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S3-2 Supplementary information to Section 3.2

Climate models and associated simulations available for the present assessment

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

In order to assess the impact and risk of projected climate changes on ecosystems or human systems, typical ESM simulations have a too coarse resolution (100 km or more) in many cases. Different approaches can be used to derive higher-resolution information. In some cases, ESMs can be run globally with very-high resolution, however, such simulations are cost-intensive and thus very rare. Another approach is to use Regional Climate Models (RCM) to dynamically downscale the ESM simulations. RCMs are limited-area models with representations of climate processes comparable to those in the atmospheric and land surface components of the global models but with a higher resolution than 100 km, generally down to 10–50 km (e.g., Coordinated Regional climate Downscaling Experiment, CORDEX, Giorgi and Gutowski 2015; Jacob et al. 2014; 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 4 km, e.g., Kendon et al. 2014; Ban et al. 2014; Prein et al. 2015). Statistical downscaling is another approach for downscaling information from global climate models to higher resolution. Its underlying principle is to develop statistical relationships that link large-scale atmospheric variables with local / regional climate variables, and to apply them to coarser-resolution models (Salameh et al. 2009; Su et al. 2016). Nonetheless, at the time of writing, we note that there are only very few studies on 1.5°C climate using regional climate models or statistical downscaling. One exception is an extension of the IMPACT2C project for Europe (see below).

There are various sources of climate model information available for the present assessment. First, there are global simulations that have been used in previous IPCC assessments and which were computed as part of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP). The IPCC Fourth Assessment Report (AR4) and Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) were mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. We note that the simulations of the CMIP3 and CMIP5 experiments were found to be very similar (e.g., Knutti and Sedláček 2012; Mueller and Seneviratne 2014).

In addition to the CMIP3 and CMIP5 experiments, there are results from CORDEX, which are available for different regions (Giorgi and Gutowski 2015). For instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et al. 2014; Jacob and Solman 2017) are newly available for 1.5°C projections.

Recently, simulations from the ‘Half a degree Additional warming, Prognosis and Projected Impacts’ (HAPPI) multi-model experiment have been performed to specifically assess climate changes at 1.5°C versus 2°C global warming (Mitchell et al. 2017). The HAPPI protocol consists of coupled land-atmosphere initial condition ensemble simulations with prescribed Sea Surface Temperatures (SSTs), sea ice, GHG and aerosol concentrations, solar and volcanic activity that coincide with three forced climate states: present-day (2006–2015), and future (2091–2100) either with 1.5°C or 2°C global warming (prescribed from the modified SST conditions).

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

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

As highlighted in previous IPCC Reports, detection and attribution is an approach which is typically applied to assess impacts of GHG forcing on observed changes in climate (e.g., Hegerl et al. 2007; Seneviratne et al. 2012; Bindoff et al. 2013). The reader is referred to these past IPCC reports, as well as to the IPCC Good Practice Guidance Paper on Detection and Attribution related to Anthropogenic Climate Change (Hegerl et al. 2010), for more background on this topic. It is noted that in the IPCC Working Group I (WGI) framework, 'attribution' is focused on the 'attribution to anthropogenic greenhouse gas forcing' (e.g., (Bindoff et al. 2013b) . In past IPCC Working Groups II (WGII) reports, attribution of observed impacts were also made to regional changes in climate, but without consideration of whether the patterns of changes in regional climate had had a detectable influence from GHG forcing. As noted in Section 3.2.2, a recent study (Hansen and Stone 2016) shows that most of the detected temperature-related impacts that were reported in the AR5 (Cramer et al. 2014) can be attributed to anthropogenic climate change, while the signals for precipitation-induced responses are more ambiguous.

Attribution to anthropogenic greenhouse gas forcing is an important field of research for the assessments of projected changes at 1.5°C and 2°C global warming in this Report (see Section 3.3, and in particular Table 3.2). Indeed, observed global warming compared to the pre-industrial conditions up to the 2006–2015 decade was 0.87°C, and approximately 1ºC at around 2017 (Section 3.2). Thus, 'climate at 1.5°C global warming' corresponds to approximately the addition of half a degree warming compared to present-day warming and observed regional climate changes and impacts associated with a ca. 0.5°C global warming can be inferred from the historical record (although there could be non-linear changes at higher levels of warming, Sections 3.2.1 and 3.2.2). This means that methods applied in the attribution of climate changes to human influences can be relevant for assessments of changes in climate at 1.5°C warming, especially in cases where no climate model simulations or analyses are available for the conducted assessments. Indeed, impacts at 1.5°C global warming can be assessed in parts from regional and global climate changes that have already been detected and attributed to human influence (e.g., Schleussner et al. 2017). This is because changes that could already be ascribed to anthropogenic greenhouse gas forcing pinpoint to components of the climate system which are most responsive to this forcing, and thus will continue to be under 1.5°C or 2°C global warming. For this reason, when specific projections are missing for 1.5°C global warming, some of the assessments provided in Section 3.3, in particular in Table 3.2, 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. Such assessments are for transient changes only (Section 3.2.1). We note that evidence from attribution analyses can also be considered in the assessment of the reliability of climate projections for 1.5°C and 2°C global warming.

The propagation of uncertainties from climate forcings to impacts on the ecosystems

The uncertainties associated with future projections of climate change are calculated using ensembles of model simulations (Flato et al. 2013). However, models are not fully independent, and the use of model spread as an estimator of uncertainty has been called into question (Annan and Hargreaves 2017). Many studies have been devoted to this issue, which is of high relevance policymakers. The sources of uncertainty are diverse (Rougier and Goldstein 2014), and they must be identified to better determine the limits of predictions. The following list includes several key sources of uncertainty:

1. Input uncertainties include a lack of knowledge about the boundary conditions and the noise affecting the forcing variables;
2. Parametric and structural uncertainties are related to the lack of knowledge about some processes (i.e., those that are highly complex or operate at very fine scales) and the lack of clear information about the parameterisations used in models and the differences among the models. It has also been shown that different combinations of parameters can yield plausible simulations (Mauritsen et al. 2012).
3. Observational errors include noise and the unknown covariance structure in the data used.
4. Scale uncertainty originates from the fact that impact studies require a finer scale than Earth System Model (ESM) outputs can provide (Khan and Coulibaly 2010).
5. The offline coupling of climate - impact models introduces uncertainty because this coupling permits only a limited number of linkage variables and does not allow the representation of key feedbacks. This procedure may cause a lack of coherency between the linked climate and impact models (Meinshausen et al. 2011).
6. Important biases also include the consequences of tuning using a restricted range of climate states, i.e., the periods from which climate data are available. Large biases in projections may be produced when future forcings are very different than those used for tuning.
7. It is also assumed that ESMs yield adequate estimates of climate, except for an unknown translation (Rougier and Goldstein 2014). Usually, this translation is estimated by performing an anomaly correction (the difference between the control simulation and the observed field). Such correction represents an additional uncertainty that is often ignored in the final estimate of the error bars.

Due to these uncertainties in the formulation, parametrisation, and initial states of models, any individual simulation represents only one step in the pathway followed by the climate system (Flato et al. 2013). The assessment of these uncertainties must therefore be done in a probabilistic way. It is particularly important when the signal to noise ratio is weak, as it could be when we want to assess the difference of risks between 1.5°C and 2°C global warming.

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S3-3 Supplementary information to Section 3.3

S3-3-1 Change in global climate

The Global Mean Surface Temperature (GMST) warming reached approximately 1°C above pre-industrial levels in 2017 (Haustein et al. 2017; see also Chapter 1). At the time of writing of the AR5 WG1 report (i.e., for time frames up to 2012, Stocker et al. 2013), Hartmann et al. (2013) assessed that the globally averaged combined land and ocean surface temperature data as calculated by a linear trend, showed a warming of 0.85°C (0.65–1.06°C), over the period 1880–2012, when multiple independently produced datasets existed, and about 0.72°C (0.49–0.89°C) over the period 1951–2012. Hence most of the global warming has occurred since 1950 and it has continued substantially in recent years. The above values are for global mean warming, however, regional trends can be much more varied (Figure S3.1). With few exceptions, most land regions display stronger trends in the global mean warming, and by 2012, i.e., with a warming of about 0.85°C (see above), some land regions already displayed warming higher than 1.5°C (Figure S3.1).

It should be noted that more recent evaluations of the observational record suggest that the estimates of global warming at the time of the AR5 may have been underestimated (Cowtan and Way 2014; Richardson et al. 2016). Indeed, as highlighted in Section 3.3.1 and also discussed in Chapter 1, sampling biases and different approaches to estimate GMST (e.g., using water versus air temperature over oceans) can sensibly impact estimates of GMST warming as well as differences between model simulations and observations-based estimates (Richardson et al. 2016).

As highlighted in Chapter 1, an area in which substantial new literature has become available since the AR5 is the GMST trend over the period 1998–2012, which has been referred to by some as the “global warming hiatus” (Stocker et al. 2013; Karl et al. 2015; Lewandowsky et al. 2016; Medhaug et al. 2017). This term was used to refer to an apparent slowdown of GMST warming over that time period (although other climate variables continued to display unabated changes during that period, including a particular intense warming of hot extremes over land, Seneviratne et al. 2014). Medhaug et al. (2017) note that from a climate point of view, with 2015 and 2016 being the two warmest years on record (based on GMST), the question of whether ‘global warming has stopped’ is no longer present in the public debate. Nonetheless, the related literature is relevant for the assessment of changes in climate at 1.5°C global warming, since this event illustrates the possibility that the global temperature response may be decoupled from the radiative forcing over short time periods. While this may be associated with cooler global temperatures as experienced during the incorrectly labeled hiatus period, this implies that there could also be time periods with global warming higher than 1.5°C even if the radiative forcing would be consistent with a global warming of 1.5°C in long-term average. Recent publications have highlighted that the ‘slow-down’ in global temperature warming that occurred in the time frame of the hiatus episode 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; Figure S3.2). This has some relevance for the definition of a ‘1.5°C climate’ (see Chapter 1 and Cross-Chapter Box 8 in Chapter 3 on 1.5°C warmer worlds). Overall, the issue of internal climate variability is the reason why a 1.5°C warming level needs to be determined in terms of ‘human-induced warming’ (see Chapter 1 for additonal background on this issue).

A large fraction of the detected global warming has been attributed to anthropogenic forcing (Bindoff et al. 2013a). The AR5 (Bindoff et al. 2013a) 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 (supplementary Figure S3.3). The AR5 (Bindoff et al. 2013a) assessed that greenhouse gases contributed a GMST increase *likely* to be between 0.5°C and 1.3°C over the period 1951–2010, with the contributions from other anthropogenic forcings *likely* to lie between –0.6°C and 0.1°C, from natural forcings *likely* to be between –0.1°C and 0.1°C, and from internal variability *likely* to be between –0.1°C and 0.1°C. Regarding observed global changes in temperature extremes, Reports from the AR5 cycle assessed that since 1950 it is *very likely* that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale, that is, for land areas with sufficient data (Seneviratne et al. 2012; Hartmann et al. 2013). This assessment is confirmed as part of the present report and highlights that further decreases in cold extremes and increases in hot extremes are projected for a global warming of 1.5°C.

Observed global changes in the water cycle, including precipitation, are more uncertain than observed changes in temperature (Hartmann et al. 2013; Stocker et al. 2013). The AR5 assessed that it is *very likely* that global near surface and tropospheric air specific humidity have increased since the 1970s (Hartmann et al. 2013). However, AR5 also highlighted that during recent years the near surface moistening over land has abated (*medium confidence*), and that as a result, there have been fairly widespread decreases in relative humidity near the surface over the land in recent years (Hartmann et al. 2013). With respect to precipitation, some regional precipitation trends appear to be robust (Stocker et al. 2013), but when virtually all the land area is filled in using a reconstruction method, the resulting time series of global mean land precipitation shows little change since 1900. Hartmann et al. (2013) highlight that confidence in precipitation change averaged over global land areas since 1901 is low for years prior to 1951 and medium after 1951. 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. 2013a).

Figures S3.4 and S3.5 display the same analyses as the left-hand panels of the Figures 3.3. and 3.4 in the main text, but based on Representative Concentration Pathway (RCP)2.6 simulations instead of RCP8.5.

S3-3-2 Regional temperature on land, including extremes

S3-3-2-1 Observed and attributed changes in regional temperature means and extremes

While the quality of temperature measurements obtained through ground observational networks tend to be high compared to that of measurements for other climate variables (Seneviratne et al. 2012), it should be noted that some regions are undersampled. Cowtan and Way (2014) highlighted issues regarding undersampling being concentrated at the Poles and over Africa, which may lead to biases in estimated changes in Global Mean Surface Temperature (GMST) (see also Section 3.3.2 and Chapter 1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature.

Despite this partly limited coverage, the attribution chapter of the AR5 (Bindoff et al. 2013a) and recent papers (e.g., Sun et al. 2016; Wan et al. 2018) assessed that over every continental region and in many sub-continental regions, anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century. For Antarctica, while changes are occurring, statistical assessment (presumably to 95% confidence) has not been achieved due primarily to the large natural variability in the weather that occurs there and the comparatively short observational record.

Regarding observed regional changes in temperature extremes, the AR5 (Hartmann et al. 2013) provided the following assessment based in part on the IPCC IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)(Seneviratne et al. 2012):

- *Likely (high confidence)* overall increases in warm days and warm nights, and decreases in cold days and cold nights in North America and Central America, Europe and Mediterranean region, in Asia, in south-east Asia and Oceania (including Australia), and in southern Africa
- *Medium confidence* overall increase in warm days and warm nights, and decreases in cold days and cold nights in South America, and North Africa and Middle East
- *Low to medium confidence* in some African regions lacking observations, but locations with observations display increases in warm days and warm nights, and decreases in cold days and cold nights.

Further, the IPCC SREX assessed (Seneviratne et al. 2012) that globally, in many (but not all) regions with sufficient data there is *medium confidence* that the length and the number of warm spells or heat waves has increased since the middle of the 20th century, and that it is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale.

Hence, observed and attributed changes in both mean and extreme temperature consistently point to a widespread influence of human-induced warming in most land regions. We should note that there are new publications regarding observed trends in temperature and precipitation means and extremes in Africa (e.g., Ringard et al. 2016; Moron et al. 2016; Omondi et al. 2013; MacKellar et al. 2014), which may allow to increase the confidence regarding observed changes on this continent.

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

As highlighted in Section 3.2, the observational record can be used to assess past changes associated with a global warming of of 0.5°C, with this type of assessment being considered as an analogue for the difference between a scenario at 1.5°C and at 2°C global warming. This approach has its limitations. For example, the methodology does not account for non-linearity in responses, including possible regional or global tipping points. Nonetheless, it can provide a first assessment of aspects of the climate system that have been identified as being sensitive to a global warming change of this magnitude. Schleussner et al. (2017) using this approach, assess observed changes in extreme indices for the 1991-2010 versus the 1960–1979 period, which corresponds to just about 0.5°C GMST difference in the observed record (based on the Goddard Institute for Space Studies Surface Temperature Analysis GISTEMP dataset, Hansen et al. 2010). They found that substantial changes due to 0.5°C warming are apparent for indices related to hot and cold extremes, as well as for the Warm Spell Duration Indicator (WSDI). Some results are displayed in Figure S3.6. and S3.7 Using two well established observational datasets (Hadley Centre Global Climate Extremes Index 2 (HadEX2) and Global Historical Climatology Network (GHCN)-Daily climate Extremes (GHCNDEX);, Donat et al. (2013a,b), these analysis show that one quarter of the land has experienced an intensification of hot extremes (TXx) by more than 1°C and a reduction of the intensity of cold extremes by at least 2.5°C (TNn). Half of the global land mass has experienced changes in WSDI of more than 6 days and the emergence of extremes outside the range of natural variability is particularly pronounced for this duration-based indicator (Figure 3.7). Results for TXx based on reanalysis products are similar for the 20CR product, but even more pronounced for the ERA reanalysis (as noted by Schleussner et al. 2017, however, results based on reanalysis products need, however, to be considered with caution). Overall, based on the analysis of Schleussner et al. (2017), the observational record suggest that a 0.5°C change in global warming has noticeable global impacts on temperature extremes.

S-3-3-2-2 Projected changes at 1.5°C vs. 2°C in regional temperature means and extremes

This supplementary information provides more detailed material as background for the assessment of

Section 3.3.2.2.

As noted in Section 3.3.2.2., there is a stronger warming of the regional land-based hot extremes compared to the mean global temperature warming in most land regions (also discussed in Seneviratne et al. 2016). The regions displaying the stronger contrast are Central North America, eastern North America, Central Europe, southern Europe/Mediterranean, Western Asia, Central Asia, and southern Africa. As highlighted in Vogel et al. (2017), these regions are characterized by transitional climate regimes between dry and wet climates, which are associated with strong soil moisture-temperature coupling (related to a transitional soil moisture regime Koster et al. 2004; Seneviratne et al. 2010). Several of these regions display enhanced drying under enhanced greenhouse forcing (see Section 3.3.4), which leads to a decrease of evaporative cooling and an additional regional warming compared to the global temperature response. In a recent study, Karmalkar and Bradley (2017) also found consistent results for the contiguous United States, with all subregions being projected to reach 2°C about 10–20 years before the global mean temperature.

In general, these transitional climate 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)(see also Section 3.3.4) and to differences in soil moisture-temperature coupling in climate models (Seneviratne et al. 2013; Stegehuis et al. 2013; Sippel et al. 2016), whereby feedbacks with clouds and surface radiation are also relevant (Cheruy et al. 2014). Furthermore, in some regions internal climate variability can also 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.

Regarding results from regional studies, Vautard et al. (2014) report that most of Europe will experience higher warming than the global average with strong distributional patterns across Europe for global warming of 2°C, which is consistent with the present assessment for 1.5°C warming (Jacob et al. 2018). For instance, a North–South (West–East) warming gradient is found for summer (winter) along with a general increase and summer extreme temperatures.

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

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

Figure 3.5 in Chapter 3 displays projected changes in the annual maximum daytime temperature (TXx) as a function of Global Mean Surface Temperature (GMST) for the main regions as specified in the IPCC SREX (See Figure 3.2 for a description of the regions) using Empirical Scaling Relationships (ESR; Section 3.2). The underlying model projections include Coupled Model Intercomparison Project Phase 5 (CMIP5)multi-model global climate simulations (based on the analyses of Wartenburger et al. 2017 and Seneviratne et al. 2016) and simulations from the ‘Half a degree Additional warming, Prognosis and Projected Impacts’ (HAPPI) multi-model experiments (Mitchell et al. 2017; based on analyses presented in Seneviratne et al. 2018). The CMIP5 analyses provide continuous estimates of the dependency of the analysed climate extremes as function of GMST, while the HAPPI-derived estimates are only available for the estimation of responses at two global warming levels, 1.5°C and 2°C. The CMIP5-based ESR analyses are computed from historical and RCP8.5 simulations from 26 CMIP5 global climate models (including up to 10 ensemble members per model). For the HAPPI analyses, changes in the indices and in the corresponding global mean temperatures (as indicated in the map and in the bar plots shown in the figures) are based on the 100 first ensemble members (#1 to #100) from five models (Canadian 4th generation Atmospheric global climate Model (CanAM4), Community Atmosphere Model version 4 (CAM4), European Center Hamburg model version 6-3-Default (Low) Resolution (ECHAM6-3-LR), Model for Interdisciplinary Research On Climate version 5 (MIROC5), and Norwegian Earth System Model version 1-HAPPI (NorESM1-happi)) following Seneviratne et al. (2018). For each of the HAPPI models and the two experiments considered (1.5°C relative to pre-industrial and 2°C relative to pre-industrial), we compute differences of the indices (scenario period – reference period, consisting of 10 years of data each per ensemble member). The reader is referred to the mentioned publications for more background on the analyses and data bases. Note that the ESR analyses are based on land data only for all of the considered regions, i.e., with a mask being applied to ocean data within the considered regions. (Ocean data points are, however, included for analyses for island regions provided in this Annex, i.e., a subset of the regions indicated asterisks (*) in Figure 3.2; see e.g., Figure S3.9 and similar).

Figure S3.8 displays similar analyses as Figure 3.5 but for the annual minimum Nighttime Temperatures, TNn. The mean response of these cold extremes displays less discrepancy with the global levels of warming (often close to the 1:1 line in many regions), however, there is a clear amplified warming in regions with snow and ice cover. This is expected given the Arctic warming amplification (Serreze and Barry 2011, see also AR5 overview on ‘polar amplification’, Masson-Delmotte et al. 2013; IPCC 2013) which is to a large extent 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 S3.6) and thus be much larger than the global temperature warming.

Figures S3.9 and S3.10 display the same analyses as Figures 3.5 (main text) and S.3.8 for the regions indicated with asterisks in Figure 3.2. It should be noted that for the island regions, the land fraction is often too small to be resolved by standard global climate models. For this reason, as mentioned above, the analyses for island regions (indicated with # sign) are based on both land and ocean air-temperatures and are representative of average climate conditions in the areas in which they are located.

Figure S3.13 displays maps of changes in the Number of Hot Days (NHD) and Number of Frost Days (NFD) at 1.5°C and 2°C GMST warming. These analyses reveal clear patterns of changes between the two warming levels, with decreases in frost days in many regions.

S3-3-3 Regional precipitation on land, including heavy precipitation and monsoons

Observed and attributed changes in regional precipitation

There is overall *low confidence* in observed trends for monsoons because of insufficient evidence (consistent with a previous assessment in the IPCC SREX, Seneviratne et al. 2012). There are, nonetheless, a few new assessments available, although they do not report consistent trends in different monsoon regions (Singh et al. 2014; Taylor et al. 2017; Bichet and Diedhiou 2018). For instance, (Singh et al. 2014) use precipitation observations (1951-2011) of the South Asian summer monsoon and show that there have been significant decreases in peak-season precipitation over the core-monsoon region and significant increases in daily-scale precipitation variability. Furthermore, Taylor et al. (2017) showed that over West African Sahel the frequency of extreme storms tripled since 1982 in satellite observations and (Bichet and Diedhiou 2018) confirm that the region has been wetter during the last 30 years but dry spells are shorter and more frequent with a decreasing precipitation intensity in the western part (over Senegal). However, there is not sufficient evidence to provide higher than *low confidence* in the assessment of observed in overall trends in monsoons

Projected changes at 1.5°C and 2°C in regional precipitation

The AR5 assessed that the global monsoon, aggregated over all monsoon systems, is likely to strengthen (Christensen et al. 2013). 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 weak projected changes in the East Asian winter monsoon as a whole relative to the reference period (1980–1999). Regionally, they found a weakening north of about 25°N in East Asia and a strengthening south of this latitude, which resulted from atmospheric circulation changes over the western North Pacific and Northeast Asia. This is linked 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 strengthening (albeit, slight) of monsoon in East China over the 21st century as a consequence of an increased land-sea thermal contrast between the East Asian continent and the adjacent western North Pacific and South China Sea. Using six CMIP5 model simulations of the RCP8.5 high-emission scenario, Jones and Carvalho (2013) found a 30% increase in the amplitude of the South American Monsoon System (SAMS) from the current level by 2045–2050. They also found an ensemble mean onset date of the SAMS which was 17 days earlier, and a demise date 17 days later, by 2045–2050. The most consistent CMIP5 projections analysed confirmed the increase in the total precipitation over southern Brazil, Uruguay, and northern Argentina. Given that scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the studies of Jiang and Tian (2013) and Jones and Carvalho (2013), there is *low confidence* regarding changes in monsoons at these low global warming levels, as well as regarding differences in responses at 1.5°C vs. 2°C.

Several analyses of GCM-RCM simulations in the framework of the Coordinated Regional Climate Downscaling Experiment for Africa (CORDEX-AFRICA) were performed to capture changes in the African climate system in a warmer climate. Sylla et al. (2015, 2016) analyzed the response of the annual cycle of high-intensity daily precipitation events over West Africa to anthropogenic greenhouse gas for the late twenty-first century. The late-21st-century projected changes in mean precipitation exhibit a delay of the monsoon season and a decrease in frequency but increase in intensity of very wet events, particularly in the premonsoon and early mature monsoon stages, more pronounced in RCP8.5 over the Sahel and in RCP4.5 over the Gulf of Guinea. The premonsoon season also experiences the largest changes in daily precipitation statistics, with increased risk of drought associated with a decrease in mean precipitation and frequency of wet days and an increased risk of flood associated with very wet events. Weber et al. assessed the changes in temperature and rainfall related climate change indices in a 1.5°C, 2°C and 3°C global warming world for the Africa continent. The results showed the daily rainfall intensity is also projected to increase for higher global warming scenarios especially for the African Sub-Saharan coastal regions.

Figure S3.14 displays the same analyses as Figure 3.9 for the regions indicated with asterisks in Figure 3.2. For the underlying methodology, a similar approach was used as for Figure 3.5 (see Section S3.3.2.2).

S3-3-4 Drought and dryness

Figure S3.15 displays the same analyses as Figure 3.12 for the regions indicated with asterisks in Figure 3.2. For the underlying methodology, a similar approach was used as for Figure 3.5 (see Section S3.3.2.2).

Supplementary Figures

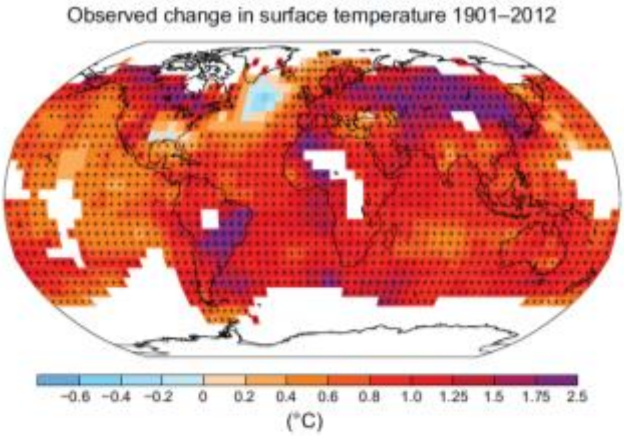


Figure S3.1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset. Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records 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).

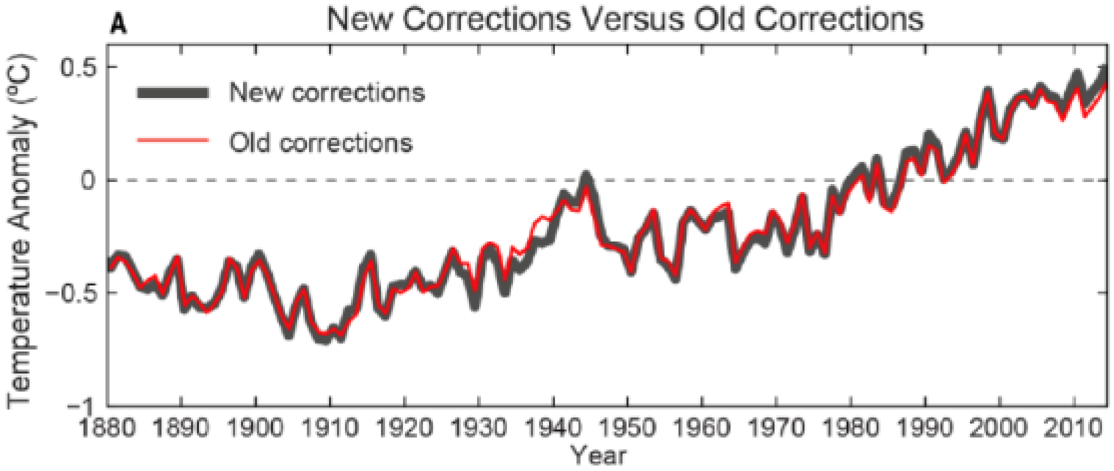
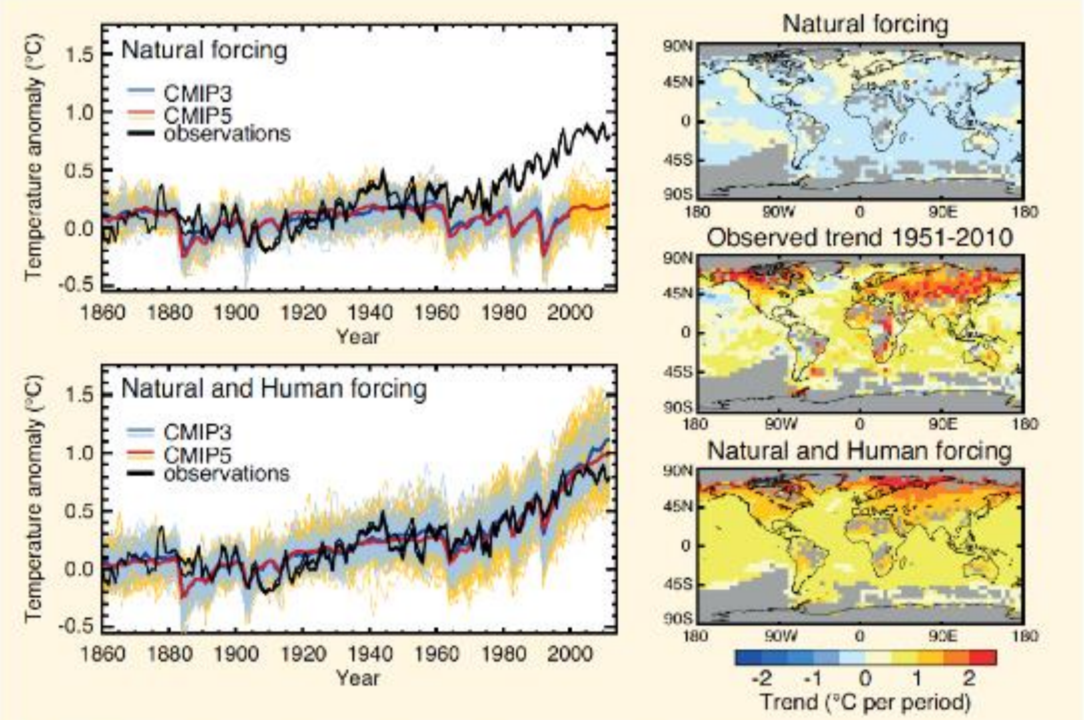


Figure S3.2: Global temperature warming using older and newer corrections (Karl et al. 2015)



FAQ 10.1, Figure 1 | (Left) Time series of global and annual-averaged surface temperature change from 1860 to 2010. The top left panel shows results from two ensemble of climate models driven with just natural forcings, shown as thin blue and yellow lines; ensemble average temperature changes are thick blue and red lines. Three different observed estimates are shown as black lines. The lower left panel shows simulations by the same models, but driven with both natural forcing and human-induced changes in greenhouse gases and aerosols. (Right) Spatial patterns of local surface temperature trends from 1951 to 2010. The upper panel shows the pattern of trends from a large ensemble of Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations driven with just natural forcings. The bottom panel shows trends from a corresponding ensemble of simulations driven with natural + human forcings. The middle panel shows the pattern of observed trends from the Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4) during this period.

Figure S3.3. Attribution of global warming change (from IPCC AR5, Bindoff et al. 2013).

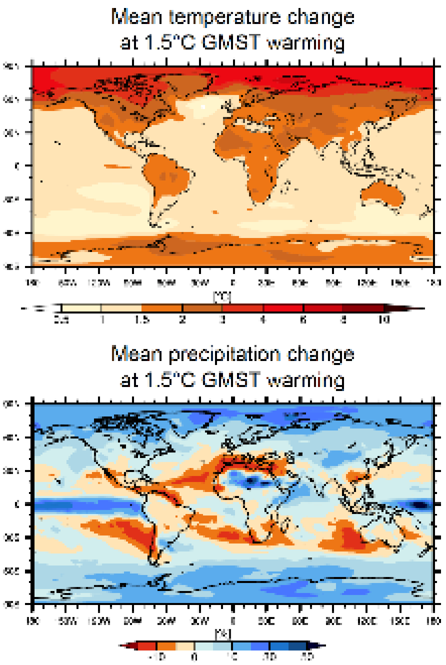
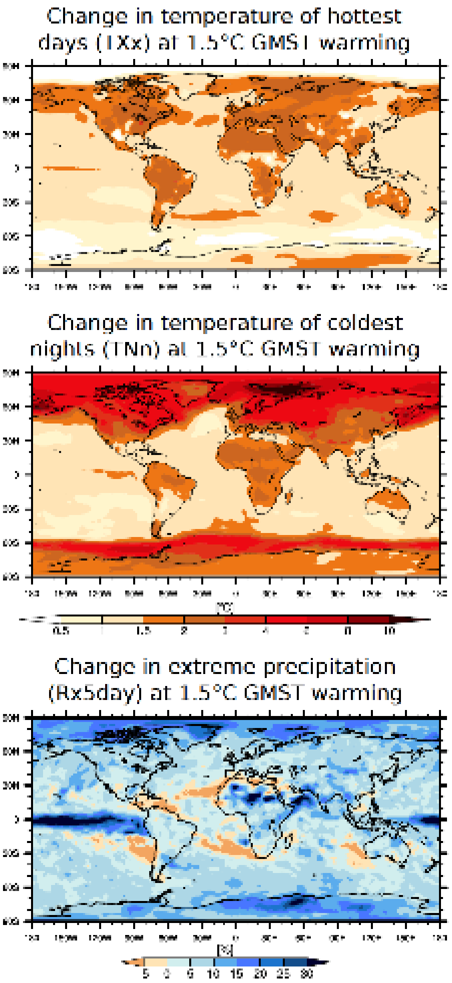


Figure S3.4: Same as left-hand plots of Figure 3.3, but based on the Representative Concentration Pathway (RCP)2.6 scenarios


Change in temperature of hottest days (TXx) at 1.5°C GMST warming

Change in temperature of coldest nights (TNn) at 1.5°C GMST warming

Change in extreme precipitation (Rx5day) at 1.5°C GMST warming

Figure S3.5: Same as left-hand plot of Figure 3.4, but based on the Representative Concentration Pathway (RCP)2.6 scenarios

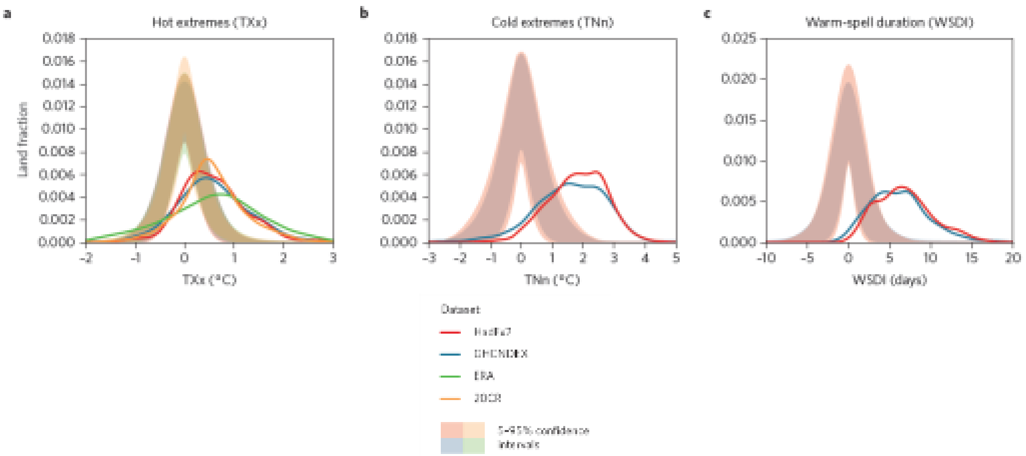


Figure S3.6 : Difference in extreme temperature event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. For TXx, the analysis includes also reanalysis data from the European Centre for Medium-Range Forecasts (ECMWF) (ECMWF Reanalysis 40 (ERA-40) and Interim (ERA-Interim), used as a combined dataset including ERA-40 until 1979 and ERA-Interim from

1979 onward) and the Twentieth Century Reanalysis (20CR) ERA and 20CR over the global land area. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years. From Schleussner et al. (2017)

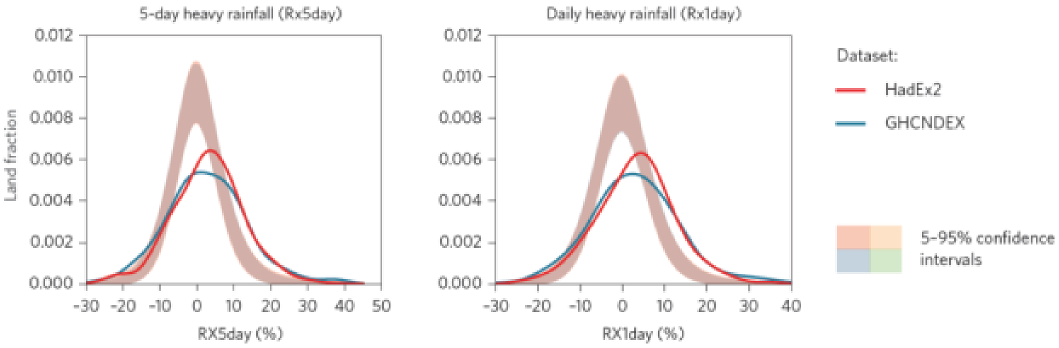


Figure S3.7 : Differences in extreme precipitation event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years. From Schleussner et al. (2017)

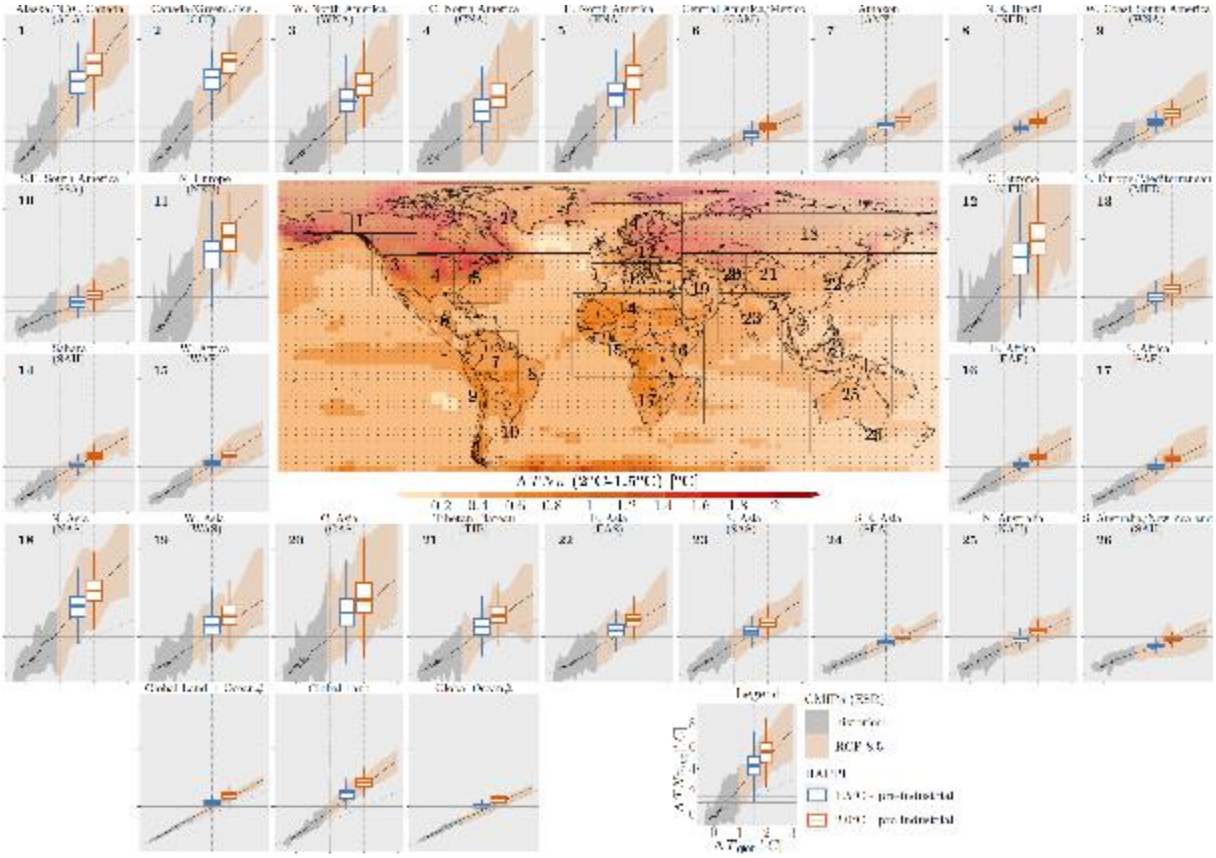


Figure S3.8 : Same analysis as Figure 3.5, but for the annual minimum night-time temperature (TNn). For more details on computation, see description of computation of Figure 3.5 in the present Annex, as well as Wartenburger et al. (2017), Seneviratne et al. (2016) and Seneviratne et al. (2018).

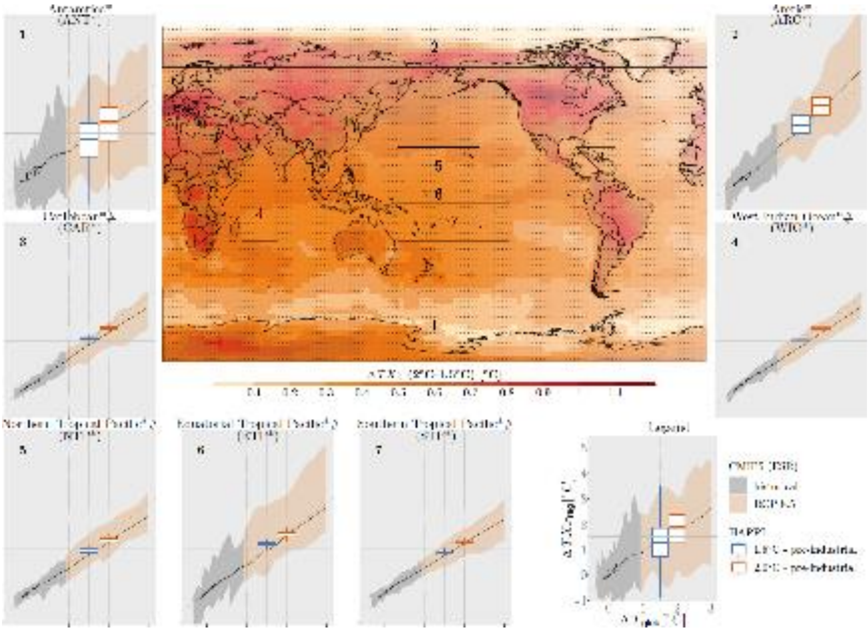


Figure S3.9: Same analysis as Figure 3.5 (projected changes in annual maximum daytime temperature (TXx) as function of global temperature warming) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses. See description of computation of Figure 3.5 in the present Annex for more details.

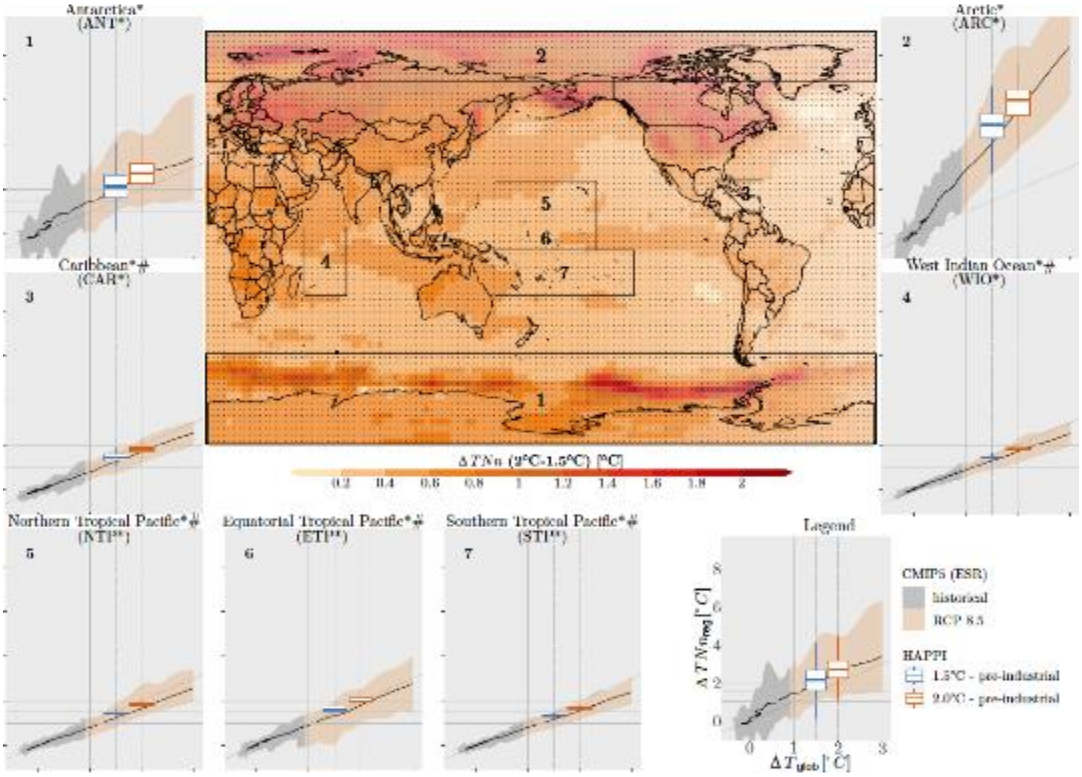


Figure S3.10: Same analysis as Figure S3.8 (projected changes in annual minimum nightime temperature (TNn) as function of global temperature warming) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

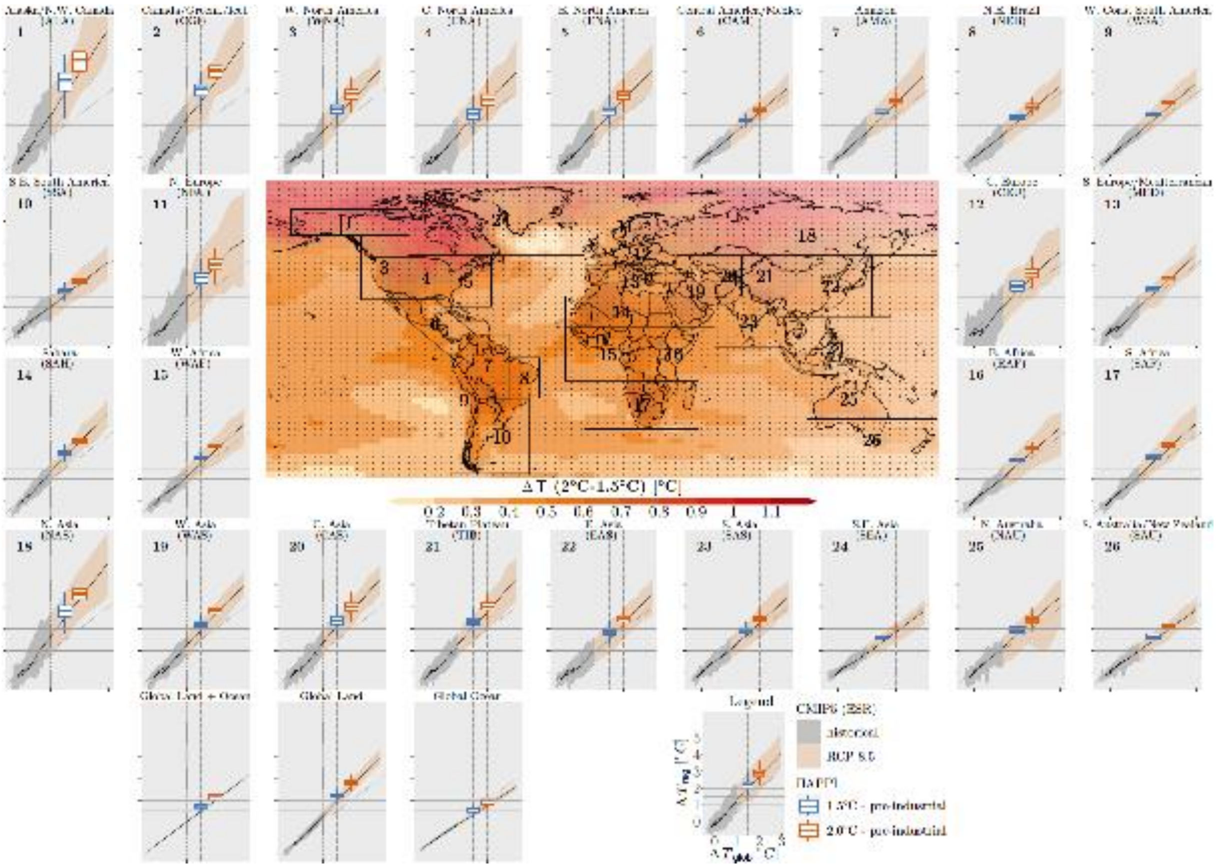


Figure S3.11: Same analysis as Figure 3.5, but for the mean surface temperature (Tmean).

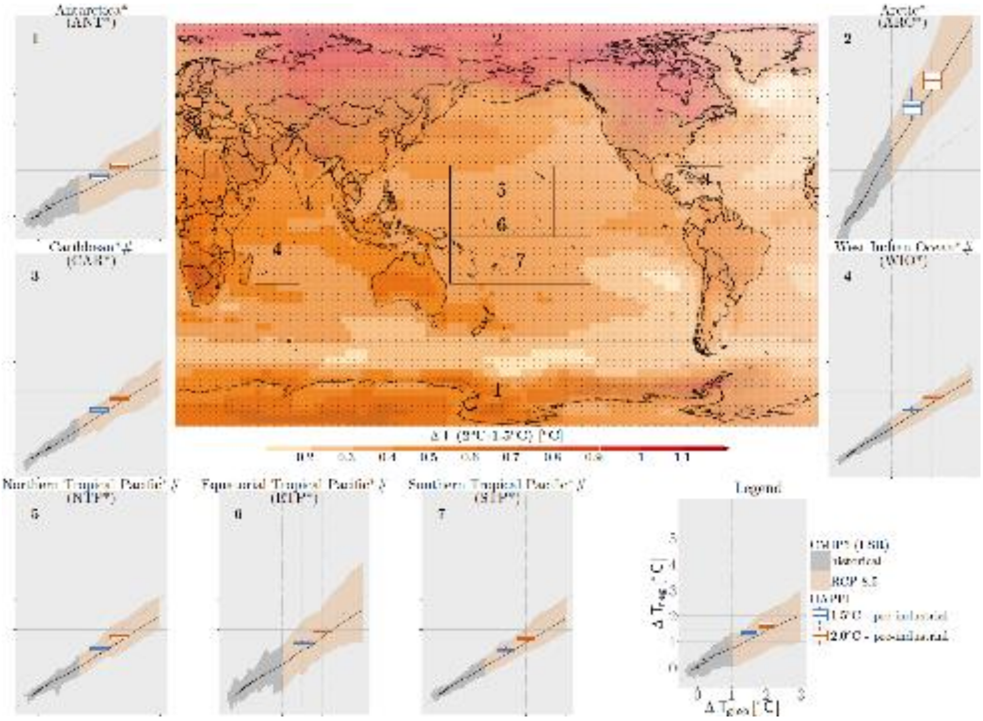


Figure S3.12: Same analysis as Figure 3.11 (projected in the changes in the mean surface temperature (Tmean) as function of the mean global temperature) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

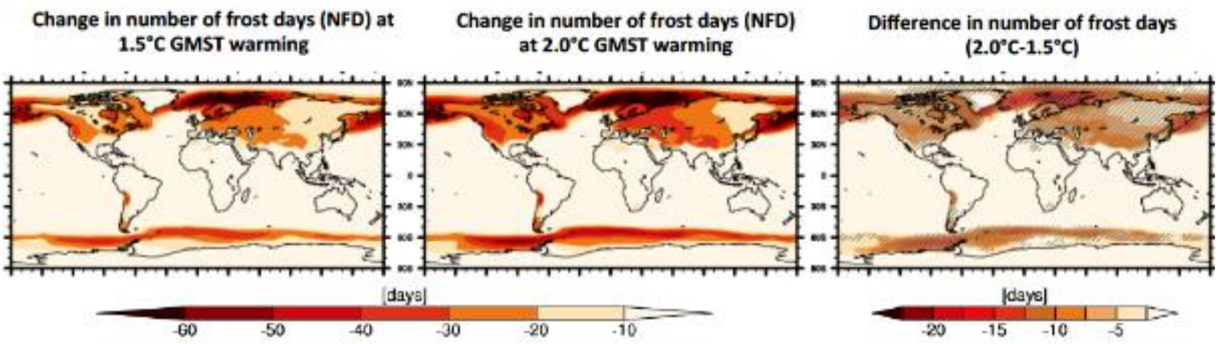


Figure S3.13: Projected changes in number of hot days (10% warmest days, top) and in number of frost days (days with T<0°C, bottom) at 1.5°C (left) and 2°C (right) GMST warming, and their difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Adapted from Wartenburger et al. (2017).

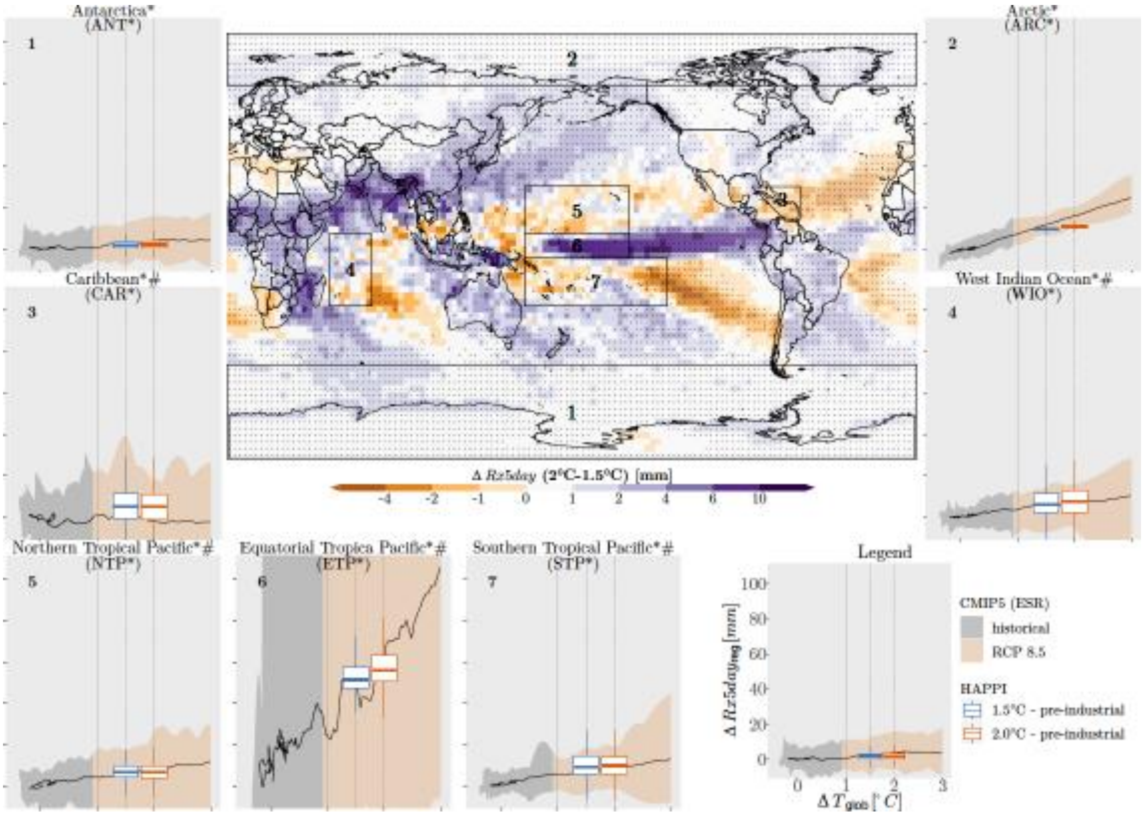


Figure S3.14: Same analysis as Figure 3.9 for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

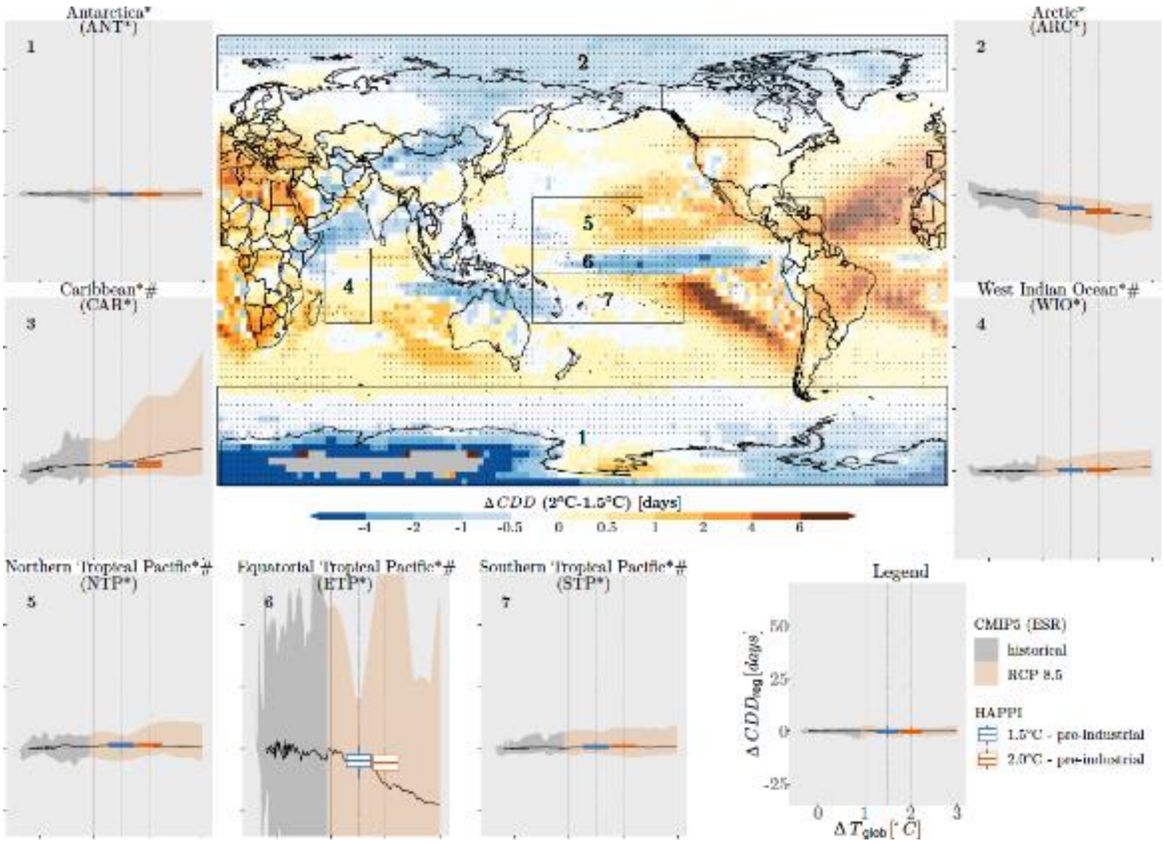


Figure S3.15: Same analysis as Figure 3.12 for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

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S3-4_ Supplementary information to Section 3.4

These tables document some of the quantitative projections of projected climate change impacts that are to be found in the literature cited in this report. They do not necessarily contain all of the quantitative projections that could be found in the literature, in particular where a single publication contains a large number of projections.

Table S1 – 3.4.2 Freshwater resources

See Excel file : « Table_SI-3.4.2.xls »

Table S2 – 3.4.3 Terrestrial and wetland ecosystems

See Excel file : « Table_SI-3.4.3.xls »

Table S3- 3.4.4 Ocean Systems

See Excel file : « Table_SI-3.4.4.xls »

Table S4 – 3.4.5 – Coastal and low-lying areas

See Excel file : « Table_SI-3.4.5.xls »

Table S5 – 3.4.6. Food security and food production systems

See Excel file : « Table_SI-3.4.6.xls »

S3-4-2_Supplementary information to Section 3.4.2

3.4.2 Freshwater resources (quantity and quality)

3.4.2.1 Water availability

In this section, Arnell and Lloyd-Hughes (2014) assess water scarcity based on the simple indicatior of average annual runoff per capita called water resources stress and define that watershed is exposed to such stress if watershed average annual runoff is less than 1000 m^3 cap^{-1} yr^{-1}. The same condition is applied to identify chronic supply-side water scarcity within a given spatial unit in the study of Gerten et al. (2013) that refer to Falkenmark and Widstrand (1992) whose index is called Withdrawal to Water Resouces (WWR) ratio. With WWR, Hanasaki et al. (2013) indicate a chronic water shortage if water withdrawal exceeds 40% of the water resources in a region. A quantitative metric of freshwater stress is defined in terms future projections of population and aridity, where freshwater stress index is caluculated as a population change index multiplied by an aridity change index Karnauskas et al. (2018). Schewe et al. (2014) apply two water scarcity classes: annual blue water availability below 500 m^3 per cabita, namely absolute water scarcity, and below 1,000 m^3 per capita that is referred to as chronic water scarcity.

3.4.2.2 Extreme hydrological events (floods and droughts)

Alfieri et al. (2017) assume population who have any positive flood depth is affected by flood to estimate the potential population affected by overlaying population density and flood hazard maps. Arnell et al. (2018) define exposure to river flooding by the average annual number of people living in major floodplains affected by floods grater than the baseline 30-year flood. Arnell and Lloyd-Hughes (2014) use an indicator in which the number of flood-prone people living in areas where the frequency of the baseline (1960–1990) 20-year flood either doubles (occurs more frequently than one in 10 years) or halves (occurs more rarely than one in 40 years) although these thresholds are arbitrary. Kinoshita et al. (2018) estimate fatalities due to flooding by multiplying exposure (population prone to flooding, defined in the study as gridded population) by vulnerability and numerically calculate fllod hazard as the extent and depth of flood, while estimating potential affected exposure by superimposing the modeled hazard on the population data. In the study, Kinoshita et al. (2018) consider exposure as gidded population whereas historical vulnerability is defined as a ratio of the observed flood consequences and potentially affected exposure at a national level in equation.

Definiton of drought. In the study of Arnell et al. (2018), drought is presented by the standardized runoff index called SRI, which is calculated from monthly runoff simulated with the MacPDM.09 global hydrological model described in Gosling and Arnell (2010), and define the occurrence of a drought that when the SRI is less than –1.5 and as for drought frequency for a given time series of monthly runoff, it is determined by counting the number of months with SRI less than –1.5. Liu et al. (2018) quantify the changes in drought characteristics, adopting Palmer Drought Severity Index (PDSI) that describes the balance between water supply (precipitation) and atmospheric evaporative demand required the precipitation estimated under climatically appropriate for existing conditions, which is described by Zhang et al. (2016) Wells et al. (2004) and Zhang et al. (2016). Liu et al. (2018) other study suggest that PDSI is commonly applicable as an indication of meteorological drought and a hydrological drought for a multiyear time series. Liu et al. (2018) assume a severe drought event when the monthly PDSI is < –3, and identify a severe drought year if a severe drought occurs for at least a month in a year, while quantifying population affected by severe drought per grid-cell as (population * annual frequency of severe drought).

3.4.2.3 Groundwater

*Definiton of groundwater recharge.*Portmann et al. (2013) assess groundwater with groundwater recharge (GWR), which is assumed to curbed by a maximum groundwater recharge rate per a day.

GWR occurs if daily precipitation exceeds 12.5 mm d^{-1} in case of medium to coarse grained soils (Portmann et al., 2013). In some regions, groundwater is often intensively used to supplement the excess demand, often leading to groundwater depletion, besides, climate change adds further pressure on water resources and exaggerates human water demands due to increasing temperatures over agricultural lands (Wada et al. 2017).

3.4.2.4 Water quality

Water temperature directly affects water quality, and the most chemical and bacteriological processes are accelerated according to the temperature rise (Watts et al. 2015). Hosseini et al. (2017) summarize that the main impact on water quality due to climate change is attributed to changing air temperature and hydrology, and particularly ambient air temperature directly affect water temperature that is projected to increase due to global warming. Watts et al. (2015) describe that water quality is affected by many factors, including water temperature, hydrological regime, nutrient status and mobilization of toxic substances as well as point source, diffuse discharge and acidification potential, referring to (Whitehead et al. 2009). Patiño et al. (2014) reveal that changes in water quality can influence the spread of harmful aquatic species, referring to the fact that toxic algae are lethal to some aquatic animals and has posed considerable ecological and economic impacts on freshwater and marine ecosystems. Bonte and Zwolsman (2010) state that salinisation due to rising sea levels as well as poor land management and excessive groundwater extractions is putting a strain on freshwater resources availability around the world. Attributing changes in river water quality to specific factors are difficult since multiple factors act at different temporal and spatial scales, and it often requires examining long-term series of continuous data (Aguilera et al. 2015).

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S3-4-4_Supplementary information to Section 3.4.4

Update of Expert assessment by Gattuso et al. (2015).

J.-P. Gattuso, A. Magnan, R. Billé, W. W. L. Cheung, E. L. Howes, F. Joos, D. Allemand, L. Bopp, S. R. Cooley, C. M. Eakin, O. Hoegh-Guldberg, R. P. Kelly, H.-O. Pörtner, A. D. Rogers, J. M. Baxter, D. Laffoley, D. Osborn, A. Rankovic, J. Rochette, U. R. Sumaila, S. Treyer, C. Turley

Published 3 July 2015, Science 349, aac4722 (2015)

DOI: 10.1126/science.aac4722

Risk assessment update: November 18, 2017 (by relevant expert team plus lead authors of Chapter 3) Special report on the Implications of 1.5°C).

This Section S3-4-4 includes:

Supplementary Text

Table S1

Full Reference List

Background information and rationale of expert judgment on the risk of impact due to CO_2 levels by 2100.

This supplementary material provides the background information and rationale for the construction of the burning embers diagrams used in Figure 3.17 to represent the risk of impacts from CO2 levels (by 2100) for keystone marine and coastal organisms and ecosystem services.

This is the expert judgment by the group on the overall risk - balancing negative, neutral and positive impacts across species and regions using current literature.

Table S6: The temperature at which transitions in the level of risk occur in response to climate change, from expert judgement by Gattuso et al. (2015) and updated in March 2018 for following three years of scientific literature. [White: no detectible risks from climate change; Yellow: Moderate levels of risk; Red: High level of risk; and Purple: Very high level of risk].
Note: these data were used to build the burning embers for representative marine organisms, ecosystems and sectors.
Note: red numbers are where the update has resulted in conclusions different to that of Gattuso et al. (2015).

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
Seagrasses (mid latitude)	White to Yellow	Begin	0.5	0.5
		End	0.8	0.8
	Yellow to Red	Begin	1.5	1.5

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
		End	1.8	1.8
	Red to Purple	Begin	2.2	2.2
		End	3	3
Mangroves	White to Yellow	Begin	1.8	1.3
		End	3	1.5 (2.5)*
	Yellow to Red	Begin	3	2.5
		End	3.2	2.7
	Red to Purple	Begin	N/A	NA
		End	N/A	NA
Warm water corals	White to Yellow	Begin	0.3	0.2
		End	0.4	0.4
	Yellow to Red	Begin	0.5	0.4
		End	0.8	0.6
	Red to Purple	Begin	0.8	0.6
		End	1.5	1.2
Pteropods (high latitude)	White to Yellow	Begin	0.7	0.7
		End	0.8	0.8
	Yellow to Red	Begin	0.8	0.8
		End	1.5	1.5
	Red to Purple	Begin	1.5	1.5
		End	2	2
Bivalves (mid latitude)	White to Yellow	Begin	0.4	0.4
		End	0.6	0.6
	Yellow to Red	Begin	0.9	0.9
		End	1.1	1.1
	Red to Purple	Begin	1.3	1.3
		End	1.5	1.5
Krill (high latitude)	White to Yellow	Begin	0.7	0.7
		End	0.9	0.9
	Yellow to Red	Begin	1	1
		End	1.6	1.6
	Red to Purple	Begin	1.8	1.8
		End	3.2	3.2

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
Finfish	White to Yellow	Begin	0.5	0.5
		End	0.7	0.7
	Yellow to Red	Begin	1.1	1.1
		End	1.3	1.3
	Red to Purple	Begin	1.4	1.4
		End	1.6	1.6
Open-ocean carbon uptake	White to Yellow	Begin	1	1
		End	1.5	1.5
	Yellow to Red	Begin	2	2
		End	3.2	3.2
	Red to Purple	Begin	N/A	N/A
		End	N/A	N/A
Coastal Protection	White to Yellow	Begin	0.5	0.5
		End	0.8	0.8
	Yellow to Red	Begin	1.5	1.5
		End	1.8	1.8
	Red to Purple	Begin	2.2	2.2
		End	3.2	3.2
Recreational services from coral reefs	White to Yellow	Begin	0.6	0.6
		End	0.8	0.8
	Yellow to Red	Begin	1	1
		End	1.5	1.5
	Red to Purple	Begin	2	2
		End	3.2	3.2
Bivalve fisheries and aquaculture (mid-latitude)	White to Yellow	Begin	1.1	1.1
		End	1.3	1.3
	Yellow to Red	Begin	1.7	1.7
		End	1.9	1.9
	Red to Purple	Begin	2.8	2.8
		End	3.2	3.2
Fin fisheries (low latitude)	White to Yellow	Begin	0.7	0.5
		End	0.9	0.7
	Yellow to Red	Begin	1	0.9

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
		End	1.2	1.1
	Red to Purple	Begin	2	2
		End	2.5	2.5
Fin fisheries (high latitude)	White to Yellow	Begin	0.7	0.7
		End	0.9	0.9
	Yellow to Red	Begin	2.2	2.2
		End	3.2	3.2
	Red to Purple	Begin	N/A	N/A
		End	N/A	N/A

Note: **Mangrove value differs from Table value but is consistent with main text.*

Expert assessment: Original assessment by Gattuso et al. (2015) using the IPCC Fifth Assessment Report (AR5) and literature published up to 2014. This current assessment updated the original assessment using literature from 2015 to early 2018. References for the current and past assessments are listed at the end of this document. This is Supplementary on-line material for the special report on the implications of 1.5oC warming.

Seagrasses (mid latitude)

Update: Recent literature supports the consensus reached by Gattuso et al., (2015) with increasing ocean temperatures a major threat, with the potential loss of key species such as *Posidonia oceanica* in the Mediterranean by mid-century (Jordà et al. 2012). Recent work has shown that increasing temperatures is a major threat to the shoot density (Guerrero-Meseguer et al. 2017) and quality of the seagrass *Zostera marina* (Repolho et al. 2017). Other studies in related systems reveal sub-chronic changes to the quality of seagrass shoots and leaves (Unsworth et al. 2014) and have speculated on the impact that these changes might have on coastal food webs (York et al. 2016). Several studies have speculated on the impact of rising seas, storms and flooding on seagrass productivity (Rasheed et al. 2014; Telesca et al. 2015; Pergent et al. 2015; Ondiviela et al. 2014). The consistency of the literature for the last two years with that examined since the AR5 suggest that the current risk levels for seagrasses proposed by Gattuso et al. (2015) are appropriate.

Therefore, seagrasses are already showing responses to climate change hence the expert consensus that the transition from undetectable to medium risks occurs between 0.5 and 0.8°C. Given the clear sensitivity of seagrass communities to rising sea temperatures, and other aspects of climate change such as sea level rise, storms and flooding, these risks transition from medium to high from 1.5°C to 1.8°C, and from high to very high over the interval from 2.2°C to 3°C.

Expert assessment by Gattuso et al. (2015; SOM):

Seagrasses, important habitats in coastal waters around the world, will be affected by climate change through a number of routes including direct effects of temperature on growth rates (Nejrup and Pedersen 2008; Höffle et al. 2011), occurrence of disease (Burge et al. 2013), mortality and physiology, changes in light levels arising from sea level changes, changes in exposure to wave action (Short and Neckles 1999), sometimes mediated through effects on adjacent ecosystems (Saunders et al. 2014), and also by changes in the frequency and magnitude of extreme weather events. There will be changes in the distribution of seagrass communities locally and regionally. Here we take the example of temperate seagrasses including *Posidonia oceanica* from the Mediterranean, *Zostera* spp from the USA, Europe, and Australia, because the information on the effects of ocean warming and acidification for these species from several field studies is robust. Results indicate that temperate seagrass meadows have already been negatively impacted by rising sea surface temperatures (Marbà and Duarte 2010). Models based on observations of natural populations indicate that at temperature increases of 1.5°C – 3°C mortality of shoots of seagrasses will be such that populations will be unsustainable and meadows will decline to the point where their ecological functions as a habitat will cease (reduction to 10% of present density of a healthy meadow; Marbà and Duarte 2010; Jordà et al. 2012; Carr et al. 2012; York et al. 2013).

The confidence level is very high under Representative Concentration Pathway (RCP)2.6 because of strong agreement in the literature. Confidence declines to high under RCP8.5 due to some uncertainty surrounding regional differences. For example, it has been suggested that the balance of effects on seagrass populations in the North East Atlantic could tip to positive due to the hypothetical opening of ecological niches with the decline of more sensitive species, and potential reduction of carbon limitation by elevated CO_2 which may help to ameliorate negative effects of other environmental drivers, such as warming, known to impact seagrass growth and survival (Brodie et al. 2014).

Mangroves

Update: Recent literature is consistent with previous conclusions regarding the complex changes facing mangroves, together with increasing concern regarding the interaction between climate change (e.g., elevated air and water temperatures, drought, sea level rise) and local factors (deforestation, damming of catchments and reduced sediment and freshwater) as outlined below (Feller et al. 2017; Alongi 2015). Decreases in the supply of sediments to deltas and coastal areas is impeding the ability of most mangroves (69% of sites) to keep pace with sea level rise through shoreward migration (Lovelock et al. 2015). At the same time, recent extremes associated with El Nino (e.g., extreme low sea level events, Duke et al., 2017; Lovelock et al., 2017). Shoreward migration is also challenged by the increasing amounts of coastal infrastructure preventing the relocation of mangroves (Saunders et al. 2014; Di Nitto et al. 2014). In some areas, mangroves are increasing in distribution (Godoy and De Lacerda 2015). The total loss projected for mangrove loss (10–15%) under a 0.6 m sea level rise continue to be dwarfed by the loss of mangroves to deforestation (1-2% per annum).

Given the scale of the die-back of mangroves in Australia’s Gulf of Carpentaria (2015-2016), however, plus evidence that similar conditions to those of 2015-2016 (extreme heat and low tides), and the projection of greater El Niño-Southern Oscillation (ENSO) variability, (Risser and Wehner 2017; Widlansky et al. 2015), the risks from climate change for mangroves were judged to be higher than assessed by AR5, and subsequently by Gattuso et al. (2015), leading to the transitions having greater risk of occurring (Figure 3.17). Formal attribution of recent extreme events on mangroves to climate change, however, is at an early stage *(medium agreement, limited data).*

Expert assessment by Gattuso et al. (2015; SOM):

Mangroves are critically important coastal habitat for numerous species. Mangrove responses to increasing atmospheric CO_2 are complex, with some species thriving while others decline or exhibit little or no change (Alongi 2015). Temperature increase alone is likely to result in faster growth, reproduction, photosynthesis, and respiration, changes in community composition, diversity, and an expansion of latitudinal limits up to a certain point (Tittensor et al. 2010). Mangroves have already been observed to retreat with sea level rise (McKee et al. 2012). In many areas mangroves can adapt to sea level rise by landward migration, but these shifts threaten other coastal habitats such as salt marshes, which have other important biogeochemical and ecological roles. It is in areas with steep coastal inclines or coastal human infrastructure limiting landward migration that mangroves are most at risk. Climate change may lead to a maximum global loss of 10 to 15% of mangrove forest for a sea level rise of 0.6 m (high end of IPCC projections in AR4), but must be considered of secondary importance compared with current annual rates of deforestation of 1–2% (Alongi 2008). A large reservoir of below-ground nutrients, rapid rates of nutrient flux microbial decomposition, complex and highly efficient biotic controls, self- design and redundancy of keystone species, and numerous feedbacks, all contribute to mangrove resilience to various types of disturbance.

Mangrove response is species-specific and interacts with temperature, salinity, nutrient availability and patterns of precipitation. Many of these parameters are also subject to regional and local variation, as well as to human-induced pressures which changes over the coming decades are difficult to assess. Thus, the confidence level decreases from high under RCP2.6 to low under RCP8.5.

Warm-water corals

Update: Exceptionally warm conditions of 2015-2017 drove an unprecedented global mass coral bleaching and mortality event which affected coral reefs in a large number of countries (information still being gathered, Normile, 2016). In the case of Australia, 50% of shallow-water reef-building corals across the Great Barrier Reef died in unprecedented back-to-back bleaching events (Hughes et al. 2017). Elevated sea temperatures and record mortality was recorded from the Central to the Far northern sectors of the Great Barrier Reef. Similar impacts occurred in a range of regions including the Indian Ocean, Western Pacific, Hawaii and Caribbean oceans (Normile 2016) . The set of events has increased risk with current conditions being of high risk, and even low levels of future climate change having series implications for coral reefs. There continues to be a high to very high level of confidence as to where the transitions between risk levels for climate change impacts lie.

The unprecedented thermal stress along many tropical coastlines over the past three years (2015-2017) has led to extraordinary changes to coral reefs across the planet (as described above). The advent of back-to-back bleaching events, which were projected to occur around midcentury, appear to have already begun to occur as demonstrated by impacts on warm water corals and hence coral reefs. While corals were already stressed from climate change, and are in decline in many parts of the world, the scale and impact of recent events suggest that risk levels for the transitions between risk categories need to be adjusted to represent the current status of corals and coral reefs. For this reason, expert consultation since 2015 concluded that the transition from undetectable to moderate risk has already occurred (0.2°C to 0.4°C). Similarly, the transition from *moderate* to high levels of risks for warm water corals occurred approximately from 0.5°C to 0.6°C. In line with these changes, the transition from *high* to *very high* levels of risk appears associated with increases in GMST from 0.7°C to 1.3°C above the pre-industrial period.

Expert assessment by Gattuso et al. (2015; SOM):

Warm-water corals form reefs that harbor great biodiversity and protect the coasts of low lying land masses. There are very high levels of confidence that impacts were undetectable up until the early 1980s, when coral reefs in the Caribbean and eastern Pacific exhibited mass coral bleaching, as well as temperature-related disease outbreaks in the Caribbean Sea (Glynn 1984). Given a conservative lag time of 10 years between the atmospheric concentration of CO_2 and changes in sea surface temperature, the atmospheric CO_2 level of 325 ppm reached in the early 1970s was sufficient to initiate widespread coral bleaching and decline of coral health worldwide (Veron et al. 2009). As the 1980s unfolded, visible impacts of increasing sea surface temperature were seen in a widening number of areas, with the first global event in 1997-1998 and the loss of 16% of coral reefs (*high confidence*; C. R. Wilkinson 2000). Further increases in atmospheric carbon dioxide and sea surface temperature have increased the risk to corals (high confidence), with multiple widespread bleaching events, including loss of a large fraction of living corals in the Caribbean in 2005 (Eakin et al. 2010) and a subsequent global bleaching in 2010 (e.g., Moore et al. 2012), and current conditions suggesting the development of a third global event in 2015–2016 (C.M. Eakin, unpublished observation). If CO_2 levels continue to increase, there is a very high risk that coral reefs would be negatively affected by doubled pre-industrial CO_2 through impacts of both warming-induced bleaching and ocean acidification (high confidence), supported by a wide array of modeling (e.g., (Hoegh-Guldberg et al. 2014, Logan et al. 2014, Hoegh-Guldberg 1999, Donner et al. 2005, van Hooidonk et al. 2014), experimental (e.g., Dove et al. 2013), and field studies (Silverman et al. 2014, De'ath et al. 2012). This leads to a very high level of confidence under RCP2.6 and a high level of confidence under RCP8.5.

Pteropods (high latitude)

Update: Literature from the last two years is largely consistent with the expert assessment by Gattuso et al. (2015). There is increasing evidence of declining aragonite saturation in the open ocean with the detection of impacts that are most pronounced closest to the surface and with the severe biological impacts occurring within inshore regions. In this regard, pteropod shell dissolution has increased by 19-26% in both nearshore and offshore waters since the Pre-industrial period (Feely et al. 2016). Impacts of ocean acidification are also cumulative with other stresses such as elevated sea temperature and hypoxia (Bednaršek et al. 2016). These changes are consistent with observations of large portions of the shelf waters associated with the Washington-Oregon-California coast being strongly corrosive, with 53% of onshore and 24% of offshore pteropod individuals showing severe damage from dissolution (Bednaršek et al., 2014). Several researchers propose that pteropod condition be used as a biological indicator which they argue will become increasingly important as society attempts to understand the characteristics and rate of change in ocean acidification impacts on marine organisms and ecosystems (Manno et al. 2017; Bednaršek et al. 2017). The last two years of research has increased confidence in our understanding of the impact of ocean acidification on pteropods under field conditions. The question of the genetic adaptation of pteropods to increasing ocean acidification remains unresolved although the observation of increasing damage to pteropods from field measurements argues against this being a significant factor in the future.

As described here and by Gattuso et al. (2015), pteropods are clearly being impacted by climate change and ocean acidification, especially in polar regions. Therefore, the transition from undetectable to medium levels of stress has been judged to occur between 0.7°C and 0.8°C. The transition from medium to high levels of risk of impact on these important organisms was judged to occur from 0.8°C to 1.5°C, with the transition from high to very high occurring from 1.5°C to 2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Pteropods are key links in ocean food webs between microscopic and larger organisms, including fish, birds and whales. Ocean acidification at levels anticipated under RCP8.5 leads to a decrease in pteropod shell production (Comeau et al. 2009, 2010; Lischka et al. 2011), an increase in shell degradation (Lischka and Riebesell 2012; Comeau et al. 2012), a decrease in swimming activity when ocean acidification is combined with freshening (Mannoa et al. 2012), and an increase in mortality that is enhanced at temperature changes smaller than those projected for RCP8.5 (Lischka et al. 2011; Lischka and Riebesell 2012). Shell dissolution has already been observed in high latitude populations (Bednaršek et al. 2012). Aragonite saturation (Ωa) levels below 1.4 results in shell dissolution with severe shell dissolution between 0.8 and 1 (Bednaršek and Ohman 2015). Despite high agreement amongst published findings, uncertainty remains surrounding the potential to adapt to environmental drivers because long-term laboratory experiments with pteropods are notoriously difficult. Hence the confidence level is *medium* under RCP2.6. However, confidence increases to very high under RCP8.5 because it is almost certain that genetic adaptation to such large and rapid changes in pH and temperature will not be possible.

Bivalves (mid latitude)

Update: Literature has rapidly expanded since 2015 with a large number of studies showing impacts of ocean warming and acidification on wide range of life history stages of bivalve molluscs (e.g., Asplund et al., 2014; Castillo et al., 2017; Lemasson et al., 2017; Mackenzie et al., 2014; Ong et al., 2017; Rodrigues et al., 2015; Shi et al., 2016; Velez et al., 2016; Waldbusser et al., 2014; Wang et al., 2016; Zhao et al., 2017; Zittier et al., 2015). Impacts on adult bivalves include decreased growth, increased respiration, and reduced calcification with larval stages tending to have an increase in developmental abnormalities and elevated mortality after exposure (Ong et al. 2017; Zhao et al. 2017; Wang et al. 2016; Lemasson et al. 2017). Many recent studies have also identified interactions between factors such as increased temperature and ocean acidification, with salinity perturbations as well as decreases in oxygen concentrations (Parker et al. 2017; Velez et al. 2016; Lemasson et al. 2017). Changes in metabolism with increasing ocean acidification has been detected in a number of transcriptome studies, suggesting a complex and wide-ranging response by bivalves to increasing CO_2 and temperature (Li et al. 2016a,b). Observations of reduced immunity which may have implications for disease management (Castillo et al. 2017). These changes are likely to impact the ecology of oysters, and may be important when it comes to the maintenance of oyster reefs, which provide important ecological structure for other species. Bivalves, for example, are more susceptible to the impacts of temperature and salinity if they have been exposed to high levels of CO_2, leading to the suggestion that there will be a narrowing of the physiological range and hence distribution of oyster species such as *Saccostrea glomerata* (Parker et al. 2017). Confidence level is adjusted to high given the convergence of recent literature. These studies continue to report growing impacts as opposed to a reduction under rapid genetic adaptation by bivalve molluscs. The overall levels of risk are retained - reflecting the moderate risk that already exists, and the potential for transformation into high very high levels of risk with relatively small amounts of further climate change.

Recent literature reinforces the conclusions of Gattuso et al. (2015) and confirms the transition of risk from low to moderate for the bivalves associated with mid-latitude environments is occurring between 0.4°C and 0.6°C. The transition for these organisms from moderate to high levels of risk occurs at 0.9°C and 1.1°C. Subsequent transition from high to very high was judged to occur between 1.3°C and 1.5°C.

Expert assessment by Gattuso et al. (2015; SOM):

Both cultured and wild bivalves are an important food source worldwide. Temperate bivalve shellfish, such as oysters, clams, mussels and scallops, have already been negatively impacted by ocean acidification. In the Northwest United States, Pacific oyster larval mortality has been associated with upwelling of natural CO_2-rich waters acidified by additional fossil fuel CO_2 (*high confidence*; Barton et al. 2012). Ocean acidification acts synergistically with deoxygenation (Gobler et al. 2014) and warming (Mackenzie et al. 2014a; Kroeker et al. 2013) to heighten physiological stress (Wittmann and Pörtner 2013) on bivalve shellfish (*high confidence*), suggesting that future ocean conditions that include warming, deoxygenation, and acidification will be particularly difficult for members of this taxon. Archaeological/geological and modeling studies show range shifts of bivalves in response to prior and projected warming (Raybaud et al. 2015) and acidification (Lam et al. 2014). Model projections also anticipate decreases in mollusk body size under continued harvesting as conditions change farther from the present (Cooley et al. 2015). Impacts are expected to be high to very high when CO_2 concentrations exceed those expected for 2100 in the RCP2.6 and 4.5 levels (*medium confidence*; Lam et al. 2014; S. R. Cooley, J. E. Rheuban, D. R. Hart, V. Luu, D. M. Glover, J. A. Hare 2015). The confidence level is medium both under RCP2.6 and RCP8.5 primarily due to the possibility of bivalves adapting over generations (Pespeni et al. 2013), or for specific species to outcompete other wild species in future conditions (e.g., A. W. Miller, A. C. Reynolds, C. Sobrino 2009).

Krill (high latitude)

Update: Sea ice continues to retreat at high rates in both polar oceans with both the Artic and Antarctica being among the fastest warming regions on the planet (Turner et al. 2017; Notz and Stroeve 2016). In Antarctic waters, a decrease in sea ice represents a loss of critical habitat for krill (David et al. 2017). Projected changes of this habitat through increasing temperature and acidification could have major impacts on food, reproduction and development, and hence the abundance of this key organism for Antarctic food webs. Differences appear to be a consequence of regional dynamics in factors such as regional variation in ice, productivity, and predation rates, and an array of other factors (Steinberg et al. 2015). Other factors such as interactions with factors such as ocean acidification and the shoaling of the aragonite saturation horizon are likely to play key roles. (Kawaguchi et al. 2013; Piñones and Fedorov 2016). While factors such as ocean acidification and the loss of sea ice (due to increasing temperature) are unambiguous in their effects, there continues to be considerable uncertainty around the details of how krill populations are likely to respond to factors such as changing productivity, storms, and food webs.

While there are considerable gaps in our knowledge about the impacts of climate change on krill, there is consensus that direct climate impacts are beginning to be detected at average global sea surface temperatures of around 0.7°C and that transition to medium stress occurs at around about 0.9°C. With a low level of confidence and hence much uncertainty, expert consensus concludes that transition from medium to high levels of risk of impact occurred between 1.0°C and 1.6°C. Subsequent transitions from high to very high levels of risk are judged to lie somewhere between 1.8°C and 3.2°C although levels of confidence are low at this time.

Expert assessment by Gattuso et al. (2015; SOM):

Krill (euphausid crustaceans) is a critical link in the food web at higher latitudes, supporting mammals and birds among many other species. Distributional changes and decreases in krill abundance have already been observed associated with temperature increase (Atkinson et al. 2004). The effect of changes in the extent of sea ice is considered to be an indirect effect of temperature. Temperature effects are predicted to be regional (Hill et al. 2013). If the extent of sea ice is maintained, populations in cooler waters may experience positive effects in response to small increases in temperature. In contrast, populations in warmer areas may experience some negative temperature effects by 2100 under RCP2.6. Since all life stages are associated with sea ice, decreases in krill stocks are projected to occur concurrently with the loss of sea ice habitat, potentially outweighing possible positive impacts (H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss et al. 2012). Increases in sea surface temperature of 1˚C –2˚C have significant impacts on krill. From Figure 4 in Flores et al. (H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss et al. 2012) severe disruptions of the life cycle are expected at a level of 2°C sea surface temperature rise and 500 µatm pCO_2. Therefore, high impact on populations would be reached approximately at the CO_2 level projected for 2100 by RCP4.5. Conditions in 2100 under the RCP2.6 scenario would be around the upper limit of the high-risk range. Negative effects of ocean acidification on reproduction, larval and early life stages have been observed above 1,250 µatm pCO_2, a value that is likely to be reached in parts of the Southern Ocean by 2100 under RCP8.5 (Kawaguchi et al. 2013). Figure 1 in H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss et al. (2012) shows that the area with strongest sea ice decline partly overlaps with areas of high krill density (from the Peninsula to the South Orkneys). There is also a significant warming trend in this area which may force populations southwards into less productive regions. Substantial decline in the viability of major krill populations in the Southern Ocean may occur within the next 100 years (Kawaguchi et al. 2013), which could have catastrophic consequences for dependent marine mammals and birds. The genetic homogeneity of krill suggests that rapid adaptation through natural selection of more tolerant genotypes is unlikely (Bortolotto et al. 2011).

Finfish

Update: Impacts and responses identified in 2015 regarding the relative risk of climate change to finfish have strengthened. In this regard, there is a growing number of studies indicating that different stages of development may also be made more complex by fish having different stages of the life-cycle in different habitats, which may each be influenced by climate change in different ways and to different extents, as well as evidence of differing sensitivities to change between different stages (Ong et al. 2017, 2015; Esbaugh 2017). Increasing numbers of fish species have been identified as relocating to higher latitudes, with tropical species being found increasingly in temperate zones ('tropicalization', Horta E Costa et al., 2014; Verges et al., 2014; Vergés et al., 2016)) and temperate species being found in some polar regions ('Borealization', Fossheim et al., 2015). Concern has been raised that greater numbers of extinctions will occur in the tropics as species relocate (García Molinos et al. 2015; Burrows et al. 2014; Poloczanska et al. 2016). Changing conditions in polar regions are particularly risky due to the rapid rates of warming (Turner et al. 2017; Notz and Stroeve 2016). One of the consequences of this is that an increasing number of fish species are expanding their distributional ranges into the Arctic, being followed by large, migratory fish predators. The borealization of fish communities in the Arctic is leading to a reorganization of species and ecological processes which is not well understood (Fossheim et al. 2015).

There is considerable evidence that changes in the distribution of finfish are, and have been, occurring over the last few decades. Evidence of the movement of tropical species to higher latitudes is unambiguous as is the shift in many pelagic species of finfish. Consequently, the distribution and abundance of finfish is already occurring, and based on the updated expert consensus of Gattuso et al. (2015), appears to have transition from undetectable to medium levels of risk at average global sea surface temperatures of 0.5°C and 0.7°C. There is little evidence that these changes are slowing and therefore risks are estimated as transitioning from medium to high levels of risk at 1.1°C to 1.3°C, and from high to very high levels of risk at 1.4°C to 1.6°C.

Expert assessment by Gattuso et al. (2015; SOM):

Marine fishes are important predators and prey in ocean ecosystems, contributing substantially to coastal economies, food security and livelihood. Warming-induced shifts in the abundance, geographic distribution, migration patterns, and phenology of marine species, including fishes, were reported and projected with very high confidence in the IPCC AR5 (Pörtner et al. 2014). Empirical and theoretical evidence of range shifts in response to temperature gradients are reported across various taxa and many geographical locations (Bates et al. 2014; Poloczanska et al. 2013; Couce et al. 2013), with observations suggesting that range shifts correspond with the rate and directionality of climate shifts or 'climate velocity' across landscapes (Pinsky et al. 2013). Observed range shifts associated with ocean warming may result in hybridization between native and invasive species through overlapping ranges, leading to reduced fitness and thus potentially increasing the risks of genetic extinction and reducing the adaptability to environmental changes (Muhlfeld et al. 2014; Potts et al. 2014). Some taxa are incapable of keeping pace with climate velocities, as observed with benthic invertebrates in the North Sea (Hiddink et al. 2015). The tropicalization of temperate marine ecosystems through poleward range shifts of tropical fish grazers increases the grazing rate of temperate macroalgae as seen in Japan and the Mediterranean (Verges et al. 2014). Such trophic impacts resulting from climate-induced range shifts are expected to affect ecosystem structure and dynamic in temperate reefs (Verges et al. 2014). Projected future changes in temperature and other physical and chemical oceanographic factors are expected to affect the distribution and abundance of marine fishes, as elaborated by species distribution models with rate of shift at present day rate under the RCP8.5 scenario (Cheung et al. 2009). Limiting emissions to RCP2.6 is projected to reduce the average rate of range shift by 65% by mid-21st century (Jones and Cheung 2015). Shifts in distribution of some species may be limited by the bathymetry or geographic boundaries, potentially resulting in high risk of local extinction particularly under high CO_2 emissions scenarios (Ben Rais Lasram et al. 2010). While evidence suggests that adult fishes can survive high levels of CO_2, behavioral studies have found significant changes in species' responses under levels of CO_2 elevated above those of the present day level (Munday et al. 2014). Long-term persistence of these phenomena remains unknown. Based on the above, fishes already experience medium risk of impacts at present day (*high confidence*). Risk increases from medium to high by end of 21st century when emissions change from RCP2.6 to RCP4.5 and become very high under RCP8.5, highlighting the potential non-reversibility of the potential impacts. Some evidence for direct and indirect impacts of ocean acidification on finfish is available but varies substantially between species. Also, understanding about the scope of evolutionary adaptation for marine fishes to climate change and ocean acidification are limited, although it is unlikely that majority of the species can fully adapt to expected changes in ocean properties without any impacts on their biology and ecology. Overall, we have robust evidence and high agreement (thus *high confidence*) from experimental data, field observations and mathematical modelling in detecting and attributing impacts for finfish in the present day and under RCP2.6. The uncertainty about the sensitivity to ocean acidification and scope for evolutionary adaptation leads to medium confidence levels for their risk under high emissions scenarios.

Open ocean carbon uptake

Update: Several recent studies have shown a decreasing CO_2 flux into the Pacific and Atlantic Oceans, southern ocean, and ocean in general (Iida et al. 2015). Concern over changes to the circulation of the ocean (e.g., Atlantic Meridional Overturning Circulation, AMOC) has grown since 2015, with the observation of cooling surface areas of the Atlantic (Rahmstorf et al. 2015).

Recent literature is consistent with the expert assessment of Gattuso et al. (2015) with risks of impact from changing ocean carbon uptake being barely detectable today but transitioning to medium risk between 1°C and 1.5°C. Risks transition from medium to high levels of risk between 2°C and 3.2°C. Higher levels of risk such as a rapid change in the circulation of the MOC are speculative at this point.

Expert assessment by Gattuso et al. (2015; SOM):

The uptake of anthropogenic carbon by the ocean in the industrial period and in the future is a service that is predominantly provided by physico-chemical processes (Prentice and J. T. Houghton et al. 2001). The sensitivity of ocean carbon uptake to increasing cumulative CO_2 emissions, including effects of changing ocean chemistry, temperature, circulation and biology, is assessed along the following lines of quantitative evidence: (i) the fraction of total cumulative anthropogenic emissions taken up by the ocean over the industrial period and the 21st century in CMIP5 Earth System Model projections for the four RPCs (27); (ii) the fraction of additional (marginal) emissions remaining airborne or taken up by the ocean for background atmospheric CO_2 following the four RCPs (Joos et al. 2013). In addition, the risk of large-scale reorganization of ocean circulation, such as a collapse of the North Atlantic overturning circulation and associated reductions in allowable carbon emissions towards CO_2 stabilization, is increasing with the magnitude and rate of CO_2 emissions, in particular beyond the year 2100. Confidence level is *high* for both RCP2.6 and RCP8.5 because the underlying physical and chemical process are well known.

Coastal protection

Update: Sea level rise and intensifying storms are placing increasing stress on coastal environments and communities. Coastal protection by ecosystems as well as man-made infrastructure are important in terms of mitigating risks ranging from the physical destruction of ecosystems and human infrastructure to the salinization of coastal water supplies and direct impacts on human safety (Bosello and De Cian 2014). Risks are particularly high for low-lying areas, such as carbonate atoll islands in the tropical Pacific where land for food and dwelling and water are limited, and effects of a rising sea plus intensifying storms create circumstances may make many of these island systems uninhabitable within decades (Storlazzi et al. 2015). Even in advantaged countries such as the United States, these factors place millions at serious risk from even modest changes in inundation, with over 4 million US based people at serious risk in response to a 90 cm sea level rise by 2100 (Hauer et al. 2016).

Both natural and human coastal protection have the potential to reduce the impacts (Fu and Song 2017). Coral reefs, for example, provide effective protection by dissipating around 97% of wave energy, with 86% of the energy being dissipated by reef crests alone (Ferrario et al. 2014). Natural ecosystems, when healthy, also have the ability to repair themselves after being damaged, which sets them apart from coastal hardening and other human responses that require constant maintenance (Barbier 2015; Elliff and Silva 2017). Recognising and restoring coastal ecosystems such as coral reefs, mangroves and coastal vegetation in general may be more cost-effective than human remedies in terms of seawalls and coastal hardening, where costs of creating and maintaining structures may not always be cost-effective (Temmerman et al. 2013).

The last two years have seen an increase in the number of studies identifying the importance of coastal ecosystems as important to the protection of people and property along coastlines against sea level rise and storms. Analysis of the role of natural habitats in the protection people and infrastructure in Florida, New York and California, for example, has delivered a key insight into the significance of the problems and opportunities for the United States (Arkema et al. 2013). Some ecosystems which are important to coastal protection can keep pace with sea level rise, but only if other factors such as harvesting (i.e., of oysters; Rodriguez et al., 2014) or sediment supply (i.e., to mangroves, Lovelock et al., 2015) are managed. Several studies have pointed to the opportunity to reduce risks promoting more holistic approaches to mitigating damage from sea level rise and storms by developing integrated coastal plans that ensure that human infrastructure enables the shoreward relocation of coastal vegetation such as mangroves and salt marsh. The latter enhancing coastal protection as well as having other important ecological functions such as habitat for fish and the sources of a range of other resources (Mills et al. 2016; Lovelock et al. 2015; Di Nitto et al. 2014).

Recent studies have increasingly stressed the coastal protection needs to be considered in the context of new ways of managing coastal land, including protecting and managing coastal ecosystems as they also undergo shifts in their distribution and abundance (André et al. 2016). These shifts in thinking require new tools in terms of legal and financial instruments, as well as integrated planning that involves not only human communities and infrastructure, but also ecosystem responses. In this regard, the interactions between climate change, sea level rise and coastal disasters are being increasingly informed by models (Bosello and De Cian 2014) with a widening appreciation of the role of natural ecosystems as an alternative to hardened coastal structures (Cooper et al. 2016).

Increase evidence of a rapid decay in ecosystems such as coral reefs and mangroves has increased the confidence surrounding conclusions that risks in coastal areas are increasing. Escalation of coastal impacts arising from Super Storm Sandy and Typhoon Haiyan (Villamayor et al. 2016; Long et al. 2016) have improved understanding of the future of coastal areas in terms of impacts, response and mitigation (Shults and Galea 2017; Rosenzweig and Solecki 2014).

Recent assessments of the last couple of years of literature confirm the expert judgement of Gattuso et al. (2015), although are emphasised by growing evidence that heat stress, ocean acidification, and intensifying storms are increasing the breakdown of natural coastal barriers that otherwise provide important protection for coastal communities, ecosystems and infrastructure. While there is growing evidence of these changes in the frequency and intensity of climate change, no changes in levels of risk from Gattuso et al. (2015) or perceived. Risk of impacts with respect to coastal protection transition from undetectable to medium at 0.5°C and 0.8°C, with the transition from medium to high levels of risk occurring from 1.5°C to 1.8°C. Further transition of impact risks from the loss of coastal protection has been judged to occur between 2.2°C and 3.2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Estimating the sensitivity of natural coastal protection to climate change requires to combine sensitivity across different ecosystems, especially coral reefs, mangrove forests and seagrass beds. Other ecosystems provide coastal protection, including salt marshes, macroalgae, oyster and mussel beds, and also beaches, dunes and barrier islands (stabilized by organisms; Spalding et al. 2014; Defeo et al. 2009) but there is less understanding of the level of protection conferred by these other organisms and habitats (Spalding et al. 2014). Although studies indicate some of these systems are already impacted by the effects of rising CO_2, or suggest they will be in the near future, levels of sensitivity are not well established, are highly variable, and in some cases their overall influence on coastal protection may be uncertain (i.e., species are replaced by functional equivalents in this context; K. B. Gedan 2009).

We reason that some coastal protection has already been lost—a result of impacts on coral reefs, seagrasses and other ecosystems from sea temperature rise. In the case of corals, this began in the late 1970s. Recent papers demonstrate collapse in three-dimensional structure of reefs in the Caribbean (Alvarez-Filip et al. 2009) and the Seychelles (Sheppard et al. 2005), the second phase of which appears to be climate-related. Other studies show that some areas have not recovered from the 1997-1998 and 2010 bleaching events and that some reefs have collapsed there (e.g., parts of the Seychelles). There is thus little doubt that the coastal protection function of some reefs has already been reduced. A decreasing protection may also be the case for seagrasses, although such effects have not been measured. It should also be noted that other human impacts have already largely destroyed, or are progressively destroying some of these ecosystems, through direct action (e.g., 85% oyster reefs lost globally and 1-2% of mangrove forests cut down per annum; Beck et al. 2011). It therefore appears that some impact on coastal protection has already occurred but we lack data to extrapolate globally, hence the confidence level is *low* in the present day.

Confidence in the loss of coastal protection decreases with increasing CO_2 emissions because coastal protection is conferred by a range of habitats and the co-dependency or interactions between them make projections difficult. For example, protection to seagrass beds conferred by coral reefs or the replacement of salt marsh with mangrove forest (Saunders et al. 2014; Alongi 2015). Additionally, human-driven pressure on these ecosystems is inherently difficult to forecast decades from now due to the possible implementation of new policies. Interacting effects of different symptoms of climate change such as increased temperature, decreasing pH, salinity, nutrient availability, patterns of precipitation and occurrence of pathogens will all influence the physiological response of individual species and ecosystems and thus further reduce the predictability of responses at higher emissions.

Recreational services from coral reefs

Update: Tourism is one of the largest industries globally. A significant part of the global tourist industry is associated with tropical coastal regions and islands (Spalding et al. 2017). Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries, particularly Small Island Developing States (SIDS; Weatherdon et al., 2016). The direct relationship between increased global temperatures, elevated thermal stress, and the loss of coral reefs (3.4.4.10; Box 3.4) has raised concern about the risks of climate change for local economies and industries based on coral reefs.

Risks to the recreational services of coral reefs from climate change are considered here. The recent heavy loss of coral reefs from tourist locations worldwide has prompted interest in the relationship between increasing sea temperatures, declining coral reef ecosystems, and tourist revenue (Normile 2016). About 30% of the world's coral support tourism which generates close to $36 billion USD on an annual basis (Spalding et al. 2017). Tourist expenditure, in this case, represents economic activity which supports jobs, revenue for business and taxes. Climate change in turn can influence the quality of the tourist experience through such aspects through changing weather patterns, physical impacts such as storms, and coastal erosion, as well as the effects of extremes on biodiversity within a region. Recent impacts in the Caribbean in 2017 highlight the impacts of climate change related risks associated with coastal tourism, with the prospect that many businesses will take years to recover from impacts such as hurricanes Harvey, Irma and Maria (Gewin 2017; Shults and Galea 2017)

A number of projects have attempted to estimate the impact (via economic valuation) of losing key coral reef ecosystems such as the Great Barrier Reef (Oxford Economics 2009; Spalding et al. 2017). A recent study by Deloitte_Access_Economics. (2017) revealed that the Great Barrier Reef contributed $6.4 billion AUD and 64,000 jobs annually to the Australian economy in 2015–16. In terms of its social, economic and iconic value to Australia, the Great Barrier Reef is worth $56 billion AUD. The extreme temperatures of 2015–2017 removed 50% of the reef-building corals on the Great Barrier Reef (Hughes et al. 2017), there is considerable concern about the growing risk of climate change to the Great Barrier Reef, not only for its value biologically, but also as part of a series of economic risks at local, state and national levels.

Our understanding of the potential impacts of climate change on tourism within small island and low-lying coastal areas in tropical and subtropical is made less certain by the flexibility and creativity of people. For example, the downturn of coral reefs in countries that are dependent on coral reef tourism doesn't necessarily mean a decline in Gross Domestic Product (GDP), given that some countries have many other options for attracting international revenue. As well, our understanding of future tourist expectations and desires are uncertain at this point.

Additional literature over the past couple of years confirm the risk from climate change to the recreational services that are derived from coral reefs, and which are important for a large number of coastal communities throughout the tropics. A transition in the risk of impacts to recreational services from coral reefs occurs between 0.6°C and 0.8°C, with a further transition from medium to high levels of risk between 1.0°C and 1.5°C. Very high levels of risk occur between 2.0°C and higher as the frequency and intensity of extreme events (i.e. storm events, coastal inundation, and/or droughts, depending on the region) become increasingly difficult to manage for coastal tourism like that associated with coral reefs. Note, the risks to corals are higher than those to the recreational services that corals provide to coastal communities. This highlights the fact that many communities today have lost coral but still are able to operate using recreational services from other sources. This difference disappears as one goes to higher levels of risk as the options for supporting recreational activities from the remnants of coral reefs are seriously reduced.

Expert assessment by Gattuso et al. (2015; SOM):

The impacts of CO_2 and sea surface temperature on the condition of coral reefs ultimately affect the flow of ecosystem goods and services to human communities and businesses. There is an interesting lag between the degradation of corals and coral reefs and a detectable effect on human users. For this reason, the risk of impacts on human recreation and tourism begins significantly later than ecosystem changes are detected by marine scientists. As of 2015, atmospheric CO_2 concentration is 400 ppm and average sea surface temperature is 0.8°C above that of the pre-industrial period. Mass bleaching and mortality events have degraded coral populations and this has negatively impacted the recreational choices of a few, but not most, clients (*high confidence*; Hoegh-Guldberg et al. 2007). This impact on tourists' choice is expected to reach moderate to high-levels as CO_2 approaches 450 ppm, at which point reefs begin net erosion and sea level, coral cover, storms, and other environmental risks become significant considerations in destination attractiveness (*medium confidence*). By 600 ppm, the breakdown of the structure of most reefs becomes obvious, other changes such as reduced coral cover and increased sea level and storm damage mean that significant coastal recreation and tourism becomes difficult in most circumstances and many operations may be discarded (Hoegh-Guldberg et al. 2007). This will have a very high impact on recreational services (*medium confidence*). Confidence levels under RCP2.6 and RCP8.5 are *medium* because predicting tourists' expectations several decades from now remains relatively uncertain.

Bivalve fisheries and aquaculture (mid latitude)

Update: Aquaculture is one of the fastest growing food sectors and is becoming increasingly essential to meeting the demand for protein for the global population (FAO 2016). Studies published over the period 2015-2017 showed a steady increase in the risks associated with bivalve fisheries and aquaculture at mid-latitude locations coincident with increases in temperature, ocean acidification, introduced species, disease and other associated risks (Clements and Chopin 2017; Clements et al. 2017; Lacoue-Labarthe et al. 2016; Parker et al. 2017). These have been met with a range of adaptation responses by bivalve fishing and aquaculture industries (Callaway et al. 2012; Weatherdon et al. 2016).

Risks are also likely to increase as a result of sea level rise and intensifying storms which pose a risk to hatcheries and other infrastructure (Callaway et al. 2012; Weatherdon et al. 2016). Some of the least predictable yet potentially most important risks are associated with the invasion of diseases, parasites and pathogens, which may be mitigated to a certain extent by active intervention by humans. Many of these have reduced the risks from these factors although costs have increased in at least some industries.

The risk of impact from ocean warming and acidification to bivalve aquaculture and fisheries is increasing - although not enough to warrant redefinition of the size and transition of risks from climate change.Therefore, literature since 2015 is consistent with the conclusion of how the risk of impact changes with greater levels of climate change. Risk to these important industries increases from nondetectable to medium at 1.1°C and 1.3°C, with the transition from medium to high levels of risk occurring from 1.7°C to 1.9°C. The transition from high to very high levels of risk is projected to between 2.8°C and 3.2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Ecosystem services provided by temperate bivalves include marine harvests (both from capture fisheries and aquaculture), water quality maintenance, and coastal stabilization. Of these, marine harvests are easiest to quantify, and have been the subject of several assessments. Confidence is high that ocean acidification has already jeopardized marine harvest revenues in the Northwest United States (Washington State Blue Ribbon Panel on Ocean Acidification 2012). Although the affected hatcheries have taken steps to enhance monitoring, alter hatchery water intake and treatment, and diversify hatchery locations (Barton et al. 2015), these adaptations will only delay the onset of ocean acidification-related problems (high confidence). Wild harvest populations are fully exposed to ocean acidification and warming, and societal adaptations like these are not applicable. Services provided by bivalves will continue even if populations migrate, decrease in size, or individuals become smaller, so effects are somewhat more delayed than those on shellfish themselves. In 2100, impacts are expected to be moderate under RCP2.6 and very high under RCP8.5. The level of confidence declines as a function of increasing CO_2 emissions due to the uncertainty about the extent of local adaptation: medium under RCP2.6 and low under RCP8.5.

Fin fisheries (low latitude)

Update: Low latitude fin fisheries, or small-scale fisheries, provide food for millions of people along tropical coastlines and hence play an important role in the food security of a large number of countries (McClanahan et al. 2015; Pauly and Charles 2015). In many cases, populations are heavily dependent on these sources of protein given the lack of alternatives (Cinner et al. 2016, 2012; Pendleton et al. 2016). The climate related stresses affecting fin fish (see Section 'Finfish' above), however, are producing a number of challenges for small scale fisheries based on these species (e.g., (Pauly and Charles 2015; Bell et al. 2017; Kittinger 2013).

Recent literature (2015–2017) has continued to outline growing threats from the rapid shifts in the biogeography of key species (García Molinos et al. 2015; Poloczanska et al. 2013; Burrows et al. 2014; Poloczanska et al. 2016) and the ongoing rapid degradation of key habitats such as coral reefs, seagrass and mangroves (see Sections above on 'Sea grasses (mid latitude)', 'Mangroves' and 'Pteropods', as well as Chapter 3, Box 3.4). As these changes have accelerated, so have the risks to the food and livelihoods associated with small-scale fisheries (Cheung et al. 2010). These risks have compounded with non-climate stresses (e.g., pollution, overfishing, unsustainable coastal development) to drive many small-scale fisheries well below the sustainable harvesting levels required to keep these resources functioning as a source of food (McClanahan et al. 2015, 2009; Pendleton et al. 2016). As a result, projections of climate change and the growth in human populations increasingly predict shortages of fish protein for many regions (e.g., Pacific, e.g., Bell et al., 2013, 2017; Indian Ocean, e.g., McClanahan et al., 2015). Mitigation of these risks involved marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Song and Chuenpagdee 2015; Kittinger 2013; McClanahan et al. 2015; Weatherdon et al. 2016). Threats to small-scale fisheries have also come from the increasing incidence of alien (nuisance) species as well as an increasing incidence of disease, although the literature on these threats is at a low level of development and understanding (Kittinger et al. 2013; Weatherdon et al. 2016).

As assessed by Gattuso et al. (2015), risks of impacts on small-scale fisheries are medium today, but are expected to reach very high levels under scenarios extending beyond RCP2.6. The research literature plus the growing evidence that many countries will have trouble adapting to these changes places confidence a high level as to the risks of climate change on low latitude in fisheries. These effects are more sensitive, hence the higher risks at lower levels of temperature change.

Small-scale fisheries are highly dependent on healthy coastal ecosystems. With the growing evidence of impacts described above, the loss of habitat for small-scale fisheries is intensifying the risks of impact from climate change. For this reason, expert consensus has judged that risks have become greater since the assessment of Gattuso et al. (2015). Therefore, the transition from undetectable to medium levels of risk is projected to occur between 0.5°C and 0.7°C, with the transition from medium to high levels of risk occurring between 0.9°C and 1.1°C. The transition from high to very high levels of risk of impact as being judged to occur between 2.0°C and 2.5°C.

Expert assessment by Gattuso et al. (2015; SOM):

Evidence of climate change altering species composition of tropical marine fisheries is already apparent globally (Cheung et al. 2013). Simulations suggest that, as a result of range shifts and decrease in abundance of fish stocks, fisheries catch is likely to decline in tropical regions (Barange et al. 2014, Cheung et al. 2010). Projections also suggest that marine taxa in tropical regions are likely to lose critical habitat (e.g., coral reefs), leading to a decrease in fisheries productivity (Bell et al. 2013). Because of the magnitude of impacts, capacity for the fisheries to reduce such risks by protection, repair or adaptation is expected to be low (Pörtner et al. 2014). Thus, these impacts increase with increasing CO_2 emissions. Risk of impacts is close to medium level in present day, and increases to high and very high when CO_2 concentration reaches the levels expected in 2100 under RCP4.5 and RCP8.5, respectively.

The scope of adaptation for low latitude fin fisheries is narrow because of the high level of impacts on ecosystems and fisheries resources, lack of new fishing opportunities from species range shifts to compensate for the impacts, and relatively lower social-economic capacity of many countries to adapt changes. Thus, confidence level is high on projected impacts on low latitude fin fisheries.

Fin fisheries (mid and high latitude)

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

Similar to the assessment by Gattuso et al. (2015), our confidence in understanding risks at higher levels of climate change and longer periods diminishes over time. The ability of fishing industries to adapt to changes is considerable although the economic costs of adapting can be high. Complex, changes in fin fisheries at high latitudes has a number of climate related risks associated with it (as described above and by Gattuso et al. (2015). In this case, risks of climate impacts on fin fisheries at high latitudes is projected to transition from undetectable to medium levels of risk at 0.7°C to 0.9°C. The shift from medium to high levels of risk is projected by the expert consensus to occur between 2.2°C and 3.2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Evidence that climate change effects altering species composition in mid and high latitude fisheries can already be observed globally, with increasing dominance of warmer-water species since the 1970s (Cheung et al. 2013). Global-scale projections suggest substantial increases in potential fisheries catch in high latitude regions (Barange et al. 2014; Cheung et al. 2010) under RCP8.5 by mid- to end-21st century. However, ocean acidification increases uncertainty surrounding the potential fisheries gain because the Arctic is a hotspot of ocean acidification (Lam et al. 2014). Risks of impacts of warming, ocean acidification and deoxygenation on mid-latitude regions are variable (Cheung et al. 2013; Barange et al. 2014). Overall, existing fish stocks are expected to decrease in catch while new opportunities for fisheries may emerge from range expansion of warmer-water. Declines in catch have been projected for fisheries in the Northeast Pacific (Ainsworth et al. 2011), Northwest Atlantic (Guénette et al. 2014), and waters around the U.K. (Jones et al. 2014) by mid 21st century under SRES A1B and A2 scenarios (equivalent to RCP6.0 to 8.5). While it is uncertain whether small-scale fisheries will have the mobility to follow shifts in ranges of target species, those with access to multiple gears types may be able to adapt more easily to climate-related changes in stock composition. Societal adaptation to reduce the risk of impacts is expected to be relatively higher than tropical fisheries. Thus, medium risk is assigned from present day, and risk increases to high when CO_2 concentration is beyond level expected from RCP4.5.

Risk to fisheries at mid and high latitudes depends on how the fishers, fishing industries and fisheries management bodies respond and adapt to changes in species composition and distribution. Prediction of the scope of such adaptive response is uncertain particularly under greater changes in fisheries resources. Thus, the confidence level is *high* under RCP2.6 and low under RCP8.5

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S3-4-13 Supplementary information to Section 3.4

Temperature-related morbidity and mortality

Detection and attribution studies show heat-related mortality in some locations has increased because of climate change (Ebi et al. 2017), alongside evidence of acclimatization and adaptation reducing mortality, particularly in high-income countries (Arbuthnott et al. 2016; Chung et al. 2017; de' Donato et al. 2015; Bobb et al. 2014; Lee et al. 2014) with future adaptation trends uncertain.

The projected risks of heat-related morbidity and mortality are generally higher under warming of 2°C than 1.5°C, with projections of greater exposure to high ambient temperatures and increased morbidity and mortality (Section 3.4.7). This indicates a transition in risk between 1.5°C and 2°C. The extent of the increase will depend on adaptation (until mid-century) and on adaptation and mitigation later in the century (Smith et al. 2014). Under 1.5°C, most risks associated with exposure to heat could be reduced through adaptation. Risks under warming of 2°C will depend on the timing of when temperature targets are met and on development choices, such as modifying urban infrastructure to reduce heat islands. The longer the delay in reaching 2°C, and the more resilient and sustainable the development pathway, the lower the expected health risks (Sellers and Ebi 2017).

Heat-related mortality	White to Yellow	Begin	0
		End	1
	Yellow to Red	Begin	1
		End	3
	Red to Purple	Begin	no transition to purple
		End	no transition to purple

Tourism

Changing weather patterns, extreme weather and climate events, and sea level rise are affecting global tourism investments, environment and cultural destination assets, operational and transportation costs, and tourist demand patterns (Section 3.4.9.1). Assets being affected include biodiversity, beaches, coral reefs, glaciers, and other environmental and cultural assets. 'Last chance' tourism markets are developing based on observed impacts on environmental and cultural heritage.

Based on limited analyses, risks to the tourism sector are higher at 2°C than at 1.5°C, with greater impacts on climate-sensitive sun, beach, and snow sports tourism markets. The degradation or loss of coral reef systems will increase the risks for coastal tourism, particularly in sub-tropical and tropical regions.

Tourism	White to Yellow	Begin	0
		End	1.5
	Yellow to Red	Begin	1.5
		End	3
	Red to Purple	Begin	no transition to purple
		End	no transition to purple

Coastal Flooding

Sea level rise (SLR) and coastal flooding have been observed or projected to be defined by all but two (iv, viii) of the overarching key risks identified by O'Neill et al. (2017). Even without climate change, flooding occurs. Hence it is important to determine the contribution climate change has made to this. Furthermore, the severity and extent of coastal flooding is highly dependent on the rate and timing of SLR based on emissions (and therefore commitment to SLR) (Section 13.4 in Church et al. 2013 AR5; this Report, Chapter 3, Section 3.3.9), plus the ability to adapt (Wong et al. 2014 AR5, Section 5.4. and 3.4.5.7).

SLR has been occurring naturally for hundreds of years (Church et al. 2013 AR5, Section 13.2; Kopp et al. 2016). It has and will be enhanced by man-made climate change, whilst acknowledging rates of decadal change due to natural conditions (e.g., White et al. 2005). Early signs of SLR departing from Holocene rates are reported since approximately 1900 (Jevrejeva et al. 2014; Dangendorf et al. 2015; Kopp et al. 2016), analogous to temperatures approximately 0.1°C above pre-industrial levels. It is very likely that global mean SLR was 1.7 [1.5–1.9] mm yr^{-1} between 1901 and 2010, but from 1993 to 2010, the rate was very likely higher at 3.2 [2.8 to 3.6] mm yr^{-1} (Church et al. 2013 AR5, Section 13.2.2.1 and Section 13.2.2.2). Climate-change induced SLR has been detectable and attributable for a few decades (Slangen et al. 2016; Kjeldsen et al. 2015; Rignot et al. 2011; Nerem et al. 2018), occurring around 0.3°C rise above pre-industrial levels.

The ability to adapt to changing sea-levels is variable between natural and human systems (Nicholls et al. 2007 AR4, Sections 6.4 and 6.6; Wong et al. 2014 AR5, Section 5.4). Adaptation may happen more effectively or be more advanced in some nations or communities more than others (Section 3.4.5.7; Araos et al. 2016; Ford et al. 2015). Whilst acknowledging that sensitive environments experience the adverse effects of climate change induced SLR today, analysis suggests that impacts could be more widespread in sensitive systems and ongoing at 1.7°C of temperature rise with respect to pre-industrial, even when considering adaptation measures.

Coastal flooding	White to Yellow	Begin	0.1
		End	0.3
	Yellow to Red	Begin	0.3
		End	1.7
	Red to Purple	Begin	1.7
		End	2.5

Fluvial Flooding

It is reported that flood frequency has increased while there was limited evidence of a decrease in flood magnitude in some region (Section 3.3.5.1). Tanoue et al. (2016) detect the increase of frequency and magnitude of flood that is attribute to climate change, and find that growing exposure of people and assets to flood according to the increase of population and economy exacerbate flood damage. Therefore, it is concluded that the current status, compared to the pre-industrial level, should be moderate.

In general, fluvial flooding at 1.5°C is projected to be higher than at 2°C, and at both levels of warming, projected changes in the magnitude and frequency of flood create regionally differentiated risks (Section 3.4.2).

The study of Alfieri et al. (2017) clearly points out a positive correlation between global warming and global flood risk. The projected number of the global population exposed to flood risk becomes quadratically increase as the temperature rises from 1.5°C to 4°C, in which the population is 100% increase at 1.5°C, 170% at 2°C and 580% at 4.0°C relative to the baseline period (1976–2005) (Alfieri et al. 2017). Relative changes in population affected (economic damage) at 2°C warming are projected to exceed 200% in 20 (19) countries, concluded that the transition to high risk should be at 2°C warming.

Warming of 4°C from pre-industrial level is projected to be a threefold increase of the proportion of the global population who are exposed to a 20th century 100-year fluvial flood compared to the warming of 1.6°C, while the 4.0°C warming is 14 times as high as present-day exposure (Hirabayashi et al. 2013).

The above-mentioned assessments assume the population is constant, although the variation between socio-economic differences is greater than the variation between the extent of the global warming, resulting in the change in the magnitude of the flood risks, however these changes are not considered in this context.

Meanwhile, Kinoshita et al. (2018) indicate that potential economic loss can be halved by autonomous adaptation. However, few studies assess quantitative mitigation by adaptation, therefore transition to very high risk (red to purple) is not applicable.

Fluvial Flooding	White to Yellow	Begin	0
		End	0.6
	Yellow to Red	Begin	0.6
		End	2
	Red to Purple	Begin	N/A
		End	N/A

Crop Yields

Scientific literature shows that climate change resulted in changes in the production levels of the main agricultural crops. Crop yields showed contrasting patterns depending on cultivar, geographical area and response to CO_2 fertilization effect, resulting in a transition from no risk (white) to moderate risk (yellow) below recent temperatures.

The projected risks for several cropping systems are generally higher under warming of 2°C than of 1.5°C (Section 3.4.6), with different impacts depending on geographical area. The most significant crop yield declines are found in West Africa, Southeast Asia, and Central and South America (Section 3.4.6), whilst less-pronounced yield reductions are expected for northern latitudes. Globally, this indicates a different adaptation capacity among the several cropping systems, thus suggesting a transition in risk from moderate (yellow) to high risk (red) between 1.5ºC and 2.5°C.

Crop Yields	White to Yellow	Begin	0,5
		End	0,8
	Yellow to Red	Begin	1,5
		End	2,5
	Red to Purple	Begin	N/A
		End	N/A

Arctic

High-latitude tundra and boreal forest are particularly at risk, and woody shrubs are already encroaching into the tundra (*high confidence*, Section 3.4.3). These impacts had already been detected at recent temperatures (0.7ºC) hence locating transition from undetected to moderate risk between 0ºC and 0.7ºC, but further impacts have been detected more recently and risks increase further with warming (3.4.2).

It is *very likely* that there will be least one sea-ice-free Arctic summer per decade at 2°C, while this is one per century at 1.5°C. (*high confidence*) (Sections 3.3.8, 3.4.4.7). Further warming is projected to cause greater effects in a 2°C world than a 1.5°C world, for example, limiting warming to 1.5°C would prevent the loss of an estimated permafrost area of 2 million km^2 over future centuries compared to 2°C (*high confidence)* (Sections 3.3.2, 3.4.3, 3.5.5). A transition from high (red) to very high (purple) risk is therefore located between 1.5ºC and 2ºC.

Arctic	White to Yellow	Begin	0
		End	0,7
	Yellow to Red	Begin	0,7
		End	1,5
	Red to Purple	Begin	1,5
		End	2

Terrestrial Ecosystems

Detection and attribution studies show that impacts of climate change on terrestrial ecosystems have been taking place in the last few decades, indicating a transition from no risk (white) to moderate risk (yellow) below recent temperatures.

The projected risks to unique and threatened terrestrial ecosystems are generally higher under warming of 2°C than 1.5°C (Section 3.4.3). Globally, effects on terrestrial biodiversity escalate significantly between these two levels of warming. Key examples of this include much more extensive shifts of biomes (major ecosystem types) and a doubling or tripling of the number of plants, animals or insects losing over half of their climatically determined geographic ranges (Section 3.4.3). This indicates a transition in risk from moderate (yellow) to high risk (red) between 1.5°C and 2°C, however since some systems and species are unable to adapt to levels of warming below 2°C, the transition to high risk is located below 2°C. By 3°C, biome shifts and species range losses escalate to very high levels and the systems have very little capacity to adapt (3.4.3).

Terrestrial Ecosystems	White to Yellow	Begin	0.3
		End	0.5
	Yellow to Red	Begin	1.5
		End	1.8
	Red to Purple	Begin	2.0
		End	3.0

Mangroves

Recent literature is consistent with previous conclusions regarding the complex changes facing mangroves, together with increasing concern regarding the interaction between climate change (e.g., elevated air and water temperatures, drought, sea level rise) and local factors (deforestation, damming of catchments and reduced sediment and freshwater) as outlined below (Feller et al. 2017; Alongi 2015). Decreases in the supply of sediments to deltas and coastal areas is impeding the ability of most mangroves (69% of sites) to keep pace with sea level rise through shoreward migration (Lovelock et al. 2015). At the same time, recent extremes associated with El Niño (e.g., extreme low sea level events, Duke et al., 2017; Lovelock et al., 2017). Shoreward migration is also challenged by the increasing amounts of coastal infrastructure preventing the relocation of mangroves (Saunders et al. 2014; Di Nitto et al. 2014). In some areas, mangroves are increasing in distribution (Godoy and De Lacerda 2015). The total loss projected for mangrove loss (10–15%) under a 0.6 m sea level rise continue to be dwarfed by the loss of mangroves to deforestation (1–2% per annum).

Given the scale of the die-back of mangroves in Australia's Gulf of Carpentaria (2015-2016), however, plus evidence that similar conditions to those of 2015-2016 (extreme heat and low tides), and the projection of greater El Niño-Southern Oscillation (ENSO) variability, (Risser and Wehner 2017; Widlansky et al. 2015), the risks from climate change for mangroves were judged to be higher than assessed by AR5, and subsequently by Gattuso et al. (2015), leading to the transitions having greater risk of occurring (Figure 3.17). Formal attribution of recent extreme events on mangroves to climate change, however is at an early stage *(medium agreement, limited data).*

See accompanying assessment by (Gattuso et al. 2015) in **Annex 3.1** S3-4-4_Supplementary information to Section 3.4.4.

Mangroves	White to Yellow	Begin	1.3
		End	1.5 (2.5)*
	Yellow to Red	Begin	2.5
		End	2.7
	Red to Purple	Begin	NA
		End	NA

Warm water corals

Exceptionally warm conditions of 2015–2017 drove an unprecedented global mass coral bleaching and mortality event which affected coral reefs in a large number of countries (information still being gathered, Normile, 2016). In the case of Australia, 50% of shallow-water reef-building corals across the Great Barrier Reef died in unprecedented back-to-back bleaching events (Hughes et al. 2017). Elevated sea temperatures and record mortality was recorded from the Central to the Far northern sectors of the Great Barrier Reef. Similar impacts occurred in a range of regions including the Indian Ocean, Western Pacific, Hawaii and Caribbean oceans (Normile 2016) . The set of events has increased risk with current conditions being of high risk, and even low levels of future climate change being largely catastrophic for coral reefs. There continues to be a very high level of confidence as to the impacts under RCP2.6, as well as a high confidence for those under RCP8.5.

The unprecedented thermal stress along many tropical coastlines over the past three years (2015-2017) has led to extraordinary changes to coral reefs across the planet (as described above). The advent of back-to-back bleaching events, which were projected to occur around midcentury, appear to have already begun to occur as demonstrated by impacts on warm water corals and hence coral reefs. While corals were already stressed from climate change, and are in decline in many parts of the world, the scale and impact of recent events suggest that risk levels for the transitions between risk categories need to be adjusted to represent the current status of corals and coral reefs. For this reason, expert consultation since 2015 concluded that the transition from undetectable to moderate risk has already occurred (0.2°C to 0.4°C). Similarly, the transition from *moderate* to high levels of risks for warm water corals occurred approximately from 0.5°C to 0.6°C. In line with these changes, the transition from *high* to *very high* levels of risk appears associated with increases in GMST from 0.7°C to 1.3°C above the pre-industrial period.

See accompanying assessment by (Gattuso et al. 2015) in Annex 3.1 S3-4-4_Supplementary information to Section 3.4.4.

Warm water corals	White to Yellow	Begin	0.2
		End	0.4
	Yellow to Red	Begin	0.5
		End	0.6
	Red to Purple	Begin	0.7
		End	1.3

Small-scale fin fisheries (low latitude)

Low latitude fin fisheries, or small-scale fisheries, provide food for millions of people along tropical coastlines and hence play an important role in the food security of a large number of countries (McClanahan et al. 2015; Pauly and Charles 2015). In many cases, populations are heavily dependent on these sources of protein given the lack of alternatives (Cinner et al. 2016, 2012; Pendleton et al. 2016). The climate related stresses affecting fin fish (see Section S3.4.4, subsection on 'Fin fish'), however, are producing a number of challenges for small scale fisheries based on these species (e.g., (Pauly and Charles 2015; Bell et al. 2017; Kittinger 2013).

Recent literature (2015–2017) has continued to outline growing threats from the rapid shifts in the biogeography of key species (García Molinos et al. 2015; Poloczanska et al. 2013; Burrows et al. 2014; Poloczanska et al. 2016) and the ongoing rapid degradation of key habitats such as coral reefs, seagrass and mangroves (see Section 3.4.4, subsections on 'Seagrasses', 'Mangroves' and 'Pteropods' and Chapter 3, Box 3.4). As these changes have accelerated, so have the risks to the food and livelihoods associated with small-scale fisheries (Cheung et al. 2010). These risks have compounded with non-climate stresses (e.g., pollution, overfishing, unsustainable coastal development) to drive many small-scale fisheries well below the sustainable harvesting levels required to keep these resources functioning as a source of food (McClanahan et al. 2015, 2009; Pendleton et al. 2016). As a result, projections of climate change and the growth in human populations increasingly predict shortages of fish protein for many regions (e.g., Pacific, e.g., Bell et al., 2013, 2017; Indian Ocean, e.g., McClanahan et al., 2015). Mitigation of these risks involved marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Song and Chuenpagdee 2015; Kittinger 2013; McClanahan et al. 2015; Weatherdon et al. 2016). Threats to small-scale fisheries have also come from the increasing incidence of alien (nuisance) species as well as an increasing incidence of disease, although the literature on these threats is at a low level of development and understanding (Kittinger et al. 2013; Weatherdon et al. 2016).

As assessed by Gattuso et al. (2015), risks of impacts on small-scale fisheries are medium today, but are expected to reach very high levels under scenarios extending beyond RCP2.6. The research literature plus the growing evidence that many countries will have trouble adapting to these changes places confidence a high level as to the risks of climate change on low latitude in fisheries. These effects are more sensitive, hence the higher risks at lower levels of temperature change.

Small-scale fisheries are highly dependent on healthy coastal ecosystems. With the growing evidence of impacts described above, the loss of habitat for small-scale fisheries is intensifying the risks of impact from climate change. For this reason, expert consensus has judged that risks have become greater since the assessment of Gattuso et al. (2015). Therefore, the transition from undetectable to medium levels of risk is projected to occur between 0.5°C and 0.7°C, with the transition from medium to high levels of risk occurring between 0.9°C and 1.1°C. The transition from high to very high levels of risk of impact as being judged to occur between 2°C and 2.5°C.

See accompanying assessment by (Gattuso et al. 2015) in Annex 3.1 S3-4-4_Supplementary information to Section 3.4.4.

Small scale fin fisheries (low latitude)	White to Yellow	Begin	0.5
		End	0.7
	Yellow to Red	Begin	0.9
		End	1.1
	Red to Purple	Begin	2
		End	2.5

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SI_S3-4-7_Supplementary information to Section 3.4.7 Human health

Table S6. Decades when 1.5°C, 2°C, and higher degrees of warming are reached for multi-climate model means

Generation	Scenario	Decade 1.5°C reached	Decade 2°C reached	dT 2080-2099	dT 2090-2099
SRES	B1	2039-2048	2065-2074	2.18	2.27
SRES	A1b	2029-2038	2045-2054	3.00	3.21
SRES	A2	2032-2041	2048-2057	3.39	3.83
RCP	2.6	2047-2056	a	1.48	1.49
RCP	4.5	2031-2040	2055-2064	2.32	2.37
RCP	6.0	2036-2045	2058-2067	2.63	2.86
RCP	8.5	2026-2035	2040-2049	3.90	4.39

[a] 2°C not reached

Table S7. Projected temperature-related risks at 1.5°C and 2°C. *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway, GMST: Global Mean Surface Temperature*

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study 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, EGMAM1, EGMAM2, EGMAM3, CM4vl	A1B	2030, 2050		In 2030, 92,207 additional heat-related deaths without adaptation (ensemble mean) and 28,055 with adaptation under BCM2	In 2050, 255,486 additional heat-related deaths without adaptation and 73,936 with adaptation under BCM2 scenario; the	Population growth and aging; improved health in elderly due to economic development; three levels of adaptation (none, partial, and full)	(Hales et al. 2014)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
							scenario; the Asia Pacific, Asia, North Africa / Middle East, Sub-Saharan Africa, Europe, and north America at higher risk.	same regions are at higher risk.		
Global	Extremely hot summers over land areas (>3 standard deviations anomalies)	1861–1880	26 models from CMIP5	RCP2.6, RCP4.5, RCP8.5	to 2100	Probability of an extremely hot summer (>3 standard deviations) in 1996–2005 (compared with 1951–1980) is 4.3%	Probability of an extremely hot summer is approximately 25.5% and probability of an exceedingly hot summer (>5 standard deviations) is approximately 7.1% above pre-industrial	Extremely hot summers are projected to occur over nearly 40% of the land area		(Wang et al. 2015)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Global	Population exposure to hot days and heatwaves	1961–1990	21 CMIP5 GCMs	Temperature change based on pattern scaling	Up to 2100	Increasing exposure to heatwaves already evident	The frequency of heatwave days increases dramatically as global mean temperature increases, although the extent of increase varies by region. Increases are greatest in tropical and sub-tropical regions where the standard deviation of warm season daily maximum temperature is least, and therefore, a smaller increase in	Overall, exposure to heatwaves is reduced by more than 75% in all models in each region if GMSTs do not increase to 2°C; the avoided impacts vary by region.		(Arnell et al. 2018)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
							temperature leads to a larger increase in heat wave frequency.			
Japan, Korea, Taiwan, USA, Spain, France, Italy	Heat-related mortality for 65+ age group	1961–1990	BCM2	A1B	2030, 2050		In 2030, heat-related excess deaths increased over baselines in all countries, with the increase dependent on the level of adaptation	In 2050, heat-related excess deaths are higher than for 2030, with the increase dependent on the level of adaptation	Three adaptation assumptions: 0, 50, and 100%	(Honda et al. 2014)
Australia (five largest cities) and UK	Temperature-related mortality	1993–2006	UKCP09 from HadCM3; OzClim 2011	A1B, B1, A1FI	2020s, 2050s, 2080s	For England and Wales, the estimated % change in mortality associated with heat exposure is 2.5% (95% CI: 1.9–3.1) per 1°C rise in	In the 2020s, heat-related deaths increase from 1,503 at baseline to 1,511 with a constant population and 1,785 with the projected	In the 2050s, heat-related deaths further increase to 2,866 with a constant population and to 4,012 with the projected population.	Projected population change	(Vardoulakis et al. 2014)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
						temperature above the heat threshold (93rd percentile of daily mean temperature). In Australian cities, the estimated overall % change in mortality is 2.1% (95% CI: 1.3, 2.9).	population. In Australia, the numbers of projected deaths are 362 and 475, respectively, with a baseline of 214 deaths.	In Australia, the numbers of projected deaths are 615 and 970, respectively		
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 in 2030; Melbourne - from 9 days at baseline to 11–13 days in 2030	Sydney – 6–12 days and Melbourne – 15–26 days in 2070		(Hanna et al. 2011)
Brisbane, Sydney, and Melbourne Australia	Temperature-related mortality	1988–2009	62 GCMs, with spatial downscaling and bias	A2, A1B, B1	2050s, 2090s		In 2030, net temperature-related mortality	In 2050, there are further net temperature		(Guo et al. 2016)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
			correction				(heat/ cold) increases in Brisbane under all scenarios, increases in Sydney under A2, and declines in Melbourne under all scenarios	related mortality (heat/cold) increases in Brisbane under all scenarios, increases in Sydney under A2 and A1B, and further declines in Melbourne under all scenarios		
Brisbane Australia	Years of life lost due to temperature extremes (hot and cold)	1996–2003		Added 1–4°C to observed daily temperature to project for 2050	2000, 2050	In 2000, 3,077 temperature-related years of life lost for men, with 616 years of life lost due to hot temperatures and 2,461 years of life lost due to cold. The	For 1°C above baseline, years of life lost increase by 1,014 (840 to 1,178) for hot temperatures and decrease by 1,112 (–1,337 to –871) for cold temperatures	For 2°C above baseline, years of life lost increase by 2,450 (2,049 to 2,845,) for hot temperatures and decrease by 2,069, (–2,484 to –1,624) for cold		(Huang et al. 2012)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
						numbers for women are 3,495 (total), 903(hot), and 2,592 (cold).		temperatures		
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 summer mortality in 2020	4–6% increase in summer mortality in 2050		(Doyon et al. 2008)
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)		In 2030, a net increase in premature deaths, with decreases in temperature-related winter mortality and increases in summer mortality; the magnitude varied by region and city with an overall increase of 11,646 heat-	In 2050, a further increase in premature deaths, with decreases in temperature-related winter mortality and increases in summer mortality; the magnitude varied by region and city with an overall increase of	Held population constant at 2010 levels; mortality associated with high temperatures decreased between 1973–1977 and 2003–2006	(Schwartz et al. 2015)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
							related deaths.	15,229 heat-related deaths.		
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 2025, 96 excess deaths in Seattle area.	Under moderate warming in 2045, 156 excess deaths in Seattle area.	Holding population constant at 2025 projections	(Jackson et al. 2010)
Boston, New York, Philadelphia, USA	Heat-related mortality	1971–2000	CMIP5 bias corrected (BCSD)	RCP4.5, RCP8.5	2010–2039, 2040–2069, 2070–2099	Baseline heat-related mortality is 2.9–4.5 / 100,000 across the three cities	In the 2020s under both RCPs, heat-related mortality increased to 5.9–10 / 100,000	In the 2050s, heat-related mortality increased to 8.8–14.3 / 100,000 under RCP4.5 and to 11.7 to 18.9 / 100,000 under RCP8.5	Population constant at 2000	(Petkova et al. 2017)
Europe	Heat-related mortality	1971–2000	SMHI RCA4/HadGEM2 ES r1	RCP4.5; RCP8.5	2035–2064; 2071–209		2035–2064 excess heat mortality to	2071–2099 excess heat mortality to		(Kendrovski et al. 2017)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
			(MOHC)				be 30,867 and 45,930	be 46,690 and 117,333 attributable deaths/year		
Europe; London, UK and Paris, France	Heat-related mortality	Present climate	Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI)	Climate stabilization at 1.5° and 2°C		Model of 2003 heat event resulted in about 735 excess deaths for Paris and about 315 for London	Compared with 2°C stabilization, mortality event is 2.4 times less likely in London and 1.6 times less likely in Paris	22% increase in mortality in Paris and 15% increase in mortality in London, compared with 1.5°C stabilization		(Mitchell 2018)
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	At baseline, 1,974 annual heat-related and 41,408 cold-related deaths	In the 2020s, in the absence of adaptation, heat-related deaths would increase to 3,281 and cold-related deaths to increase to 42,842	In the 2050s, the absence of adaptation, heat-related deaths projected to increase 257% by the 2050s to 7,040 and cold-related mortality to decline about 2%	Population projections to 2081	(Hajat et al. 2014)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Netherlands	Temperature-related mortality	1981–2010	KNMI’ 14; G-scenario is a global temperature increase of 1°C and W-scenario an increase of 2°C		2050 (2035–2065)	At baseline, the attributable fraction for heat is 1.15% and for cold is 8.9%; or 1511 deaths from heat and 11,727 deaths from cold	Without adaptation, under the G scenario, the attributable fraction for heat is 1.7–1.9% (3,329–3,752 deaths) and for cold is 7.5–7.9% (15,020-15,733 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	Without adaptation, under the W scenario, the attributable fraction for heat is 2.2–2.5% (4,380-5,061 deaths) and for cold is 6.6–6.8% (13,149-13,699 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	Three adaptation scenarios, assuming a shift in the optimum temperature, changes in temperature sensitivity, or both; population growth and declining mortality risk per age group	(Huynen and Martens 2015)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Korea	Burden of disease from high ambient temperatures	2011	CMIP5	RCP4.5; RCP8.5	2030; 2050	DALY for all-cause mortality in 2011 was 0.49 (DALY/1000) DALY for cardio-and cerebrovascular disease was 1.24 DALY/1000	In 2030 DALY for all-cause mortality, 0.71 (DALY/1000) DALY for cardio-and cerebrovascular disease is 1.63 (1.82) DALY/1000	In 2050, DALY for all-cause mortality, 0.77 (1.72) (DALY/1000) DALY for cardio-and cerebrovascular disease is 1.76 (3.66) DALY/1000		(Chung et al. 2017)
Beijing, China	Heat-related mortality	1970–1999	Downscaled and bias corrected (BCSD) 31 GCMs in WCRP CMIP5; monthly change factors applied to daily weather data to create a projection	RCP4.5, RCP8.5	2020s (2010–2039), 2050s (2040–2069), 2080s (2070–2099)	Approximately 730 additional annual heat-related deaths in 1980s	In the 2020s, under low population growth and RCP4.5 and RCP8.5, heat-related deaths projected to increase to 1,012 and 1,019, respectively. Numbers of deaths are higher with	In the 2050s under low population growth, and RCP4.5 and RCP8.5, heat-related deaths projected to increase to 1,411 and 1,845, respectively.	Adults 65+ years of age; no change plus low, medium, and high variants of population growth; future adaptation based on Petkova et al. 2014, plus shifted mortality 5%, 15%, 30%,	(Li et al. 2016c)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
							medium and high population growth.		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	Cardiovascular mortality could increase by an average percentage of 18.4% in the 2020s under RCP4.5 and by 16.6% under RCP8.5. Statistically significant increases are projected for respiratory mortality.	Cardiovascular mortality could increase by an average percentage of 47.8% and 69.0% in the, 2050s and 2080s under RCP4.5, and by 73.8% and 134% under RCP8.5. Similar increases are projected for respiratory mortality.		(Li et al. 2015)
Africa	Five thresholds for number of hot days per year when health	1961–2000	CCAM (CSIRO) forced by coupled GCMs: CSIRO,	A2	2011–2040, 2041–2070, 2071–2100	In 1961–1990, average number of hot days (maximum	In 2011–2040, annual average number of hot days (maximum	In 2041–2070, annual average number of hot days (maximum	Projected population in 2020 and 2025	(Garland et al. 2015)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
	could be affected, as measured by maximum apparent temperature		GFDL20, GFDL 21, MIROC, MPI, UKMO. CCAM was then downscaled. Biased corrected using CRU TS3.1 dataset			apparent temperature ≥ 27°C) ranged from 0 to 365, with high variability across regions.	apparent temperature ≥ 27°C) projected to increase by 0–30 in most parts of Africa, with a few regions projected to increase by 31–50.	apparent temperature ≥ 27°C) projected to increase by up to 296, with large changes projected in southern Africa and parts of northern Africa		

Table S8. Projected air quality-related health risks at 1.5°C and 2°C. *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway ; CV : Cardio-Vascular*

Region	***Health outcome metric***	***Study baseline***	***Climate model(s) and air pollution models***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Global	PM 2.5 and O_3-related mortality	2000	ACCMIP model; CESM	RCP2.6; RCP4.5; RCP6.0; RCP8.5	2000; 2030; 2050; 2100	Global O_3 mortality 382,000 (121,000–728,000) deaths year -1; global mortality burden of PM2.5 1.70 (1.30–2.10) million deaths year^{-1}	PM2.5-related mortality peaks in 2030 (2.4–2.6 million deaths/year — except for RCP6.0)	O_3-related mortality peaks in 2050 (1.84–2.6 million deaths per year)	Population projected from 2010–2100	(Silva et al. 2016)
Global & Europe and France	PM2.5-related CV- and O_3-related respiratory mortality	2010	IPSL-cm5-MR, LDMz-INCA, CHIMERE	RCP4.5 (for Europe and France)	2010; 2030-2050	Global CV mortality 17,243,000	In 2030, in Europe PM2.5-related CV mortality decreases by 3.9% under CLE; and 7.9% under MFR. In 2030 O_3-related respiratory mortality decreases by 0.3% under MFR	In 2050, 4.5% decrease in PM2.5 related CV mortality under CLE and 8.2% MFR.	Population 2030–sensitivity analysis	(Likhvar et al. 2015)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s) and air pollution models***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
UK	O_3-related morbidity and mortality	2003	EMEP-WRF	A2, B2	2003, 2030	O_3-attributable mortality and morbidity in 2003: 11,500 deaths and 30,700 hospitalizations	With no threshold for O_3, increase of premature mortality and hospitalization of 28% (under B2 + CLE scenario) – greatest health effects; A2 premature morbidity and mortality projections: 22%. With 35 ppbv, 52% increase in mortality and morbidity (under B2+CLE)	Increases in temperatures by 5°C, projected O_3 mortality will increase from 4% (no O_3 threshold) to 30% (35 ppbv O_3 threshold)	Population projections increase, +5°C scenario	(Heal et al. 2013)
Poland	PM2.5 mortality	2000	ECHAM5-RegCM3, CAMx	A1B	1990s; 2040s; 2090s	39,800 premature deaths related to PM2.5 air pollution	0.4–1°C in 2040; 6% decrease in PM2.5 related mortality in 2040s	2–3°C in the 2090s; 7% decrease in PM25 related mortality in 2090s		(Tainio et al. 2013)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s) and air pollution models***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Korea	O_3 summer mortality	2001–2010	ICAMS	RCP2.6; RCP4.5; RCP6.0; RCP8.5	1996–2005; 2016–2025; 2046–2055		In the 2020s, summer mortality to increase by: 0.5%, 0.0%, 0.4%, and 0.4% due to temperature change. In the 2020s, due to O_3 concentration change, mortality to increase by 0.0%, and 0.5%	In the 2050s, summer mortality to increase by: 1.9%, 1.5%, 1.2% and 4.4% by temperature change. In the 2050s, due to O_3 concentration, mortality to increase by 0.2%, 0.4% and 0.6%	Current mortality trends expected to increase, temperature effects compared	(Lee et al. 2017)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s) and air pollution models***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
U.S. (12 metropolitan areas)	O_3 inhalation exposures	2000	APEX, CESM, MIP5, WRF, CMAQ	RCP4.5; RCP6.; RCP8.5	1995-2005; 2025-2035	At least on exceeded/year	Comparing 2030 to 2000, almost universal trend with at least three exceedances (of DM8H exposure above the 60 ppb and 70 bbp thresholds)	Health implications Increase as population exposures to O_3 increases based on the degree of radiative forcing in 2100	Population projections using IPCC SRES and adapted for U.S.	(Dionisio et al. 2017)

Table S9. Projected vectorborne disease risks at 1.5°C and 2°C. *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway*

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Malaria										
China	Malaria vectors *Anopheles dirus, A. minimus, A. lesteri, A. sinensis*	2005–2008	BCC-CSM1-1, CCCma_CanESM2, CSIRO-Mk3.6.0 from CMIP5	RCP2.6, RCP4.5, RCP8.5	2020–2049, 2040–2069		In the 2030s, environmentally suitable areas for *A. dirus* and *A. minimus* increase by an average of 49% and 16%, respectively	In the 2050s environmentally suitable areas for *A. dirus* and *A. minimus* decrease by 11% and 16%, respectively. An increase of 36% and 11%, in environmentally suitable area of *A. lesteri* and *A. sinensis*	Land use, urbanization	(Ren et al. 2016)
Northern China	Spatial distribution of malaria	2004–2010	GCMs from CMIP3	B1, A1B, A2	2020, 2030, 2040, 2050	Average malaria incidence 0.107% per annum in northern China	In 2020, malaria incidence increases 19–29%, and increases	In 2040, malaria incidence increases 33–119% and 69–182% in	Elevation, GDP, water density index held constant	(Song et al. 2016)

							43–73% in 2030, with increased spatial distribution	2050, with increased spatial distribution		
Sub-Saharan Africa	Malaria	2006–2016	21 CMIP5 models	RCP4.5, RCP8.5	2030, 2050, 2100		In 2030, under RCP8.5, many parts of western and central Africa will have no malaria, but significant malaria hotspots will be along the Sahel belt, eastern and southern parts of Africa.	Climate change will redistribute the spatial pattern of future malaria hotspots especially under RCP8.5.	Various environmental variables	(Semakula et al. 2017)
Aedes										
Global	Global niche models for autochthonous Chikungunya transmission	Current climate	CESM 1 bcg, FIO ESM, GISS e2-r, INM CM4 and MPI-ESM-lr	RCP4.5, RCP8.5	2021–2040; 2041–2060; 2061–2080	Current distribution of Chikungunya transmission	In 2021–2040, climatically suitable areas projected to increase in multiple regions,	In 2041–2060, greater geographic expansion		(Tjaden et al. 2017)

							including China, Sub-Saharan Africa, the United States, and continental Europe			
North America, United States	Climate suitability for *Aedes albopictus* vector for dengue, Chikungunya, and vectorborne zoonoses such as West Nile Virus (WNV), Eastern Equine Encephalitis virus, Rift Valley Fever virus, Cache Valley virus and LaCrosse virus	1981-2010	8 RCMs: CanRCM4, CRCM5, CRCM 4.2.3, HIRHAM5, RegCM3, ECPC, MM5I, WRF	RCP4.5, RCP8.5, A2	2020s (2011–2040), 2050s (2041–2070).	Index of precipitation and temperature suitability was highly accurate in discriminating suitable and non-suitable climate	In 2011–2040 under RCP4.5, climate suitability increases across US, with the magnitude and pattern dependent on parameter projected and RCM	In 2041–2070 under RCP4.5, areal extent larger than in earlier period; under RCP8.5, areal extent larger	Climatic indicators of *Ae. albopictus* survival; overwintering conditions (OW); OW combined with annual air temperature (OWAT); and an index of suitability	(Ogden et al. 2014a)

Mexico	Dengue	1985–2007	National Institute of Ecology; added projected changes to historic observations	A1B, A2, B1	2030, 2050, 2080	National: 1.001/100.000 cases annually Nuevo Leon: 1.683/100.000 cases annually Queretaro: 0.042/100.000 cases annually Veracruz: 2.630/100.000 cases annually	In 2030, dengue incidence increases 12–18%	In 2050, dengue incidence increases 22–31%.	At baseline, population, GDP, urbanization, access to piped water	(Colón-González et al. 2013)
Europe, Eurasia and the Mediterranean	Climatic suitability for Chikungunya outbreaks	1995-2007	COSMO-CLM, building on ECHAM5	A1B and B1	2011-2040, 2041–2070, 2071–2100	Currently, climatic suitability in southern Europe. The size of these regions will expand during the 21st century	In 2011–2040, increases in risk are projected for Western Europe in the first half of the 21st century	In 2041–2070, projected increased risks for central Europe.		(Fischer et al. 2013)
Europe	Potential establishment of *Ae.*	Current bioclimatic data	Regional climate model COSMO-	A1B, B1	2011–2040, 2041–2070, 2071–2100		In 2011–2040, higher	Between 2011–40 and 2041–		(Fischer et al. 2011)

	albopictus	derived from monthly temperature and rainfall values	CLM				values of climatic suitability for *Ae. albo pictus* increases in western and central Europe	2070, for southern Europe, only small changes in climatic suitability are projected. Increasing suitability at higher latitudes is projected for the end of the century.		
Europe	Dengue fever risk in 27 EU countries	1961–1990	COSMO-CLM (CCLM) forced with ECHAM5/MPIOM	A1B	2011–2040, 2041–2070, 2071–2100	Number of dengue cases are between 0 and 0.6 for most European areas, corresponding to an incidence of less than 2 per 100,000 inhabitants	In 2011–2040, increasing risk of dengue in southern parts of Europe	In 2041–2070, increased dengue risk in many parts of Europe, with higher risks towards the end of the century. Greatest increased risk around the Mediterrane	Socioeconomic variables, population density, degree of urbanization and log population	(Bouzid et al. 2014)

								an and Adriatic coasts and in northern Italy		
Tanzania	Distribution of infected *Aedes aegypti* co-occurrence with dengue epidemics risk	1950–2000	CMIP5		2020, 2050	Currently high habitat suitability for *Ae. aegypti* in relation to dengue epidemic, particularly near water bodies	Projected risk maps for 2020 show risk intensification in dengue epidemic risks areas, with regional differences	In 2050, greater risk intensification and regional differences		(Mweya et al. 2016)
West Nile Virus										
Europe, Eurasia, and the Mediterranean	Distribution of human WNV infection	Monthly temperature anomalies relative to 1980–1999, environmental variables for 2002–2013	NCAR CCSM3	A1B	2015-2050		In 2025, progressive expansion of areas with an elevated probability for WNV infections, particularly at the edges of the current transmission areas	In 2050, increases in areas with a higher probability of expansion	Prevalence of WNV infections in the blood donor population	(Semenza et al. 2016)

Lyme disease and other tick-borne diseases										
North America (mainly Ontario and Quebec, Canada, and Northeast and Midwest, U.S)	Capacity of Lyme disease vector (*Ixodes scapularis)* to reproduce under different environmental conditions	1971–2010	CRCM4.2.3, WRF, MM5I, CGCM3.1, CCSM3	A2	1971–2000, 2011–2040, 2041–2070	In 1971–2010, reproductive capacity increased in North America increased consistent with observations	In 2011–2040, mean reproductive capacity increased, with projected increases in the geographic range and number of ticks	In 2041–2070, further expansion and numbers of ticks projected. R_0 values for *I. scapularis* are projected to increase 1.5–2.3 times in Canada. In the U.S. values are expected to double.		(Ogden et al. 2014b)
Southeastern US, NY	Emergence of *I. scapularis*, leading to Lyme disease	1994–2012			2050	19 years of tick and small mammal data (mice, chipmunks)	In the 2020s, the number of cumulative degree-days enough to advance the	In the 2050s, the nymphal peak advances by 8–11 days, and the		(Levi et al. 2015)

							average nymphal peak by 4–6 days, and the mean larval peak by 5–8 days, based on 1.11–1.67°C increase in mean annual temperature	mean larval peak by 10–14 days, based on 2.22–3.06°C increase in mean annual temperature		
Other										
Venezuela	Chagas disease: number of people exposed to changes in the geographic range of five species of triatomine species	1950–2000	CSIRO3.0	A1B, B1	2020, 2060, 2080		In 2020 decreasing population vulnerability	In 2060, effects more pronounced, with less of a change under B1	MaxEnt model of climatic niche suitability	(Ceccarelli and Rabinovich 2015)
Colombia	Visceral leishmaniasis caused by the trypanosomatid	Present	CSIRO, Hadley	A2A, B2A	2020, 2050, 2080		In 2020, shift in the altitudinal distribution in the Caribbean	In 2050, even greater geographic area of potential occupancy,	MaxEnt model; three topographical variables	(González et al. 2014)

	parasite *Leishmania infantum*						Coast and increase in the geographic area of potential occupancy under optimistic scenarios	with a greater impact under A2.		

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SI_S3-4-7_Supplementary information to Key Economic Sectors

Table S10. Key Economic Sectors (Energy, Tourism, Transport, Water)

Projected Risks at 1.5°C and 2°C

Sector (sub sector)	***Region***	***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***
Energy (thermal and hydro plants; cooling demand)	Global	Cooling demand (absolute growth in annual cooling degree days (CDD)); hydroclimate risk to power production	1971‒2000	5 GCMS GFDL-ESM2M; HadGEM2-ES; IPSL-CM5A-LR; MIROC-ESM-CHEM; NorESM1-M	RCP8.5 SSP1-3	1.5°C (2002‒2048) 2.0°C (2014‒2065)			Increased CCD, especially in tropical areas. Increased risk to thermal and hydro power plants in Europe, N. America, south and SE Asia, and SE Brazil		(Byers et al. 2018)
Energy (Wind)	Europe	Daily wind power output (transformed from daily near surface wind speeds)	2006‒2015	HAPPI		1.5°C (2106‒2115		Great potential for wind energy in Northern Europe, especially in the UK		Limited spatial resolution	(Hosking et al. 2018)
Energy (Electrici	US	Electric sector models:		MIT IGSM-CAM	REF CS3	2015‒2050			Increase in electricity		(McFarland et al. 2015)

ty demand)		GCAM-USA ReEDS IPM			REF CS6 POL4.5 CS3 POL3.7 CS3 TEMP 3.7 CS3				demand by 1.6–6.5% in 2050		
Energy (demand)	Global	Economic and end-use energy model Energy service demands for space heating and cooling			RCP2.6 (2°C) RCP8.5 (4°C) RCP8.5 constant after 2020 (1.5°) SSP1 SSP2 SSP3	2050−2100		Economic loss of 0.31% in 2050 and 0.89% in 2100 globally	GDP negative impacts in 2100 are highest (median: -0.94%) under 4.0°C (RCP8.5) scenario compared with a GDP change (median: −0.05%) under 1.5°C scenario		(Park et al. 2018)
Energy (heating and cooling demand)	Global and Regional	Degree days above or below 18°C	1961−1990	21 CMIP5		2100		Cooling energy demand: 31% impacts avoided Heating energy demand: 27% impacts			(Arnell et al. 2018)

								avoided, relative to 2°C			
Energy (Hydropower)	US (Florida)	Conceptual rainfall-runoff (CRR) model: HYMOD MOPEX	1971−2000	CORDEX (6 RCMs) CMIP5, bias corrected	RCP4.5	2091−2100			Based on a min/max temp. increase of 1.35−2°C, overall stream flow to increase by an average of 21% with pronounced seasonal variations, resulting in increases in power generation (72% winter, 15% autumn) and decreasing (-14%) in summer		(Chilkoti et al. 2017)
Energy (Hydropower)	Global	Gross hydropower potential; global mean cooling water discharge	1971–2000	5 bias-corrected GCMs	RCP2.6 RCP8.5	2080			Global gross hydropower potential expected to increase (+2.4% RCP2.6;	Socio-economic pathways	(van Vliet et al. 2016)

									+6.3% RCP8.5) Strongest increases in central Africa, Asia, India, and northern high latitudes. 4.5−15% decrease in global mean cooling water discharge with largest reductions in US and Europe		
Energy (Hydropower)	Brazil	Hydrological Model for natural water inflows (MGB)	1960−1990	HadCM3 Eta-CPTEC-40		2011−2100		A decrease in electricity generation of about 15% and 28% for existing and future generation systems starting in 2040		Other water use and economic development scenarios	(de Queiroz et al. 2016)

Energy (Hydropower)	Ecuador	CRU TS v.3.24 monthly mean temperature, precipitation and potential evapotranspiration (PET) conceptual hydrological model assessing runoff and hydropower electricity model	1971−2000	CMIP5 bias corrected using PET	RCP8.5 RCP4.5 RCP2.6	2071−2100			Annual hydroelectric power production to vary between −55 and +39% of the mean historical output. Inter-GCM range of projections is extremely large (−82%−+277%)	ENSO impacts	(Carvajal et al. 2017)

Energy (Wind)	Europe	Near surface wind data: Wind energy density means; Intra and inter annual variability	1986–2005	21 CMIP5 Euro-CORDEX	RCP8.5 RCP4.5	2016–2035 2046–2065 2081–2100		No major differences in large scale wind energetic resources, inter-annual or intra-annual variability in near term future (2016–2035)	Decreases in wind energy density in eastern Europe, Increases in Baltic regions (−30% vs. +30%). Increase of intra-annual variability in Northern Europe, decrease in Southern. Inter-annual variability not expected to change	Changes in wind turbine technology	(Carvalho et al. 2017)
Energy (Wind)	Europe	Near Surface Wind Speed Wind Power Simulated energy mix scenario		Euro-CORDEX	RCP4.5 RCP8.5	2050		Changes in the annual energy yield of the future European wind farms fleet as a whole will remain within ±5%			(Tobin et al. 2016)
Energy (Wind)	Europe	Potential wind power		ENSEMBLES 15 RCM	SRES A1B				In Europe, changes in		(Tobin et al. 2015)

		generation		6 GCM					wind power potential will remain within ±15% and ±20%		
Energy (Solar)	Europe	Mean PV power generation potential (PVPot); Surface wind velocity (SWV); radiation (RSDS); Surface air temp (TAS)	1970−1999	Euro-CORDEX	RCP4.5 RCP8.5	2070−2099			Solar PV supply by the end of 2100 should range from −14_+2% with largest decreases in Northern countries	Solar spectrum distribution and the air mass effect	(Jerez et al. 2015)
Energy (solar)	Global	Energy yields of photovoltaic (PV) systems		CMIP5	RCP8.5	2006−2049		Decreases in PV outputs in large parts of the world, but notable exceptions with positive trends in large parts of Europe, South-East of North America and the South-East of			(Wild et al. 2015)

								China.			
Energy (Electricity: wind, solar PV, hydro, thermal)	Europe	Wind power production; PV power generation potential; gross hydropower potential (VIC model); thermoelectric power generation (VIC-RBM models)	1971−2000	Euro-CORDEX (ensemble of 3 RCMs and 3 GCMs)	RCP4.5 RCP8.5	+1.5°C (2004-2043) +2.0°C (2016−2059) +3.0°C (2037−2084)		Impacts remain limited for most countries. PV and wind power potential may reduce 10%, hydro and thermal may reduce 20%	At 2.0°C impacts across sub-sectors remain limited, negative impacts double at 3°C. Impacts more severe in southern Europe	No spatial distribution accounted for in analysis	(Tobin et al. 2018)
Energy (hydropower)	Suriname	VHM hydrological model	1960−1990	CMIP5	RCP2.6 RCP4.5 RCP6.0 RCP8.5	1.5°C (2070−2100)		40% decrease in hydropower potential (RCP2.6)	50% decrease in hydropower potential (RCP4.5) 80% decrease in hydropower potential at 3°C GMST increases (RCP8.5)		Donk et al. 2018
Tourism	Europe	Climate Index for Tourism; Tourism Climatic Index (three variants)		Euro-CORDEX	RCP4.5 RCP8.5	+2°C			Varying magnitude of change across different indices; Improved		(Grillakis et al. 2016)

									climate comfort for majority of areas for May to October period; June to August period climate favorability projected to reduce in Iberian peninsula due to high temperatures		
Tourism	Southern Ontario (Canada)	Weather-visitation models (peak, shoulder, off-season)				1–5°C warming		Each additional degree of warming experienced annual park visitation could increase by 3.1%, annually.		Social variables e.g., weekends or holidays	(Hewer et al. 2016)
Tourism	Europe	Natural snow conditions (VIC); Monthly overnight stay;	1971−2000	Euro-CORDEX	RCP2.6 RCP4.5 RCP8.5	+2°C periods: 2071−2100 2036−2			Under a +2°C global warming up to 10 million overnight	Tourism trends based on economic conditions	(Damm et al. 2017)

		Weather Value at Risk				065 2026−2055			stays are at risk (+7.3 million nights) Austria and Italy are most affected.		
Tourism	Sardinia (Italy) and the Cap Bon peninsula (Tunisia)	Overnight stays; weather/climate data (E-OBS)	1971−2000	EU-FP6 ENSEMBLES (ECH-REM, ECH-RMO, HCH-RCA and ECH-RCA)		2041−2070			Climate-induced tourism revenue gains especially in the shoulder seasons during spring and autumn; threat of climate-induced revenue losses in the summer months due to increased heat stress.	GDP; Prices, Holidays; Events	(Köberl et al. 2016)
Tourism	Iran (Zayandehroud River route)	Physiologically equivalent temperature (PET)	1983−2013	HADCM3	B1 A1B	2014–2039		The PET index shows a positive trend with a reduction in number of			(Yazdanpanah et al. 2016)

								climate comfort days (18 < PET < 29), particularly in the western area			
Tourism	Portugal	Arrivals of inbound tourists; GDP						Increasing temperatures are projected to lead to a decrease of inbound tourism arrivals between 2.5% and 5.2%, which is expected to reduce Portuguese GDP between 0.19% and 0.40%.			(Pintassilgo et al. 2016)
Transportation (shipping)	Arctic Sea (North Sea route)	Climatic loses; Gross gains; Net gains		PAGE-ICE	RCP4.5 RCP8.5 SSP2	2013–2200		Large-scale commercial shipping is unlikely possible until 2030 (bulk) and 2050 (container) under	The total climate feedback of NSR could contribute 0.05% to global mean temperature rise by 2100	Business restrictions	(Yumashev et al. 2017)

								RCP8.5.	under RCP8.5 adding $2.15 Trillion to the Net Present Value of total impacts of climate change over the period until 2200. The climatic losses offset 33% of the total economic gains from NSR under RCP8.5 with the biggest losses set to occur in Africa and India.		
Transportation (shipping)	Arctic Sea	Sea-ice ship speed (in days) Sea Ice Thickness (SIT)	1995−2014	CMIP5	RCP2.6 RCP4.5 RCP8.5	2045−2059 2075−2089			Shipping season 4−8 under RCP8.5, double that of RCP2.6 Average transit times decline to 22		(Melia et al. 2016)

									days (RCP2.6) and 17 days (RCP8.5)		
Transportation (shipping)	Arctic Sea (Northern Sea Route)	Mean time of NSR transit window; Sea ice concentration	1980−2014	CMIP5	RCP4.5 RCP8.5	2020−2100			Increase in transit window by 4 (RCP4.5) and 6.5 (RCP8.5) months		(Khon et al. 2017)
Water	Europe	Runoff Discharge Snowpack based on hydrological models: E-HYPE Lisflood WBM LPJmL		CMIP5 CORDEX (11) Bias corrected to E-OBS	RCP2.6 RCP4.5 RCP8.5	1.5°C 2°C 3°C		Increases in runoff affect the Scandinavian mountains; Decreases in runoff in Portugal	Increases in runoff in Norway, Sweden, & N. Poland; Decreases in runoff around Iberian, Balkan, and parts of French coasts.		(Donnelly et al. 2017)
Water	Global (8 river regions)	River runoff Glob-HM Cat-HM		HadGEM2-ES IPSL-CM5A-LR; MIROCESM-CHEM; GFDL-ESM2; NorESM1-M;	RCP8.5	1°C 2°C 3°C 1971−2099		Projected runoff changes for the Rhine (decrease), Tagus (decrease) and Lena (increase) with global	Increased risk of decreases in low flows (Rhine) (−11% at 2°C to −23% at 3°C) Risk of increases in high		(Gosling et al. 2017)

								warming	flows increases for Lena +17% (2°C) to +26% (3°C)		

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SI_S3_Supplementary information to Cross-Chapter Box 6 Food Security

Table S11. ***Projected health risks of undernutrition and dietary change at 1.5°C and 2°C.*** *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway*

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Global and 21 regions	Undernutrition	1961–1990	BCM2.0, EGMAM1, EGMAM2, EGMAM3, CM4vl	A1B	2030, 2050		In 2030, 95,175 additional undernutrition deaths without adaptation and (ensemble mean) 131,634 with adaptation under the low growth scenario and 77,205 under the high growth scenario; Asia, and sub-Saharan Africa, at highest risk	In 2050 risks are generally lower in most regions because of underlying trends, with 84,695 additional undernutrition deaths without adaptation, 101,484 with adaptation under the low growth scenario and 36,524 under the high growth scenario	Population growth; improved population health; crop models include adaptation measures	(Hales et al. 2014)

Global and 17 regions	Undernourished population; DALY (disability) caused by underweight of a child under 5 years of age	2005–2100	5 models from ISIMIP (GFDL-ESM2, NorESM1-M, IPSL-CM5A-LR, HadGEM2-ES, MIROC-ESM-CHEM)	RCP2.6 and 8.5 with SSP2 and SSP3	2005–2100	Baseline assumed no climate change (no temperature increase from present)	In 2025 under SSP3, global undernourished population is 530–550 million at 1.5°C. Global mean DALYs of 11.2 per 1,000 persons at 1.5°C.	In 2050 under SSP3, global undernourished population is 540–590 million at 2.0 °C. Global mean DALYs of 12.4 per 1,000 persons at 2°C.	Population growth and aging; equity of food distribution	(Hasegawa et al. 2016)
Global divided into 17 regions	DALYs from stunting associated with undernutrition	1990–2008	12 GCMs from CMIP5	Six scenarios: RCP2.6 + SSP1, RCP4.5 + SSPs 1–3, RCP8.5 + SSP2, SSP3	2005–2050	57.4 million DALYs in 2005	In 2030, DALYs decrease by 36.4 million (63%), for RCP4.5, SSP1, and by 30.4 million (53%) and 16.2 million (28%) for RCP8.5, SSP2 and SSP3, respectively	By 2050, DALYs decrease further to 17.0 million for RCP4.5, SSP1, and to 11.6 million for RCP8.5, SSP2. DALYs increase to 43.7 million under RCP8.5, SSP3	Future population and per capita GDP from the SSP database	(Ishida et al. 2014)

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