatory frameworks to avoid human, environmental and security problems in the newr-and medium-term future (Dawson et al. 2014).

Box 3.8: Box on Sub-Saharan Africa

[This is a placeholder. The Box will be completed for the Second Order Draft]

Box 3.9: 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 (Daughters 2016; Cabello and Godfrey 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.

Box 3.10: Economic Damage from Climate Change in the United States and the Value of Limiting the Increase in Global Mean Temperature to 1.5ºC or 2ºC

Working from the median ‘no-policy’ baseline trajectory in Fawcett et al. 2015, (Box 3.10, Figure 1 (a)) brings global emissions to roughly 93 $GtCO_2$ per year by the end of the century. It is defined by two boundary conditions. For 2010, annual global emissions begin around 30 $GtCO_2$ and grow initially at approximately 6% per year. Emissions reach 93 $GtCO_2$ by 2100 because the rate of growth depreciates by 0.5% per year.

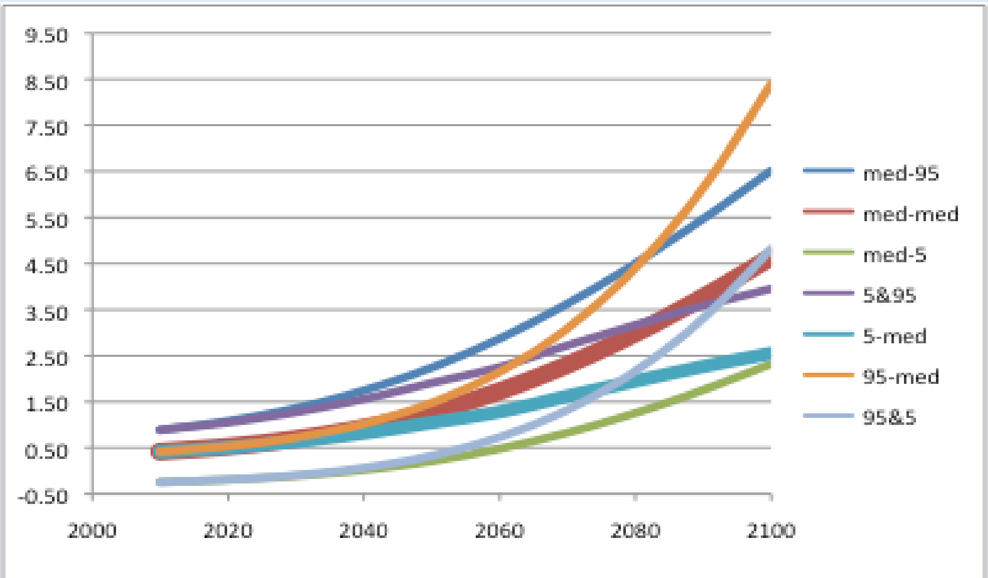
Corresponding transient temperature trajectories can be calculated from a linear relationship between contemporaneous cumulative emissions and transient temperature reported in NRC (2010, page 82): 1.75ºC per 1000 GtC is the median estimate. Uncertainty, here, is driven by uncertainty about the behavior of sinks in higher 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 rtrajectories that limit the median estimated increases in transient temperature to 1.5ºC and 2ºC above preindustrial levels. They are ‘ideal’ and 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 $GtCO_2$, 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.

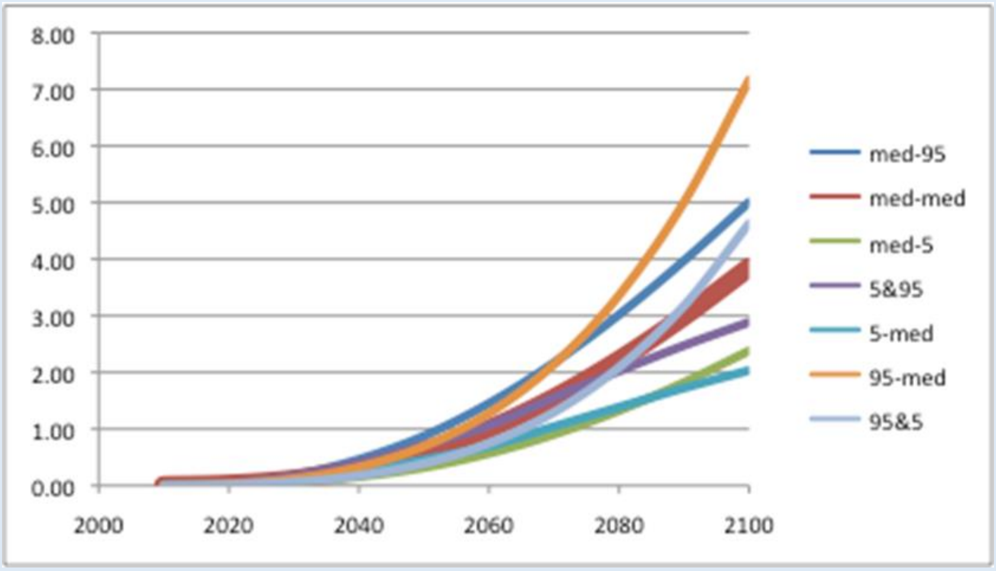
Aggregate economic damages from warming are calibrated in terms of the percentage loss of GDP to the median, 5th percentile, and 95th percentile temperature reaction functions by Hsiang et al. (2017), Box 3.10, Figure 1 (c). Box 3.10, Figure 1 (a) displays transient trajectories of aggregate economic damages (real GDP) from climate change in decadal increments for the United States through the year 2100 along the 'no-policy' baseline described above. Box 3.10, Figure 1 (b) shows the avoided damages along a trajectory whose median outcome achieves a 1.5ºC temperature limit through 2100. Box 3.10, Figure 1 (c) shows the avoided damages along a trajectory whose median outcome achieves a 2.0 ºC temperature limit through 2100. Box 3.10, Figure 1 (d): compares the avoided damages along a trajectory whose median outcome achieves a 1.5ºC temperature limit through 2100 against a trajectory whose median outcome achieves the higher 2ºC temperature limit through 2100; i.e., it reflects the value of extending mitigation efforts to achive the lower temperature target (with the median trajectory).

The results for the 'no-policy' show 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 1.5ºC 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 2ºC 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 1.5ºC temperature limit rather than a 2ºC is modest; along the 'median-median' case, it is around 0.35% by 2100 surrounded a range of 0.20% and 0.65%.

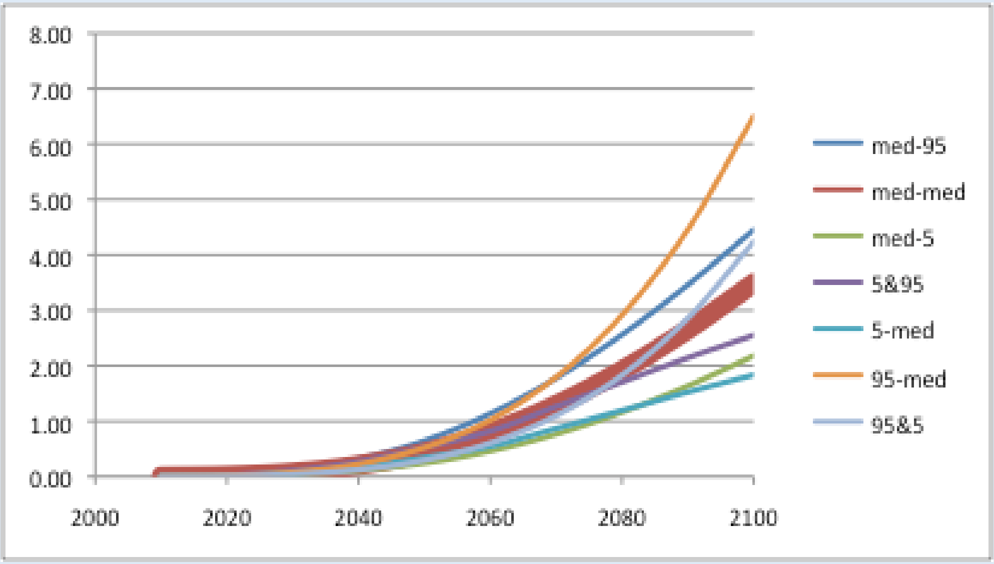
Even though the 'no-policy' baseline shows significant damage diversity across temperature and damage trajectories almost immediately, the values of achieving either temperature limit do not diverge significantly until roughly 2040 when their difference tracks between 0.05% and 0.13%. Thereafter, the differences between the two temperature targets do, however, begin to diverge substantially in the second half of the century. This means that patience will be required while we to notice potentially value in proceeding toward the more aggressive 1.5ºC mitigation temperature target.



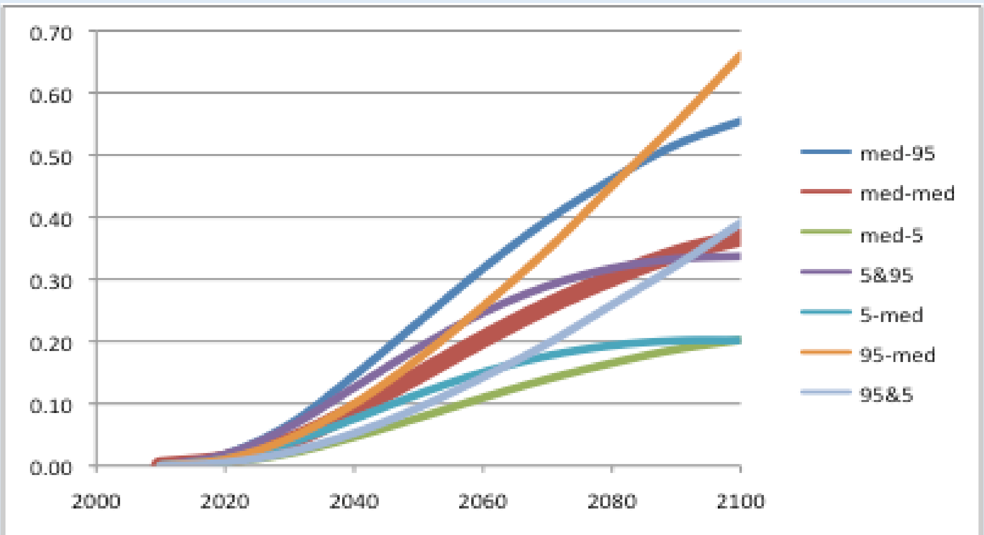
Box 3.10, Figure 1 (a): Panel A: The Economic Value of Damages along the No-policy Baseline Emissions Trajectories (difference in percentage of average US GDP loss per year) *



Box 3.10, Figure 1 (b): Panel B: The Economic Value of Achieving a 1.5ºC Temperature Target Compared to Baseline Economic Damages (difference in percentage of average US GDP loss per year. *



Box 3.10 Figure 1 (c): Panel C: The Economic Value of Achieving a 2ºC Temperature Target Compared to Baseline Economic Damages (difference in percentage of average US GDP loss per year. *



Box 3.10, Figure 1 (d): Panel D: The Economic Value of Achieving a 1.5ºC Temperature Target Compared to Achieving a 2ºC Target (difference in percentage of average US GDP loss per year. *

* ‘med-95’ is the combination of the median emissions trajectory and the 95th percentile damage function; ‘med-med’ is the combination of the median emissions trajectory with the median damage function; etc

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

3.6.1 Introduction

A framework that aggregates projected risks as a function of global mean temperature change into five categories known as ‘Reasons for Concern’ was provided by Oppenheimer et al. (2014, AR5, Chapter 19). 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) was recently reviewed, confirming most judgements made in the light of more recent literature (O’Neill et al. 2017). This approach of Oppenheimer et al. (2014), with updates in terms of the risk aggregations as informed by the most recent literature, is therefore adopted 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

From the basis of the analysis of the five reasons of concern (explored in Section 3.6.2), the economic benefits to be obtained by achieving the global temperature goal of 1.5°C, compared to 2°C and less ambitious temperature goals are discussed (Section 3.6.3). Regional benefits to be obtained by 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 1.5ºC compared to higher degrees of global warming (Section 3.6.6).

3.6.2 Aggregated avoided impacts and reduced risks at 1.5°C versus 2°C, 3°C, 4°C of global warming

In the following sections, a brief summary of the accrual of RFC with global warming as assessed in IPCC WGII AR5 is provided, 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. As a result of the update, an attempt at a modified figure 19.4 from AR5 WGII is provided immediately below with the ensuing text describing 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, a 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 1ºC above recent temperatures, now occur at 1.5ºC above pre-industrial levels.

[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. 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.]

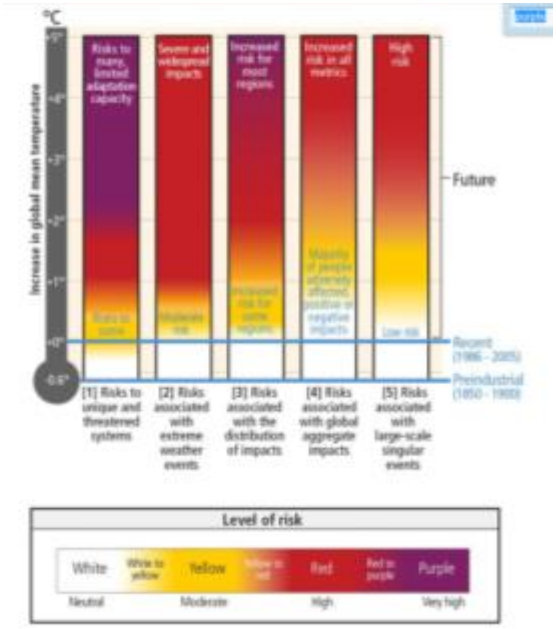


Figure 3.21: Figure 19.4 of AR5 WGII *[To be updated and developed to highlight more clearly the recent literature on the differences between risks for 1.5°C/2°C warming]. [Placeholder caption]* The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated and adapted from WGII AR5 Ch 19, Figure 19.4 and highlighting the nature of this dependence between 0 and 2ºC warming above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual 'reason'. The transition from red to purple, introduced for the first time in AR4, is defined by very high risk and the presence of significant irreversibility *or* persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMT. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation (RFC 1, 3, 5) independently of development pathway. The rate and timing of impacts were taken into account in assessing RFC 1 and 5. The levels of risk illustrated reflect the judgements of the Ch 3 authors. [*Note to reviewers: In WGII AR5 Ch 19 and more recently in O'Neill et al. 2017 the need to detail how how these kinds of figures vary with socioeconomic pathway is noted and suggestions are made therein as to how this might be done. That is seen as a task for IPCC AR6, and beyond the scope of what is feasible to do for SR1.5*]

3.6.2.1 RFC 1- Unique and threatened systems

AR5 Ch 19 found that some unique and threatened systems are at risk from climate change at recent temperatures, with increasing numbers at risk of severe consequences at global mean warming of around 1.6ºC above pre-industrial levels, and many species and systems with limited ability to adapt subject to very high risk at warming of around 2.6ºC, 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 recent temperatures (because there was at least medium confidence in attribution of a major role for climate change for impacts on some of the unique and threatened systems); a transition from yellow to red was located at 1.6ºC, and a transition to purple at around 2.6ºC. This AR5 analysis already implies a significant reduction in risks to unique and threatened systems if warming is limited to 1.5ºC as compared with 2ºC.

3.6.2.1.1 Coral reefs

Since AR5, new literature allows a closer focus on the comparative levels of risk at 1.5ºC versus 2ºC global warming (see Section 3.3). Reaching 2ºC will triple the frequency of mass coral bleaching compared to the present day (about 10 bleaching events per decade; Hoegh-Guldberg 1999; Hoegh-Guldberg et al. 2014). This is likely to result in the total loss of tropical coral reefs. Restricting overall warming to 1.5ºC is likely to still result in about 2-4 bleaching events per decade and in a downward trend in average coral cover - but will prevent the total loss of coral reefs. Moreover, the remaining reefs will benefit from an increasingly stable set of ocean conditions by the mid-to-late 21st century. For this system, this indicates a transition in risk from high to very high (red to purple) at 1.5ºC warming and contributes to a lowering of the transition from red to purple in this RFC1 compared to AR5.

[*Note: the 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.*]

3.6.2.1.2 Arctic ecosystems

In AR5 WGI, substantial losses of Arctic Ocean ice were projected for global warming of 1.6ºC and a nearly ice-free Arctic Ocean was projected for a warming of greater than 2.6ºC. Since AR5, the importance of a threshold between 1ºC and 2ºC has been further emphasized in the literature, with a the sea ice persisting throughout the year for global warming less than 1.5ºC but having vanishingly small probability for global warming greater than 2ºC (Section 3.3).

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

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

3.6.2.1.3 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 succuluent Karoo areas of S. Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, it has been shown that impacts accrue with greater warming and thus impacts at 2ºC would be expected to be greater than those at 1.5ºC (*medium confidence*). Since the AR5, one study has shown that constraining global warming to 1.5ºC warming would maintain the functioning of the prairie pothole ecosystem (N America) in terms of its productivity and biodiversity, whilst a warming of 2ºC would not do so (Carter Johnson et al. 2016)

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

3.6.2.1.4 Small island states

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

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

3.6.2.1.5 Unique socioecological systems dependent on glacier melt

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

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

3.6.2.2 RFC 2- Extreme weather events

In this sub-subsection reduced risks in terms of the likelihood of occurrence of extreme weather events are discussed for 1.5ºC compared to 2ºC of global warming – for those extreme events where current evidence is available. It should be noted that for some extreme events of significant potential impact, such as tropical cyclones and regional flood events, reduced risks (by achieving the 1.5ºC target) in terms of frequency of occurrence and intensity has to date not been reported in peer-reviewed literature - or that the current state of climate science cannot distinguish between risks across 0.5ºC of global warming.

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

3.6.2.2.1 Temperature

It is very likely that further increases in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes will occur under 1.5ºC of global warming compared to present-day climate (1°C warming), with further increases towards 2ºC of warming (section 3.3). As highlighted 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 scale, based on observations (Schleussner et al. 2017) and on climate model analyses (Seneviratne et al. 2016; Wartenburger et al.). At 2ºC of global warming, it is likely that temperature increases of more than 2°C will occur over most land regions in terms of extreme temperatures (on average between 3-8°C depending on region and considered extreme index) (see Figure 3.3.2, Section 3.3.2). Under 1.5°C of global warming, regional increases in temperature extremes can be reduced to 2° C – 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 1.5ºC is sufficient for critical thresholds to be exceeded, within the context of wide-ranging aspects such as crop yields, human health and the sustainability of ecosystems.

With the El Niño of 2015/16 associated with the onset of unprecedented temperature extremes across the globe occurring in conjunction with the first two calendar years during which the average global surface temperature was 1ºC above the pre-industrial value, it is noteworthy that evidence exists for increasing human mortality from heat extremes (Gasparrini et al. 2015; Ebi et al. 2017). For example, mortality in Stockholm, Sweden in recent decades from heat extremes doubled what would have occurred at pre-industrial temperatures (Astrom et al. 2013). Because human morbidity and mortality are linearly related to ambient temperature, all else being equal, higher temperatures will result in greater health impacts (Section 3.5.4.3). The extent of vulnerability reduction required to maintain current burdens of heat-related mortality in the 2050s for adults over 65 years of age in Southern Europe would be 75% under RCP4.5 (Åström et al. 2017), highlighting that even if the Paris targets are realized, there could still be a significant adaptation needed for vulnerable populations. Further analysis is needed of the benefits to be obtained in terms of heat extremes at 1.5ºC of global warming compared to 2ºC.

3.6.2.2.2 Heavy precipitation

For heavy precipitation, the AR5 assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al. 2013). 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 between climate at 1.5°C and 2°C global warming. These results are consistent with analyses of climate projections (Wartenburger et al.), although they also highlight a strong 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 1.5ºC compared to 2ºC of global warming in many regions and at global scale.

3.6.2.2.3 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 wetting (Greve et al., Figure 3.12).

Limiting global mean temperature warming to 1.5°C as opposed to 2°C could substantially reduce the risk of experiencing extreme reductions in regional water availability (Greve et al.). Regions that are to benefit include much of South America, southern Africa, Australia and the Mediterranean.

3.6.2.2.4 Fire

The increased amount of evidence that anthropogenic climate change has already caused significant increases in fire area in N America (see 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 1.5ºC warming relative to the present day: in one study, projections on the basis of the CMIP3 ensemble of climate models (SRES A2 scenario) indicated with high 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 1.2ºC; as compared with over 61.9% of the global land area in 2070-2099, corresponding to a warming of approximately 3.5ºC (Figure 10.5 panel A, Meehl et al. 2007, which indicates an ensemble average projection of 0.7ºC or 3ºC above 1980-1999, which is itself 0.5ºC above pre-industrial) (Figure 10.5 panel A, Meehl et al. 2007). Romero-Lankao et al. (2014), Box 26-1) also indicated significantly lower wildfire risks in North America for near term warming (2030-2040, which may be considered a proxy for 1.5ºC) than at 2ºC.

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

3.6.2.3 RFC 3- Distribution of impacts

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 and because of high underlying vulnerabilities (AR5, 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 (AR5 *medium confidence*). The lower regional temperatures implied by 1.5°C warming as compared with 2°C imply reduced global risks in terms of impacts such as water losses through evaporation, enhanced energy demand (towards achieving human comfort in air conditioned buildings) and decreases in crop yield – although global reduced risks at 1.5°C still need to be better quantified.

Climate change is projected to reduce renewable surface water resource significantly in most dry subtropical regions (robust evidence, *high agreement*), in contrast, water resources are projected to increase at high latitudes (AR5-WGII Chapter 3). Reduction of water resource availabilities under 2ºC global mean temperature (GMT) rises compared to pre-industrial conditions is projected to be greater than 1.5ºC GMT rise, although changes in socioeconomics could have a greater influence.

Globally millions of people may be at risk from sea-level rise during the 21st century (Hinkel et al. 2014; Hauer et al. 2016), particularly if there is no further adaptation. By 2030, if sea level rises by 0.3m, 400 million people could be living in 23 coastal megacities, 370 million in Asia, Africa and South America. Subsidence will enhance those exposed (Jevrejeva et al. 2016). Jevrejeva et al. (2016) report with 2°C of warming, more than 70% of global coastlines will experience sea-level rise greater than 0.2m. With 4°C of warming, 80% of coastlines could experience 0.6m of sea-level rise (by 2083 under RCP8.5). The highest sea-levels are projected for small island nations in low to mid latitude Pacific islands and India Ocean islands. The amplification of flooding, for high and/or low frequency events (Buchanan et al. 2017) and different forcing factors, including waves (Arns et al. 2017; Vitousek et al. 2017; Storlazzi et al. 2015) is also cause for concern even with sea-level rise associated with a rise in temperatures of 2°C, or within the next few decades.

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

3.6.2.4 RFC 4 - Global aggregate impacts

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

3.6.2.4.1 Global economic impacts

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

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

In Oppenheimer et al. (2014) it was noted that the global aggregated damages associated with large scale singular events were not well explored, and reviews of integrated modelling exercises have noted the potential underestimation of global aggregate damages due to the lack of consideration of the potential for these events in many studies. At the time of the AR5, a small number of studies and reviews indicated that higher values of agrgegate economic damage, and/or social costs of carbon, accrue in modelling calculations that take into account the potential for catastrophic climate change associated with large scale singular events (Stern 2006, Since AR5, a further analysis of the potential economic consequences of triggering these large scale singular events (Cai et al 2016), also indicates a much larger economic impact associated with a warming of 3ºC than most previous analyses, is in line with earlier critiques (Lenton and Ciscar 2013; Dietz 2011; Revesz et al. 2014). Specifically, Cai et al. (2016) modifies a well established modelling approach to incorporate the prospect of future multiple interacting tipping points. Combining this with realistic assumptions about policymakers’ preferences under uncertainty increases the social cost of carbon in the model from $15/t$CO_2$ to $116/t$CO_2$ which results in the model’s calculating that if welfare impacts are to be minimised, global warming would need to be constrained to 1.5ºC above pre-industrial levels. This increases the confidence since AR5 that at 3ºC warming there is a significant further increase in the magnitude and likelihood of aggregate economic risks.

3.6.2.4.2 Biome shifts, riks of species extinction and ecosystem functioning and services

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

Oppenheimer et al. (2014) reports on the large amount of evidence for escalating risks of species range loss, extirpation and extinction based on studies for global temperatures execeding 2°C above pre-industrial levels. (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) (AR4 Ch 4) 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’. Since the AR5, new global scale evidence attributing species extirpations (local extinctions) has accrued (Wiens 2016). Warren et al. (2013) simulated climatic range loss for 50,000 terrestrial species and projected that with 4°C warming, and realistic dispersal rates, 34+/-7% of the animals, and 57+/-6% of the plants, would lose 50% or more of their climatic range by the 2080s. In comparison these projected losses were reduced by 60% if warming were constrained to 2°C. Since the AR5, information relating to 1.5°C warming has now been estimated from this earlier study, indicating that with 1.5°C warming, and realistic dispersal rates, the losses are projected to be reduced by approximately 80% (79-82%) compared to those at 4°C warming) and 50% (range 46-56%) (compared to those at 2°C warming). Hence at 1.5°C, 7+/-2% animals and 10+/-2% plants are projected to lose 50% or more of their climatic range (Smith et al.).

Oppenheimer et al. (2014) assessed risks to marine fish stocks and resultant global aggregate losses of marine ecosystem services. Since AR5 new literature indicates that impacts on marine fish stocks and fisheries are lower in 1.5-2.0°C global warming relative to pre-industrial level when compared to higher warming scenarios (Section 3.4). Sensitivity to the 1.5-2°C relative to other warming scenarios differ between regions, with fish stocks and fisheries being highly sensitivity in tropical and polar systems. Direct benefits of achieving the 1.5°C global warming target can be substantial (Cheung et al. 2016) from increases in fisheries revenues and contribution to protein and micronutrients availability particularly to the most vulnerable coastal communities (tropical developing countries and SIDS) (Section 3.4).

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

3.6.2.5 Large scale singular events

Components of the global earth system that are thought to hold the risk of reaching critical tipping points under climate change, and that can result in or be associated with major shifts in the climate system include:

- The cryosphere: West-Antarctic ice sheet, Greenland ice sheet
- The thermohaline circulation (Atlantic Meridional Overturning Current and the formation of Antarctic Bottom Water).
- The El Niño Southern Oscillation (ENSO) as a global mode of climate variability
- The Southern Ocean as a carbon sink in terms of its role in the global carbon cycle.

These are known as large-scale singular events. AR5 assessed that risks associated with these events becomes moderate between 0.6 and 1.6°C above pre-industrial levels due to early warning signs and that risk becomes high between 1.6 and 4.6°C due to the potential for commitment to large irreversible sea level rise from sea ice loss (*medium confidence*). The increase in risk between 1.6 and 2.6°C above pre-industrial levels was assessed to be disproprortionately large. New findings since AR5 are detailed below (see also Box 3.5 on tipping points).

3.6.2.5.1 Greenland and West-Antarctic ice sheets

Various feedbacks between the Greenland ice sheet and the wider climate system (most notably those related to the dependence of ice melt on albedo and surface elevation) make irreversible loss of the ice sheet a possibility. Two definitions have been proposed for the threshold at which this loss is initiated. The first is based on the surface temperature at which net Surface Mass Balance (SMB, the difference between mass loss, mostly melt and subsequent runoff, and gain, mostly snowfall) first becomes negative for the current ice-sheet geometry. Church et al. (2013) assess this threshold to be 2°C or above (relative to pre-industrial). A second definition is based on the evolution of a dynamical model of the ice sheet when forced in an ensemble of prescribed warmings. (Robinson et al. 2012) find a very likely range for this threshold of 0.8 to 3.2°C. In both cases, the timescale for eventual loss of the ice sheet can be tens of millennia and assumes constant surface temperature forcing during this period. Were temperature to cool subsequently, the ice sheet may regrow although the amount of cooling required is likely to be highly dependent on the duration and rate of the previous retreat.

3.6.2.5.2 Thermohaline circulation

Evidence that thermohaline circulation is slowing has been building over the past years, including the detection of the cooling of surface waters in the north Atlantic plus strong evidence that the Gulf Stream has slowed by 30% since the late 1950s. These changes have serious implications for the reduced movement of heat to many higher latitude countries. Increasing average surface temperature to 1.5°C will increase these risks although precise quantification of the added risk due to an additional increase to 2°C is difficult to access. The surface layers of the ocean will continue to warm and acidify but rates will continue to vary regionally. Ocean conditions will eventually reach stability around mid-century under scenarios that represent stabilization at or below 1.5°C.

3.6.2.5.3 Role of the Southern Ocean in global carbon cycle

The critical role of the Southern Ocean as a net sink of carbon may reduce under global warming, and assessing this effect under 1.5ºC to 2ºC of global warming is a priority.

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

3.6.3 Economic benefit analysis for a 1.5°C vs. 2°C global temperature goals

This section reviews the available evidence and literature that estimates the economic benefits to be obtained through impacts that are avoided for the case of 1.5°C *vs.* 2°C warming. The focus here is on evidence pertaining to specific regions and sectors, rather on global aggregated benefits (which were previously discussed above in Section 3.6.2).

3.6.3.1 Fisheries

Achieving an increase in average global temperature of 1.5°C will reduce the rate of warming and hence will significantly slowdown (and eventually stabilise) the movement of organisms towards higher latitudes and warming regions. This will reduce impacts on fisheries from mobile fish stocks, reduce the incidence of disease, and of invasive species, benefiting fisheries, aquaculture and coastal communities as compared to conditions under 2°C or more (medium evidence, high certainty).

Clear differences between 1.5 ºC *vs.* 2 ºC are likely to exist at regional scales in fisheries productivity. Remaining at 1.5ºC would reduce the extent of the reduction of NPP in tropical regions (stabilise up-welling as compared to continual decreases expected at 2ºC of higher) with implications for fisheries productivity and food availability. Increased NPP in some systems is likely to lead to decreases in oxygen and, in cases, increased anoxia at depth (low confidence).

Avoided risks at 1.5ºC *vs.* 2ºC or higher include smaller relocation distances and eventually stabilised redistribution of pelagic fisheries (e.g. Tuna). Decreases in catch and species diversity in tropical reef fisheries are likely to be lower at 1.5°C *vs.* 2°C. Limiting atmospheric CO_2 concentrations associated with 1.5°C will reduce the impact of ocean acidification on early stages of shellfish. Stabilisation of atmospheric levels of CO_2 will also increase the use of resistant cultivars for aquaculture (i.e. relatively more resistant to ocean acidification).

The broad and insidious effects of ocean acidification are proportional to atmospheric CO_2 content, hence keeping concentrations of CO_2 lower than 450 ppm (i.e., associated with 1.5°C) will result in a proportional decrease in risk to a range of systems. Commercial oysters will have greater survival at the CO_2 equivalent of 1.5 ºC *vs.* 2 ºC, with associated industries remaining viable for longer. Coral reefs will have a more positive carbonate balance and hence will be able to retain their carbonate structures for longer, thereby reducing the risks from increasingly unprotected coastal areas and decreases in fish habitat (i.e. important for reef fisheries and coastal livelihoods of tens of millions of people).

Fisheries are affected by a range of climate related factors. As a result, impacts produce a number of effects on fisheries such as the decreased production of global shellfish fisheries as a result of ocean acidification (high confidence), global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes (*medium confidence*), and the movement of valuable stock such as tuna away from countries currently enjoying the revenue and benefits (*high confidence*). In addition, the loss of coral reef structures has also reduced the habitat and hence availability of reef fish important for small scale fisheries across the world's tropical regions, with growing risks for coastal communities, especially in the tropical regions where other options to fisheries protein are limited.

Impacts of hypoxia would impact many valuable fisheries, with increasing loss to be accounted for in terms of costs and availability to industries such as fishing, tourism and aquaculture (Cheung et al. 2010; Weatherdon et al. 2016). Avoiding increases beyond 1.5ºC are expected to have significant cost savings accompanying them as the decreases at 2ºC and above are avoided (Cheung, Reygondeau, and Frölicher 2016).

3.6.3.2 Storms and coastal areas

Restraining warming to 1.5°C is likely to drive lower numbers of intense storms than expected at 2°C above the preindustrial level. Combined with higher sea levels, inundation and storm damage will be significantly higher at 2°C as compared to 1.5°C (*medium confidence*).

3.6.3.3 Human health

Given that human morbidity and mortality are linearly related to ambient temperature, all else being equal, higher temperatures will result in greater health impacts (Section 3.5.4.3). The extent of vulnerability reduction required to maintain current burdens of heat-related mortality in the 2050s for adults over 65 years of age in Southern Europe would be 75% under RCP4.5 (Astrom et al. 2017), highlighting that even if the Paris targets are realized, there could still be significant adaptation needed for vulnerable populations - with associated implications in costs. Moreover, noting that nearly all deaths during a heatwave are preventable, any reduction in heat-related mortality during heatwaves would provide a large economic benefit, depending on the value of a statistical life (that is, the economic costs of heatwaves are large).

Further analysis is needed of the cost benefits to be obtained in terms of heat extremes at 1.5ºC of global warming compared to 2ºC.

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

3.6.4.1 Summary of benefits of 1.5°C or 2°C of global warming compared to temperature increases associated with the Paris Agreement Nationally Determined Contributions, 3°C and 4°C of global warming

A number of studies quantify the risks avoided from constraining warming to various levels, for example 2°C relative to 4°C. A review in preparation (Arnell et al.) concludes that 1.8°C warming avoids 32-88% of the impacts accruing by 2100 (depending on sector) compared to impacts for 4°C of warming, whereas 2°C warming avoids 24-82% of the risks accruing by 2100 (this is a multi-sectoral study covering human exposure to water stress, fluvial flooding, coastal flooding, and heatwaves; loss of crop suitability; and biodiversity loss - an important input to Section 3.6). Moreover, (Warren et al., the study is called AVOID will to provide an update to Arnell et al. and quantifies the impacts avoided at 1.5°C relative to the same 4°C baseline, encompassing a slightly wider set of risk metrics.

Some impacted sectors/systems display a non-linear relationship between the magnitude of the risks and°C of global warming, in which impacts increase rapidly during lower levels of warming and then rise more slowly or not at all as warming continues, as most of the sector has already been impacted. The most prominent examples are coral reef bleaching, which increases very rapidly between 1° and 2°C warming, at which point most of the impacts that could occur are realised; water scarcity, which increases rapidly between 0° and 2°C warming, and more slowly as warming continues; and cropland stability, which decreases rapidly between 1° and 3°C warming, decreasing slowly thereafter. This means that the benefits of constraining warming to 1.5°C are projected to be large for coral reefs, water scarcity, and cropland stability (Ricke et al. 2015)

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

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

Currently (July 2017) the analysis in Section 3.3 to 3.5 is largely based on impacts studied for the transient definition of 1.5 vs 2ºC (that is, the global temperature reaches thresholds of 1.5°C or 2°C of warming and then continues to increase), whilst the analysis of impacts for stabilisation at 1.5° and 2ºC (as strictly per the Paris agreement definition) still is being undertaken. To what extent do impacts calculated for say a 20-year period around the year when a 1.5°C increase first occurs differ from impacts associated with a 1.5°C stabilisation scenario? This question is important to answer from a pragmatic perspective, since most studies on climate change impacts under different global temperature goals based on the CMIP5 GCMs and CORDEX RCMs make use of exactly this latter definition. Moreover, reduced benefits associated with ‘overshoot’ scenarios, where temperature initially exceeds the 1.5°C threshold but then decreases until it stabilises at or below this threshold are to be analysed in this sub-subsection (as published research becomes available). These reduced benefits are also to be discussed in this section (pending peer-reviewed research becoming available).

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

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

3.6.5.1 Arctic sea-ice

For global warming above 2°C, probabilities are relatively high (estimated to be in the order of 43%) for the Arctic to be nearly ice-free in September (Screen and Williamson 2017, also see Section 3.3). This risk is avoided almost entirely if the global mean temperature change can be kept below 1.5°C (Screen and Williamson 2017), with risks becoming increasingly larger in the 1.5° to 2°C range of global temperature increase (Collins et al. 2013; Mahlstein and Knutti 2012).

3.6.5.2 Arctic land regions

There is a clear amplified warming in terms of cold extremes in regions with snow and ice cover

(Seneviratne et al. 2016). This is expected given the Arctic warming amplification (Serreze and Barry 2011), which is to a large part due to snow-albedo-temperature feedbacks (Hall and Qu 2006). In some regions and for some model simulations, the warming of TNn at 1.5°C global warming can reach up to 8°C regionally (e.g. Northern Europe, Figure 3.7) and thus may be much larger than the global temperature warming. To what extent changes in cold extremes (including frost days) are reduced at 1.5ºC *vs.* 2ºC of warming remains to be analysed. Projected biome shifts are already extremely severe in the Arctic and in alpine regions at 1.5ºC warming and increase further for 2ºC warming (Gerten et al. 2013).

3.6.5.3 Alpine regions

For example, projected biome shifts are already extremely severe in the Arctic and in alpine regions at 1.5ºC warming and increase further for 2ºC warming (Gerten et al. 2013 Figure 1b).

3.6.5.4 Tibetan Plateau

Half of naturally vegetated land surface in China could be under moderate or severe risk at the end of the 21st century under the middle and high emission scenarios. The areas with high risk are the Tibetan Plateau region and an area extended northeastward from the Tibetan Plateau to northeast China. The geographic patterns of the risk are generally consistent across different scenarios (Yin et al. 2016). To what extent such impacts can be reduced at 1.5ºC *vs.* 2ºC of global warming remains to be analysed.

3.6.5.5 Coastal plains

Schleussner et al. (2016) highlights areas at risk of coastal flooding due to sea level rise as benefiting strongly from constraining warming to 1.5°C compared to 2°C.

3.6.5.6 Southern Europe/Mediterranean

Stronger warming of the regional land-based hot extremes compared to the mean global temperature warming are projected to occur in the Mediterranean. To what extent such impacts can be reduced at 1.5ºC *vs.* 2ºC of global warming remains to be analysed.

3.6.5.7 West Africa and the Sahel

Schleussner et al. (2016) highlights agriculture in West Africa as benefiting strongly from constraining warming to 1.5°C compared to 2°C.

3.6.5.8 Sub-Saharan Africa

Stronger warming of the regional land-based hot extremes compared to the mean global temperature warming are projected to occur in southern Africa (Section 3.3; Engelbrecht et al. 2015). To what extent such impacts can be reduced at 1.5ºC *vs.* 2ºC of global warming remains to be analysed.

3.6.5.9 Tropics

The tropics may be a hot-spot in terms of the projected increases in the number of hot days. To what extent such impacts can be reduced at 1.5ºC *vs.* 2ºC of global warming remains to be analysed.

3.6.5.10 Islands

Island biodiversity is also projected to be especially at risk from climate change, for example in Pacific Island Developing Regions (Taylor and Kumar 2016, find other citations if available). To what extent such impacts can be reduced at 1.5ºC *vs.* 2ºC of global warming remains to be analysed. For several small island developing states (SIDS), particularly across the Caribbean region, a substantial fraction (~25%) of the large overall freshwater stress projected under 2°C at 2030 can be avoided by limiting global warming to 1.5°C (Karnauskas et al.).

3.6.5.11 Fynbos and shrub biomes

By 2070, two ecosystems in the southwestern USA lose about 4000 (15 %) and 7000 (31 %) km^2 of suitable climate area within their current boundaries (the Western Great Plains Sandhill Steppe and Sonora-Mojave Creosotebush-White Bursage Desert Scrub ecosystems, respectively) under RCP8.5. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters. The extent to which impacts on shrub and Fynbos systems can be reduced at 1.5ºC *vs.* 2ºC of global warming remains to be analysed.

3.6.5.12 Transboundary Kailash Sacred Landscape

Large and substantial shifts in bioclimatic conditions can be expected throughout the area of the transboundary Kailash Sacred Landscape (KSL) of China, India and Nepal by the year 2050 under CIMP5 Scenarios, within all bioclimatic zones and ecoregions. Over 76% of the total area may shift to a different stratum, 55 % to a different bioclimatic zone, and 36.6 % to a different ecoregion. Potential impacts include upward shift in mean elevation of bioclimatic zones (357 m) and ecoregions (371 m), decreases in area of the highest elevation zones and ecoregions, large expansion of the lower tropical and sub-tropical zones and ecoregions, and the disappearance of several strata representing unique bioclimatic conditions within the KSL, with potentially high levels of biotic perturbance by 2050 (Zomer et al. 2014). The extent to which impacts on shrub and Fynbos systems can be reduced at 1.5ºC *vs.* 2ºC of global warming remains to be analysed.

3.6.5.13 Maize crop regions

Impact studies for major cereals showed that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with warming of 3°C to 5°C. However, all crops showed negative yield impacts for 3°C of warming without adaptation (Porter et al. 2014) and at low latitudes under nitrogen stress conditions (Rosenzweig et al. 2014). Relatively little progress have been made since AR5 if considering studies focused on the impacts on cropping systems for scenarios where global mean temperatures increase within 1.5°C. Schleussner et al. (2016) project that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and Central and South America. Ricke et al. (2015) highlight how globally, cropland stability declines rapidly between 1º and 3ºC warming. Similarly, Bassu et al. (2014) suggested that an increase of air temperature negatively influence the modeled maize yield response of -0.5 Mg ha^{-1} per°C and which even a conservative target of 2°C global mean warming would lead to losses of 8-14% in global maize production. Challinor et al. (2014) indicated high vulnerability of wheat and maize production in tropical regions, whilst Niang et al. (2014) using the near term (2030-2040) as a proxy for 1.5ºC warming, projected a significant lower risks to crop productivity in Africa compared to 2ºC warming. According to World Bank (2013), for Sub-Saharan Africa a 1.5°C warming by 2030 may reduce of 40% the present maize cropping areas and 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 indicated further yields losses and damages to the main African crops (i.e. maize, sorghum, wheat, millet, groundnut, cassava). For South East Asia a 2°C warming by 2040 indicated a one third decline in per capita crop production (Nelson et al. 2010) associated with a general crop yield decreases.

Table 3.7: Emergence and intensity of climate change hot-spots under different degrees of global warming

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C	Warming of more than 3°C
Arctic sea-ice	Ice-free Arctic in September is highly likely to be avoided.	The risk of an ice free Arctic in September becomes increasingly higher.	Relatively high probability (~43%) of Arctic becoming ice-free in September.	Arctic likely to be ice-free in September.
Arctic land regions	TBC	TBC	TBC	TBC
Alpine regions	TBC	TBC	TBC	TBC
Tibet Plateau	TBC	TBC	TBC	TBC

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C	Warming of more than 3°C
Coastal plains	TBC	TBC	TBC	TBC
Small Islands	TBC	TBC	TBC	TBC
Mediterranean	Reduction in runoff about 9% (likely range: 4.5–15.5 %)	Reduction in runoff doubles to 17% (8–28 %)	TBC	TBC
West African and the Sahel	TBC	TBC	TBC	TBC
Southern African savannahs and drought	TBC	TBC	TBC	TBC
Tropics	TBC	TBC	TBC	TBC
Fynbos biome	TBC	TBC	TBC	TBC
Transboundary Kailash Sacred Landscape	TBC	TBC	TBC	TBC
Maize crop regions	TBC	TBC	TBC	TBC

3.6.6 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. Critical to the climate change mitigation effort is an understanding of the sensitivities of tipping points in the physical climate system, ecosystems and human systems. This subsection reviews tipping points across these three main areas of relevance, 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 1.5ºC and 2ºC of global warming – note that tipping points in the global climate system, referred to as large scale singular events, have already been discussed in Section 3.6.2. A summary of regional tipping points is provided in Table 3.8.

3.6.6.1 Arctic sea-ice

3.6.6.2 Tundra

3.6.6.3 Permafrost

3.6.6.4 Indian Monsoon

3.6.6.5 West African Monsoon and the Sahel

3.6.6.6 Rain forests

3.6.6.7 Boreal forests

3.6.6.8 Heat-waves, unprecedented heat and human health

Above a temperature at which mortality is lowest for a region, increases in ambient temperature are linearly related with hospitalizations and deaths (so there isn't a tipping point per se). However, some regions may, once a particular threshold in global temperature is exceeded, for the first time experience wide-spread impacts of heat-waves where coping strategies of communities with low adaptive capacity is exceeded.

3.6.6.9 Agricultural systems: key staple crops

3.6.6.10 Agricultural systems: livestock in the savannahs

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

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2° - 3°C	Warming of more than 3°C
Arctic becomes nearly sea-ice free in September	Highly likely that tipping point is avoided.	The risk of an ice free Arctic in September becomes increasingly higher.	Relatively high probability (~43%) of Arctic becoming ice-free in September.	Arctic likely to be ice-free in September.
Tundra	TBC	TBC	TBC	TBC
Permafrost	TBC	TBC	TBC	TBC
Indian Monsoon	TBC	TBC	TBC	TBC
West African Monsoon and the Sahel	TBC	TBC	TBC	TBC
Rainforests	TBC	TBC	TBC	TBC
Boreal forests	TBC	TBC	TBC	TBC
Heat-waves, unprecedented heat and human health	TBC	TBC	TBC	TBC
Key staple crops	TBC	TBC	TBC	TBC
Livestock in the savannahs	TBC	TBC	TBC	TBC

3.7 Implications for impacts, adaptation and vulnerability of different mitigation pathways reaching 1.5°C

This section draws together the previous discussion about expected changes, impacts and implications into a number of trajectories or pathways, focusing on two groups: (1) those that increase to 1.5°C without an overshoot and (2) those have an overshoot (and then a trend back down toward 1.5°C).

Many of the considered '1.5°C' scenarios include an overshoot, and so a time period with global warming higher than 1.5°C before stabilizing at 1.5°C (see Chapters 1 and 2). It is thus important in the assessment of impacts associated with specific socio-economic pathways to consider if overshooting is happening within the 21st century, how long it persists, and if patterns in climate changes and extremes after a return to 1.5°C by 2100 are substantially different from those for scenarios without overshoot.

The reasons for overshoot arise from momentum within the climate system, as well as socio-economic drivers and emission reduction pathways (Chapter 2). While the average global temperature of 1.5°C may be achieved, the pathway may lead to unacceptable impacts and tipping points which mean that the cost of undergoing an overshoot may rule against it being a suitable pathway.

This section also considers other impacts on climate of socio-economic pathways, for instance associated with land use changes, and changes in non-CO_2 atmospheric compounds (aerosols, methane) concentrations (Section 3.7.2). In addition, other options beside CO_2 mitigation that could target specific changes in global temperature (e.g. Solar Radiative Management, SRM, Section 3.7.3), would have a very different regional footprint in terms of impacts compared to a scenario with reduced CO_2 emissions for the same global temperature warming, possibly creating novel risks. This question is addressed in Section 3.7.3. Finally, Section 3.7.4 address long-term implications of given socio-economic pathways and associated emissions scenarios, including irreversible changes.

3.7.1 Gradual vs Overshoot in 1.5ºC scenarios

3.7.1.1 Likely pattern of extremes and other changes in climate system

[This section will draw on work done in Section 3.3 considering both pathways which trend upwards and stabilise at or below 1.5°C, and pathways that include overshooting. Particular attention will be paid to expected extremes as well as trends, and associated changes that are expected in the climate system. Results from scenarios with and without overshoot will be contrasted.]

3.7.1.2 Implications for impacts on physical and biophysical systems

[This section will draw on work done in Sections 3.4 and 3.5 considering both pathways which trend upwards and stabilise at or below 1.5°C, and pathways that include overshooting. Results from scenarios with and without overshoot will be contrasted. There will also be a discussion of the implications for humans, potentially highlighting positive and negative elements of achieving stabilisation without vs with overshoot.]

3.7.2 Non CO_2 implications and projected risks of mitigation pathways

3.7.2.1 Land use changes

3.7.2.1.1 Land use changes in mitigation scenarios

Of the 116 climate change mitigation scenarios produced by integrated assessment models and reviewed in IPCC AR5 that limit global warming to less than 2°C above pre-industrial levels with more than 66% probability, 87% rely on extensive use of negative emission technologies (Smith et al. 2016) in the second half of the 21st century, 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 et al. 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) with negative emission technologies such as BECCS being required to achieve this. Similarly, 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 cropand and/or reforestation are a fundamental element (Chapter 2; Guillod et al.). In the development of these scenarios, implications of these land use changes beside their potential impacts on the carbon cycle are generally not considered. However, there are substantial impacts that need to be factored in, in particular 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 GtC/yr (Smith et al. 2016). 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 are extremely large, with estimates reaching up to 18% of the land surface (Wiltshire et al. 2015). Other estimates reach 380-700 Mha/21-64% current arable cropland (Smith et al. 2016); 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, hence risks to biodiversity conservation and agricultural production are projected to result from mitigation pathways that rely heavily on BECCS sourced from primary biofuels (Tavoni and Socolow 2013; Smith et al. 2013). In the absence of global forest protection, increasing bioenergy deployment also leads to increases in greenhouse gas emissions from land use change (Smith et al. 2013, 2016). 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, which can greatly offset the 'negative emissions' benefit of the BECCS itself (Wiltshire et al. 2015) with estimates ranging from 14-113 $GtCO_2$ eq cumulatively by 2100 (Popp et al. 2014). Many published estimates of the potential of BECCS do not consider this offset: however those that do include it 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) depending on future assumptions about population, agricultural intensification and productivity, and dietary changes. Most estimates of the potential land area available for biofuel cropping do not consider the need to set aside land for biodiversity conservation, although some integrated modelling studies simulate the effects of a carbon tax applied to greenhouse gas emissions from land use change as well as from fossil fuel use: in this case, forest area remains constant whilst biofuel cropland increases at the expense of agricultural land (particularly given the aim set out in Article 2 of the UNFCCC which requires that climate change be limited such that 'ecosystems can adapt naturally' and that 'food production is not threatened'.

In order for ecosystems to adapt to climate change, land use would need to be carefully managed to allow biodiversity to disperse to areas that become newly climatically suitable (see Section 3.4.1) as well as protecting the areas where the climate remains suitable in the future: this implies a need for a considerable expansion of the protected area network (Warren et al.). At the same time, adaptation to climate change in the agricultural sector (Rippke et al. 2016) can require transformational approaches and new approaches to land use management; whilst in order to meet the rising future food demand of a growing human population, additional land is projected to be needed to be brought into production, unless there are large increases in agricultural producitivity (Tilman et al. 2011). Hence, reliance on BECCS using primary biofuels has the potential for large negative consequences for food production and biodiversity conservation (and hence, ecosystem services)) (Smith and Torn 2013). Furthermore, the literature also reports that irrigation for bioenergy crops would greatly increase agricultural water withdrawals. One estimate considers finds that BECCS at 3.3 GtC/yr would require an additional 3% of the water currently appropriated to human use (Smith et al. 2016) whilst another finds that the global requirement for water withdrawal for irrigation could double, yet if such additional withdrawals are prohibited, demand for land (for BECCS) instead increases by 41% (Bonsch et al. 2016).

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

Many of the same issues relating to competition for land surround the potential use of afforestation and reforestation as a negative emission technology if this were to be used instead of BECCS. Similar rates of sequestration of 3.3 GtC/ha require 970 Mha of afforestation and reforestation (Smith et al. 2016). Humpenöder et al. (2014) estimates that afforestation would require 2800 Mha by the end of the century to constrain warming to 2°C. Hence the amount of land required if mitigation is implemented by afforestation and reforestation is 3 to 5 times greater than the required by BECCS. However, not all of this land use is in competition with biodiversity protection: where reforestation is the restoration of natural ecosystems, this benefits both carbon sequestration and conservation of biodiversity and ecosystem services.

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

3.7.2.1.2 Biophysical feedbacks on regional climate associated with land use changes

Changes in the biophysical characteristics of the land surface are known to have an impact on local and regional climates through changes in albedo, roughness, evapotranspiration and phenology that can lead to a change in temperature and precipitation. This includes changes in land use through agricultural expansion/intensification (e.g. Mueller et al. 2015) or reforestation/revegetation endeavours (e.g. Feng et al. 2016; Sonntag et al. 2016; Bright et al. 2017) and changes in land management (e.g. Luyssaert et al. 2014; Hirsch et al. 2017) that can involve double cropping (e.g. Jeong et al. 2014; B. Mueller et al. 2015; Seifert & Lobell 2015), irrigation (e.g. Sacks et al. 2009; Lobell et al. 2009; Cook et al. 2011; Qian et al. 2013; de Vrese et al. 2016; Pryor et al. 2016; Thiery et al. 2017), tillage (e.g. Lobell et al. 2006; Davin et al. 2014) and wood harvest (e.g. Lawrence et al. 2012).

The magnitude of the biophysical impacts has been found to be potentially large for extreme temperatures. Indeed, both changes induced by modifications in moisture availability and irrigation, or by changes in surface albedo, tend to be larger for hot extremes than for mean temperatures (e.g. Seneviratne et al. 2013; Davin et al. 2014; Wilhelm et al. 2015; Hirsch et al. 2017; Thiery et al. 2017). For moisture availability, the reason is related to a strong contribution of moisture deficits to the occurrence of hot extremes in mid-latitude regions (Mueller and Seneviratne 2012; Seneviratne et al. 2013). In the case of surface albedo, cooling associated with higher albedo (e.g. in the case of no-till farming) is more effective at cooling hot days because of the higher incoming solar radiation for these days (Davin et al. 2014a). The overall effect of either irrigation or albedo has been found to be at the most of the order of *ca.* 1-2°C regionally for temperature extremes. This can be particularly important in the context of low-emissions scenarios because the overall effect is in this case of similar magnitude to the response to the greenhouse gas forcing (Hirsch et al. 2017, see Figure 3.28).

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

It should be noted that the important role of land use change for climate change projections and socio-economic pathways will be addressed in depth in the upcoming IPCC Special Report on Land (REF). Also some aspects are treated in more depth in the cross-chapter box on competition for land (Box 3.11).

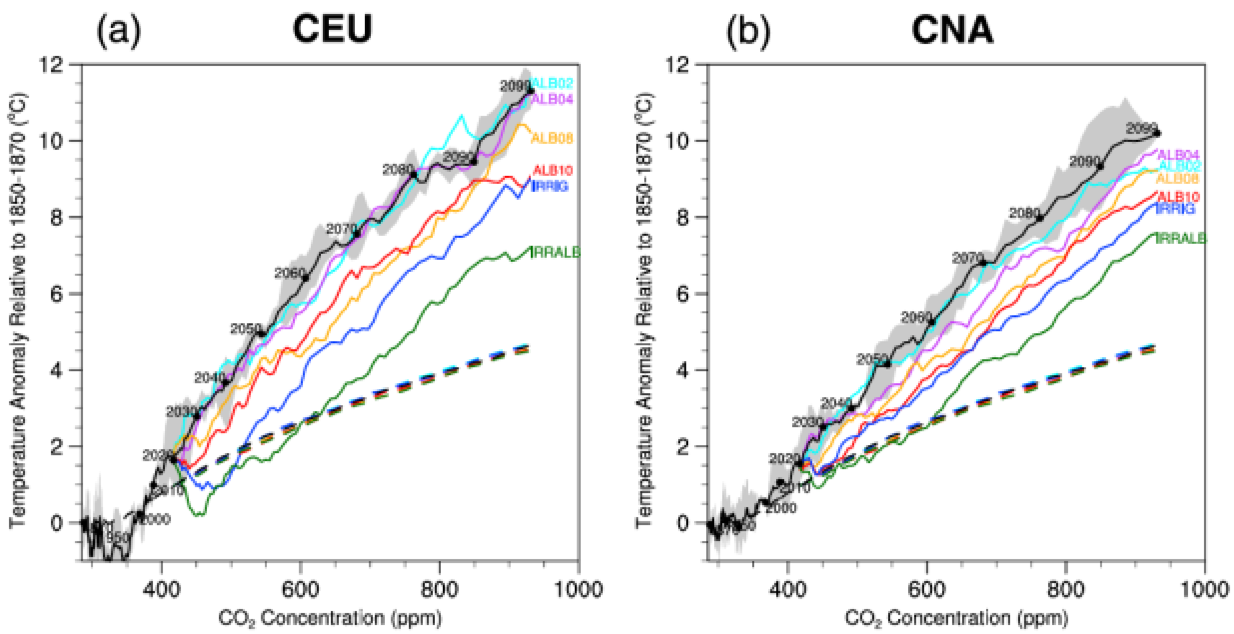


Figure 3.22: Regional temperature scaling with CO_2 concentration (ppm) over 1850 to 2099 for two different SREX regions: Central Europe (CEU) (a) and Central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TXx) anomaly and dashed lines correspond 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).

3.7.2.2 Atmospheric compounds (aerosols and methane)

Anthropogenic driven changes in aerosols cause important modifications to global climate (Mirle et al. 2013; Wang et al. 2016a; Boucher et al. 2013a; Sarojini et al. 2016; Wu et al. 2013), and 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 CO_2 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 (Wang et al. 2016a; Navarro et al. 2017). Thus regional impacts, especially on precipitation are very sensitive to the pathway used to obtain less than 1.5°C warming.

Pathways which rely strong on reductions in methane versus CO_2 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 CO_2 (Myhre et al. 2013; Pierrehumbert 2014). In addition, the dominant loss mechanism for methane is oxidation during atmospheric photochemistry, and this conversion modifies ozone creation and destruction in the troposphere and stratosphere, thus modifying the contribution of ozone to radiative forcing, as well as feedbacks onto the oxidation rate of methane itself (Myhre et al. 2013).

Atmospheric aerosols and gases can also modify the land and ocean uptake of anthropogenic carbon dioxide, but some compounds enhance uptake, while others reduce uptake (Ciais et al. 2013). Thus while CO_2 emissions tend to encourage more uptake of carbon by the land and the ocean(Ciais et al. 2013), methane emissions can enhance (or reduce) ozone pollution, depending on nitrogen oxide and other organic species concentrations, and ozone tends to reduce land productivity (Myhre et al. 2013). Aerosols and associated nitrogen-based compounds tend to enhance the uptake of carbon dioxide in land and ocean systems through the deposition of nutrients (Mahowald et al. 2017; Ciais et al. 2013).

3.7.3 Solar Radiation Management

Solar Radiation Management (SRM) is a geoengineering approach discussed in the literature, which involves deliberate changes to the albedo of the Earth system (Chapter 1; Chapter 4, Box 4.2). As highlighted in Chapter 1, and consistent with previous IPCC reports (Edenhofer et al. 2012), SRM is not investigated as a mitigation option in Chapter 2. Nonetheless, given the existing literature on this topic and the fact that a box is addressing it in Chapter 4 (Box 4.2), the present chapter provides some background on regional impacts of SRM (for the considered different techniques, their impacts on global temperature, and possible effects on the carbon cycle, see Box 4.2). We distinguish hereafter between global-scale SRM (i.e approaches that affect the Earth's albedo globally or over a very large fraction of its area) and regional- to local-scale changes in albedo which have been rather considered in the context of the adaptation literature and could be achieved with changes in land use or urban surface properties.

Global-scale SRM is mostly assessed in the literature based on two implementation methods, i) Sunshade Geoengineering (SG), which is mostly hypothetical but easier to implement in climate model simulations, and ii) Stratospheric Aerosol Injections (SAI), which is most commonly proposed as implementation, and mimics the effect of volcanic eruptions in reducing global average temperatures temperatures (Rasch et al. 2008; see also Chapter 1). These global SRM approaches are designed to offset the global mean warming induced by a certain level of increase in GHG. SG can be considered as a very idealized model experiment, which represents some of the first-order climatic effects of SAI, but with significant differences in climate response (e.g., Robock 2014; Irvine et al. 2016). Both SG and SAI are set up to balance a particular radiative forcing (e.g., $4xCO_2$ or RCP4.5), but SAI may produce a non-uniform forcing depending on where and in what form aerosols are inserted in stratosphere (e.g., Muri et al. 2014; Laakso et al. 2012). For the same global mean temperature reduction, SAI produces a greater change in the hydrological cycle than SG and would lead to greater regional change in climate, particularly in the tropics (e.g., Irvine et al. 2016,). For both SG and SAI an abrupt termination of employment would lead to a 'termination-shock' with rapid global warming and unknown consequences for the Earth system (e.g., Jones et al. 2013).

In general, global model experiments suggest that in case of a global SRM implementation surface temperatures would be reduced most in regions with expected greatest warming under elevated GHG conditions (i.e. high-latitudes) and lead to less temperature and precipitation extremes (Curry et al. 2014). However, this would be accompanied by an overcooling of tropical ocean (Curry et al. 2014), a shift in the diurnal cycle (i.e. shift in night-time vs. day-time warming) (Lunt et al. 2008) and a residual temperature increase over high-latitude land regions and in polar regions (Curry et al. 2014), SRM model experiments indicate a reduction in the intensity of the hydrological cycle compared to a 4xCO_2 warming with substantial regional differences in the hydrological cycle patterns, for instance, a reduction of precipitation on land, particularly in monsoon regions, and more low-intensity rainfall events (e.g., Bala et al. 2008; Tilmes et al. 2013). SRM methods may further induce shifts in the ITCZ, Walker and Hadley cell circulations with implications for precipitation changes in affected regions and towards prevailing La Niña like conditions, for instance, by emitting sea salt (Niemeier et al. 2013). The weakening of tropical circulation as projected under increased GHG would not be reduced by SAI (Ferraro et al. 2014). Atlantic hurricane storm surges may be reduced by half (only marginally statistically significant) with further implications for coastal flood levels due to reduced sea level rise (Moore et al. 2015).

Ricke et al. (2010) point out that it would physically not be feasible by means of SRM to simultaneously stabilize global precipitation and temperature as long as GHG continue to rise. While SRM deployed along with emissions cuts could make it possible to reach a 2°C or even 1.5°C global-mean temperature warming, the associated climate would be very different from a °C or 1.5°C climate associated with greenhouse gas mitigation only (see cross-chapter Box 3.12 on '1.5°C warmer worlds'). Tilmes et al. (2016) for instance emphasize that the climate impacts by stringent emissions cuts would be different from those of moderate emissions cuts supplemented by SRM cooling. This means that global mean temperature would not be a good proxy for aggregate climate risks if solar geoengineering were to be deployed (Irvine et al. 2017). The changes in spatial and temporal distributions of temperature, precipitation and wind conditions induced by SRM would affect regions in different ways with recognizable economic consequences. Specifically, under RCP4.5 of implementing SRM economic benefits are small, and may become negative. While global GDP may increase, regions with negative benefits (i.e. losses) from SRM cannot be avoided (Aaheim et al. 2015), thus SRM would inevitably create winners and losers (e.g., Kravitz et al. 2014; Hegerl and Solomon 2009).

Because of these recognized shortcomings and risks associated with SRM, more recent publications have also discussed moderate deployments of SRM as potentially more realistic options (Keith and MacMartin 2015). Nonetheless, a main issue remains the fact that traditionally considered SRM implementations such as SAI do not have scope for regional adjustment of the applied radiative forcing (MacMartin et al. 2012).

Beside SAI, also modifications of the land surface reflectivity, for example by changes in the albedo of agricultural land or urban areas (Irvine et al. 2011; Davin et al. 2014b; Seneviratne et al.) may be considered. These land-surface radiation management methods have a smaller spatial footprint than SAI or SG, because the forcing is more restricted in space. The land-surface radiation management approaches are potentially better suited than SAI to affect local and regional temperature but would have at most only a negligible effect on global temperature (e.g. Seneviratne et al.). They should be thus considered in a different framework than traditional SRM approaches, and may have more direct impact in the context of regional-scale adaptation (Boucher et al. 2013b), although such regional effects may be relevant in the development of realistic global socio-economic pathways (see Chapter 2 and cross-chapter Box 3.12 on '1.5°C warmer worlds').

It is important to note that independently of any regional footprint of application, changes in temperature that result from changes in radiative forcing (such as with SAI-based SRM, but also land-based changes in surface albedo) do not address non-temperature impacts of greenhouse-gas concentrations, and in particular ocean acidification (see Chapter 3, Section 3.3.11; c.f. also (IPCC 2014b).

Finally, risks that are specific to SAI are a further reason for concern with respect to the potential consideration of SAI in adaptation. Most importantly: i) the lack of testing of the proposed schemes (e.g.

Schäfer et al. 2013), ii) potential associated depletion of stratospheric ozone (Tilmes et al. 2008) which remain very uncertain (Irvine et al. 2016), iii) possible tropospheric impacts (Irvine et al. 2016) , and iv) effects on vegetation and crop production. This latter point is very uncertain and of particularly strong relevance for sustainable development (Chapter 5). The overall impacts on food production and ecosystems would result from the combined effects of a) changes in regional climate (with potential benefits, Pongratz et al. (2012), but also negative modifications on regional scale in particular with respect to the water cycle, thus creating new 'winners and losers' as discussed above), b) changes in the ratio of incoming direct and diffuse radiation (Pongratz et al. 2012), and c) the extent of CO_2 effects on plant photosynthesis (Wenzel et al. 2016; Mystakidis et al. 2017) and their possible reduction through nutrient or water limitation (Ciais et al. 2013; Reichstein et al. 2013). Given the level of uncertainty in the various underlying processes, and the lack of comprehensive assessments in the literature, it is not possible at the present state in time to confidently assess what would be the impacts of SAI deployment on food production and ecosystem health. Factoring in the precautionary principle and the inequalities introduced by creating 'winner and loser' regions in terms of climate effects leads to the assessment with *medium confidence* (expert judgment) that the risks of SAI deployment for global food security and ecosystem health would outweigh the benefits, even for low levels of application, at the present state of knowledge.

3.7.4 Beyond the end of the century implications

3.7.4.1 Sea ice

Sea ice is often cited as a tipping point with in the climate system (Lenton 2012). Detailed (Schroeder and Connolley 2007; Sedlacek et al. 2011; Tietsche et al. 2011) using climate models designed to test this hypothesis suggest that Summer sea ice can return within a few years after its rapid removal. Further studies (Armour et al. 2011; Boucher et al. 2012; Ridley et al. 2012) remove sea ice by raising CO_2 concentrations and study subsequent regrowth by lowering CO_2 at the same rate. These studies also suggest changes in Arctic sea ice are neither irreversible nor exhibit bifurcation behavior. It is therefore plausible that the extent of Arctic sea ice may quickly re-equilibrate to end-of-century climate in the event of an overshoot scenario.

3.7.4.2 Sea level

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

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

For Greenland, where melting from the ice sheet's surface is important, a well-known instability exists where the surface of a thinning ice sheet, encounters progressively warmer air temperatures that further promote melt and thinning. A useful index associated with this instability is the threshold at which mass loss from the ice sheet by surface melt exceeds mass gain by snowfall. Previous estimates (Gregory and Huybrechts 2006) put this threshold around 1.9 to 5.1°C above preindustrial, however more recent work suggests 0.8 to 3.2°C (Robinson et al. 2012). The continued decline of the ice sheet after this threshold has been passed is highly dependent on future climate and varies between ~80% loss after 10,000 years to complete loss after as little as 2000 years (contributing ~6 m to sea level). It is important to note, however, that regrowth is not excluded if future climate becomes more cooler and the point at which loss becomes truly irreversible is poorly contrained other than that the degree by which warming would have to be ameliorated increases through time as the size of the ice sheet declines.

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

3.7.4.3 Permafrost

The slow rate of permafrost thaw in comparison to the size of this store of ice introduces a lag between transient permafrost loss and contemporary climate, so that the equilibrium (or committed) response is likely to be 25 to 38% greater than the transient response simulated in climate models (Slater and Lawrence 2013). The long-term, committed Arctic permafrost loss to global warming is analysed by Chadburn et al. (2017). They use an emperical relation between recent mean annual air temperatures and permafrost cover coupled to CMIP5 stabilization projections to 2300 for RCPs 2.6 and 4.5. Their estimate of the sensitivity of permafrost to warming is 2.9 is to 5.0 million km^2 °C^{-1} (likely range), which suggests that stabilizing climate at 1.5°C as opposed to 2°C would save roughly 2 million km^2 permafrost or 13% of present-day cover (stabilizing at 73 as opposed to 60% of present-day values).

3.8 Knowledge gaps and research needs

There is emerging literature on changes in global climate, regional climate and extremes at 1.5°C vs 2°C and higher levels of warming. However, literature is not yet available on some on-going assessments such as results from climate model experiments especially targeted at 1.5°C scenarios. For this reason, the available evidence for the physical climate basis is derived from observational studies and modelling studies deriving empirical responses of climate at 1.5°C from simulations stabilizing or reaching higher levels of warming.

The assessment has identified some mismatches between the available scientific literature on projected climate change risks associated with 1.5°C *vs.* 2°C warming, and the clear policy need for information on this topic. This is particularly the case for the quantification of projected risks at 1.5°C warming. There is more information about projected risks at 1.5°C warming in natural and managed systems than in human systems, but even in natural and managed systems the literature is not yet extensive or comprehensive.

Therefore, the quantification of the risks avoided in a 1.5°C warming world compared to +2°C can only partly be answered at the moment. Relatively little literature is designed to study the impacts of the two warming levels, although much more is expected imminently.

Some specific research needs have been identified:

- More specific literature is needed to assess impacts, risks, opportunities and consequence for 1.5°C versus 2°C warming in particularly vulnerable regions and sectors, such as coastal low-lying areas, and urban populations in tropical regions. There is limited information about the global (and regional) aggregate economics for global warming levels of 1.5ºC versus 2ºC.
- More specific literature is needed to assess the relative levels of risks to particular unique and threatened ecosystems at 1.5°C versus 2°C, including in particular mountain and Arctic ecosystems.
- More literature is needed on the evaluation of assumptions underlying the scenarios of Chapter 2 for impacts, in particular with respect to land use changes (impacts on food security, biophysical feedbacks).

- There is a limited incorporation of of other driving factors for risks to human and natural systems, including development choices, population growth, governance and institutions.

- Further basic research is needed to understand risks at different degrees of temperature change within the context of (for human systems) socioeconomic and other drivers of adverse outcomes. The magnitude and pattern of these risks need to be understood at the level of the scale of the decision to be taken.

- There is little knowledge on understanding the extent to which adaptation could avoid some projected risks. Assuming adaptation will be efficient and effective, then there is a need to understand the residual risks that will need to be managed. These risks need to be understood not just individually, but collectively for a region because risks will interact in complex ways that could ameliorate or synergize in ways to alter experienced impacts.

- Little information is currently available on economic impacts.

Box 3.11: Cross-chapter box on land use

Introduction

- In 2010, emissions from the agriculture, forestry and land use sector (AFOLU) were close to 10 $GtCO_2$-eq/yr, comprising 24.87% of annual greenhouse gas emissions of which land use change contributed about 40% (AR5 WGIII Figure SPM2, Figure 11.2). Reducing these emissions would be necessary if warming is to be limited to 1.5°C or 2°C above pre-industrial levels. However, two of the key climate change mitigation technologies that achieve 'negative' emissions (hereafter referred to as negative emission technologies, 'NETS') have a large land use footprint when applied at scales necessary to limit warming to 1.5°C and 2°C.

- The box will explore the extent to which NETS such as bioenergy with carbon capture and storage (BECCS) and afforestation (AFF) could induce direct and indirect land use change (iLUC). This could have negative effects on agriculture and ecosystems, and on sustainable development generally, owing to competition for land. Explain that in AR5 most of the scenarios limiting warming to 2°C had extensive BECCS. The box will conclude by exploring whether it is possible to design mitigation policies using or excluding various NETS that would minimise humanity's land use footprint through, perhaps, use of second-generation biofuels, marginal land, and reforestation with native trees.

- Discuss LULUCF and other land-based mitigation options, e.g. REDD+

Detail

- Explain basics of carbon cycle and how mitigation technologies affect the carbon cycle, including negative emission technologies (BECCS and Afforestation).

Box 3.11, Figure 1: Schematic representation of how the carbon cycle responds to human activity

- Discuss the pros and cons of BECCS and AFF in turn, in relation to the way they use land and sequester carbon. Discuss what metrics can be used to compare the environmental effects of these technologies, including the land use footprint, but also other metrics. Discuss the amounts of mitigation necessary to achieve 1.5°C/2°C warming, and how much land would be required if each of the negative emissions technologies are used to achieve this (Table 3.X showing amounts required, with ranges)

Box 3.11, Figure 2: (to be created): Comparison of NETS using a variety of metrics.

- Explore the extent to which NETS such as bioenergy with carbon capture and storage (BECCS) and afforestation (AFF) could induce indirect land use change (iLUC). Include in the discussion the potential role of other land-based mitigation options such as REDD+ and carbon taxes on fossil/land carbon.

Box 3.11, Figure 3: – create a diagram to illustrate this land competition

- Cover the negative consequences of induced land use change: explain that this land use change then emits GHG, which can compromise the goals of the negative emission technologies (review literature estimating size of this problem). It also competes for land with agricultural production and biodiversity conservation. Food prices could rise and natural ecosystems might be converted to biofuel croplands or eucalyptus plantations. In order for the agricultural sector to adapt to climate change, crops might need to be grown in new places, and in order to help biodiversity adapt to climate change, protected area networks would need to be expanded. This would be difficult in a world with extensive LUC.

- *Subsection* on how land use changes affect albedo and reflection on some interaction with above discussion (there are interactions but doesn't change overall message).

- *Subsection* on water requirements (another table, if enough data) Mention that the water use through irrigation could substantially affect the regional temperatures and water cycle, and thus need to be factored in.

- *Subsection* on nutrient requirements, and associated GHG emissions (another table, if enough data)

- Mention that land use occurs for other reasons than climate change mitigation, and review the trends in the RCP scenarios and any other scenarios relevant, and compare with recent trends.

- Discuss how mitigation might be designed to achieve large emission reductions whilst largely avoiding this land competition between biofuel cropping, food production and biodiversity conservation. Discuss competition for water also. Discuss the biophysical feedbacks and the fact that they need to be factored in more broadly. Discuss potential role of agricultural and forest residues and waste, marginal land, agricultural intensification, and changes in diet, and of re-forestation with native trees in creating a sustainable solution.

- *Subsection* on implementation issues and problems associated with the enaction of mitigation policies, including difficulties in preventing negative consequences for equity and biodiversity considerations.

Conclusion

Concludes that when aiming for 1.5°C global warming target, in order to avoid negative impacts on agriculture, ecosystems, and sustainable development, it would be essential for mitigation to be designed to minimize conflicts with food production, biodiversity conservation and sustainable development. The question of how mitigation is implemented then becomes very important.

Box 3.12: 1.5°C Warmer Worlds

Introduction

The Paris Agreement provides climate goals in terms of global mean temperature (1.5°C or 2°C global mean warming above pre-industrial times). However, there are several aspects that remain open regarding what a '1.5°C warmer world' could be like, both in terms of mitigation and adaptation, as well as in terms of projected warming and associated regional climate change, overlaid on anticipated and differential vulnerabilities. **Alternative '1.5°C warmer worlds' resulting from mitigation and adaptation choices, as well as from climate variability (climate noise), can be vastly different** as highlighted in this cross-chapter box. In addition, the spread of models underlying 1.5°C projections also needs to be factored in.

Detail

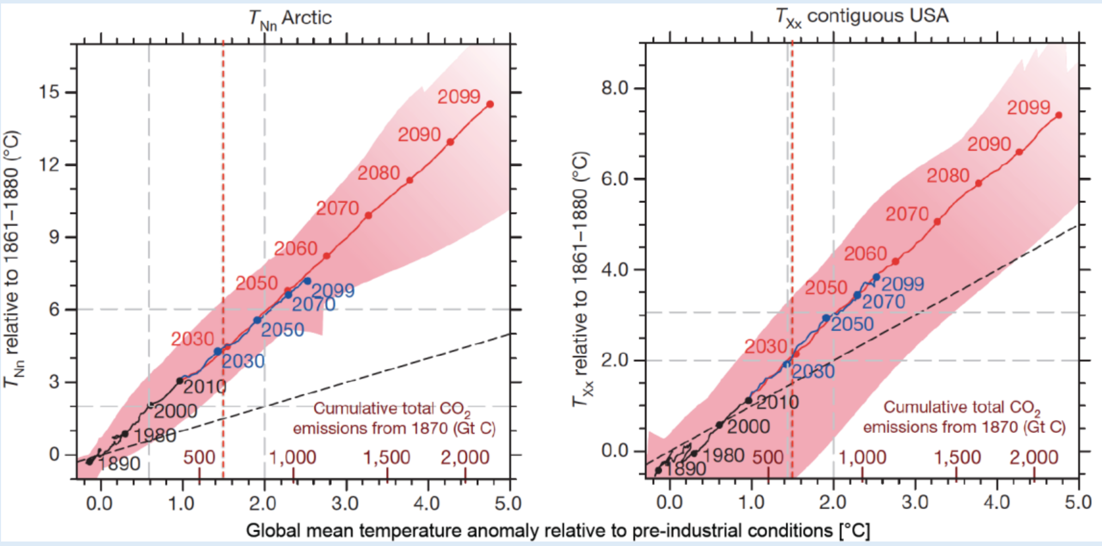
What is a 1.5° global mean warming, how is it measured, and what temperature warming does it imply at single locations and at specific times? Global mean temperature is a construct: It is the globally averaged temperature of the Earth, which can be derived from point-scale ground observations or computed in climate models. Global mean temperature is additionally defined over a given time frame, e.g. averaged over a month, a year, or multiple decades. Because of climate variability, a climate-based global mean temperature typically needs to be defined over several decades (at least 30 years under the definition of the World Meteorological Organization). Hence, as highlighted in Chapter 1, to determine a 1.5°C global temperature warming, one needs to agree on a reference period (assumed here to be 1850-1879 inclusive), and on a time frame over which a 1.5°C mean global warming is observed (assumed here to be of the order of a several decades, see Chapter 1). By definition, because the global mean temperature is an average in time and space, there will be locations and time periods in which 1.5°C warming is exceeded, even if the global mean temperature warming is at 1.5°C. In some locations, these anomalies can be particularly large (Box 3.12 Figure 1).

[This figure will show the highest and lowest temperature anomalies at each location that are reached in any

single month within 20-year time frames when global temperature warming is equal to 1.5°C within the 21st century.]

Many impacts will be different in a world in which temperatures have stabilised at 1.5°C *versus* a world in which average temperatures have temporarily reached 1.5°C and are continuing to warm. Land-sea temperature contrast is greater and the intensification of the global hydrological cycle is reduced in a world at 1.5°C that continues to warm *versus* a world that is approaching equilibrium. Hence impacts when temperatures reach 1.5°C on an overshoot scenario are not fully indicative of impacts after stabilisation at 1.5°C.

What is the impact of climate model spread for projected changes in climate at 1.5°C global warming? The range between single model simulations of projected changes at 1.5°C can be substantial for regional responses (Chapter 3). For instance, for the warming of cold temperature extremes in a 1.5°C warmer world, some model simulations project a 3°C warming and others more than 6°C warming in the Arctic land areas (**Box 3.12, Figure 2**). For warm temperature extremes in the contiguous United States, the range of model simulations includes colder temperatures than pre-industrial (-0.3°C) and a warming of 3.5°C (**Box 3.12 Figure 2**). Some regions display even larger spreads (e.g. 1°C to 6°C regional warming in hot extremes in Central Europe at 1.5°C warming, Chapter 3). This large spread is due both to modelling uncertainty and internal climate variability. While the range is large, it also highlights risks that can be near certainly avoided in a 1.5°C warmer world compared to worlds at higher levels of warming (e.g. a 8°C warming in cold extremes in the Arctic is not reached at 1.5°C global warming in the multi-model ensemble, but it could happen at 2°C mean global warming, Box 3.12 Figure 2). Inferred projected ranges of regional responses (mean value, minimum and maximum) for different mitigation scenarios of Chapter 2 are displayed in Table 3.9



Box 3.12, Figure 2: Spread of projected multi-model changes in minimum annual night-time temperature in the Arctic land (left) and in maximum annual day-time temperature 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. The dashed red line indicates projections for a 1.5°C warmer world. [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, and so 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 CO2 budget available for emissions is very small, which implies that large and immediate global efforts need to be invested in mitigation (Table 3.9)

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 global warming are determined based on their probability of reaching 1.5°C by 2100 (Chapter 2) given current knowledge of the climate system response. Typically, this probability is set at 66% (i.e. 2/3 chances of reaching a 1.5°C global warming or lower). However, this implies that there is a 33% probability that this goal will not be achieved (i.e. exceedance of 1.5°C global warming), even if a 1.5°C pathway is followed, including some possibility of being substantially over this value (generally about 10% probability, see Table 3.9). These alternative outcomes need to be factored in the decision-making process. ‘Adaptive’ mitigation scenarios in which emissions are continually adjusted to achieve a temperature goal are implicit in the Paris global stocktake mechanism, and would transfer the risk of higher-than-expected warming to a risk of faster-than-expected mitigation efforts, but have thus far received less attention in the literature.

The transformation towards a 1.5°C warmer world can be implemented in a variety of ways, for example by decarbonizing the economy with an emphasis on demand reductions and sustainable lifestyles, or, alternatively, with an emphasis on large-scale technological solutions, amongst many other options (Chapter 2). **Different portfolios of mitigation measures come with distinct synergies and trade-offs for other societal objectives**. Integrated solutions and approaches are required to achieve multiple societal **objectives simultaneously.**

Risks and opportunities in 1.5°C warmer worlds. The risks to natural, managed, and human systems in a 1.5°C warmer world will depend not only on uncertainties in the regional climate which results from this level of warming, but also depend very strongly upon the methods that humanity has used to limit warming to 1.5°C. This is particularly the case for natural ecosystems and agriculture (see cross chapter Box 3.11 on land use). The risks to human systems will also depend on the magnitude and effectiveness of policies and measures implemented to increase resilience to the risks of climate change, and will depend on development choices over coming decades that will influence underlying vulnerabilities.

Aspects not considered or only partly considered in the mitigation scenarios from Chapter 2 include biophysical impacts of land use, water constraints on energy infrastructure, and regional implications of choices of specific scenarios for tropospheric aerosol concentrations or the modulation of concentrations of short-lived greenhouse gases. For comprehensive assessments of the regional implications of mitigation and adaptation measures, such aspects of development pathways would need to be factored in.

Could solar radiation management help limit global temperature warming to 1.5°C? Using SRM could modify the global temperature, but it would create an entirely novel global and regional climate, and could substantially reduce tropical precipitation as compared to a world without SRM. There would be minimal and indirect effects on CO_2 concentrations (see Box 4.13 on SRM) and thus ocean acidification. It would also have a high potential for cross-boundary conflicts because of creating new ‘winners’ and ‘losers’ (Box 4.13). Hence, while the global mean temperature might be close to a 1.5°C warming, the implications would be very different from those of a 1.5°C global warming reached with early reductions of CO_2 emissions and stabilization of CO_2 concentrations

Commonalities of all 1.5°C warmer worlds: Because the lifetime of CO_2 in the atmosphere is more than 1000 years, the global mean temperature of the Earth responds to the cumulative amount of CO_2 emissions. Hence all **1.5°C stabilization scenarios require both net CO_2 emissions and multi-gas CO_2-forcing-equivalent emissions to be zero** at some point in time (Chapter 2). This is also the case for stabilization scenarios at higher levels of warming (e.g. at 2°C), the only difference would be the time at which the net CO_2 budget is zero. Hence, **a transition to a decarbonisation of energy use is necessary in all scenarios**. It should be noted that **all scenarios of Chapter 2 include carbon capture and storage** to achieve the net-zero CO_2 emission budget, but to varying degrees. Because no scenarios explicitly tried to achieve their target without carbon capture and storage, it is nonetheless an open question whether this option is absolutely mandatory. CO_2-induced warming by 2100 is determined by the difference between the total amount of CO_2 generated (which can be reduced by early decarbonisation) and the total amount permanently stored out of the atmosphere, for example by geological sequestration.

Storylines of '1.5°C warmer worlds': Box 3.12 Table 2 display possible storylines based on the scenarios of Chapter 2 and the impacts of Chapter 3. These storylines are not comprehensive of all possible future outcomes, but plausible scenarios of 1.5°C warmer worlds with two of them including a stabilization at 1.5°C (Scenarios 1 and 2) and one only achieving a temporary stabilization through SRM before further warming and a warming stabilization at higher level (Scenario 3).

Conclusions

There is not only one '1.5°C warmer world'. Important aspects to consider (beside that of global temperature) are how a 1.5°C global warming stabilization is achieved, including how the policies influence resilience for human and natural systems, and what are the regional and sub-regional risks. **The time frame to initiate major mitigation measures is essential** in order to reach a 1.5°C (or even a 2°C) global stabilization of climate warming (Table 3.10).

Box 3.12, Table 1: Different '1.5° warmer worlds' based on Chapter 2 scenarios and Chapter 3 assessments of changes in regional climate.

		Mitigation pathways (Chapter 2)							
		WB1.5 (well below 1.5°C) with 2/3 'lucky' outcome[1]	WB1.5 (well below 1.5°C) with 1/10 'unlucky' outcome[2]	Med1.5 (median 1.5°C) with with 2/3 'lucky' outcome[1]	Med1.5 (median 1.5°C) with 1/10 'unlucky' outcome[2]	WB2 (well below 2°C) with 2/3 'lucky' outcome[1]	WB2 (well below 2°C) with 1/10 'unlucky' outcome[2]	WB2.5 (2.5°C scenario) with 2/3 'lucky' outcome[1]	WB3 (3°C scenario) with 2/3 'lucky' outcome[2]
General characteristics of pathway	**Overshoot > 1.5°C in 21st century[3]**	**Yes (21/21)**	**Yes (21/21)**	**Yes (13/13)**	**Yes (13/13)**	**Yes (25/27)**	**Yes (20/27)**	**Yes (26/26)**	**Yes (26/26)**
	Overshoot > 2°C in 21st century	**No (0/21)**	**Yes (17/21)**	**No (0/13)**	**Yes (13/13)**	**No (0/27)**	**Yes (27/27)**	**Yes (26/26)**	**Yes (26/26)**
	Carbon capture and storage	Yes (SOD: GtC by when)	Yes (SOD: GtC by when)	Yes (SOD: GtC by when)	Yes (SOD: GtC by when)	Yes (SOD: GtC by when)	Yes (SOD: GtC by when)	Yes (SOD: GtC by when)	Yes (SOD: GtC by when)
	Cumulative CO_2 emissions up to peak warming (relative to 2016)[4]	640—750	620—720	690—970	670—900	940—1110	850—1080	1610—1940	2410—2750
	Cumulative CO_2 emissions up to 2100	150—360		250—490		810—1030		1600—1940	2410—2750

[1] 66% likelihood estimates for global temperature of remaining below threshold (Table 2.2.1)
[2] 90% likelihood estimates for global temperature, i.e. 10% highest value (at or above threshold; Table 2.2.1)
[3] All 1.5°C scenarios from Chapter 2 include a substantial probability of overshooting above 1.5°C global warming before returning to 1.5°C
[4] The range indicates the interquartile range (25th percentile and 75th percentile)

	(relative to 2016)[4] [GtCO$_2$]								
	Global GHG emissions in 2030[4] [GtCO$_2$ y-1]	18—26		26—39		26—38		35—41	40—45
	Years of global net zero CO$_2$ emissions[4]	2063—2073		2065—2069		2080—2090		2087—2095 or after 2100	after 2100
Possible climate range at peak warming (reg+glob)	**Global mean temperature anomaly at peak warming**	**1.7°C (1.65—1.75°C)**	**2.05°C (2.02—2.13°C)**	**1.78°C (1.75—1.89°C)**	**2.14°C (2.11—2.31°C)**	**1.9°C (1.85—1.94°C)**	**2.41°C (2.31—2.44°C)**	**2.37°C (2.33—2.43°C); similar to 2100**	**No transition to decline phase in 21st century**
	Warming in the Arctic[5] (TNn[6])	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)	See 2100	See 2100
	Warming in the contiguous United States[5] (TXx[7])	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)	See 2100	See 2100
	Warming in Central Brazil[5] (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)	See 2100	See 2100
	Drying in the Mediterranean region[5]	-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)	See 2100	See 2100
	Increase in heavy precipitation events[8] in Southern Asia[5]	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)	See 2100	See 2100
Possible climate	**Global mean temperature**	**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)**	**2.37°C (2.34—2.42°C)**	**2.89°C (2.77—2.91°C)**

[5] The regional projections in these rows provide the range [mean (minimum, maximum)] associated with the global temperature outcomes of the considered mitigation scenarios at peak warming. The values are computed based on multi-decadal averages of global climate model simulations from the 5th Phase of the Coupled Modeling Intercomparison Project (CMIP5). The mean value correspond to the mean regional response in the considered indicators (e.g. TNn warming in the Arctic land [°C], TXx warming in the contiguous United States[°C], TXx warming in Central Brazil [°C], Drying in the Mediterranean region [in units of standard deviations of late 20th century variability], Increase in heavy precipitation events in Southern Asia [%], [ONE OCEAN INDICATOR TO BE INCLUDED FOR THE SOD]) for the mean value of considered mitigation scenario. The minimum value corresponds to the minimum regional response for the minimum global warming response. The maximum value corresponds to the maximum regional response for the maximum global warming response. The estimates of the regional responses for the given global temperature projections are derived based on Seneviratne et al. (2016).

[6] TNn: annual minimum night-time temperature

[7] TXx: annual maximum day-time temperature

[8] Based on annual maximum consecutive 5-day precipitation, Rx5day

	warming by 2100								
	Warming in the Arctic[9] (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)	7.03°C (4.43-9.19)	8.64°C (5.87-11.7)
	Warming in the contiguous United States[9] (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)	3.43°C (0.96-5.5)	4.41°C (1.84-6.47)
	Warming in Central Brazil[9] (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)	3.88°C (2.73-5.65)	4.7°C (3.26-6.81)
	Drying in the Mediterranean region[9]	-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)	-1.71 (-6.06 – 0.89)	-2.13 (-6.16 – 9.58)
	Increase in heavy precipitation events in Southern Asia[9]	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)	17.02% (-0.11-43.34)	20.68% (2.51 – 56.49)

[9] Same as footnote 5, but for the regional responses associated with the global temperature outcomes of the considered mitigation scenarios by 2100.

Box 3.12, Table 2: Storylines of possible '1.5° 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.

Scenario 1: 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.	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. 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 leaving 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 is 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. By 2100, global mean temperature is on average warmer than in 2018 by 0.5°C. 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 series 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. 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 21^{st} century. The Earth system, while warmer, is still recognizable compared to the 2000s and no major tipping points were hit. Crop yields have remained relatively stable. Aggregate economic impacts of climate change damage are relatively small, although there are some local losses associated with extreme weather events. The quality of life remains similar to that in 2018.
Scenario 2: Delayed action, warmer decade in the 2020s due to internal climate variability, stabilization at 1.5°C after overshoot at 2°C	The international community continues to support the Paris Agreement and agree in 2018 on reduction targets for CO_2 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 would be consistent with a warming of 1.2°C or 1.3°C. Deadly 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. As a result, financial markets are increasingly destabilized because of the planned fast decarbonisation. 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 key ecosystems such as coral reefs. 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. 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, and levels of poverty and disadvantage has increased very significantly.
Scenario 3: Uncoordinated action, short-term SRM deployment and 1.5°C global temperature in mid-century, 2100 stabilization at 3°C	Some countries withdraw from the Paris agreement in 2020. In the following years, reduced CO_2 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 and the Rockies. 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. A major 5-year 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, 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 stores dwindle in most countries. 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 CO_2 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 an intense 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. 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.

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