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

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Executive summary

3.1 Background and framing

This chapter presents the scientific evidence published since AR4 on observed and projected impacts and risks of global warming on natural and human systems. In addition, an assessment of avoided impacts and reduced risks at 1.5 °C compared to 2 °C warming is presented, and the implications for impacts, adaption and vulnerability of different mitigation pathways reaching 1.5 °C with and without overshooting are reviewed.

3.1.1 Scope and road map: structure of chapter

[We will develop this after we reached the final structure of the chapter. Here we also explain our approach to regional changes and hot spot regions and the box topics.]

3.1.2 Conclusions from previous assessments (SREX, AR5)

[For Internal Draft references to SREX and AR5 are made in the sub sections. We might want to state a few general findings related to a 1.5 °C warming from previous assessments. We will be prepared for the FOD after a discussion in the LAM2 on where (here or in the sub-sections) the findings should be mentioned.]

3.1.3 Refer to definitions of key terms

[Will be developed at the LAM2. Key terms will be collected from the sub-sections.]

3.1.4 Overview, storyline and relationship to other chapters

[Content will be developed at the LAM2, when we have text from all sub-sections in place. We are aiming for a coherent story line throughout the entire chapter. Here, we will also explain, how we are dealing with information coming from pathways with and without overshoot, the different time periods, and methods.]

3.1.5 End point chapter

[A paragraph about this chapter's contents - including its scope and limitations - in relation to the subsequent chapters of the report will be included.]

3.2 Methods of assessment

3.2.1 Introduction

This section presents the methods of assessment used in this chapter. These methods are varied given the breadth of the chapter, which covers both changes in climate variables, typically addressed in IPCC WG1 reports, and changes in impacts to (natural and managed) ecosystems and humans, which are typically addressed in IPCC WG2 reports. For this reason the underlying data and literature basis for our chapter is very broad. For instance, the main relevant prior IPCC material covers two chapters of the IPCC SREX report (Seneviratne et al. 2012; Handmer et al. 2012), as well as at least 5 chapters of the IPCC WG1 AR5 report (Hartmann et al. 2013; Bindoff et al. 2013; Collins et al. 2013; Church et al. 2013; Christensen et al. 2013) and significant parts of at least 10 chapters of the IPCC WG2 AR5 report (….). We note additionally, that several other chapters of past IPCC reports are providing 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. In addition, the fact that changes at 1.5 °C global warming was not a focus of past IPCC reports means 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. Section 3.2.4 presents the methods applied to address avoided impacts in Section 3.6. Finally, in Section 3.2.5, we present the approach followed to identify "hot spots" of changes between climate at 1.5 °C vs 2 °C global warming. Background on the IPCC calibrated language, which we apply 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

3.2.2.1 Overview

Climate models are necessary for the investigation of the climate system response to various forcings, to perform climate predictions on seasonal to decadal time scales, and to compute projections of future climate over the coming century. On these various time frames, global climate models or downscaled output from global climate models (Section 3.2.2.3) are also being 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, IPCC 2013), climate model simulations were generally used in the context of given "climate scenarios". This means that emissions scenarios (Nakićenović and Swart 2000) were used to drive climate models, providing different projections for given emissions pathways. The results were consequently used in a "storyline" framework, i.e. presenting the development of climate in the course of the 21st century and beyond if a given emissions' (and development) pathway was followed. Results were assessed for different time slices within the model projections, e.g. for 2016-2035 ("near term" (Kirtman et al. 2013), 2046-65 (mid 21st century, Collins et al. 2013), and 2081-2100 (end of 21st century, Collins et al. 2013). With a focus on climate at a given mean global temperature response (1.5 °C or 2 °C), methods of analysis needed to be developed and/or adapted for this report in order to use existing climate model simulations for this specific purpose.

In the following subsections we address the following topics. In Section 3.2.2.2, we first address the question of how to derive "climate scenarios" for given global warming limits (e.g. 1.5 °C or 2 °C warming). In

Section 3.2.2.3, we then present the climate models and associated simulations available to assess these changes in climate at given global temperature limits. In Section 3.2.2.4, we then introduce 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 for such assessments.

3.2.2.2 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 following aspects:

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 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, which is projected to increase by … m within the 21st century independent of 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. 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 …., see Chapter 2). 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 overshooting (see next point), include some probability of reaching a global climate warming higher than 1.5 °C or 2 °C. For this reason, 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 (?), see chapter 2).

C. Some of the "1.5 °C or 2 °C emissions scenarios" of Chapter 2 include temperature overshooting over 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 3-4 °C) before stabilization at 1.5 °C or 2 °C is achieved by 2100. In the years of overshooting, impacts would thus 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. We note that this topic cannot be addressed in its full complexity given the short timeline of the present report and the number of aspects that would need to be addressed. Most importantly, different overshooting scenarios may have very distinct impacts depending on a) the peak temperature at overshooting, b) the length of overshooting, c) the associated rate of changes of global temperature over the time period of overshooting. While we briefly address some of these issues in Sections 3.3 and 3.6 whenever literature was available to assess these questions, we note that this question will need to be addressed more comprehensively as part of the IPCC AR6 report.

D. It was not defined prior to this report what a "1.5 °C or 2 °C" climate exactly meant. This requires an agreement on a reference time period (for 0 °C warming) and the time frame over which the global warming is assessed (e.g. 1 year, 20 years, or longer time period). As highlighted in Chapter 1, the decision for this report was to define a 1.5 °C climate as the climate in a 20-year period which displays a 1.5 °C global mean warming compared to the time period 1861-1880. We have used this definition in all assessments of this chapter. We note that this implies that mean temperature of a "1.5 °C climate" can be regionally and temporally much higher (e.g. regional annual temperature extremes displaying a warming of more than 6 °C, see Section 3.3).

Because of the short timeline of the SR15 report, 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 would need 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, we provide an assessment on this topic as part of the cross-chapter box *[location TBC]*.

For the assessment of transient responses in climate at 1.5 °C vs 2 °C and higher levels of warming (Section 3.3), this assessment generally uses the same approach as Seneviratne et al. (2016), which consists of sampling the response at 1.5 °C global temperature warming from all available global climate model scenarios for the 21st century. This approach is also referred to as "time sampling" approach (James et al. 2017). Alternatively, pattern scaling, i.e. a statistical approach deriving relationships of specific climate responses as a function of global temperature change can also be used. Some assessments of this chapter are also based on this method. Its disadvantage, 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) and known projected changes at 3 °C or 4 °C (see Section 3.2.2.4).

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. Note nonetheless that for some variables (temperature and precipitation extremes) evidence 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 not available at present.

3.2.2.3 Climate models and associated simulations and datasets 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), i.e. they entail a comprehensive representation of Earth system processes, including biogeochemical processes.

In many cases, 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). 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, 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 (SD) is another approach for downscaling information from global climate models to higher resolution. The underlying principle of SD 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). More details on SD approaches are provided in Section 3.2.3.2.

There are various sources of climate model and downscaling 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 report was mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. In addition, there are results from coordinated regional climate model experiments (CORDEX), which are available for different regions.

[Other topics that will discussed in the FOD]

Pre-CMIP6 simulations: Global simulations already run before the SR15 publication deadline which consider some aspects of CMIP6 (e.g. driven with Chapter 2 scenarios, etc.)

- Other models available to assess changes in regional and global climate system: e.g. models for sea level rise, hydrological models for floods, droughts, and freshwater input to oceans, cryosphere/snow models, models for sea ice, models for glaciers and ice sheets [no details but references to relevant prior IPCC chapters]

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

As highlighted in previous IPCC reports, detection and attribution is an approach commonly 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). We refer the reader 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. We note that in the IPCC framework, “attribution” means strictly “attribution to anthropogenic greenhouse gas forcing”. In some literature reports, in particular related to impacts, the term “attribution” is sometimes used in the sense of an observed impact that can be attributed to observed (regional or global) change in climate, however, 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, we note 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 our 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 part from regional and global climate changes that have already been detected and attributed to human influence. 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, i.e. 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. We note that such assessments are for transient changes only (see Section 3.2.2.2).

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

3.2.3.1 Overview

Impacts are observed from datasets that are used to understand the underlying processes thanks to the development of reliable models. These models must be designed, parameters must be estimated and boundary condition set up by using data of high quality. Independent data must be used also to check the quality of the model to reproduce some present states or very different states chosen in a more or less far past (paleodata). These models are necessary to understand the complex functioning of the systems and to project future changes and then assess the risks related to changes.

The point of departure for the assessment of the analysis of impacts are local observations of physical and biological systems in all the parts of the world. The approach is inductive. Local data are collected and correlations between variables characterizing the system of study and climatic variables (mainly temperature and precipitation) are established. So syntheses by types of systems and by regions enable generalization in some way. For example, field and satellite measurements indicate substantial changes in freshwater and terrestrial ecosystems in many areas. Vegetation productivity has systematically increased over the past few decades. These changes correspond to expectations, based on experiments, models, and paleoecological responses to past warming. The particular strength of warming over the last 50 years further facilitates attribution of a major role of climate change. But a robust attribution of these changes to warming needs a better assessment of causal relationships, which is most often done using models. Signals emerging at the regional or global scale are also acknowledged as robust and may be related to global forcings.

The global distribution of observed impacts shown in AR5 (WGII chap 18) demonstrates that analyses can now detect impacts in systems strongly influenced by confounding factors and hence where climate change plays only a minor role. Enhanced research efforts would probably add additional observations of impacts with a minor, but important, role of climate to the global map.

Cascading effects must also be taken into account. Changes in atmospheric and ocean properties of the climate have driven changes in the cryosphere, on the land surface, the land subsurface, and the ocean surface. These changes have in turn led to changes in multiple aspects of hydrology and ecosystems, and in some regions changes in these systems have impacted human livelihoods. In all these cases, confidence in the role of climate change decreases for effects further down each impact chain.

3.2.3.2 Definition of a "1.5 °C or 2 °C impact projection"

As 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 needs specific methodologies. Schleussner et al. (2016) have calculated the differential effect of 1.5 °C and 2 °C global warming for the assessment of water availability and agricultural impacts. The assessment is based on an ensemble of simulations derived under the RCP8.5 scenario, using time slices centred around these specific levels of warming ("time sampling" approach that is mostly used in this chapter for transient projections of changes in climate at 1.5 °C, see Section 3.2.2.2). Schleussner et al. (2016) used the statistical comparison of the effects of both levels to conclude on their significance.

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). However, only few such simulations are available at the time of writing.

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.

3.2.3.3 Modelling approaches

Impact models are particularly important to simulate the functioning of the natural and human systems in response to climate changes. These include hydrological models and catchment basin models for water resources, vegetation dynamic models, soil models, ocean geobiochemical models, epidemiological models for health impacts, land use and land cover models, etc. Impact models often use output of regional or global climate models (see section 3.2.2.3) as input, which thus allows the computation of projected impacts (e.g. Schewe et al. 2014; Rosenzweig et al. 2014; Guiot and Cramer 2016).

Dynamical and statistical downscaling of climate models (see also Section 3.2.2.3) is particularly important for assessing impacts, given that these generally happen at a smaller scale than that simulated by global climate models. We note that while they produce climatic information at scales finer than the initial projections, both dynamical and statistical downscaling involve additional information, data, and assumptions, leading to further uncertainties and limitations of the results. This is particular true for SD because the relationships are calibrated on present-day climate and thus do not account for possible changes in climate regimes, which could affect the links between the coarser-scale and local-scale climates. In addition to issues related to resolution and model complexity, errors and uncertainties arise from observational uncertainty in evaluation data and parameterizations, choice of model domain and application of boundary conditions (driving data). In the case of SD, sources of model errors and uncertainties depend on the choice of method, including the choice of the predictors, the estimation of empirical relationships between predictors and predictands from limited data sets, and also the data used to estimate the predictors (Frost et al. 2011).

In many cases, the impacts of climate change will be experienced more profoundly in terms of the frequency, intensity or duration of extreme events (e.g., heat waves, droughts, extreme rainfall events). Extreme events are realizations of the tail of the probability distribution of weather and climate variability. They are higher-order statistics and thus generally more difficult to realistically represent in climate models. Shorter time scale extreme events are often associated with smaller scale spatial structure, which may be better represented as model resolution increases (Seneviratne et al. 2012). There is an increasing number of studies of downscaling of extremes (e.g., Katz et al. 2002; Monier and Gao 2015; Vrac and Naveau 2007; Wang et al. 2008; Emanuel et al. 2008).

3.2.3.4 Detection & attribution methods

Separation of drivers (anthropogenic climate change versus natural factors or other anthropogenic factors) from a responding system is a crucial element of formal detection and attribution analysis. The wealth of observations in ecological systems permits the application of quantitative tools for synthesis assessment of detection and attribution (Root et al. 2005). These tools include associative pattern analyses (e.g., Rosenzweig et al. 2008) and regression analyses (Chen et al. 2011), which compare expected changes due to anthropogenic climate change across multiple studies against observed changes (WGII, box 18-1).

3.2.3.5 Synthesizing aggregated impacts

To synthesize its findings in support of a risk analysis the IPCC developed the “Reasons for Concern” (RFC) concept (Smith et al. 2001), which was extensively adopted in IPCC AR4 and elaborated in (Smith et al. 2009). The goal is to establish, qualitatively, the evidence of impacts already observed that are relevant to these categories (see Glossary). The first RFC (risks to unique and threatened systems) is concerned with the potential for increased damage to systems. The second RFC is related to extreme events, which have substantial consequences on ecosystems and societies. The third RFC focuses on the disparities of impacts between regions, countries, and populations. The fourth RFC is associated with aggregate impacts, i.e. economic impacts, damages, and risks that are specifically driven by climate change at a globally aggregated level. The fifth RCP is associated with large-scale singular events or tipping points, which may be accompanied by very large impacts. The AR5 has presented the risk associated to these RFC with burning embers diagrams for which the colours vary from white (undetectable risk), yellow (moderate risk), red (high risk), to purple (very high risk), according to the global warming level.

Another method used to present the risk associated to environmental changes is the planetary boundary approach which aims to define a safe operating space for human societies to develop and thrive, based on our evolving understanding of the functioning and resilience of the Earth system (Steffen et al. 2015). The results are presented on a circular diagram with a colour gradient related to the risk probability. The operating space may be defined on the basis of the various impacts and risks analysed in this chapter: water resource (quality, quantity), ecosystem services, food security, human health, human security, etc.

3.2.4 Assessing avoided impacts at 1.5 °C vs. 2 °C and higher levels of warming

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

3.3.1 Global changes in climate

3.3.1.1 Introduction

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. 2016b; Seneviratne et al. 2016; Wartenburger et al.). 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). Table 3.1 provides a summary of the main global changes in climate associated with a 1.5 °C global warming as assessed in the following subsections.

3.3.1.2 Global changes in temperature and precipitation

3.3.1.2.1 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 (Chapters 1 and 2). At the time of writing 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 few exceptions, most land regions display stronger trends in the global mean average, and by 2012, i.e. with a warming of ca. 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.

[INSERT FIGURE 3.1 HERE]

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)

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 supplementary 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 be 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.

An area in which substantial new literature is available since the AR5 is the global mean surface temperature trend during the so-called "global warming hiatus" (Stocker et al. 2013; Karl et al. 2015; Lewandowsky et al. 2016). This term was used to refer to an apparent slowdown of GMST warming since 1998. Recent publications have highlighted that this "slow-down" was possibly overestimated at the time of the AR5 due to issues with data corrections, in particular related to coverage (Cowtan and Way 2014; Karl et al. 2015; see Figure S3.2). In addition, there is evidence that this response was due in part to lower surface heating of the oceans but higher heating at depth, and thus that it did not reflect any 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), unabated increase in global sea level (Stocker et al. 2013), and a continued strong warming of hot extremes over land (Seneviratne et al. 2014) during that time period. For this reason, as pointed by some authors (e.g. Seneviratne et al. 2014; Yang et al. 2016), one should note that the GMST warming is not necessarily the most accurate measure to assess the level of greenhouse gas forcing on the Earth's climate system in a transient climate context.

Observed global changes in the water cycle 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, it 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).

3.3.1.2.2 Projected changes at 1.5 °C

Figure 3.2 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 3.2. 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 3.2.1, 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 (see Supplementary Figure S3.3).

[INSERT FIGURE 3.2 HERE]

Figure 3.2: Projected local mean temperature warming at 1.5 °C global warming (left), 2.0 °C global warming (middle), and difference (right). 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 Supplementary Figure S3.3).

Figures 3.2 and 3.3 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 3.1). In addition, as highlighted in Seneviratne et al. (2016), this feature is even stronger for temperature extremes (Figure 3.2; see also Section 3.3.2 for a more detailed discussion). Second, even for a small change in global warming (0.5 °C) 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 3.2) 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.

[INSERT FIGURE 3.3 HERE]

Figure 3.3: 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). 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 Supplementary Figure S3.4).

Figure 3.4 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 3.1 and 3.2 (see also Methods, Section 3.2.2). The differences for precipitation are less clear than for temperature mean and extremes. 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, although the differences are generally small between 1.5 °C and 2 °C global warming (Figure 3.4).

[INSERT FIGURE 3.4 HERE]

Figure 3.4: 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). 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 Supplementary 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 already between 1.5 °C and 2 °C, both on global and regional scale (Fischer and Knutti 2015; see also Figure 3.5, left). The differences are more moderate for heavy precipitation (Figure 3.5, right), also consistent with the analyses in Figure 3.4.

[INSERT FIGURE 3.5 HERE]

Figure 3.5: 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)].

3.3.1.3 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° and 2° 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 HappiMIP experiment *[Not yet available]*, Mitchell et al. (2017). More details on the applied methods are provided in Section 3.2.

[INSERT TABLE 3.1 HERE]

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 over-shoot)**	**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. 3.3.1]	**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. 3.3.1]	Not yet availa-ble (Happi-MIP experi-ments)	Not yet availa-ble (Happi-MIP experi-ments)
Mean precipitation	**Globally*: Low confidence*** in global trends in mean precipitation [H13] ***Low confidence*** in trends in monsoons because of insuffi-cient 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

	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°
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 [assessment based on observed and attributed changes, and based on Fig. 3.3.2] **Regionally**: ***Likely*** increase in most land regions [Fig. 3.3.2; Section 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 [Fig. 3.3.2; Section 3.3.2] **Globally**: - **Regionally: *Likely*** higher warming than 2°C in most land regions (on average between 3°-8° depending on region and considered extreme index) [Fig. 3.3.2; Section 3.3.2]	Not yet availa ble	Not yet availa ble
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 [Fig. 3.3.3]	**Globally: *Medium confidence*** in further increase in more regions than in regions with decrease [Fig. 3.3.3]	Not yet availa ble	Not yet availa ble

	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°
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 [assessment based on observed trends, Fig. 3.3.3, Fig. 3.3.4.X, and Section 3.3.4]	**Globally:** *Medium confidence* that some trends patterns could be enhanced, in particular in the Mediterranean region [assessment based on observed trends, Fig. 3.3.3, Fig. 3.3.4.X, and Section 3.3.4]	Not yet availa ble	Not yet availa ble
Storms and tropical cyclones	**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 availa ble	Not yet availa ble

	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°
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 availa ble	Not yet availa ble
Winds	**Globally:** ***Low confidence*** in trends due to insufficient evidence [S12]	**Globally:** ***Low confidence*** in the causes of trends due to insufficient evidence. [S12]	**Globally:** ***Low confidence*** in projected changes [based on observed and attributed changes and lack of assessments for 1.5°C global warming]	**Globally:** ***Low confidence*** in projected changes [based on observed and attributed changes and lack of assessments for 2°C global warming]	Not availa ble	Not availa ble
Snow 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 availa ble	Not availa ble

	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°
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 availa ble	Not availa ble
Ocean circulation	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	Not availa ble	Not availa ble
Sea ice	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	Not availa ble	Not availa ble
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 availa ble	Not yet availa ble

3.3.2 Temperature on land, including extremes

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

3.3.2.1 Observed and attributed changes

The AR5 assessed that it is *certain* that globally averaged land surface air temperature has risen since the late 19th century and that this warming has been particularly marked since the 1970s (Hartmann et al. 2013). While the quality of temperature 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 3.3.1.2.1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature. 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 anthropogenic influence has *likely* contributed to temperature change in many sub-continental regions.

Regarding observed changes in temperature extremes, the IPCC SREX report assessed (Seneviratne et al. 2012) 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 (see also Table 3.1). It also assessed that it is *likely* that such changes have occurred at the continental scale in North America, Europe, and Australia, 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 Seneviratne et al. (2012) assessed 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.

3.3.2.2 Projected changes in temperature at 1.5 °C vs. 2 °C

We can expect that a further increase of 0.5 °C or 1 °C will be detectable because changes in mean and extreme temperatures can already be detected at global and also continental scale (see previous subsection), i.e. for a global warming of 1 °C.

We provide 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 3.6 displays for 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.), 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 the equilibrium response (corresponding to the RCP2.6 simulations).

[INSERT FIGURE 3.6 HERE]

Figure 3.6: Projected changes in annual maximum daytime temperature (TXx9 as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger et al.).

[INSERT FIGURE 3.7 HERE]

Figure 3.7: 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.).

We see 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 enhanced drying in these regions (see Section 3.3.4), 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. 2013a; 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 3.6).

Figure 3.7 displays similar analyses as Figure 3.6 but for the annual minimum nighttime temperatures, TNn. The mean response of these cold extremes display 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 3.8 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 3.6). The changes in the number of frost days are expectedly particularly strong in the Arctic (decrease of 60 days in some regions, i.e. about 2 months). These changes are also of high relevance for changes in snow and ice cover in the affected regions (see discussion of changes in snow and permafrost, and sea ice in Sections 3.3.8 and 3.3.11, respectively).

[INSERT FIGURE 3.8 HERE]

Figure 3.8: Projected changes in number of hot days (10% warmest days) and in number of frost days (days with T<0 °C) at 1.5 °C (left) and 2 °C (right) GMST warming, and their difference (right). Adapted from (Wartenburger et al.)

3.3.3 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 3.1.2, observed and projected changes in precipitation are more uncertain than for temperature.

3.3.3.1 Observed and attributed changes

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 have been provided (Seneviratne et al. 2012).

For monsoons, the SREX assessed that there is *low confidence* in trends in monsoons because of insufficient evidence (Seneviratne et al. 2012; see also Table 3.1). There are a few new available assessments (Singh et al. 2014), who showed 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 in precipitation at 1.5 °C vs. 2 °C

Section 3.3.1.2.2 summarizes the projected changes in mean precipitation displayed in Figure 3.4. 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. We note that the assessment of insignificant differences between 1.5 °C and 2 °C scenarios for tropical Africa is consistent with the results of Figure 3.4.

Regarding changes in heavy precipitation, Figure 3.9 displays projected changes in the 5-day maximum precipitation (Rx5day) as function of global temperature warming, using a similar approach as in Figures 3.6 and 3.7. 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. suggests that for Eastern Asia, there are substantial differences in heavy precipitation at 1.5 °C vs. 2 °C.

[More regional details to be added in FOD]

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 result 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) showed that future changes in the South American Monsoon System (SAMS) are increased in seasonal amplitudes, early onsets, late demises and durations of the SAMS. The simulations for this scenario project a 30% increase in the amplitude from the current level by 2045-50. In addition, the RCP8.5 scenario projects 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), we assess that 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.

[INSERT FIGURE 3.9 HERE]

Figure 3.9: 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.).

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 (Seneviratne et al. 2012). It also assessed 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 there is *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.

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 ca. 4 °C global warming) are uncertain in many regions, and also dependent on considered drought indices (e.g. Seneviratne et al. 2012; Orlowsky and Seneviratne 2013). Uncertainty is 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. Figure 3.10 from (Greve *XXXX*), 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 a wetting, 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 *XXXX*). 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 *XXXX*).

[INSERT FIGURE 3.10 HERE]

Figure 3.10: 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 *XXXX*).

3.3.5 Wind

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.

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. 2013b). 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 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.

3.3.6 Storms and tropical cyclones

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 result 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). It should be noted that these results are 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. This theory 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, uncertainties in quantitative changes are large (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.

3.3.7 Runoff and flooding

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

There has been progress since the 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 World’s 200 major rivers with negative trends outnumbering the positive ones. However, although streamflow trends are mostly statistically insignificant, they 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; Luo et al. 2016). Alkama et al. (2013) show 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) show 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 influences 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 analysis 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. 2015; 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). They show regional projected changes in flooding and extreme streamflow consistent with the projected patterns in precipitation.

[TBC: Results from projections for 1.5 °C global warming, new literature is expected]

3.3.8 Snow and permafrost

3.3.9 Ocean chemistry

Changing atmospheric gas concentrations as well as ocean temperature and mixing have resulted in profound changes to ocean chemistry (Andrews et al. 2013). Around 30% of CO_2 emitted by human activities has been absorbed by the ocean where it has combined with water to create a dilute acid (ocean acidification; IPCC WG1 AR5; Cao et al. 2007). Impacts on ocean chemistry increase with further addition of CO_2 from human activities.

Increasing levels of CO_2 in the atmosphere have decreased pH of the ocean by 0.1 pH units since the Preindustrial Period, as well as having changed the concentration of key ions such as protons, carbonate and bicarbonate (Haugan and Drange 1996). Total acidity and bicarbonate ion concentrations have increased by around 30%, while carbonate concentrations have decreased by a similar amount (Cao and Caldeira 2008; AR5 WGII Box CC-OA; WGI AR5 Box 3.2; WGI AR5 Figure SM30-2).

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; Honish et al. 2012). Periods of high atmospheric concentrations of CO_2 in the paleo-record have been accompanied by a major reduction in calcifying ecosystems such as coral reefs (e.g. KT Boundary; (Veron 2008). The time taken to reverse ocean acidification by continental weathering processes takes tens of thousands of years (Honish et al. 2012) and hence consideration must be given to the irreversibility of the emerging risks associated with changes to ocean chemistry.

Acidification of the ocean is not uniform across the ocean and is highest in areas where temperatures are lowest (Polar Regions, low temperature, increased CO_2 solubility), or near upwelling areas or areas where coastal effluents affect the chemistry of seawater (Doney et al. 2009). There is a growing number of impacts on biological systems in the ocean from these changes (Kroeker et al. 2013; Gattuso et al. 2015). Ecosystems characterized by high rates of calcium carbonate deposition (e.g., coral reefs, some plankton communities) are sensitive to decreases in the saturation states of the two forms of calcium carbon crystals (i.e. aragonite and calcite).

Other aspects of ocean chemistry have been changing. Oxygen concentrations vary regionally, and are highest at 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 increase the frequency of areas ('dead zones') where oxygen has fallen to levels which are unable to sustain oxygenic life (Altieri and Gedan 2015). Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e. evaporation and inundation). 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).

Existing risks are likely to rise steadily as atmospheric CO_2 concentrations increase (e.g. risks to 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, 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). Risks associated with declining oxygen have not been comprehensively assessed, and should be the focus of future research.

3.3.10 Ocean circulation and temperature (e.g., 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.*XX* °C, 0.*YY* °C, and 0.*ZZ* °C for the Indian, Atlantic and Pacific oceans respectively), with the greatest changes occurring at the highest latitudes (Artic - Equator: +0.*TT* °C).

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 Engelbrecht et al., 2017 *in prep*). 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 (Engelbrecht et al., 2017; *in prep*).

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.

Risk for biological and human systems in coastal and low-lying areas will escalate through 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.

The risk of negative consequences of reduced upwelling, as well as the slowing thermohaline circulation of the ocean, increase as 1.5 °C is reached. With that comes an increasing risks of disruption to food security in many regions, along with associated changes to human well-being. These changes are very likely to influence human systems, which will also benefit from a slowing and stabilisation of ocean temperature by mid-century onward. Under these conditions of stabilisation, risks and costs associated with adaptation to climate change are significantly reduced.

3.3.11 Sea ice

3.3.12 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. 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.

It is virtually certain that GMSL will continue to rise beyond 2100. This is true of 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 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 (Zichfeld, Bouttes).

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 (e.g Zichfeld, Bouttes). 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 (Figure 13.11). 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). 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 between 45 and 85% of current ice volume will survive to the end of the century (Clark et al., *XXXX*). Mass lose 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.

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, Furst 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. 2013to be the ‘most realistic’ such model). Furst et al 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. (*XXXX*) 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.

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. De Conto and Pollard (*XXXX*) and Golledge et al. (*XXXX*) both suggest that RCP2.6 is the only RCP scenario leading to millennial-scale contributions to sea level of below 1 m, and de Conto and Pollard (*XXXX*) indicate a contribution to GMSL rise of 0 to 0.22 m by the end of the century. Cornford et al. 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., Clark et al.) are greater in A1B which compensates the increased outflow and leads to a reduced contribution to GMSL rise. The difference between these two set of projections can most likely be attributed to both the numerical treatment of grounding-line migration (e.g., Durand and Pattyn) and detailed forcing employed (Cornford used results from regional atmosphere and ocean modelling, including Helmer et al.). De Conto and Pollard (*XXXX*) introduce a new mechanism by which ice can be lost rapidly from Antarctica (cliff collapse), however amount of surface warming required to initiate this process seems very unlikely for reduced emission scenarios, such as RCP2.6. Levermann et al. (*XXXX*) develop response functions for the ice sheet based on the idealised SEARISE inter-comparison (Bindschadler et al.) 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 *XXXX*) 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.

3.3.13 Identified hot spots based on regional climate changes and associated hazards.

3.4 Observed impacts and projected risks in natural and managed ecosystems

3.4.1 Introduction

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. 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:

- 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.

3.4.2 Terrestrial and wetland ecosystems

3.4.2.1 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 (AR5-WGII Chapter 4).

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. 2015). 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.

3.4.2.1.1 Palaeoecological evidence

The paleoecological records provide high confidence that large global climate change, comparable in magnitude to that projected for the 21st century, can result in large ecological changes, including large-scale biome shifts, reshuffling of communities, and species extinctions (Lorenzen et al. 2011). Most of the world regions have known a significant land use after 250 years BP, except Europe, Mediterranean Basin, Asia, Central America where significant changes occurred 1000 to 3000 years ago (Ellis et al. 2013).

The regional annual mean warming during the Holocene was about 0.5 °C to 1.5 °C above preindustrial in some continental-scale regions (AR5-WGII Chapter 4). In some regions (NW Europe, East Canada, south Africa) the warming largely passed the +2 °C and even +3 °C, but in others, it is rather a cooling (Mediterranean, west North America) (Bartlein et al. 2011). So, the direct analogy with the paleoecological record is unwarranted because past climatic changes were not global and because future climate change will interact with other global changes such as land use change, invasive species, pollution, and overexploitation of natural resources, which are projected to be more intense in the future. The paleoecological record and models provide high confidence that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2 °C to 3 °C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Armsworth et al. 2015).

Paleoecology may also help to throw light on species extinction. So the St Paul Island in Alaska mammoth seemed to extinct because of the synergistic effects of shrinking island area (due to sea-level rising) and freshwater scarcity due to climate change in mid-Holocene (Graham et al. 2016). This is confirmed for the Mediterranean Islands (Médail 2017). This illustrates the vulnerability of small island populations to environmental change, even in the absence of human influence.

3.4.2.1.2 Global overview of impacts on major ecosystem components and functions

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 (Jones et al., 2009) (AR5-WGII-chap4).

Phenology:

A combined analysis of 203 species suggests NH spring advancement of -2.8 ± 0.35 days per decade (Parmesan, 2007). A global review by Parmesan and Hanley (2015) confirms this fact for 72% of the species, but they highlight that the response is often more complex and need community-level experiments. For plants, remote sensing studies show that, between 30°N and 80°N, the start of growing season significantly advanced, while the growing season end was delayed (Jeong et al., 2011). It is confirmed for some regions (Wu et al. 2016; Dugarsuren and Lin 2016; Crabbe et al. 2016) but not everywhere (Zhang et al. 2016; Liu et al. 2016). Keenan and Richardson (2015 Global Ch Biol) showed that, for US tree species, the timing autumn senescence is significantly correlated with timing of spring bud burst, more than autumn temperature, confirming the key role of the spring phenology for future climate change impact. For animals, although a number of non-climatic 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). A global synthesis for trout (Kovach et al. 2016) shows that the changes in hydrology are more important for trout demography and growth that changes in temperature.

Since 1985, timing of phenological spring, summer and autumn in Harbin, Heilongjiang Province of China have been advanced by 7 days, 6 days and 19 days respectively, while timing of phenological winter has been delayed by 2 days. Temperature changes before the majority of phenophases is probably the main reason for the changes of phenological season during 1985-2012 (Xu et al. 2015).

Primary productivity:

Primary production is fundamental to the global carbon cycle and underpins provisioning ecosystem services such as food, timber, and grazing. 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. 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. After a typhoon (which are projected to be more frequent and more intense), the soil is enriched with organic matter and nutrients for several months, which provide better conditions for the spread of fast-growing species (Wang et al. 2016).

Biomass and carbon stocks:

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 interannual variability of global land C sink has grown by 50-100% over the past 50 years and that interannual land C sink variability is most strongly linked to tropical nighttime warming, likely through respiration. Spring warming has largely stimulated ecosystem productivity at latitudes between 30 degrees and 90 degrees N, but suppressed productivity in other regions (Xia et al. 2014). The analysis of long-term forest dynamics research sites (CTFS-ForestGEO) shows a significant aboveground biomass increase and a positive trend in abundance of lianas in the tropical forests between 2000 and 2012 (Anderson-Teixeira et al. 2015). From 1901 to 2010, Fisher et al (2015) assess from nine land surface models that the African rain forest was an increased sink of carbon but with also an increasing uncertainty. A green effect due to fertilization is often observed in the tropics (Murray-Tortarolo et al. 2016; Zhu et al. 2016). Yang et al. (2015) show a significant upward trend between the mid-1980s and the 2000s as a result of more frequent fires in ecosystems with high carbon storage, such as peatlands and tropical forests (reduction of the carbon sink of global terrestrial ecosystems by 0.57 PgC/yr. Lal (2014, Soil Carbon) 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. (Munoz-Rojas et al. 2016) demonstrated increased rates of soil respiration in semi-arid ecosystems in burnt areas versus unburnt ones.

Evapotranspiration and water use efficiency: Summary from AR5

AR5 Chapter 4 concluded that there has been no significant evapotranspiration trend since approximately 2000, possibly due to soil moisture limitation and that intrinsic water use efficiency (iWUE) increased since preindustrial times (1850 or before) at several forest and grassland sites (Penuelas et al., 2011; (Silva and Anand 2013) but iWUE decreased by 30% between 1950 and 2014 in phosphorus limited subtropical forests (Huang et al, 2015; New Phyt). Remote-sensing data reveals that land-cover and land-use change in recent years has led to a decline in global water use efficiency Tang et al. (2014). Mediterranean summertime ecosystem WUE was about 66% higher during Mistral northerly wind than other days, so that the historical decrease of Mistral frequency in Sardinia reduced the estimated summertime WUE by 30% (Montaldo and Oren 2016).

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. Uncertainties concerning attribution to climatic change remain important. Responses at the "trailing edge" of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the "leading edge" (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes and difficulties in detecting local extinction with confidence (Thomas et al., 2006). Average range shifts across taxa and regions were approximately 17 km poleward and 11 m up in altitude per decade, velocities that are two to three times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin et al., 2007), but these responses differ greatly among species groups. In the tropics, habitat loss and land-use change had the largest impact on species richness, whereas in the boreal forest and Northern temperate forests, species invasions had the largest impact on species richness (Murphy and Romanuk 2014).

Of the more than 800 global extinctions documented by the International Union for Conservation of Nature (IUCN) in its red list, only 20 have been tenuously linked to recent climate change (Cahill et al., 2013). Using the same red list, Taylor and Kumar (2016, Trop Conserv Sc) have investigated literature for terrestrial vertebrate and vascular plant species, in the Pacific Islands, and found that on 305 species, 42 were near threatened, 78 were vulnerable, 44 were endangered, and 34 were critically endangered. This is confirmed by Wiens (2016) who found 47% of local extinctions, especially in tropical regions, in animals (relative to plants), and in freshwater habitats. The extinction of the Bramble Cay Melomys in the Torres Strait has been attributed as likely due to climate-change induced increases in storm surges and sea level rise which have led to habitat destruction (Gynther, I., Waller, N. & Leung 2016) see also Section 3.3.6 where observed changes in storm surges are discussed).

3.4.2.1.3 Observed impacts on major regions and ecosystem types

Regions that exhibit relatively high projected temperature changes (often greater than the global mean by 50% or more) are high-latitude Northern Hemisphere land areas and the Arctic, especially in December–January–February, and Central North America, portions of the Amazon, the Mediterranean, and Central Asia in June–July–August (AR5 Chapter 4, p. 1159). Precipitation patterns are much more heterogeneous, but semi-arid and arid regions know decrease of precipitation (winter in North Africa, spring in East Africa, austral summer in south Africa, low to medium confidence).

Regional impacts – Summary from AR5

WGII AR5 noted that the observed impacts of climate change on terrestrial ecosystems are particularly pronounced:

- In Africa with emerging evidence on shifting ranges of some species and decrease of water resources (with impact on the agriculture) particularly due to elevated carbon dioxide, climate change beyond the effects of land use change and other non-climate stressors (high confidence)
- In Europe, effects are measurable on the distribution, phenology, and abundance of animal, fish, and plant species (high confidence)
- In many parts of Asia, terrestrial systems have responded to recent climate change with shifts in the phenologies, growth rates, and the distributions of plant species, and with permafrost degradation (high confidence)
- In Australasia, recent extreme climatic events show significant vulnerability of some ecosystems and many human systems to current climate variability (very high confidence).
- North American ecosystems are under increasing stress from rising temperatures, carbon dioxide (CO2) concentrations, and sea levels, and are particularly vulnerable to climate extremes (very high confidence)
- In some areas of Antarctica and the Arctic, impacts on terrestrial and freshwater ecosystems are due to ecological effects resulting from reductions in the duration and extent of ice and snow cover and enhanced permafrost thaw (*very high confidence*).

New literature confirms these findings or attributes additional changes in terrestrial ecosystems in tropical regions: NPP decrease associated to dryness (Shufen et al. 2015), recent increase of sink of carbon in rain forests (Fisher et al, 2015), but decrease sink after forest fires Yang et al. (2015), increase of species extinctions and endangering (Wiens 2016). In the arctic ecosystems, (Mortensen et al. 2014) (2015; Pol Biol) 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; An Rev Ecol Evol Syst) show that (1) delays in winter onset affect tundra carbon balance, faunal hibernation, and migration but are unlikely to lengthen the plant growing season, (2) mild periods in winter followed by a return to freezing have negative consequences for plants and invertebrates. 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). In very man disturbed ecosystems, such in China or Ethiopia, the attribution to climate change is more difficult: China (Xu et al. 2016; Piao et al., 2015 Glob Ch Biol; Jacob et al. 2015). In semi-arid biomes of the SW USA, recent drought conditions had a strong negative impact on vegetation production (Barnes et al. 2016).

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 regions worldwide, 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 ($p < 0.05$) while 32% vegetation was affected by air temperature ($p < 0.05$). The spatial patterns of the normalized difference vegetation index (NDVI) variations in Central Asia were consistent with the spatial patterns of precipitation variations. However, the temperature responses of vegetation NDVI differed across the northeast and the mountainous regions in Central Asia (Zhang et al. 2016).

Forest and Woodlands – Summary from AR5

WGII AR5 concluded that deforestation has slowed over the last decade, including in the tropical regions. Nevertheless, the carbon taken up by intact and regrowing forests was counterbalanced by a release due to land use change due mostly to tropical deforestation and forest degradation. 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 and lack of adaptation. The world's temperate forests act as an important carbon sink (robust evidence and high agreement), representing 65% of the global net forest carbon sink. Moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods (*medium evidence, high agreement*). Keenan (2015) did a review of literature on climate change impacts in forest management. He found that 76% of 1172 papers involved assessment of climate change impacts or the sensitivity or vulnerability of forests to climate change. Laurance (2015, Ann Miss. Bot Garden) highlights that tropical forest mainly threatened until now by industrial exploitation and human population growth is now also threatened by climatic change and many species are harmed by emerging pathogens. All the dangers often operate in concert. Shestakova et al. (2016 PNAS) demonstrate how an intensified climatic influence on tree growth during the last 120 years has increased spatial synchrony in annual ring-width patterns within contrasting (boreal and Mediterranean) Eurasian biomes and on broad spatial scales.

Dryland ecosystems: Savannas, shrublands, grasslands, deserts – summary from AR5

According to 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. 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, Aq Inv). The area percentage of actual grassland 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; JGR) found that the rainy season length has strong nonlinear impacts on tree fractional cover of dry forests and savannas.

Rivers, lakes, wetlands, peatlands: summary from AR5

According to 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 (EWC) of the alpine ecosystem of the Source Region of the Yellow River (SRYR) has a slightly decreasing trend of -1.15 mm/a during the period of 1981-2010.In the southeast of the SRYR with sub-humid climate, both decreased precipitation and increased potential evapotranspiration induce the significant negative changes in the EWC. Meanwhile, in the northern part with semi- arid climate, increased precipitation is the main climatic factor leading the EWC to increase (Yunhe et al. 2016).

Tundra, alpine and permafrost systems

According to 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. 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 HydroEarthSysSc). Both of these processes facilitate conditions for woody species establishment in tundra areas. 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

(Vongraven and Richardson, 2011).

3.4.2.2 Projected risks and potential adaptation (including limits)

3.4.2.2.1 Global overview of projected risks to major ecosystem components and functions

The focus of this section is to compare projected risks to terrestrial and wetland ecosystems at 2 versus 1.5 ºC warming. However, the outcomes of emission reduction strategies (in terms of projected global warming) are probabilistic: therefore, the benefit of a mitigation strategy aimed at constraining warming to 1.5 ºC is also a greatly reduced chance to incur the risks associated with 4 ºC warming

Biome Shifts: Summary from AR5

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 2 °C warming than under 1.5 °C warming (Figure 3). 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 1.6 °C 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).

Changes in species range, abundance and extinction: Summary from AR5

Fischlin *et al* 2009 (AR4 Chapter 3) 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) also mentioned these risks. 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.

Settele et al. (2014) state 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’.

A recent update to Warren et al. (2013) incorporating 80,000 species is included in (Smith *et al.* in prep) explores the outcome for 2 versus 1.5 °C warming. At 2 °C, 15+/-3% animals and 19+/-3% plants are projected to lose 50% or more of their climatic range, whilst at 1.5 °C warming this falls to 7+/-2% animals and 9+/-2% plants. Constraining warming to 1.5 °C thus avoids approximately 53% of the impacts that would otherwise occur at 2 °C warming. The study also identifies areas where at least 75% of species currently present (and included in the simulations) can remain under a changed climate. It finds that the increase in the area of climatic refugia for plants (under 1.5 ºC vs. 2 ºC) is equivalent in size to the current global protected area network overall. These benefits accrue in the absence of temperature overshoot – if overshoot occurs, for example to, these benefits would be reduced or even negated, depending on the length of time of the overshoot (Smith *et al.* in prep).

Biomass and carbon stocks: Summary from AR5

Irreversible regional scale change: Summary from AR5

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’ was identified (Settele et al. 2014).

Invasive species: Summary from AR5,

Constraining warming to 1.5 °C would significantly reduce the risk associated with the spread of invasive species, for example 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)

Limits to adaptation: Summary from AR5

Oppenheimer et al. (2014) (AR4 Chapter 19) project that unique and threatened systems would be unable to adapt to levels of warming exceeding 2 ºC. Settele et al. (2014) summarise how rates of climate change also affect the ability of terrestrial ecosystems to adapt, and show how many species will be unable to track suitable climates under mid and high rates of warming during the 21st century. Constraining warming to 1.5 ºC within this century, without an overshoot, would also reduce the rates of warming, increasing the potential for these species to track their climate space and for unique ecosystems to adapt. It will also allow more time for conservation management strategies to be enhanced to allow for changing climates (Warren et al.) *submitted*)

3.4.2.2.2 Projected risks to major regions and ecosystem types

Regional Risks

Projected risks exist for all geographical regions for warming of 1.5 °C or 2 ºC. However, projected biome shifts are already extremely severe in the Artic and in alpine regions at 1.5 ºC warming and increase further for 2 ºC warming (Gerten et al. 2013 Figure 1b,). Island biodiversity is also projected to be at risk.

Forest and Woodlands

Projected impacts on forests including increases in the intensity of storms, wildfires and pest outbreaks were also highlighted (Settele et al. 2014), 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 1.5 ºC than at 2 °C).

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 °C and 2 ºC warming (Schleussner et al. 2016b; Guiot and Cramer 2016b). Using a large ensemble of climate and hydrological model projections the former identifies that at 1.5 ºC warming, median water availability is projected to decline by 9% relative to the period 1986-2005 (by which time warming of 0.6 °C above pre-industrial levels had occurred, see IPCC 2013) in comparison to 17% at 2 ºC, whilst the length of dry spells increases by 7% under 1.5 ºC warming compared to 11% under 2 °C warming. The latter finds that only 1.5 ºC warming constrains the region's climate to lie within Holocene climate variability – whilst 2 ºC warming results in transformation of 12-15% of the Mediterranean biome area. 4 ºC 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.

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.

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.

Tundra, alpine and permafrost systems

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

3.4.3.1 Observed impacts

3.4.3.2 Projected impacts

3.4.4 Ocean systems including coral reefs

3.4.4.1 Observed impacts

3.4.4.1.1 Background
Around 71% of the Earth's surface is covered by an ocean that is a critical component of the Earth's climate system (AR5 WGI Ch3). Not only does the ocean play a dominant role in maintaining stable global temperatures, climates and atmospheric gas content, but the ocean is home to vast number of organisms and ecosystems which provide ecosystem goods and services that are worth trillions of dollars ($US) each year (BCG 2016). Many of the most disadvantaged communities depend on the ocean for food and income, with inequities projected to increase as coastal and ocean resources deteriorate under the influence of climate change and other human pressures (Spalding et al. 2014).

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 rising atmospheric greenhouse gas concentrations on ocean habitats, ecosystems and human users. Knowledge of basic ocean systems, as well as threats and challenges, have increased significantly over the past decade. The world's largest habitat, the deep sea, remains one of the least understood on the planet, despite the fact that there is increasing evidence that's changes in the deep ocean are potentially momentous 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.

3.4.4.1.2 Impacts arising from rising ocean temperatures
Ocean organisms and ecosystems are very sensitive to changes in temperature that differ from those to which they have adapted to over evolutionary time. Increased temperatures can influence physiological processes such as respiration, photosynthesis, gas exchange, and calcification, with the rate of these processes rising with temperature until a threshold level is attained, at which time rates of most physiological processes will decline rapidly (Portner et al. 2014). While there is some understanding of physiological and ecological thresholds, more work needs to be done to understand how, why and when thresholds are likely to occur. These responses to temperature can drive significant changes in organisms and ecosystems that include changes to community composition, food webs and ecosystem dynamics (Hoegh-Guldberg et al. 2014; Gattuso et al. 2015).

Organisms from phytoplankton to sharks are moving to higher latitudes as they warm, with implications for biodiversity, food webs, and ecosystem structure, with the implication that biodiversity will decrease at the equator and will increase at higher latitudes (Poloczanska et al. 2013). In other cases, responses to temperature can be abrupt, with ecosystems such as coral reefs, kelp forests and seagrass beds undergoing fundamental and sudden shifts in state (e.g. mass mortality events) at specific threshold temperatures. Threshold temperatures for many tropical organisms and ecosystems usually sit around 1 ^{o}C above the long-term summer maxima (relative to the period 1986-1992). Warming of the global ocean increases the frequency and extent to which these thresholds are exceeded.

Recent intensification of ecological impacts such as mass coral bleaching and mortality (and similarly, the progressive loss of kelp forests and other marine ecosystems) suggests that even attaining a long-term goal of an average global temperature that does not exceed 1.5 °C will still result in up to 90% of these important ecosystems disappearing over the next few decades (Frieler et al. 2012; AR5 WGII Ch30). As global temperatures rise from 1 °C to 1.5 °C above the preindustrial period, the risks of negative outcomes of these changes increase, with implications for ecosystem services such as fisheries, tourism, cultural values, and coastal protection. The exceptional warming of 2016 led to 20% of corals dying on the Great Barrier Reef (Hughes et al. 2017), with probably similar yet unmeasured amounts of change in many other coral reef systems.

Coral reefs provide important insights into the sensitivity of marine ecosystems, with considerable evidence that the additional 0.5 °C in temperature to 1.5 °C drives a further loss of 90% of reef-building corals (Hoegh-Guldberg 1999, Donner et al. 2006, Frieler et al. 2013). These changes strongly suggest that reducing non-climate stresses on coral reefs will be important to ensure that come corals survive until stabilisation around mid-century.

3.4.4.1.3 Impacts from changing ocean chemistry

Changes in ocean chemistry have the potential to cause profound effects on the biology and ecology of the ocean. While impacts such as mass fish kills from declining oxygen in the deep ocean are episodic, other impacts (ocean acidification) tend to occur gradually over time. Sub-chronic effects of changing ocean chemistry include ocean acidification influencing physiological processes such as calcification and decalcification, reproduction and development, growth, and primary productivity leading to significant changes in ecosystem structure and function (Portner et al. 2014; Kroecker et al. 2013). Given the importance of protons, oxygen, carbonate and bicarbonate ions to the biology of the sea, changing ocean chemistry comes with inherent risks for organisms, food webs and ecosystems within the ocean, and hence communities and industries (Gattuso et al. 2015).

Physiological responses to changing ocean chemistry (e.g. reduced calcification) lead to important ecological impacts (e.g. reduced reef growth, maintenance and hence shoreline protection) which are likely to, although profound, occur gradually (Dove et al. 2013). Impacts of changing ocean chemistry, therefore, despite their often-profound nature, are unlikely to produce sudden shifts in ocean ecosystems (with the exception of mass mortality events driven by more frequent and pervasive dead zones).

Given this, impacts from changes in ocean are likely to grow in size as the world travels from today's atmospheric carbon dioxide concentration (405 ppm) to those associated an average global surface temperature of 1.5 °C. The increase of concentrations of CO_2 to those associated with 2 °C and higher (> 450-500 ppm) will become increasing influential, with an increasing risk of fundamental and potentially irreversible negative changes across a broad scope of physiological and ecological processes. Changes in ocean chemistry and the impacts on biology are affecting industry (e.g. dead zones and fish kills => fisheries; changing ocean pH => coastal aquaculture: Feely et al.). While the consequences for human systems is poorly known, irreversibility plus the fundamental nature of these changes poses significant risks for the future.

3.4.4.1.4 Other climate change drivers

Increased sea temperatures are driving more intense storm systems, although the frequency of storms overall is not increasing. Intensifying storm systems are also contributing and increased frequency of destructive events which are impacting ecosystems such as coral reefs through the breakage of corals and the souring effects of waves and storm surge (De'ath et al. 2012). Other coastal ecosystems may be similarly affected by storms surge and waves (e.g. mangroves, seagrass). Sea level rise in low-lying and coastal areas are already changing the distribution of coastal vegetation, with ecosystems like mangroves and salt marsh moving landward as coastal areas flood.

Other factors such as changes to inundation present additional risks by changing the quality of coastal water quality through sediment and nutrients mobilized as part of an intensified drought-flood cycle. These threats are exacerbated by human activities such as coastal deforestation and farming methods that lead to increased erosion in the catchments of coastal rivers.

3.4.4.1.5 Impacts on fisheries

As discussed above, the distribution and potential catches of marine fishes and invertebrates are affected by changes in ecosystem drivers, including temperature, oxygen level, acidity and net primary production that scale with atmospheric warming (and thus cumulative carbon emission). Globally, sea surface changes in ecosystem system drivers are projected to scale linearly with atmospheric warming (from 0 °C to 4 °C) while sub-surface changes are more non-linear (*possible Figure 1* – projected scaling between atmospheric warming and ecosystem drivers, including surface and bottom, by ocean regions);

Impacts on marine fish stocks and fisheries are lower in 1.5-2 °C global warming relative to pre-industrial level when compared to higher warming scenarios (*possible Figure 2* - scaling of observed and projected impacts between impact indicators and atmospheric warming). 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 from increases in fisheries revenues and contribution to protein and micronutrients availability particularly to the most vulnerable coastal communities (tropical developing countries and SIDS) (*possible Figure 3* – maps of change in potential catches and revenues, with vulnerable countries highlighted).

3.4.4.2 Projected risks and adaptation options

Non-climate factors can play important roles by interacting, exacerbating and dampening impacts related to climate change. Separating out the individual effects of climate change stressors such as those associated with increasing temperature versus ocean acidification is difficult or impossible given the complex ways that they interact, synergistically and / or antagonistically. Given the role that some non-climate stresses play in determining the resilience of biological systems in response to climate change, reducing non-climate change related factors has potential to reduce the risk and outcome of climate change related impacts.

Other impacts include those stemming from the combined impacts of intensifying storms, sea level rise, and other non-climate change related stresses (e.g. pollution, coastal development). Reducing the stress of non-climate factors has potential to reduce the impact of climate change in some cases, and buy important time while the international community restrains emissions such that average global temperature will the maintained well below 2 °C and 1.5 °C and the long-term.

Stabilization of ocean temperature by mid-century is an important characteristic of the 1.5 °C trajectory (RCP1.9 and RCP2.6) in that it enables biological and human systems to adapt and eventually re-establish vibrant and productive marine ecosystems. Adapting to further change in average global surface temperature of 0.5 °C will require considerable investment and time. However, investments are likely to be returned through the benefits of resilient ecosystems, industries and communities.

The increasing stability of ocean environments also has longer term benefits in terms of enabling genetic adaptation to occur through the redistribution of genotypes to new locations where stable conditions match those that the organisms have been adapted to, or where evolution has had enough time to take place. In each case, the length of time involved is likely to be long (i.e. decades to centuries).

Industries are likely to be less affected with significant savings if the 1.5 ºC target is achieved. Scope of risk-reduction through adaptation through improved fisheries management, habitat restoration / enhancement and / or diversification of sources of food and livelihood increases substantially with under the 1.5 ºC.

To achieve 1.5 ºC Celsius global warming target, negative mitigation measures may alter pattern of ocean biogeochemistry and primary productivity, and increase intensity of changes in ecosystem stressors in some regions (e.g. lower oxygen level in deeper waters) which impacts fish stocks and fisheries. In contrast, nature-based solutions such as blue carbon may generally have co-benefits in enhancing fish stocks and fisheries.

Potential non-linearity scaling of sub-surface ecosystem drivers and the resulting effects on fish and fisheries implies that carbon mitigation pathways with bigger overshoot to achieve 1.5 °C by the end of the 21st century may have higher impacts.

3.4.5 Freshwater Resources (quantity and quality)

3.4.5.1 Observed impacts

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 (AR5-WGII Chapter 3).

3.4.5.1.1 Stream flow

Summary from AR5

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 (AR5-WGII Chapter 3).

New information since AR5:

The number of studies on detection and attribution of observed changes in streamflow has 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. 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 (Jiang and Wang, 2016).

[Add more quantitative information in the FOD]

3.4.5.1.2 Groundwater

Summary from AR5

Attribution of observed changes in groundwater level, storage, or discharge to climatic changes is difficult owing to additional influences of land use changes and groundwater abstractions (Stoll et al., 2011). Observed trends are largely attributable to these additional influences. The extent to which groundwater abstractions have already been affected by climate change is not known. 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. (AR5 WGII Chapter 3)

New information since AR5

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).

[Add more information based on long-term observed data in the FOD]

3.4.5.1.3 Water quality

Summary from AR5

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. Even though some studies extend over as many as 80 years, most are short term. The linkages between observed effects on water quality and climate should be interpreted cautiously and at the local level, considering the type of water body, the pollutant of concern, the hydrological regime, and the many other possible sources of pollution (high confidence, AR5 WGII Chapter 3).

New information since AR5

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).

[Add more information based on long-term observed data in the FOD]

3.4.5.1.4 Soil erosion and sediment load.

Summary from AR5

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, AR5-WGII Chapter 3)

New information since AR5

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).

[Add more information based on long-term observed data in the FOD]

3.4.5.1.5 Extreme hydrological events (floods and droughts)

Summary from AR5

There is low confidence, due to limited evidence, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale. The strength of the evidence is limited mainly by lack of long-term records from unmanaged catchments. 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 (AR5 WGII Chapter 3).

New information since AR5

Since AR5, the number of studies based on long-term observed data has been limited yet. For example, Flood vulnerability is 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. 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).

3.4.5.2 Projected risks and potential adaptation (including limits)

3.4.5.2.1 Stream flow including availability of water resources and water use

[Add potential adaptation effect under 1.5 ºC GMT and 2.0 ºC GMT]

Availability of water resources:

Summary from AR5

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. Proportional changes are typically one to three times greater for runoff than for precipitation. (AR5-WGII Chapter 3)

New information since AR5:

Reduction of water resource availabilities under 2.0 ºC global mean temperature (GMT) rises is projected to be greater than 1.5 GMT rise, however socioeconomic condition might be greater than variation between GMT rises.

At the global scale, under GMT rises of around 1.5 ºC (transition GMT rise of RCP2.6 in 2011–2040) and around 2 ºC (transition of RCP2.6 in 2041–2070) compared to pre-industrial conditions, the projected ranges of changes in global irrigation water withdrawal are 0.9–1.8 and -0.0–2.0% respectively (one global hydrological model (GHM) by three GCMs) (Hanasaki *et al.*, 2013). Mean global warming levels of 1.5 ºC and 2 ºC (MAGICC6 with 19 GCMs using a pattern-scaling) are projected to expose an additional 4% and 8% 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 and 2.7 °C above pre-industrial period (transition of RCP2.6 in 2041–2070), the multi-model medians with eleven GHMs by four GCMS project reduction in water resources, by at least one of the two criteria (experience a discharge reduction >20% and >1σ), about 8% and 14% of the global population, respectively (Schewe *et al.*, 2014). GMT rises of 1.5 ºC (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 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, In the United States, over the course of the 21st century and under one set of consistent socioeconomics, the reductions in water stress from slower rates of climate change resulting from emission mitigation are overwhelmed by the increased water stress from the emissions mitigation itself (Hejazi *et al.*, 2015).

Potential adaptation (including limit)

3.4.5.2.2 Water use

Summary from AR5

Significant reduction of renewable surface water and groundwater resources in most dry subtropical regions will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security (limited evidence, medium to high agreement).

New information since AR5

Increase of water demand under 2.0 ºC GMT rises is projected to be similar to 1.5 ºC GMT rise.

Agriculture: Twenty five (five GHMs by five GCMs) ensemble projections under 1.5 ºC and 2 ºC (transition GMT rise of RCP2.6 and RCP4.5 in 2035–2065) compared to pre-industrial conditions show global irrigation water demand increases by ~8.6% and ~9.4%, respectively (Wada *et al.*, 2013).

[Energy Production, Municipal Services, Freshwater Ecosystems, etc. will be added in the FOD]

Potential adaptation (including limit)

3.4.5.2.3 Groundwater

[Add potential adaptation effect under 1.5 ºC GMT and 2.0 ºC GMT]

Summary from AR5

Climate change is projected to reduce groundwater resources significantly in most dry subtropical regions (robust evidence, high agreement). Climate change is likely to increase the frequency of short hydrological droughts (less surface water and groundwater) in presently dry regions (medium evidence, medium agreement). There is no evidence that groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions (limited evidence, high agreement). This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change. Carbon capture and storage can decrease groundwater quality.

New information since AR5
Climate change under 1.5 ºC GMT rise is projected to reduce groundwater resources significantly in some regions.

For a GMT rise of 1.5 ºC (transition of RCP 8.5) compared to pre-industrial conditions, 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%) for a GMT rise of 2 ºC (transition of RCP8.5) (Portmann *et al*., 2013). From 0.5–2 ºC 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).

Potential Adaptation including limit

3.4.5.2.4 Water quality
[Add potential adaptation effect under 1.5 ºC GMT and 2.0 ºC GMT]

Summary from AR5
Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (medium evidence, high agreement). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods.

New information since AR5
Reduction of water quality under 1.5 ºC and 2.0 ºC GMT rises is projected to be similar degree.
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 1.5 ºC and 2 ºC (Bonte and Zwolsman, 2010).

Potential Adaptation including limit

3.4.5.2.5 Soil erosion and sediment load
Summary from AR5
Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (medium evidence, high agreement). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods.

New information since AR5
Published papers in respect of climate change impacts on soil erosion have been increasing since 2000 over the world (Li and Fang, 2016)

Potential Adaptation including limit

3.4.5.2.6 Extreme hydrological events (floods and droughts)
Summary from AR5
Floods. Flood hazards are projected to increase in parts of South, Southeast, and Northeast Asia; tropical Africa; and South America (limited evidence, medium agreement). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (high confidence). Global flood risk will increase in the future partly due to climate change (limited evidence, medium agreement).

Droughts. Climate change is likely to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions by the end of the 21st century under the RCP8.5 scenario (medium confidence). This is likely to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (medium evidence, medium agreement). Projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand.

New information since AR5

Floods. GMT rises of 1.5 ºC would reduce exposure to increased flooding compared to impacts under the 2 ºC, however socioeconomic condition might be greater than variation between GMT rises.

GMT rises of 1.5 ºC (transition of RCP2.6 in 2050, SSP1-5, 19 GCMs) would reduce exposure to increased flooding by 23–34 million compared to impacts under the 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). Impacts of global warming of 1.5 ºC and 2 ºC (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.*).

The difference of projected river discharge (three hydrological models and five GCMs) between global warming of 2 ºC (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 0.5 ºC could lead to more flood events in the in the Upper Yangtze River Basin (Chen *et al.*, 2017).

Droughts

Potential Adaptation including limit.

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).

3.4.6 Food security and food production systems (including fisheries)

3.4.6.1 Observed impacts

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 to determine these.

3.4.6.1.1 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).

The 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; Chen et al., 2014; He and Zhou 2016) to 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., 2013; Moriondo et al., 2013).

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., 2011a); 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., 2010; Supit et al., 2010; Gregory and Marshall, 2012; Sun et al., 2015; Chen et al., 2014; 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., 2014).

Crop productions are strongly affected by increases in extreme events, but the quantification of these changes is more difficult. There is evidences 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; chilling damage Jiao et al., 2016).

In addition to these, it is necessary to taken in to 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 through 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.

3.4.6.1.2 Livestock production

The impacts of climate change on livestock production was considerably less studied than previous food systems. Attention was 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.

3.4.6.1.3 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). Moreover, specific attention was dedicated to fishery in coral reef ecosystems, where declines in coral reef cover, due to overfishing and rising ocean temperatures, led to declines in abundance of the majority of fish species associated with coral reefs (Wilson et al., 2006).

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).

3.4.6.1.4 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., 2011a estimated that prices of traded food commodities increase due to the role of temperature and rainfall trends on food supply (+19%), that, however, was lower when increased CO_2 was considered (+6%).

3.4.6.2 Projected risks and potential adaptation (including limits)

3.4.6.2.1 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).

Relatively few studies considered 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 C&S America. Ricke et al. (2016) highlight how globally, cropland stability declines rapidly between 1 and 3ºC warming. Similarly, using the near term (2030-2040) as a proxy for 1.5 ºC warming, Niang et al. (2016) project significantly lower risks to crop productivity in Africa at this level than at 2 ºC warming.

3.4.6.2.2 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.

In temperate climate 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).

3.4.6.2.3 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, 2009a). 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).

3.4.6.2.4 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.

[INSERT BOX 3.1 HERE]

Box 3.1: 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 2016b; 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., 2016)

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 Nina 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. 2016) 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., 2015).

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. 2015). 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., 2014). 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). This lead to the conclusion that future precipitation deficits amplified by high temperature are of high risk for the Mediterranean natural and managed ecosystems.

Box 1, Figure 1: Time series of precipitation in Middle East 3000 BP and 20-21st century

[END BOX 3.1 HERE]

3.5 Observed impacts and projected risks in human systems

3.5.1 Introduction

The human systems assessed in the Working Group II contribution to the IPCC AR5 were urban areas; rural areas; key economic sectors and services; human health; human security; and livelihoods and poverty. 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 --transport, energy, water, housing (including slums/informal settlements)

3.5.2.1 Observed impacts

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; Birkman 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 1.5 °C and 2 ºC

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).

[START BOX 3.2 HERE]

Box 3.2: Urban Climate

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 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 population or city size; in summer; and at night (Arnfield 2003).

Multiple mechanisms have been cited for causing the UHI (Rizwan et al. 2008; Zhao et al. 2014). Urban areas have relatively high levels of impermeable surfaces, leading to high runoff and hence lower evaporation due to lower moisture availability. This moves the surface temperature balance towards more sensible heat and higher temperatures. Common building materials such as concrete can store more energy than typical soils, causing a large diurnal shift in the surface energy balance. The release of this stored energy at night is a major cause of the night-time UHI. The arrangement of urban structures into street canyons typically reduces the effective albedo causing more energy to be absorbed. Street canyons also reduce the amount of open sky that can be seen from a point on the ground, and hence reduces the efficiency with which long-wave radiation can exit the urban environment. The effectiveness with which convection can mix temperatures from the surface into the lower atmosphere depends on the relative roughness of the city compared to nearby rural land. Human and industrial activities themselves emit heat that is directly added to the urban environment, this is called anthropogenic heat.

Studies have been conducted to estimate the UHI intensity in many cities. These studies have used a wide variety of methodologies (Mirzaei and Haghighat 2010), from observations (in-situ and remote sensing) to modelling across a wide range of scales. 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).

The urban environment can also affect the production of precipitation in and near the city (Han et al. 2014). Observational studies show that precipitating systems can be disrupted by cities while passing over them, and this can either increase or decrease precipitation depending on a complex interaction of factors including

UHI, city surface roughness, higher aerosol concentrations, local geography and water vapour supply. In some locations, such as tropical cities, this precipitation affect can be the dominant urban influence on the local climate (Argüeso et al. 2016).

Few studies into the combined effect of UHI and global warming have been conducted. McCarthy et al. (2010) run a global climate model at 300 km resolution, they found that UHI intensity could increase by as much as 30% but on average decreased by 6% for a doubling of CO2. 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.

[END BOX 3.2 HERE]

3.5.3 Rural areas

3.5.3.1 Observed impacts

Climate and non-climate stressors, including under-investment in agriculture, challenges with policies on land and natural resource use, and environmental degradation affect rural populations (Arent et al. 2014). Rural economies and livelihoods rely on a wide range of factors to support development, with climate change at the latter stages of complex interactions. Water supply, food security, and agricultural income will be the primary climate-mediated impacts through which climate change will operate. Cases of observed impacts on rural areas often suffer from problems of attribution, but evidence for observed impacts, is increasing. Impacts are expected to be substantial for low- and middle-income countries based on their dependence on agriculture and natural resources, low capacity to prepare for and manage change, and vulnerable geographic locations.

3.5.3.2 Projected risks at 1.5 °C and 2 °C

[To be completed for the FOD]

3.5.4 Key economic sectors and services

3.5.4.1 Introduction of context and expectations

Analyses of the key vulnerabilities (and opportunities) across economic sectors and services have, at least implicitly, appropriately cast their approaches in terms of risk – the product of likelihood and consequence. Limiting increases of global mean temperature from pre-industrial norms to 1.5 ºC instead of 2.0 ºC (or an additional 0.9 ºC instead of 1.4 ºC from the current 2017 benchmark) would change the likelihood of the intensities of potential impacts (as well as reduce the likelihood of experiencing amplified damages (or diminished net benefits) associated with even higher temperature stabilization limits. Chapter 10 of the WGII-AR5 correctly noted, at the top of its Executive Summary (page 662), that consequences will depend on a litany of confounding factors: “population, age, (the distribution of) income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development” that will “have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change {10.10}”. These confounding factors are site-specific and development path dependent, and they affect the degree to which observed and projected ranges of impacts can be attributed to anthropogenic warming (the point of Chapter 10 of the WGII-AR5). It follows that the discussion in this section is similarly focused in time and space. It is therefore far from comprehensive in the sense of supporting aggregate portraits of overall economic risk even at a regional level; the literature will simply fall short in coverage to produce a credible version of the big picture.

The NAS report on Climate Stabilization Targets (Solomon, et al, 2010) adds even more complication by differentiating between transient and equilibrium warming. First of all, the observed economic impacts that frame the baseline for any consideration of projected futures depend on transient temperatures (that are roughly 50% of committed equilibrium temperatures). They are therefore simply snapshots of conditions that are characterized both by point estimates of temperature and associated other climate changes and their rates of change. Secondly since changes in global mean temperature depending on atmospheric concentrations at any point in time and because concentrations depend on cumulative emissions, only uncertain but instructive insights can be drawn between cumulative emissions (a viable indicator as the future unfolds) and the likelihoods of limiting temperature increases (at least with respect to the long run equilibrium). Combining Table 5.1 (page 23) and Figure Syn.1 (page 5) from the Solomon panel report (*XXXX*), it is possible, for example, to link equilibrium temperature targets of 1.0 ºC (plus or minus 0.3 ºC), 2.2 ºC (plus or minus 0.8 ºC) and 3.1 ºC (plus or minus 1.1 ºC) to cumulative emission limits of roughly 5600 (plus or minus 3000), 11000 (plus or minus 4000), and 17000 (plus or minus 7000) gigatonnes of carbon emissions, respectively (and anchored by the current total of about 5500 gigatonnes).

This brief discussion does not necessarily describe what the literature has done, but working through a risk-based organizational reading of past and more current literature informed by the confounding factors and the sources of fundamental scientific uncertainties provides insight into the criteria with which confidence in reported results can be assessed on analytical grounds – rigorous threads between global mean temperature and climate impacts that influence risks through the relative likelihoods of calibrated consequences, similarly rigorous process understanding of confounding factors, and (hopefully) how and when adaptation options might be undertaken to ameliorate either likelihoods or consequences. Doing so consistently offers the promise identifying the many knowledge gaps that still exist. Independent care should also be taken to note explicitly the geographic coverage of credible analyses and the inherent recognition of general equilibrium style interdependencies that will increasingly characterize the working of the global economy in autonomously spreading risk.

3.5.4.2 Identifying key sectors for possible coverage

Chapters 10 and 19 of WGII AR5 have identified key economic and services sectors and canvased literature that was available through 2013:

1. *Energy demand* (heating and cooling, at least, influenced directly by temperature change, but confounding factors can influence demand for transportation, agriculture, manufacturing, etc.)
2. *Energy supply* (depending on resources (water, wind, sunlight, technology, location), extreme weather events, etc.).
3. *Energy distribution infrastructure and economic organization* (the power grid, pipelines, river and ocean transport, etc.).
4. *Water supply infrastructure and water demand* (flooding, scarcity, competition for supply, etc.
5. *Transportation infrastructure* (flooding, intense heat or cold, extreme weather events (like intense precipitation, cyclones, etc.).
6. *Insurance and financial systems* (changes in the intensity and frequency of extreme weather events and associated consequences – droughts and wildfires, riverine and coastal flooding, extreme heat waves and severe cold spells, extreme precipitation and/or wind events, cyclones, etc.).
7. *Health Sector* (see Section 3.5.2.4)
8. *Agriculture* (temperature and precipitation, changes in the intensity and frequency of extreme weather events and associated consequences – droughts, flooding , extreme heat waves and severe cold spells, extreme precipitation and/or wind events, cyclones, etc.).
9. *Manufacturing and associated supply chains and distribution networks* (again, extreme weather events, sea level rise etc.).
10. *Retailing and associated supply chains* (business interruptions on the demand side and supply interruptions on the other, etc.).
11. *Coastal communities and commerce* (sea level rise, coastal storms of all magnitude, extreme weather

events, etc.).

12. *Recreation and Tourism* (extreme weather events, persistent changes in climate, etc.).

[START Box 3.3 HERE]

Box 3.3: Key economic sectors and services **-** An illustrative box example for coastal communities

Yohe et al. (2011) built on earlier work to consider economic damages distributions along the shoreline of Quincy, MA (a community in urban Boston, MA). They drew from quantitative estimates of the links between global mean temperature, sea level rise, and the return time of coastal storms of all severities to produce distributions of damages associated estimated from the pattern of coastal storms over a 30 year historical record. Damages were tied to breaching designated contours within Quincy and to property values. The impacts of rising seas (along two projected scenarios: 0.6 m and 1.0 m through 2100) were calibrated by tracing correlated changes in the mean of the historical distribution of damages under the assumption that the second moment of the distribution was fixed. The confounding factor of growing property values was captured by statistically estimated correlations with population and income and tracing projections of both into the future.

Box 3 Table 1 displays some results for the two sea level rise scenarios. The difference between the two panels could be a reflection of working to limit global mean temperature to 1.5 oC instead of 2.0 oC or 3.0 oC – if only starting along a lower emissions path reduced the likelihood of the 1.0m scenario relative to the 0.6m alternative.

[INSERT Box 3, Table 1 HERE]

Box 3, Table 1: Projected Annual Property Damage from Coastal Flooding for Selected Years through the Current Century. Source: Yohe, et al., 2010.

Panel A: Annual Damages Along a Sea Level Rise Scenario that Reaches 1.0m by 2100 (in millions of 2010 dollars)			
Year	**10th Percentile**	**Median**	**90th Percentile**
Current	$0	$0	$110
2030	$0	$50	$220
2050	$50	$110	$250
2070	$160	$230	$350
2090	$220	$290	$400
Panel B: Annual Damages Along a Sea Level Rise Scenario that Reaches 0.6m by 2100 (in millions of 2010 dollars)			
Year	**10th Percentile**	**Median**	**90th Percentile**
Current	$0	$0	$0
2030	$0	$0	$50
2050	$0	$40	$200
2070	$30	$110	$260
2090	$90	$150	$300

One $50 million adaptation project (a protecting barrier) was considered. Along the 1.0 m sea level rise scenario, the project would reduce expected damages by roughly $8 m per year from the date of installation; along the 0.6 m, by $2 per year. Two alternative decision rules were also considered. The first assumed that city planners applied a straight discounted expected benefit minus cost calculation. The second assumed that the planners recognized some aversion to risk so that economic value had to be calculated in terms of the discounted stream of certainty equivalents. For the 1.0 m scenario and a modest aversion to risk suggested that the internal rate of return for the adaptation project would exceed a interest rate threshold of 3% in 4 years' time (i.e., start now to build it) and a 5% threshold in 9 years' time. Along the 0.6 m scenario, those thresholds would be crossed in 25 years and 35 years, respectively. Knowing that global temperatures were heading toward the 1.5 °C limit would therefore buy city planners a considerable amount of time. If these planners were operating with an expected benefit-cost perspective, they would wait 9 years and 30 years with a 3% discount rate along the high and low scenarios, respectively; and they would wait 20 and 40 years with a 5% discount rate. Aversion to risk biases decisions toward the present and increases the value of information about the feasibility of low global mean temperature limits.

[END BOX 3.3 HERE]

[START BOX3.4 HERE]

Box 3.4: Key economic sectors and services **-** An illustrative box example for agriculture

Gourdji et al. (2013), report that the yields of major food source crops are relatively stable at current levels up to crop specific thresholds of maximum local temperatures during brief critical flowering stages early in the cycle of plant growth and crop maturity. For wheat, maize, rice, and soy, these thresholds are 34-35 °C, 35-36 °C, 36-37 °C, and 39-40 °C, respectively. A few days of exposure to temperatures above those threshold during flowering can kill the plants' flowers and thereby cause catastrophic reductions in yield. Box 4 Figure 1 shows the ranges of the percent of total harvested area that experience these the coincidence of exceeding the thresholds and the flowing period for these four major crops. The left portions of each panel reflect recent observations and explain (at least in part) the current relative stability in yields. The right portions display projected ranges in these percentages based on mean CMIP5 model projections for five decadal intervals from 2010 through 2050 along the SRES A1B scenario. Box 4 Figure 1 offers comparable evidence of geographic coverage across the globe. Since change in global mean temperature along A1B is projected to be between 0.8 °C and 1.2 °C in the 2020's and between 1.5 °C and 2.0 °C in the 2040's, comparisons of the 2020's and the 2040's is suggestive of the value (calibrated in crop specific yields whose values depend on location) of holding global mean temperatures below 1.5 °C rather than 2 °C; and comparisons up to the 2050's is suggestive of the value of reducing the likelihood of allowing warming up to 3.0 °C or beyond. It should be noted, though, in judging confidence in these conclusions, that the climate system would produce its own confounding factor – precipitation (and not just extreme weather events like severe downpours or prolonged drought). Plentiful and regular supplies of water and associated stable levels of ground moisture are not sufficient to eliminate the severity of these temperature thresholds.

[INSERT Box 3.4, Figure 1 HERE]

Box 3.4, Figure 1: Percent of total harvested area with at least 1, 5, or 10 reproductive days above the threshold over the recent past, as well as five decadal increments through 2050. Source: Figure 4 in Gourdji, et al. (2013).

[INSERT Box 3.4, Figure 2 HERE]

Box 3.4, Figure 2: Geographically differentiated projections for the 2030's (left column) and 2050's (right column) in reproductive days over the critical temperature thresholds during flowering for all four crops along from the CMIP5 models for scenario A1B. Source: Figure 3 in Gourdji,et al. (2013)

The economic implications of these results are also obscured by a myriad of socio-economic confounding factors, because they depend on the demand side of the markets for agricultural product which, in an integrated world economy, depends on global, regional, and national distributions of income and population as well as the willingness people around the world to substitute one source of necessary caloric intact for another. These are among the major factors that will frame the context for international trade over time, work with changing supply schedules to generate the uncertain evolution of relative prices of agricultural products, and thus distributions of the profitability of farming, itself, from one location to another). In addition, location-specific and development-path dependent adaptation options are available on the micro-scale supply side depending on available information about evolving local climate variability and longer-term projections of climate change, itself. The former can support responsive adaptation (like changing planting dates from one year to the next); the later can inform more expensive anticipatory adaption investments like crop switching. Both are more likely in developed nations, assuming that governmental research and monitoring programs for critical locally specific indicators of change produce robust and timely advice; government insurance and relief programs might also be expected in these countries. This essential support may not, however, be forthcoming even in relatively wealthy nations if their governments deliberately dismiss climate change as a source of risk. In developing countries, the capacity to adapt could be limited by scarcity in all of the above.

[END BOX 3.4 HERE]

3.5.4.3 Concluding remarks

Literature with which to fill this section will likely be very sparse because the complications of geography and confounding factors are enormous. Moreover, the authors of Chapter 10 of WGII AR5 are probably still correct in their assessment that these confounding factors will be more important in driving the economics of these key sectors than climate change for relatively small changes in global mean temperature (like 1.5 ºC or even 2.0 ºC). Moreover, most studies that do focus on climate change have not generally progressed beyond calibration the baselines drawn from recent observations of impacts calibrated in scientific metrics and not currency. Some studies might add projections of the economic impacts of specific but arbitrary climate change benchmarks that have no anchor in time and thus no way of placement along climate *cum* socio-economic scenarios. As evidence by the illustrations, few studies will provide detailed analysis of adaptation and global coverage.

3.5.5 Human health

3.5.5.1 Observed impacts

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 included:

- 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 behavioural 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 was lacking of associated changes in the distribution of Lyme disease.

3.5.5.2 Detected impacts since AR5

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 at 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 (1) climate change is affecting the frequency, intensity, and duration of heatwaves (IPCC 2013); and (2) exposure to high ambient temperatures is associated with excess morbidity and mortality (e.g. Gasparrini et al. 2015). Two studies undertook event attribution in Egypt and Europe. The risk of heat-related mortality increased about 70% in Central Paris and about 20% in London during the European heatwave of 2003 because of anthropogenic climate change, based on a comprehensive description of the heatwave, thousands of climate simulations of a high-resolution regional climate change generating a comprehensive description of the heatwave, and a health impact assessment using a percent increase in mortality per 1 °C increase in maximum apparent temperature (includes temperature and humidity) above city-specific thresholds (Mitchell et al. 2016). Anthropogenic climate change increased the likelihood of the 2015 Egyptian heatwave by 69% (± 17%), which increased heat stress (Mitchell 2016). The principal driver of human discomfort was high temperature, but relatively high humidity levels also played a role.

Taking another approach, mortality in Stockholm, Sweden in recent decades from heat extremes (days with temperatures above the 98th percentile of the 1900-1929 distribution) was double what would have occurred without climate change, adjusting for urbanization and the urban heat island effect, based on comparing mortality due to temperature extremes during the period 1980-2009 with expected mortality with 1900-1929 temperatures (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 cycle occurrence and efficiency (and thus the proportion of ticks infected); and the likelihood of transmission to humans. Lyme disease emerged in North America in the 1970s, with emergence associated with landscape change driven by socioeconomic factors that allowed abundance of a key animal host of the tick vector of Lyme disease (white-tailed deer) to rebound (Barbour and Fish 1993). Until the early 2000's there was only one known *I. scapularis* population in Canada. In the early 2000s, studies undertaken to explore what factors may limit the northward geographic spread of the tick (and Lyme disease risk) into Canada revealed that the habitat appeared suitable (Ogden et al. 2006a), with ticks being regularly dispersed into Canada (Ogden et al. 2006c), but that temperature conditions were likely too cold for the ticks in most of Canada (Ogden et al. 2005). A population model of *I. scapularis* incorporating known impacts of temperature on the tick was used to predict the geographic occurrence of current climatic suitability (Ogden et al. 2006b). Field studies in 2007 to validate the model predictions detected that incursion of the tick had begun (Ogden et al. 2008b). Since then, studies confirmed that tick vector populations and Lyme disease risk in Canada have emerged in a spatial pattern strongly associated with climate. Consistent positive associations have been found between the presence and abundance of *I. scapularis* ticks on animal hosts (rodents and deer) and temperature, accounting for a range of alternative potential drivers for tick occurrence (Bouchard et al. 2013a; Bouchard et al. 2013b; Gabriele-Rivet et al. 2015; Ogden et al. 2008b; Ogden et al. 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 this 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 has been associated with steadily increasing numbers of Lyme disease cases, confirming that the ecological phenomenon of climate change-driven spread of the tick, accompanied by *B. burgdorferi* transmission cycles, with public health consequences in Canada (Ogden et al. 2014b; Ogden et al. 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, primarily *V. vulnificus* and *V. cholerae* (non O1/O139) wound infections, were identified in the Baltic Sea region (Baker-Austin et al. 2013) with the vast majority reported from 1997 onwards (234 cases, 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).

3.5.5.3 Projected risks at 1.5 ºC and 2 ºC

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).

Table 3.2 summarizes the projected risks to human health from studies assessed in the AR5 (Smith et al. 2014).

[INSERT TABLE 3.2 HERE]

Table 3.2: Projected risks to human health: studies cited in Smith et al. (2014)

Region	*Health outcome metric*	*Baselines*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
Global and 21 regions	Heat-related mortality in adults over 65 years of age	1961-1990	BCM2.0; EGMAM 1; EGMAM 2; EGMAM 3; CM4vl	A1B	2030; 2050				Population growth and aging; improved health in elderly due to economic development; three levels of adaptation (none, partial, and full)	Hales et al. 2014
Global	Heatwave area calculated as the area with heatwave	1971-2000	HadGEM 2-ES, bias corrected, from ISIMIP	RCP2.6 with SSP1; RCP6.0 with SSP2;	2030-2050; 2080-2100				Population density, % of population over 65 years of	Dong et al. 2015

	s divided by the total land area; number of heatwave days			RCP8.5 with SSP3					age; per capita GDP; education levels	
Global	Extremely hot summers over land areas (>3 SD anomalies)	1861-1880	26 models from CMIP5	RCP2.6; RCP4.5; RCP8.5	to 2100s	Temperature anomalies relative to 1951-1980		If the global mean temperature increases 2°C relative to the pre-industrial level, “extremely hot” summers are projected to occur over nearly 40% of the land area		Wang et al. 2015
Australia (five largest cities) and UK	Temperature-related mortality	1993-2006	UKCP09 from HadCM3; OzClim 2011	A1B, B1, A1FI	2020s; 2050s; 2080s				Projected population change	Vardoulakis et al. 2014
Australia	Temperature-related morbidity and mortality; days per year above 35°C	1971-2000	CSIRO	2030 A1B low and high; 2070 A1FI low and high	2030; 2070	4-6 dangerously hot days per year for un-acclimatized individuals	Sydney: from 3.5 days at baseline to 4.1-5.1 days; Melbourne: from 9 days at baseline to 11-13 days			Hanna et al. 2011
Brisbane, Sydney, and Melbourne Australia	Temperature-related mortality	1988-2009	62 GCMs, with spatial downscaling and bias correction	A2, A1B, B1	2050s; 2090s					Guo et al. 2016
Brisbane Australia	Years of life lost due to	1996-2003		Added 1 to 4C to observed	2000; 2050			Years of life lost increase		Huang et al. 2012

	temperature extremes (hot and cold)			daily temperature to project for 2050				by 1,104 (840-1,178) and cold days decrease by 1,112 (-1,337 to -871)		
Quebec, Canada	Heat-related mortality	1981-1999	Ouranos Consortium; SDSM downscaled HADCM3	A2 and B2 (projected impacts the same)	2020 (2010 – 2039); 2050 (2040 – 2069); 2080 (2070 – 2099)		*2% increase in 2020*	*4-6% increase in 2050*		Doyon et al. 2008
Montreal, Canada	Heat-related mortality	June – August 1990 - 2007	Canadian Global Circulation Model, 3.1; CSIRO Mark 3.5; ECHAM5; MRRC (Canadian regional climate model)	B1, A1B, A2	June-August 2020-2037				Assumed no change in mean daily death count; no demographic change; no change in ozone levels; no adaptation	Benmarhnia et al. 2014
USA	Heat-related mortality	1999-2003	GISS-II downscaled using MM5	A1B	2048-2052				Projected population change	Voorhees et al. 2011
USA	Avoided climate impacts of heatwaves and cold spells	1981-2005	CESM-LE with RCP8.5; CEMS-ME with RCP4.5. Includes urban heat island effect	RCP4.5; RCP8.5	2061-2080	Mean annual total heatwave days range from 4.4-6.3; similar range for cold spells				Oleson et al. 2015
USA, 209 cities	Heat- and cold-related mortality	1990 (1976-2005)	Bias corrected (BCCA) GFDL-CM3; MIROC5	RCP6.0	2030 (2016-2045); 2050 (2036-2065); 2100 (2086-2100)		Projected a net increase in premature deaths, with decreases in		Held population constant at 2010 levels; mortality associated with high temperatu	Schwartz et al. 2015

							temperature-related winter mortality and increases in summer mortality; the magnitude varied by region and city		res decreased between 1973-1977 and 2003-2006	
USA, 209 cities	Mortality associated with cold spells	1960-2050	CMIP5; 20 biased corrected (BCCAv2) multi-model dataset	RCP2.6; RCP4.5; RCP6.0; RCP8.5	1960-2050				Assumed no change in demography or baseline mortality rate	Wang et al. 2016
USA, 82 communities	High-mortality heatwaves that increase mortality by 20%	1981-2005	CESM-LE with RCP85; CESM-ME with RCP4.5	RCP4.5; RCP8.5	2061-2080	Depending on modeling approach, 5-6 high mortality heatwaves annually, with approximately 2 million person-days of exposure per year			Projected population change (SSP3, SSP5) and three scenarios of adaptation (no, lagged, on pace:	Anderson et al. 2016
Washington State, USA	Heat-related mortality	1970-1999	PCM1; HadCM	Average of PCM1-B1 and HadCM-A1B; humidex baseline; number & duration of heatwaves calculated	2025; 2045; 2085		*Under moderate warming in 2045, 156 excess deaths in Seattle area*	*Under moderate warming in 2085, 280 excess deaths in Seattle area*	*Holding population constant at 2025 projections*	Jackson et al. 2010
Eastern	Heat-	2002-	CESM1.0	RCP8.5	2057-				Projected	Wu et

USA	related mortality	2004	downscaled using WRF		2059				population change in 2050	al. 2014
Rhode Island, USA	Heat-related emergency department admissions and heat-related morality	2005-2012	CMIP5 multi-model ensemble bias corrected (BCCA)	RCP 4.5; RCP 8.5	2046-2053; 2092-2099	Between 2005 and 2012, an increase in maximum daily temperature from 75 to 85F was associated with 1.3% and 23.9% higher rates of all cause and heat-related emergency department visits. Between 1999-2011, there was a 4.0% increase in heat-related mortality.				Kingsley et al. 2016
Boston, New York, Philadelphia, USA	Heat-related mortality	1971-2000	CMIP5 bias corrected (BCSD)	RCP 4.5; RCP 8.5	2010 – 2039; 2040 – 2069; 2070 - 2099				Population constant at 2000	Petkova et al. 2013
New York City, NY	Heat-related mortality	Each model's 30-year baseline average	Downscaled and bias corrected (BCSD) WCRP CMIP5, including 33 GCMs	RCP 4.5; RCP 8.5	2020s (2010-2039); 2050s (2040-2069); 2080s (2070-2099)	Decadal models from 1900 to 2006; heat-related mortality was relatively constant during			Five scenarios of population projections by gender; two adaptation scenarios plus no adaptation scenario	Petkova et al. 2017

						the first part of the 20th century, then decreased from the 1970s to 2000s				
Houston, Texas	Heat-related non-accidental mortality	1991-2010	CESM simulations for RCP8.5 and for RCP4.5; used HRLDAS for downscaling	RCP45; RCP8.5	2061-2080				Demographics and income in SSP3 and SSP5; urban heat island	Marsha et al. 2016
Europe	Heat-related respiratory hospital admissions	1981-2000	RCA3 dynamically downscaled results from CCCSM3, ECHAM5, HadCM3, ECHAM4	A1B; A2	2021-2050	The estimated proportion of respiratory hospital admissions due to heat was 0.18% at baseline in the EU27; the rate was higher for Southern Europe (0.23%)			Population projections	Astrom et al. 2013
UK	Temperature-related mortality	1993-2006	9 regional model variants of HadRm3-PPE-UK, dynamically downscaled	A1B	2000-2009; 2020-2029; 2050-2059; 2080-2089				Population projections to 2081	Hajat et al. 2014
Netherlands	Temperature-related	1981-2010	KNMI' 14; G-scenario		2050 (2035-2065)	At baseline, the	Without adaptation,	Without adaptation, under the	Three adaptation scenarios,	Huynen and Marten

	mortality		is a global temperature increase of 1°C and W-scenario an increase of 2°C			attributable fraction for heat was 1.15% and for cold was 8.9%; or 1511 deaths from heat and 11,727 deaths from cold	under the G scenario, the attributable fraction for heat is 1.7-1.9% (3329-3752 deaths) and for cold is 7.5-7.9% (15,020-15,733 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	W scenario, the attributable fraction for heat is 2.2-2.5% (4380-5061 deaths) and for cold is 6.6-6.8% (13,149-13699 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	assuming a shift in the optimum temperature, changes in temperature sensitivity, or both; population growth and declining mortality risk per age group	s 2015
Skopje, Macedonia	Heat-related mortality	1986-2005; May - September	MRI-CGCM3; IPSL-CM5A-MR; GISS-E2-R	RCP8.5	2026-2045; 2081-2100				Two models to project population growth; PM10	Martinez et al. 2016
Japan, Korea, Taiwan, USA, Spain, France, Italy	Heat-related mortality for 65+ age group	1961-1990	BCM2	A1B	2030; 2050				Three adaptation assumptions: 0, 50, and 100%	Honda et al. 2014
Beijing, China	Heat-related mortality	1970-1999	Downscaled and bias corrected (BCSD) 31 GCMs in WCRP CMIP5; monthly change factors were applied to daily	RCP4.5; RCP8.5	2020s (2010-2039), 2050s (2040-2069), 2080s (2070-2099)	Approximately 730 additional annual heat-related deaths in 1980s			Adults 65+ years of age; no change plus low, medium, and high variants of population growth; future adaptation based on Petkova et	Li et al. 2016

			weather data to create a projection						al. 2014, plus shifted mortality 5%, 15%, 30%, 50%	
Beijing, China	Cardiovascular and respiratory heat-related mortality	1971-2000	Access 1.0; CSIRO Mk3.6.0; GFDL-CM3; GISS E2R; INM-CM4	RCP4.5; RCP8.5	2020s; 2050s; 2080s	Baseline cardiovascular mortality 0.396 per 100,000; baseline respiratory mortality 0.085 per 100,000				Li et al. 2015
Africa	Five thresholds for number of hot days per year when health could be affected, as measured by maximum apparent temperature	1961-2000	CCAM (CSIRO) forced by coupled GCMs: CSIRO; GFDL20; GFDL 21; MIROC; MPI; UKMO. CCAM was then downscaled. Biased corrected using CRU TS3.1 dataset	A2	2011-2040; 2041-2070; 2071-2100				Projected population in 2020 and 2025	Garland et al. 2015

3.5.6 Human security

3.5.6.1 Observed impacts

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.

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.

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).

3.5.6.2 Projected risks at 1.5 °C and 2 ºC

3.5.7 Livelihood and poverty

3.5.7.1 Observed impacts

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 socioeconomic 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.

3.5.7.2 Projected risks at 1.5 °C and 2 °C

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.

3.5.8 Observed adaptation effectiveness and barriers

3.5.8.1 Investments in adaptation

Developed countries set a roadmap of climate finance reaching US$ 100 billion annually, with half earmarked for adaptation (Parker et al. 2014). Current projections suggest that even if doubled, adaptation funds will not reach the target (Carty et al. 2016). In 2014, assistance for adaptation was 6.9% of the $392 billion spent globally on climate action (CPI 2015, Olhoff et al. 2016). Of the $27 billion in adaptation funds spent globally in 2014, about 84% came from development finance institutions and 3% from the international climate change adaptation funds (CPI 2015, Olhoff et al. 2016). East Asia and the Pacific received 46%, followed by Sub-Saharan Africa, and Latin America and the Caribbean. Nearly 55% of adaptation money was invested in water and wastewater management and another 13% for agriculture and forestry management. Other major sectors included disaster management, infrastructure, energy and built environment, and coastal protection. Upper estimates of the global adaptation costs are $300 billion by 2030 and $500 billion by 2050 (Olhoff et al. 2016).

3.5.8.2 Effectiveness of adaptation investments

3.5.8.3 Evidence of barriers and limits to adaptation

3.5.8.4 Maladaptation

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 (see AR5 Chapter 19 for details and findings). A recent paper reviewed the framework's conceptual basis and the risk judgments made in Oppenheimer et al. (2014), confirming most judgements made in the light of more recent literature (O'Neill, *XXXX*). The 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 and narrative presented in Section 3.6.

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

1. Unique and threatened systems (text to be added to Section 3.6.2.2 using Section 3.4 when complete)
2. Extreme weather events (text to be added to Section 3.6.2.1 using Section 3.3)
3. Distribution of impacts (text to be added using Section 3.5)
4. Global aggregate impacts (text to be added once using Sections 3.1 to 3.5)
5. Large scale singular events (text to be completed using Section 3.3)

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 3.11. Note that this follows the analysis of Oppenheimer et al. (2014), but with the risk assessments based on the most recent literature.

[INSERT FIGURE 3.11 HERE]

Figure 3.11: How reasons for concern accrue with global warming of between 0 and 2 °C above pre-industrial levels. The portion of the diagram that relates to warming of 1.5 °C versus 2 °C is magnified.

3.6.2 Synthesis on previous sections (3.3-3.5)

3.6.2.1 The physical climate system

[Assessment of avoided changes in climate extremes and the physical climate system in general, for 1.5 °C vs 2 °C of global warming, will be based on Section 3.3.]

3.6.2.1.1 Changes in climatological averages (Section 3.3 text to serve as input)
3.6.2.1.2 Changes in extreme weather events (Section 3.3 text to serve as input)
3.6.2.1.3 Large scale singular events (Section 3.3 text to serve as input)

3.6.2.2 Natural and managed ecosystems

[Unique and threatened systems (Section 3.4 text to be used as input)]

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 a 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 to be reported on in more detail in a next version of the section). Moreover, (Warren et al. *in prep*, the study is called AVOID) is 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 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, 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. 2016).

Similarly Schleussner et al. (2016) highlights coral reefs, water supplies, and tropical agriculture (including in West Africa, SE Asia, N&C America) as benefiting strongly from constraining warming to 1.5 °C compared to 2 °C. Also highlighted as benefiting strongly are Mediterranean regions (confirmed by a variety of other studies, see Section 3.4.1) and areas at risk of coastal flooding due to sea level rise (see Section 3.3.12)

3.6.2.3 Human systems

[Assessment of avoided impacts on human systems, for 1.5 °C vs. 2 °C, will be based on Section 3.5.]

3.6.2.4 Global aggregate impacts (will be composed using section 3.3 to 3.5 as key inputs)

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

Benefits of achieving the 1.5 °C temperature goal, as opposed to the 2 °C goal, have been outlined summarized in Section 3.6.2 in terms of avoided risks to the physical climate system, natural and managed ecosystems and human systems. 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 warming vs. 2 °C warming. Potential trade-offs, in terms of higher mitigation costs to achieve the 1.5 °C temperature goals as opposed to the 2 °C goal, are also analysed.

3.6.3.1 Reduced climate costs under 1.5 °C vs. 2 °C of global warming.

3.6.3.2 Potential trade-offs: mitigation costs associated with achieving 1.5 °C vs. 2 °C of global warming.

3.6.4 Compare 1.5 °C vs. 2 °C and NDCs/other baselines; consider impacts of alternative interpretations of 1.5 scenarios

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

3.6.4.1.1 Summary of benefits of 1.5 °C or 2 °C of global warming compared to temperature increases associated with the Paris Agreement NDCs

3.6.4.1.2 Summary of benefits of 1.5 °C or 2 °C of global warming compared to temperature increases associated with low mitigation: 3 °C and 4 °C of global warming

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

The definition of 1.5 °C of global warming, as defined in the Paris Agreement, refers to the stabilisation of global average surface temperature increase to 1.5 °C above the pre-industrial average. 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. Also to be discussed is the value of studying impacts associated with 1.5 °C of global warming from "transient" simulations, where the global temperature reaches thresholds of 1.5 °C or 2 °C of warming, and then continues to increase. 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 numerous 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.

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

This section will use the analysis of Section 3.3.14 (analysis of hots spots in the physical climate system under 1.5 °C and 2 °C of global warming) as its key input – towards describing the extent that climate change hot spots may be expected to be avoided, reduced or lessened in impact by restricting the global temperature increase to 1.5 °C or less. The subsection will discuss similarly the reductions of hots spots in natural systems and socio-economic human systems for 1.5 °C vs. 2 °C of global warming, building on the analysis of Sections 3.4 and 3.5.

3.6.5.1 The physical climate system

3.6.5.2 Natural and managed ecosystems

3.6.5.3 Socio-economic human systems

3.6.6 Tipping points

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 to understand 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.

3.6.6.1 Tipping points in the physical climate system

The cryosphere: West-Antarctic ice sheet, Greenland ice sheet, Arctic sea-ice.
Ocean circulation: Thermohaline circulation (Atlantic Meridional Overturning Current and the formation of Antarctic Bottom Water).
Monsoon systems: Indian Monsoon, West African Monsoon, East African Monsoon.
Global modes of variability: El Niño Southern Oscillation (ENSO)
Global carbon cycle: Role of the Southern Ocean as a carbon sink; permafrost
The discussion to be developed will follow to some extent that of Lenton et al. (2008).

3.6.6.2 Tipping points in ecosystems

Biomes: Rain forests (focus on Amazon), boreal forests, tundra.
Coral reefs under global temperature goals and ocean acidification (e.g. Hoegh-Goldberg et al., 2007).

3.6.6.3 Tipping points in human socio-economic systems

Heat-waves, unprecedented heat and human health
Agricultural systems (key staple crops and livestock production under different degrees of global warming)

[INSERT TABLE 3.3 HERE]

Table 3.3: Summary of enhanced risks in the exceedance of tipping points for 3 °C and 2 °C vs. 1.5 °C of global warming.

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

This section will draw 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). We will be developing this further when we are in Exeter - after having input and literature from the authorship team. Given the work still to be done, we have left this with minimal text with the idea that we will develop it as we head towards FOD and in the Exeter meeting.

Special attention will be given to when the overshooting is happening throughout the 20th century and if patterns in climate changes and extremes are different to those at 1.5 °C in 2100, in case literature is available.

Many climate models exhibit an overshoot of the final average global temperature. This has become highly likely in many scenarios that ultimately trend toward 1.5 °C above preindustrial period. The reasons for overshoot arise from momentum within the climate system, as well as socio-economic drivers and emission reduction pathways. In situations where pathways overshoot, average global temperatures increase to beyond 1.5 °C before 2100 but may come down several decades later. 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.

3.7.1 Pathways without overshoot

3.7.1.1 Likely pattern of extremes and other changes in climate system

This section will draw on work done in previous chapters with respect to pathways which trend upwards and stabilise at or below 1.5 °C. Particular attention will be paid to expected extremes as well as trends, and yet associated changes that are expected in the climate system. Drawing on previous chapters, this section will also describe the sorts of changes expected at local and global levels under a gradual rise to 1.5 °C and stabilisation.

3.7.1.2 Implications for natural and human systems

The ramifications for natural systems of a 1.5 °C increase in average global surface temperature are explored here, drawing on the observations and conclusions from previous parts of chapter 3. There would also be a discussion of the implications for humans, potentially highlighting positive and negative elements of achieving stabilisation without overshoot.

3.7.1.3 Adaptation options

This section would explore the adaptation options in the light of a climate that stabilizes at 1.5 °C. It is anticipated that this discussion will investigate and highlight the options for adaptation for a stabilization scenario, in preparation for the next section which looks at the challenges associated with overshoot.

3.7.2 Pathways with overshoot

3.7.2.1 Likely pattern of extremes and other changes in climate system

This section will explore the changes that are likely to occur in pathways which include an overshoot relative to the final stabilization point of 1.5 °C. In addition to temperature, this section will draw on previous discussions of the types of changes that occur at different levels (e.g. 2 °C or higher).

3.7.2.2 Implications for natural and human systems

Implications of these pathways will be explored - especially the consequences of pathways which go through different levels of overshoot. As with the previous section it will draw on our understanding of responses by biological and human systems, and will assess risks that arise.

3.7.2.3 Adaptation options

This section will investigate how risks associated with pathways which include an overshoot relative to the final stabilization point of 1.5 °C might be mitigated through adaptation strategies.

3.7.3 Non-greenhouse gas implications and projected risks of mitigation scenarios

3.7.3.1 Influence on weather and climate extremes

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) 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. 2013b). 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. 2014). 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 3.12).

3.7.3.2 Impacts on natural and human systems (e.g. competition for land/water and food/energy security)

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, 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). The reductions in yield driven by climate change and/or land management decisions 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).

[INSERT FIGURE 3.12 HERE]

Figure 3.12: 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 Figure 3 of Hirsch et al. (2017).

3.7.4 Long-term implications

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