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In Section 3.4, new literature is explored and the assessment of impacts and projected risks is updated for a large number of natural and human systems. This section also includes an exploration of adaptation opportunities that could be important steps towards reducing climate change, thereby laying the ground for later discussions on opportunities to tackle both mitigation and adaptation while at the same time recognising the importance of sustainable development and reducing the inequities among people and societies facing climate change. Working Group II (WGII) of the IPCC Fifth Assessment Report (AR5) provided an assessment of the literature on the climate risk for natural and human systems across a wide range of environments, sectors and greenhouse gas scenarios, as well as for particular geographic regions (IPCC, 2014a, b)369. The comprehensive assessment undertaken by AR5 evaluated the evidence of changes to natural systems, and the impact on human communities and industry. While impacts varied substantially among systems, sectors and regions, many changes over the past 50 years could be attributed to human driven climate change and its impacts. In particular, AR5 attributed observed impacts in natural ecosystems to anthropogenic climate change, including changes in phenology, geographic and altitudinal range shifts in flora and fauna, regime shifts and increased tree mortality, all of which can reduce ecosystem functioning and services thereby impacting people. AR5 also reported increasing evidence of changing patterns of disease and invasive species, as well as growing risks for communities and industry, which are especially important with respect to sea level rise and human vulnerability. One of the important themes that emerged from AR5 is that previous assessments may have under-estimated the sensitivity of natural and human systems to climate change. A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016)370 confirmed that many impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of changes related to precipitation are by comparison less clear. Moreover, there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016)371. The observed changes in human systems are amplified by the loss of ecosystem services (e.g., reduced access to safe water) that are supported by biodiversity (Oppenheimer et al., 2014)372. Limited research on the risks of warming of 1.5°C and 2°C was conducted following AR5 for most key economic sectors and services, for livelihoods and poverty, and for rural areas. For these systems, climate is one of many drivers that result in adverse outcomes. Other factors include patterns of demographic change, socio-economic development, trade and tourism. Further, consequences of climate change for infrastructure, tourism, migration, crop yields and other impacts interact with underlying vulnerabilities, such as for individuals and communities engaged in pastoralism, mountain farming and artisanal fisheries, to affect livelihoods and poverty (Dasgupta et al., 2014)373. Incomplete data and understanding of these lower-end climate scenarios have increased the need for more data and an improved understanding of the projected risks of warming of 1.5°C and 2°C for reference. In this section, the available literature on the projected risks, impacts and adaptation options is explored, supported by additional information and background provided in Supplementary Material 3.SM.3.1, 3.SM.3.2, 3.SM.3.4, and 3.SM.3.5. A description of the main assessment methods of this chapter is given in Section 3.2.2. Working Group II of AR5 concluded that about 80% of the world's population already suffers from serious threats to its water security, as measured by indicators including water availability, water demand and pollution (Jiménez Cisneros et al., 2014)374. UNESCO (2011)375 concluded that climate change can alter the availability of water and threaten water security. Although physical changes in streamflow and continental runoff that are consistent with climate change have been identified (Section 3.3.5), water scarcity in the past is still less well understood because the scarcity assessment needs to take into account various factors, such as the operations of water supply infrastructure and human water use behaviour (Mehran et al., 2017)376, as well as green water, water quality and environmental flow requirements (J. Liu et al., 2017)377. Over the past century, substantial growth in populations, industrial and agricultural activities, and living standards have exacerbated water stress in many parts of the world, especially in semi-arid and arid regions such as California in the USA (AghaKouchak et al., 2015378; Mehran et al., 2015)379. Owing to changes in climate and water consumption behaviour, and particularly effects of the spatial distribution of population growth relative to water resources, the population under water scarcity increased from 0.24 billion (14% of the global population) in the 1900s to 3.8 billion (58%) in the 2000s. In that last period (2000s), 1.1 billion people (17% of the global population) who mostly live in South and East Asia, North Africa and the Middle East faced serious water shortage and high water stress (Kummu et al., 2016)380. Over the next few decades, and for increases in global mean temperature less than about 2°C, AR5 concluded that changes in population will generally have a greater effect on water resource availability than changes in climate. Climate change, however, will regionally exacerbate or offset the effects of population pressure (Jiménez Cisneros et al., 2014)381. The differences in projected changes to levels of runoff under 1.5°C and 2°C of global warming, particularly those that are regional, are described in Section 3.3.5. Constraining warming to 1.5°C instead of 2°C might mitigate the risks for water availability, although socio-economic drivers could affect water availability more than the risks posed by variation in warming levels, while the risks are not homogeneous among regions (medium confidence) (Gerten et al., 2013; Hanasaki et al., 2013; Arnell and Lloyd-Hughes, 2014; Schewe et al., 2014; Karnauskas et al., 2018)382. Assuming a constant population in the models used in his study, Gerten et al. (2013)383 determined that an additional 8% of the world population in 2000 would be exposed to new or aggravated water scarcity at 2°C of global warming. This value was almost halved – with 50% greater reliability – when warming was constrained to 1.5°C. People inhabiting river basins, particularly in the Middle East and Near East, are projected to become newly exposed to chronic water scarcity even if global warming is constrained to less than 2°C. Many regions, especially those in Europe, Australia and southern Africa, appear to be affected at 1.5°C if the reduction in water availability is computed for non-water-scarce basins as well as for water-scarce regions. Out of a contemporary population of approximately 1.3 billion exposed to water scarcity, about 3% (North America) to 9% (Europe) are expected to be prone to aggravated scarcity at 2°C of global warming (Gerten et al., 2013)384. Under the Shared Socio-Economic Pathway (SSP)2 population scenario, about 8% of the global population is projected to experience a severe reduction in water resources under warming of 1.7°C in 2021–2040, increasing to 14% of the population under 2.7°C in 2043–2071, based on the criteria of discharge reduction of either >20% or >1 standard deviation (Schewe et al., 2014)385. Depending on the scenarios of SSP1–5, exposure to the increase in water scarcity in 2050 will be globally reduced by 184–270 million people at about 1.5°C of warming compared to the impacts at about 2°C. However, the variation between socio-economic levels is larger than the variation between warming levels (Arnell and Lloyd-Hughes, 2014)386. On many small islands (e.g., those constituting SIDS), freshwater stress is expected to occur as a result of projected aridity change. Constraining warming to 1.5°C, however, could avoid a substantial fraction of water stress compared to 2°C, especially across the Caribbean region, particularly on the island of Hispaniola (Dominican Republic and Haiti) (Karnauskas et al., 2018)387. Hanasaki et al. (2013)388 concluded that the projected range of changes in global irrigation water withdrawal (relative to the baseline of 1971–2000), using human configuration fixing non-meteorological variables for the period around 2000, are 1.1–2.3% and 0.6–2.0% lower at 1.5°C and 2°C, respectively. In the same study, Hanasaki et al. (2013)389 highlighted the importance of water use scenarios in water scarcity assessments, but neither quantitative nor qualitative information regarding water use is available. When the impacts on hydropower production at 1.5°C and 2°C are compared, it is found that mean gross potential increases in northern, eastern and western Europe, and decreases in southern Europe (Jacob et al., 2018; Tobin et al., 2018)390. The Baltic and Scandinavian countries are projected to experience the most positive impacts on hydropower production. Greece, Spain and Portugal are expected to be the most negatively impacted countries, although the impacts could be reduced by limiting warming to 1.5°C (Tobin et al., 2018)391. In Greece, Spain and Portugal, warming of 2°C is projected to decrease hydropower potential below 10%, while limiting global warming to 1.5°C would keep the reduction to 5% or less. There is, however, substantial uncertainty associated with these results due to a large spread between the climate models (Tobin et al., 2018)392. Due to a combination of higher water temperatures and reduced summer river flows, the usable capacity of thermoelectric power plants using river water for cooling is expected to reduce in all European countries (Jacob et al., 2018; Tobin et al., 2018)393, with the magnitude of decreases being about 5% for 1.5°C and 10% for 2°C of global warming for most European countries (Tobin et al., 2018)394. Greece, Spain and Bulgaria are projected to have the largest reduction at 2°C of warming (Tobin et al., 2018)395. Fricko et al. (2016)396 assessed the direct water use of the global energy sector across a broad range of energy system transformation pathways in order to identify the water impacts of a 2°C climate policy. This study revealed that there would be substantial divergence in water withdrawal for thermal power plant cooling under conditions in which the distribution of future cooling technology for energy generation is fixed, whereas adopting alternative cooling technologies and water resources would make the divergence considerably smaller. Working Group II of AR5 concluded that socio-economic losses from flooding since the mid-20th century have increased mainly because of greater exposure and vulnerability (high confidence) (Jiménez Cisneros et al., 2014)397. There was low confidence due to limited evidence, however, that anthropogenic climate change has affected the frequency and magnitude of floods. WGII AR5 also concluded that there is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly owing to increased water demand (Jiménez Cisneros et al., 2014)398. Since AR5, the number of studies related to fluvial flooding and meteorological drought based on long-term observed data has been gradually increasing. There has also been progress since AR5 in identifying historical changes in streamflow and continental runoff (Section 3.3.5). As a result of population and economic growth, increased exposure of people and assets has caused more damage due to flooding. However, differences in flood risks among regions reflect the balance among the magnitude of the flood, the populations, their vulnerabilities, the value of assets affected by flooding, and the capacity to cope with flood risks, all of which depend on socio-economic development conditions, as well as topography and hydro-climatic conditions (Tanoue et al., 2016)399. AR5 concluded that there was low confidence in the attribution of global changes in droughts (Bindoff et al., 2013b)400. However, recent publications based on observational and modelling evidence assessed that human emissions have substantially increased the probability of drought years in the Mediterranean region (Section 3.3.4). WGII AR5 assessed that global flood risk will increase in the future, partly owing to climate change (low to medium confidence), with projected changes in the frequency of droughts longer than 12 months being more uncertain because of their dependence on accumulated precipitation over long periods (Jiménez Cisneros et al., 2014)401. Increases in the risks associated with runoff at the global scale (medium confidence), and in flood hazard in some regions (medium confidence), can be expected at global warming of 1.5°C, with an overall increase in the area affected by flood hazard at 2°C (medium confidence) (Section 3.3.5). There are studies, however, that indicate that socio-economic conditions will exacerbate flood impacts more than global climate change, and that the magnitude of these impacts could be larger in some regions (Arnell and Lloyd-Hughes, 2014; Winsemius et al., 2016; Alfieri et al., 2017; Arnell et al., 2018; Kinoshita et al., 2018)402. Assuming constant population sizes, countries representing 73% of the world population will experience increasing flood risk, with an average increase of 580% at 4°C compared to the impact simulated over the baseline period 1976–2005. This impact is projected to be reduced to a 100% increase at 1.5°C and a 170% increase at 2°C (Alfieri et al., 2017)403. Alfieri et al. (2017)404 additionally concluded that the largest increases in flood risks would be found in the US, Asia, and Europe in general, while decreases would be found in only a few countries in eastern Europe and Africa. Overall, Alfieri et al., (2017)405 reported that the projected changes are not homogeneously distributed across the world land surface. Alfieri et al. (2018)406 studied the population affected by flood events using three case studies in European states, specifically central and western Europe, and found that the population affected could be limited to 86% at 1.5°C of warming compared to 93% at 2°C. Under the SSP2 population scenario, Arnell et al. (2018)407 found that 39% (range 36–46%) of impacts on populations exposed to river flooding globally could be avoided at 1.5°C compared to 2°C of warming. Under scenarios SSP1–5, Arnell and Lloyd-Hughes (2014)408 found that the number of people exposed to increased flooding in 2050 under warming of about 1.5°C could be reduced by 26–34 million compared to the number exposed to increased flooding associated with 2°C of warming. Variation between socio-economic levels, however, is projected to be larger than variation between the two levels of global warming. Kinoshita et al. (2018)409 found that a serious increase in potential flood fatality (5.7%) is projected without any adaptation if global warming increases from 1.5°C to 2°C, whereas the projected increase in potential economic loss (0.9%) is relatively small. Nevertheless, their study indicates that socio-economic changes make a larger contribution to the potentially increased consequences of future floods, and about half of the increase in potential economic losses could be mitigated by autonomous adaptation. There is limited information about the global and regional projected risks posed by droughts at 1.5°C and 2°C of global warming. However, hazards by droughts at 1.5°C could be reduced compared to the hazards at 2°C in some regions, in particular in the Mediterranean region and southern Africa (Section 3.3.4). Under constant socio-economic conditions, the population exposed to drought at 2°C of warming is projected to be larger than at 1.5°C (low to medium confidence) (Smirnov et al., 2016; Sun et al., 2017; Arnell et al., 2018; Liu et al., 2018)410. Under the same scenario, the global mean monthly number of people expected to be exposed to extreme drought at 1.5°C in 2021–2040 is projected to be 114.3 million, compared to 190.4 million at 2°C in 2041–2060 (Smirnov et al., 2016)411. Under the SSP2 population scenario, Arnell et al. (2018)412 projected that 39% (range 36–51%) of impacts on populations exposed to drought could be globally avoided at 1.5°C compared to 2°C warming. Liu et al. (2018)413 studied the changes in population exposure to severe droughts in 27 regions around the globe for 1.5°C and 2°C of warming using the SSP1 population scenario compared to the baseline period of 1986–2005 based on the Palmer Drought Severity Index (PDSI). They concluded that the drought exposure of urban populations in most regions would be decreased at 1.5°C (350.2 ± 158.8 million people) compared to 2°C (410.7 ± 213.5 million people). Liu et al. (2018)414 also suggested that more urban populations would be exposed to severe droughts at 1.5ºC in central Europe, southern Europe, the Mediterranean, West Africa, East and West Asia, and Southeast Asia, and that number of affected people would increase further in these regions at 2°C. However, it should be noted that the PDSI is known to have limitations (IPCC SREX, Seneviratne et al., 2012)415, and drought projections strongly depend on considered indices (Section 3.3.4); thus only medium confidence is assigned to these projections. In the Haihe River basin in China, a study has suggested that the proportion of the population exposed to droughts is projected to be reduced by 30.4% at 1.5°C but increased by 74.8% at 2°C relative to the baseline value of 339.65 million people in the 1986–2005 period, when assessing changes in droughts using the Standardized Precipitation-Evaporation Index, using a Penman–Monteith estimate of potential evaporation (Sun et al., 2017)416 . Alfieri et al. (2018)417 estimated damage from flooding in Europe for the baseline period (1976–2005) at 5 billion euro of losses annually, with projections of relative changes in flood impacts that will rise with warming levels, from 116% at 1.5°C to 137% at 2°C. Kinoshita et al. (2018)418 studied the increase of potential economic loss under SSP3 and projected that the smaller loss at 1.5°C compared to 2°C (0.9%) is marginal, regardless of whether the vulnerability is fixed at the current level or not. By analysing the differences in results with and without flood protection standards, Winsemius et al. (2016)419 showed that adaptation measures have the potential to greatly reduce present-day and future flood damage. They concluded that increases in flood-induced economic impacts (% gross domestic product, GDP) in African countries are mainly driven by climate change and that Africa's growing assets would become increasingly exposed to floods. Hence, there is an increasing need for long-term and sustainable investments in adaptation in Africa. Working Group II of AR5 concluded that the detection of changes in groundwater systems, and attribution of those changes to climatic changes, are rare, owing to a lack of appropriate observation wells and an overall small number of studies (Jiménez Cisneros et al., 2014)420. Since AR5, the number of studies based on long-term observed data continues to be limited. The groundwater-fed lakes in northeastern central Europe have been affected by climate and land-use changes, and they showed a predominantly negative lake-level trend in 1999–2008 (Kaiser et al., 2014)421. WGII AR5 concluded that climate change is projected to reduce groundwater resources significantly in most dry subtropical regions (high confidence) (Jiménez Cisneros et al., 2014)422. In some regions, groundwater is often intensively used to supplement the excess demand, often leading to groundwater depletion. Climate change adds further pressure on water resources and exaggerates human water demands by increasing temperatures over agricultural lands (Wada et al., 2017)423. Very few studies have projected the risks of groundwater depletion under 1.5°C and 2°C of global warming. Under 2°C of warming, impacts posed on groundwater are projected to be greater than at 1.5°C (low confidence) (Portmann et al., 2013; Salem et al., 2017)424. Portmann et al. (2013)425 indicated that 2% (range 1.1–2.6%) of the global land area is projected to suffer from an extreme decrease in renewable groundwater resources of more than 70% at 2°C, with a clear mitigation at 1.5°C. These authors also projected that 20% of the global land surface would be affected by a groundwater reduction of more than 10% at 1.5°C of warming, with the percentage of land impacted increasing at 2°C. In a groundwater-dependent irrigated region in northwest Bangladesh, the average groundwater level during the major irrigation period (January–April) is projected to decrease in accordance with temperature rise (Salem et al., 2017)426. Working Group II of AR5 concluded that most observed changes to water quality from climate change are from isolated studies, mostly of rivers or lakes in high-income countries, using a small number of variables (Jiménez Cisneros et al., 2014)427. AR5 assessed that climate change is projected to reduce raw water quality, posing risks to drinking water quality with conventional treatment (medium to high confidence) (Jiménez Cisneros et al., 2014)428. Since AR5, studies have detected climate change impacts on several indices of water quality in lakes, watersheds and regions (e.g., Patiño et al., 2014; Aguilera et al., 2015; Watts et al., 2015; Marszelewski and Pius, 2016; Capo et al., 2017)429. The number of studies utilising RCP scenarios at the regional or watershed scale have gradually increased since AR5 (e.g., Boehlert et al., 2015; Teshager et al., 2016; Marcinkowski et al., 2017)430. Few studies, have explored projected impacts on water quality under 1.5°C versus 2°C of warming, however, the differences are unclear (low confidence) (Bonte and Zwolsman, 2010431; Hosseini et al., 2017)432. The daily probability of exceeding the chloride standard for drinking water taken from Lake IJsselmeer (Andijk, the Netherlands) is projected to increase by a factor of about five at 2°C relative to the present-day warming level of 1°C since 1990 (Bonte and Zwolsman, 2010)433. Mean monthly dissolved oxygen concentrations and nutrient concentrations in the upper Qu'Appelle River (Canada) in 2050–2055 are projected to decrease less at about 1.5°C of warming (RCP2.6) compared to concentrations at about 2°C (RCP4.5) (Hosseini et al., 2017)434. In three river basins in Southeast Asia (Sekong, Sesan and Srepok), about 2°C of warming (corresponding to a 1.05°C increase in the 2030s relative to the baseline period 1981–2008, RCP8.5), impacts posed by land-use change on water quality are projected to be greater than at 1.5°C (corresponding to a 0.89°C increase in the 2030s relative to the baseline period 1981–2008, RCP4.5) (Trang et al., 2017)435. Under the same warming scenarios, Trang et al. (2017)436 projected changes in the annual nitrogen (N) and phosphorus (P) yields in the 2030s, as well as with combinations of two land-use change scenarios: (i) conversion of forest to grassland, and (ii) conversion of forest to agricultural land. The projected changes in N (P) yield are +7.3% (+5.1%) under a 1.5°C scenario and –6.6% (–3.6%) under 2°C, whereas changes under the combination of land-use scenarios are (i) +5.2% (+12.6%) at 1.5°C and +8.8% (+11.7%) at 2°C, and (ii) +7.5% (+14.9%) at 1.5°C and +3.7% (+8.8%) at 2°C (Trang et al., 2017)437. Working Group II of AR5 concluded that there is little or no observational evidence that soil erosion and sediment load have been altered significantly by climate change (low to medium confidence) (Jiménez Cisneros et al., 2014)438. As the number of studies on climate change impacts on soil erosion has increased where rainfall is an important driver (Lu et al., 2013)439, studies have increasingly considered other factors, such as rainfall intensity (e.g., Shi and Wang, 2015; Li and Fang, 2016)440, snow melt, and change in vegetation cover resulting from temperature rise (Potemkina and Potemkin, 2015)441, as well as crop management practices (Mullan et al., 2012)442. WGII AR5 concluded that increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices (Jiménez Cisneros et al., 2014)443. While the number of published studies of climate change impacts on soil erosion have increased globally since 2000 (Li and Fang, 2016)444, few articles have addressed impacts at 1.5°C and 2°C of global warming. The existing studies have found few differences in projected risks posed on sediment load under 1.5°C and 2°C (low confidence) (Cousino et al., 2015; Shrestha et al., 2016)445. The differences between average annual sediment load under 1.5°C and 2°C of warming are not clear, owing to complex interactions among climate change, land cover/surface and soil management (Cousino et al., 2015; Shrestha et al., 2016)446. Averages of annual sediment loads are projected to be similar under 1.5°C and 2°C of warming, in particular in the Great Lakes region in the USA and in the Lower Mekong region in Southeast Asia (Cross-Chapter Box 6 in this chapter, Cousino et al., 2015; Shrestha et al., 2016)447. Latitudinal and elevational shifts of biomes (major ecosystem types) in boreal, temperate and tropical regions have been detected (Settele et al., 2014)448 and new studies confirm these changes (e.g., shrub encroachment on tundra; Larsen et al., 2014)449. Attribution studies indicate that anthropogenic climate change has made a greater contribution to these changes than any other factor (medium confidence) (Settele et al., 2014)450. An ensemble of seven Dynamic Vegetation Models driven by projected climates from 19 alternative general circulation models (GCMs) (Warszawski et al., 2013)451 shows 13% (range 8–20%) of biomes transforming at 2°C of global warming, but only 4% (range 2–7%) doing so at 1°C, suggesting that about 6.5% may be transformed at 1.5°C; these estimates indicate a doubling of the areal extent of biome shifts between 1.5°C and 2°C of warming (medium confidence) (Figure 3.16a). A study using the single ecosystem model LPJmL (Gerten et al., 2013)452 illustrated that biome shifts in the Arctic, Tibet, Himalayas, southern Africa and Australia would be avoided by constraining warming to 1.5°C compared with 2°C (Figure 3.16b). Seddon et al. (2016)453 quantitatively identified ecologically sensitive regions to climate change in most of the continents from tundra to tropical rainforest. Biome transformation may in some cases be associated with novel climates and ecological communities (Prober et al., 2012)454. Advancement in spring phenology of 2.8 ± 0.35 days per decade has been observed in plants and animals in recent decades in most Northern Hemisphere ecosystems (between 30°N and 72°N), and these shifts have been attributed to changes in climate (high confidence) (Settele et al., 2014)457. The rates of change are particularly high in the Arctic zone owing to the stronger local warming (Oberbauer et al., 2013)458, whereas phenology in tropical forests appears to be more responsive to moisture stress (Zhou et al., 2014)459. While a full review cannot be included here, trends consistent with this earlier finding continue to be detected, including in the flowering times of plants (Parmesan and Hanley, 2015)460, in the dates of egg laying and migration in birds (newly reported in China; Wu and Shi, 2016)461, in the emergence dates of butterflies (Roy et al., 2015)462, and in the seasonal greening-up of vegetation as detected by satellites (i.e., in the normalized difference vegetation index, NDVI; Piao et al., 2015)463. The potential for decoupling species–species interactions owing to differing phenological responses to climate change is well established (Settele et al., 2014)464, for example for plants and their insect pollinators (Willmer, 2012; Scaven and Rafferty, 2013)465. Mid-century projections of plant and animal phenophases in the UK clearly indicate that the timing of phenological events could change more for primary consumers (6.2 days earlier on average) than for higher trophic levels (2.5–2.9 days earlier on average) (Thackeray et al., 2016)466. This indicates the potential for phenological mismatch and associated risks for ecosystem functionality in the future under global warming of 2.1°C–2.7°C above pre-industrial levels. Further, differing responses could alter community structure in temperate forests (Roberts et al., 2015)467. Specifically, temperate forest phenology is projected to advance by 14.3 days in the near term (2010–2039) and 24.6 days in the medium term (2040–2069), so as a first approximation the difference between 2°C and 1.5°C of global warming is about 10 days (Roberts et al., 2015)468. This phenological plasticity is not always adaptive and must be interpreted cautiously (Duputié et al., 2015)469, and considered in the context of accompanying changes in climate variability (e.g., increased risk of frost damage for plants or earlier emergence of insects resulting in mortality during cold spells). Another adaptive response of some plants is range expansion with increased vigour and altered herbivore resistance in their new range, analogous to invasive plants (Macel et al., 2017)470. In summary, limiting warming to 1.5°C compared with 2°C may avoid advance in spring phenology (high confidence) by perhaps a few days (medium confidence) and hence decrease the risks of loss of ecosystem functionality due to phenological mismatch between trophic levels, and also of maladaptation coming from the sensitivity of many species to increased climate variability. Nevertheless, this difference between 1.5°C and 2°C of warming might be limited for plants that are able to expand their range. AR5 (Settele et al., 2014)471 concluded that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming: approximately 17 km poleward and 11 m up in altitude per decade. Recent trends confirm this finding; for example, the spatial and interspecific variance in bird populations in Europe and North America since 1980 were found to be well predicted by trends in climate suitability (Stephens et al., 2016)472. Further, a recent meta-analysis of 27 studies concerning a total of 976 species (Wiens, 2016)473 found that 47% of local extinctions (extirpations) reported across the globe during the 20th century could be attributed to climate change, with significantly more extinctions occurring in tropical regions, in freshwater habitats and for animals. IUCN (2018)474 lists 305 terrestrial animal and plant species from Pacific Island developing nations as being threatened by climate change and severe weather. Owing to lags in the responses of some species to climate change, shifts in insect pollinator ranges may result in novel assemblages with unknown implications for biodiversity and ecosystem function (Rafferty, 2017)475. Warren et al. (2013)476 simulated climatically determined geographic range loss under 2°C and 4°C of global warming for 50,000 plant and animal species, accounting for uncertainty in climate projections and for the potential ability of species to disperse naturally in an attempt to track their geographically shifting climate envelope. This earlier study has now been updated and expanded to incorporate 105,501 species, including 19,848 insects, and new findings indicate that warming of 2°C by 2100 would lead to projected bioclimatic range losses of >50% in 18% (6–35%) of the 19,848 insects species, 8% (4–16%) of the 12,429 vertebrate species, and 16% (9–28%) of the 73,224 plant species studied (Warren et al., 2018a)477. At 1.5°C of warming, these values fall to 6% (1–18%) of the insects, 4% (2–9%) of the vertebrates and 8% (4–15%) of the plants studied. Hence, the number of insect species projected to lose over half of their geographic range is reduced by two-thirds when warming is limited to 1.5°C compared with 2°C, while the number of vertebrate and plant species projected to lose over half of their geographic range is halved (Warren et al., 2018a)478 (medium confidence). These findings are consistent with estimates made from an earlier study suggesting that range losses at 1.5°C were significantly lower for plants than those at 2°C of warming (Smith et al., 2018)479. It should be noted that at 1.5°C of warming, and if species' ability to disperse naturally to track their preferred climate geographically is inhibited by natural or anthropogenic obstacles, there would still remain 10% of the amphibians, 8% of the reptiles, 6% of the mammals, 5% of the birds, 10% of the insects and 8% of the plants which are projected to lose over half their range, while species on average lose 20–27% of their range (Warren et al., 2018a)480. Given that bird and mammal species can disperse more easily than amphibians and reptiles, a small proportion can expand their range as climate changes, but even at 1.5°C of warming the total range loss integrated over all birds and mammals greatly exceeds the integrated range gain (Warren et al., 2018a)481. A number of caveats are noted for studies projecting changes to climatic range. This approach, for example, does not incorporate the effects of extreme weather events and the role of interactions between species. As well, trophic interactions may locally counteract the range expansion of species towards higher altitudes (Bråthen et al., 2018)482. There is also the potential for highly invasive species to become established in new areas as the climate changes (Murphy and Romanuk, 2014)483, but there is no literature that quantifies this possibility for 1.5°C of global warming. Pecl et al. (2017)484 summarized at the global level the consequences of climate-change-induced species redistribution for economic development, livelihoods, food security, human health and culture. These authors concluded that even if anthropogenic greenhouse gas emissions stopped today, the effort for human systems to adapt to the most crucial effects of climate-driven species redistribution will be far-reaching and extensive. For example, key insect crop pollinator families (Apidae, Syrphidae and Calliphoridae; i.e., bees, hoverflies and blowflies) are projected to retain significantly greater geographic ranges under 1.5°C of global warming compared with 2°C (Warren et al., 2018a)485. In some cases, when species (such as pest and disease species) move into areas which have become climatically suitable they may become invasive or harmful to human or natural systems (Settele et al., 2014)486. Some studies are beginning to locate 'refugial' areas where the climate remains suitable in the future for most of the species currently present. For example, Smith et al., (2018)487 estimated that 5.5–14% more of the globe's terrestrial land area could act as climatic refugia for plants under 1.5°C of warming compared to 2°C. There is no literature that directly estimates the proportion of species at increased risk of global (as opposed to local) commitment to extinction as a result of climate change, as this is inherently difficult to quantify. However, it is possible to compare the proportions of species at risk of very high range loss; for example, a discernibly smaller number of terrestrial species are projected to lose over 90% of their range at 1.5°C of global warming compared with 2°C (Figure 2 in Warren et al., 2018a)488. A link between very high levels of range loss and greatly increased extinction risk may be inferred (Urban, 2015)489. Hence, limiting global warming to 1.5°C compared with 2°C would be expected to reduce both range losses and associated extinction risks in terrestrial species (high confidence). Working Group II of AR5 (Settele et al., 2014)490 concluded that there is high confidence that net terrestrial ecosystem productivity at the global scale has increased relative to the pre-industrial era and that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis. There is, however, no clear and consistent signal of a climate change contribution. In northern latitudes, the change in productivity has a lower velocity than the warming, possibly because of a lack of resource and vegetation acclimation mechanisms (M. Huang et al., 2017)491. Biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (high confidence), but they are vulnerable to loss of carbon to the atmosphere as a result of projected increases in the intensity of storms, wildfires, land degradation and pest outbreaks (Settele et al., 2014; Seidl et al., 2017)492. These losses are expected to contribute to a decrease in the terrestrial carbon sink. Anderegg et al. (2015)493 demonstrated that total ecosystem respiration at the global scale has increased in response to increases in night-time temperature (1 PgC yr–1°C–1, P=0.02). The increase in total ecosystem respiration in spring and autumn, associated with higher temperatures, may convert boreal forests from carbon sinks to carbon sources (Hadden and Grelle, 2016)494. In boreal peatlands, for example, increased temperature may diminish carbon storage and compromise the stability of the peat (Dieleman et al., 2016)495. In addition, J. Yang et al. (2015)496 showed that fires reduce the carbon sink of global terrestrial ecosystems by 0.57 PgC yr–1 in ecosystems with large carbon stores, such as peatlands and tropical forests. Consequently, for adaptation purposes, it is necessary to enhance carbon sinks, especially in forests which are prime regulators within the water, energy and carbon cycles (Ellison et al., 2017)497. Soil can also be a key compartment for substantial carbon sequestration (Lal, 2014; Minasny et al., 2017)498, depending on the net biome productivity and the soil quality (Bispo et al., 2017)499. AR5 assessed that large uncertainty remains regarding the land carbon cycle behaviour of the future (Ciais et al., 2013)500, with most, but not all, CMIP5 models simulating continued terrestrial carbon uptake under all four RCP scenarios (Jones et al., 2013)501. Disagreement between models outweighs differences between scenarios even up to the year 2100 (Hewitt et al., 2016; Lovenduski and Bonan, 2017)502. Increased atmospheric CO_2 concentrations are expected to drive further increases in the land carbon sink (Ciais et al., 2013; Schimel et al., 2015)503, which could persist for centuries (Pugh et al., 2016)504. Nitrogen, phosphorus and other nutrients will limit the terrestrial carbon cycle response to both elevated CO_2 and altered climate (Goll et al., 2012; Yang et al., 2014; Wieder et al., 2015; Zaehle et al., 2015; Ellsworth et al., 2017)505. Climate change may accelerate plant uptake of carbon (Gang et al., 2015)506 but also increase the rate of decomposition (Todd-Brown et al., 2014; Koven et al., 2015; Crowther et al., 2016)507. Ahlström et al. (2012)508 found a net loss of carbon in extra-tropical regions and the largest spread across model results in the tropics. The projected net effect of climate change is to reduce the carbon sink expected under CO_2 increase alone (Settele et al., 2014)509. Friend et al. (2014)510 found substantial uptake of carbon by vegetation under future scenarios when considering the effects of both climate change and elevated CO_2. There is limited published literature examining modelled land carbon changes specifically under 1.5°C of warming, but existing CMIP5 models and published data are used in this report to draw some conclusions. For systems with significant inertia, such as vegetation or soil carbon stores, changes in carbon storage will depend on the rate of change of forcing and thus depend on the choice of scenario (Jones et al., 2009; Ciais et al., 2013; Sihi et al., 2017)511. To avoid legacy effects of the choice of scenario, this report focuses on the response of gross primary productivity (GPP) – the rate of photosynthetic carbon uptake – by the models, rather than by changes in their carbon store. Figure 3.17 shows different responses of the terrestrial carbon cycle to climate change in different regions. The models show a consistent response of increased GPP in temperate latitudes of approximately 2 GtC yr–1 °C–1. Similarly, Gang et al. (2015)512 projected a robust increase in the net primary productivity (NPP) of temperate forests. However, Ahlström et al. (2012)513 showed that this effect could be offset or reversed by increases in decomposition. Globally, most models project that GPP will increase or remain approximately unchanged (Hashimoto et al., 2013)514. This projection is supported by findings by Sakalli et al. (2017)515 for Europe using Euro-CORDEX regional models under a 2°C global warming for the period 2034–2063, which indicated that storage will increase by 5% in soil and by 20% in vegetation. However, using the same models Jacob et al. (2018)516 showed that limiting warming to 1.5°C instead of 2°C avoids an increase in ecosystem vulnerability (compared to a no-climate change scenario) of 40–50%. At the global level, linear scaling is acceptable for net primary production, biomass burning and surface runoff, and impacts on terrestrial carbon storage are projected to be greater at 2°C than at 1.5°C (Tanaka et al., 2017)517. If global CO_2 concentrations and temperatures stabilize, or peak and decline, then both land and ocean carbon sinks – which are primarily driven by the continued increase in atmospheric CO_2 – will also decline and may even become carbon sources (Jones et al., 2016)518. Consequently, if a given amount of anthropogenic CO_2 is removed from the atmosphere, an equivalent amount of land and ocean anthropogenic CO_2 will be released to the atmosphere (Cao and Caldeira, 2010)519. In conclusion, ecosystem respiration is expected to increase with increasing temperature, thus reducing soil carbon storage. Soil carbon storage is expected to be larger if global warming is restricted to 1.5°C, although some of the associated changes will be countered by enhanced gross primary production due to elevated CO_2 concentrations (i.e., the 'fertilization effect') and higher temperatures, especially at mid-and high latitudes (medium confidence). A large number of threatened systems, including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems, were assessed in AR5. These include Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succulent Karoo areas of South Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, it has been shown that impacts accrue with greater warming, and thus impacts at 2°C are expected to be greater than those at 1.5°C (medium confidence). The High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century (Section 3.3; Settele et al., 2014)520. The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016)521. Both of these processes facilitate the establishment of woody species in tundra areas. Arctic terrestrial ecosystems are being disrupted by delays in winter onset and mild winters associated with global warming (high confidence) (Cooper, 2014)522. Observational constraints suggest that stabilization at 1.5°C of warming would avoid the thawing of approximately 1.5 to 2.5 million km2 of permafrost (medium confidence) compared with stabilization at 2°C (Chadburn et al., 2017)523, but the time scale for release of thawed carbon as CO_2 or CH_4 should be many centuries (Burke et al., 2017)524. In northern Eurasia, the growing season length is projected to increase by about 3–12 days at 1.5°C and 6–16 days at 2°C of warming (medium confidence) (Zhou et al., 2018)525. Aalto et al. (2017)526 predicted a 72% reduction in cryogenic land surface processes in northern Europe for RCP2.6 in 2040–2069 (corresponding to a global warming of approximately 1.6°C), with only slightly larger losses for RCP4.5 (2°C of global warming). Projected impacts on forests as climate change occurs include increases in the intensity of storms, wildfires and pest outbreaks (Settele et al., 2014)527, potentially leading to forest dieback (medium confidence). Warmer and drier conditions in particular facilitate fire, drought and insect disturbances, while warmer and wetter conditions increase disturbances from wind and pathogens (Seidl et al., 2017)528. Particularly vulnerable regions are Central and South America, Mediterranean Basin, South Africa, South Australia where the drought risk will increase (see Figure 3.12). Including disturbances in simulations may influence productivity changes in European forests in response to climate change (Reyer et al., 2017b)529. There is additional evidence for the attribution of increased forest fire frequency in North America to anthropogenic climate change during 1984–2015, via the mechanism of increasing fuel aridity almost doubling the western USA forest fire area compared to what would have been expected in the absence of climate change (Abatzoglou and Williams, 2016)530. This projection is in line with expected fire risks, which indicate that fire frequency could increase over 37.8% of the global land area during 2010–2039 (Moritz et al., 2012)531, corresponding to a global warming level of approximately 1.2°C, compared with over 61.9% of the global land area in 2070–2099, corresponding to a warming of approximately 3.5°C.The values in Table 26-1 in a recent paper by Romero-Lankao et al. (2014)532 also indicate significantly lower wildfire risks in North America for near-term warming (2030–2040, considered a proxy for 1.5°C of warming) than at 2°C (high confidence). The Amazon tropical forest has been shown to be close to its climatic limits (Hutyra et al., 2005)533, but this threshold may move under elevated CO_2 (Good et al., 2011)534. Future changes in rainfall, especially dry season length, will determine responses of the Amazon forest (Good et al., 2013)535. The forest may be especially vulnerable to combined pressure from multiple stressors, namely changes in climate and continued anthropogenic disturbance (Borma et al., 2013; Nobre et al., 2016)536. Modelling (Huntingford et al., 2013)537 and observational constraints (Cox et al., 2013)538 suggest that large-scale forest dieback is less likely than suggested under early coupled modelling studies (Cox et al., 2000; Jones et al., 2009)539. Nobre et al. (2016)540 estimated a climatic threshold of 4°C of warming and a deforestation threshold of 40%. In many places around the world, the savanna boundary is moving into former grasslands. Woody encroachment, including increased tree cover and biomass, has increased over the past century, owing to changes in land management, rising CO_2 levels, and climate variability and change (often in combination) (Settele et al., 2014)541. For plant species in the Mediterranean region, shifts in phenology, range contraction and health decline have been observed with precipitation decreases and temperature increases (medium confidence) (Settele et al., 2014)542. Recent studies using independent complementary approaches have shown that there is a regional-scale threshold in the Mediterranean region between 1.5°C and 2°C of warming (Guiot and Cramer, 2016; Schleussner et al., 2016b)543. Further, Guiot and Cramer (2016)544 concluded that biome shifts unprecedented in the last 10,000 years can only be avoided if global warming is constrained to 1.5°C (medium confidence) – whilst 2°C of warming will result in a decrease of 12–15% of the Mediterranean biome area. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters. It is projected to lose about 20%, 45% and 80% of its current suitable climate area under 1°C, 2°C and 3°C of global warming, respectively, compared to 1961–1990 (high confidence) (Engelbrecht and Engelbrecht, 2016)545. In Australia, an increase in the density of trees and shrubs at the expense of grassland species is occurring across all major ecosystems and is projected to be amplified (NCCARF, 2013)546. Regarding Central America, Lyra et al. (2017)547 showed that the tropical rainforest biomass would be reduced by about 40% under global warming of 3°C, with considerable replacement by savanna and grassland. With a global warming of close to 1.5°C in 2050, a biomass decrease of 20% is projected for tropical rainforests of Central America (Lyra et al., 2017)548. If a linear response is assumed, this decrease may reach 30% (medium confidence). Freshwater ecosystems are considered to be among the most threatened on the planet (Settele et al., 2014)549. Although peatlands cover only about 3% of the land surface, they hold one-third of the world's soil carbon stock (400 to 600 Pg) (Settele et al., 2014)550. When drained, this carbon is released to the atmosphere. At least 15% of peatlands have drained, mostly in Europe and South east Asia, and are responsible for 5% of human derived CO_2 emissions (Green and Page, 2017)551. Moreover, in the Congo basin (Dargie et al., 2017)552 and in the Amazonian basin (Draper et al., 2014)553, the peatlands store the equivalent carbon as that of a tropical forest. However, stored carbon is vulnerable to land-use change and future risk of drought, for example in northeast Brazil (high confidence) (Figure 3.12, Section 3.3.4.2). At the global scale, these peatlands are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Magrin et al., 2014)554. Wetland salinization, a widespread threat to the structure and ecological functioning of inland and coastal wetlands, is occurring at a high rate and large geographic scale (Section 3.3.6; Herbert et al., 2015)555. Settele et al. (2014)556 found that rising water temperatures are projected to lead to shifts in freshwater species distributions and worsen water quality. Some of these ecosystems respond non-linearly to changes in temperature. For example, Johnson and Poiani (2016)557 found that the wetland function of the Prairie Pothole region in North America is projected to decline at temperatures beyond a local warming of 2°C–3°C above present-day values (1°C local warming, corresponding to 0.6°C of global warming). If the ratio of local to global warming remains similar for these small levels of warming, this would indicate a global temperature threshold of 1.2°C–1.8°C of warming. Hence, constraining global warming to approximately 1.5°C would maintain the functioning of prairie pothole ecosystems in terms of their productivity and biodiversity, although a 20% increase of precipitation could offset 2°C of global warming (high confidence) (Johnson and Poiani, 2016)558. In summary, constraining global warming to 1.5°C rather than 2°C has strong benefits for terrestrial and wetland ecosystems and their services (high confidence). These benefits include avoidance or reduction of changes such as biome transformations, species range losses, increased extinction risks (all high confidence) and changes in phenology (high confidence), together with projected increases in extreme weather events which are not yet factored into these analyses (Section 3.3). All of these changes contribute to disruption of ecosystem functioning and loss of cultural, provisioning and regulating services provided by these ecosystems to humans. Examples of such services include soil conservation (avoidance of desertification), flood control, water and air purification, pollination, nutrient cycling, sources of food, and recreation. The ocean plays a central role in regulating atmospheric gas concentrations, global temperature and climate. It also provides habitat to a large number of organisms and ecosystems that provide goods and services worth trillions of USD per year (e.g., Costanza et al., 2014; Hoegh-Guldberg et al., 2015)559. Together with local stresses (Halpern et al., 2015)560, climate change poses a major threat to an increasing number of ocean ecosystems (e.g., warm water or tropical coral reefs: virtually certain, WGII AR5) and consequently to many coastal communities that depend on marine resources for food, livelihoods and a safe place to live. Previous sections of this report have described changes in the ocean, including rapid increases in ocean temperature down to a depth of at least 700 m (Section 3.3.7). In addition, anthropogenic carbon dioxide has decreased ocean pH and affected the concentration of ions in seawater such as carbonate (Sections 3.3.10 and 3.4.4.5), both over a similar depth range. Increased ocean temperatures have intensified storms in some regions (Section 3.3.6), expanded the ocean volume and increased sea levels globally (Section 3.3.9), reduced the extent of polar summer sea ice (Section 3.3.8), and decreased the overall solubility of the ocean for oxygen (Section 3.3.10). Importantly, changes in the response to climate change rarely operate in isolation. Consequently, the effect of global warming of 1.5°C versus 2°C must be considered in the light of multiple factors that may accumulate and interact over time to produce complex risks, hazards and impacts on human and natural systems. Physical and chemical changes to the ocean resulting from increasing atmospheric CO_2 and other GHGs are already driving significant changes to ocean systems (very high confidence) and will continue to do so at 1.5°C, and more so at 2°C, of global warming above pre-industrial temperatures (Section 3.3.11). These changes have been accompanied by other changes such as ocean acidification, intensifying storms and deoxygenation (Levin and Le Bris, 2015)561. Risks are already significant at current greenhouse gas concentrations and temperatures, and they vary significantly among depths, locations and ecosystems, with impacts being singular, interactive and/or cumulative (Boyd et al., 2015)562. As atmospheric greenhouse gases have increased, the global mean surface temperature (GMST) has reached about 1°C above the pre-industrial period, and oceans have rapidly warmed from the ocean surface to the deep sea (high confidence) (Sections 3.3.7; Hughes and Narayanaswamy, 2013; Levin and Le Bris, 2015; Yasuhara and Danovaro, 2016; Sweetman et al., 2017)563. Marine organisms are already responding to these changes by shifting their biogeographical ranges to higher latitudes at rates that range from approximately 0 to 40 km yr–1 (Burrows et al., 2014; Chust, 2014; Bruge et al., 2016; Poloczanska et al., 2016)564, which has consequently affected the structure and function of the ocean, along with its biodiversity and foodwebs (high confidence). Movements of organisms does not necessarily equate to the movement of entire ecosystems. For example, species of reef-building corals have been observed to shift their geographic ranges, yet this has not resulted in the shift of entire coral ecosystems (high confidence) (Woodroffe et al., 2010; Yamano et al., 2011)565. In the case of 'less mobile' ecosystems (e.g., coral reefs, kelp forests and intertidal communities), shifts in biogeographical ranges may be limited, with mass mortalities and disease outbreaks increasing in frequency as the exposure to extreme temperatures increases (very high confidence) (Hoegh-Guldberg, 1999; Garrabou et al., 2009; Rivetti et al., 2014; Maynard et al., 2015; Krumhansl et al., 2016; Hughes et al., 2017b; see also Box 3.4)566. These trends are projected to become more pronounced at warming of 1.5°C, and more so at 2°C, above the pre-industrial period (Hoegh-Guldberg et al., 2007; Donner, 2009; Frieler et al., 2013; Horta E Costa et al., 2014; Vergés et al., 2014, 2016; Zarco-Perello et al., 2017)567 and are likely to result in decreases in marine biodiversity at the equator but increases in biodiversity at higher latitudes (Cheung et al., 2009; Burrows et al., 2014)568. While the impacts of species shifting their ranges are mostly negative for human communities and industry, there are instances of short-term gains. Fisheries, for example, may expand temporarily at high latitudes in the Northern Hemisphere as the extent of summer sea ice recedes and NPP increases (medium confidence) (Cheung et al., 2010; Lam et al., 2016; Weatherdon et al., 2016)569. High-latitude fisheries are not only influenced by the effect of temperature on NPP but are also strongly influenced by the direct effects of changing temperatures on fish and fisheries (Section 3.4.4.9; Barange et al., 2014; Pörtner et al., 2014; Cheung et al., 2016b; Weatherdon et al., 2016570). Temporary gains in the productivity of high-latitude fisheries are offset by a growing number of examples from low and mid-latitudes where increases in sea temperature are driving decreases in NPP, owing to the direct effects of elevated temperatures and/or reduced ocean mixing from reduced ocean upwelling, that is, increased stratification (low-medium confidence) (Cheung et al., 2010; Ainsworth et al., 2011; Lam et al., 2012, 2014, 2016; Bopp et al., 2013; Boyd et al., 2014; Chust et al., 2014; Hoegh-Guldberg et al., 2014; Poloczanska et al., 2014; Pörtner et al., 2014; Signorini et al., 2015)571. Reduced ocean upwelling has implications for millions of people and industries that depend on fisheries for food and livelihoods (Bakun et al., 2015; FAO, 2016; Kämpf and Chapman, 2016)572, although there is low confidence in the projection of the size of the consequences at 1.5°C. It is also important to appreciate these changes in the context of large-scale ocean processes such as the ocean carbon pump. The export of organic carbon to deeper layers of the ocean increases as NPP changes in the surface ocean, for example, with implications for foodwebs and oxygen levels (Boyd et al., 2014; Sydeman et al., 2014; Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015)573. Storms, wind, waves and inundation can have highly destructive impacts on ocean and coastal ecosystems, as well as the human communities that depend on them (IPCC, 2012; Seneviratne et al., 2012)574. The intensity of tropical cyclones across the world's oceans has increased, although the overall number of tropical cyclones has remained the same or decreased (medium confidence) (Section 3.3.6; Elsner et al., 2008; Holland and Bruyère, 2014)575. The direct force of wind and waves associated with larger storms, along with changes in storm direction, increases the risks of physical damage to coastal communities and to ecosystems such as mangroves (low to medium confidence) (Long et al., 2016; Primavera et al., 2016; Villamayor et al., 2016; Cheal et al., 2017)576 and tropical coral reefs (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017)577. These changes are associated with increases in maximum wind speed, wave height and the inundation, although trends in these variables vary from region to region (Section 3.3.5). In some cases, this can lead to increased exposure to related impacts, such as flooding, reduced water quality and increased sediment runoff (medium-high confidence) (Brodie et al., 2012; Wong et al., 2014; Anthony, 2016578; AR5, Table 5.1). Sea level rise also amplifies the impacts of storms and wave action (Section 3.3.9), with robust evidence that storm surges and damage are already penetrating farther inland than a few decades ago, changing conditions for coastal ecosystems and human communities. This is especially true for small islands (Box 3.5) and low-lying coastal communities, where issues such as storm surges can transform coastal areas (Section 3.4.5; Brown et al., 2018a)579. Changes in the frequency of extreme events, such as an increase in the frequency of intense storms, have the potential (along with other factors, such as disease, food web changes, invasive organisms and heat stress-related mortality; Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016; Clements et al., 2017)580 to overwhelm the capacity for natural and human systems to recover following disturbances. This has recently been seen for key ecosystems such as tropical coral reefs (Box 3.4), which have changed from coral-dominated ecosystems to assemblages dominated by other organisms such as seaweeds, with changes in associated organisms and ecosystem services (high confidence) (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017; Hoegh-Guldberg et al., 2017; Hughes et al., 2017a, b)581. The impacts of storms are amplified by sea level rise (Section 3.4.5), leading to substantial challenges today and in the future for cities, deltas and small island states in particular (Sections 3.4.5.2 to 3.4.5.4), as well as for coastlines and their associated ecosystems (Sections 3.4.5.5 to 3.4.5.7). The movement of water within the ocean is essential to its biology and ecology, as well to the circulation of heat, water and nutrients around the planet (Section 3.3.7). The movement of these factors drives local and regional climates, as well as primary productivity and food production. Firmly attributing recent changes in the strength and direction of ocean currents to climate change, however, is complicated by long-term patterns and variability (e.g., Pacific decadal oscillation, PDO; Signorini et al., 2015)582 and a lack of records that match the long-term nature of these changes in many cases (Lluch-Cota et al., 2014)583. An assessment of the literature since AR5 (Sydeman et al., 2014)584, however, concluded that (overall) upwelling-favourable winds have intensified in the California, Benguela and Humboldt upwelling systems, but have weakened in the Iberian system and have remained neutral in the Canary upwelling system in over 60 years of records (1946–2012) (medium confidence). These conclusions are consistent with a growing consensus that wind-driven upwelling systems are likely to intensify under climate change in many upwelling systems (Sydeman et al., 2014; Bakun et al., 2015; Di Lorenzo, 2015)585, with potentially positive and negative consequences (Bakun et al., 2015)586. Changes in ocean circulation can have profound impacts on marine ecosystems by connecting regions and facilitating the entry and establishment of species in areas where they were unknown before (e.g., 'tropicalization' of temperate ecosystems; Wernberg et al., 2012; Vergés et al., 2014, 2016; Zarco-Perello et al., 2017)587, as well as the arrival of novel disease agents (low-medium confidence) (Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016)588. For example, the herbivorous sea urchin Centrostephanus rodgersii has been reached Tasmania from the Australian mainland, where it was previously unknown, owing to a strengthening of the East Australian Current (EAC) that connects the two regions (high confidence) (Ling et al., 2009)589. As a consequence, the distribution and abundance of kelp forests has rapidly decreased, with implications for fisheries and other ecosystem services (Ling et al., 2009)590. These risks to marine ecosystems are projected to become greater at 1.5°C, and more so at 2°C (medium confidence) (Cheung et al., 2009; Pereira et al., 2010; Pinsky et al., 2013; Burrows et al., 2014)591. Changes to ocean circulation can have even larger influence in terms of scale and impacts. Weakening of the Atlantic Meridional Overturning Circulation (AMOC), for example, is projected to be highly disruptive to natural and human systems as the delivery of heat to higher latitudes via this current system is reduced (Collins et al., 2013)592. Evidence of a slowdown of AMOC has increased since AR5 (Smeed et al., 2014; Rahmstorf et al., 2015a, b; Kelly et al., 2016)593, yet a strong causal connection to climate change is missing (low confidence) (Section 3.3.7). Ocean chemistry encompasses a wide range of phenomena and chemical species, many of which are integral to the biology and ecology of the ocean (Section 3.3.10; Gattuso et al., 2014, 2015; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014)594. While changes to ocean chemistry are likely to be of central importance, the literature on how climate change might influence ocean chemistry over the short and long term is limited (medium confidence). By contrast, numerous risks from the specific changes associated with ocean acidification have been identified (Dove et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015; Albright et al., 2016)595, with the consensus that resulting changes to the carbonate chemistry of seawater are having, and are likely to continue to have, fundamental and substantial impacts on a wide variety of organisms (high confidence). Organisms with shells and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a large number of organisms and processes such as de-calcification, although there are some taxa that have not shown high-sensitivity to changes in CO_2, pH and carbonate concentrations (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015)596. Risks of these impacts also vary with latitude and depth, with the greatest changes occurring at high latitudes as well as deeper regions. The aragonite saturation horizon (i.e., where concentrations of calcium and carbonate fall below the saturation point for aragonite, a key crystalline form of calcium carbonate) is decreasing with depth as anthropogenic CO_2 penetrates deeper into the ocean over time. Under many models and scenarios, the aragonite saturation is projected to reach the surface by 2030 onwards, with a growing list of impacts and consequences for ocean organisms, ecosystems and people (Orr et al., 2005; Hauri et al., 2016)597. Further, it is difficult to reliably separate the impacts of ocean warming and acidification. As ocean waters have increased in sea surface temperature (SST) by approximately 0.9°C they have also decreased by 0.2 pH units since 1870–1899 ('pre-industrial'; Table 1 in Gattuso et al., 2015; Bopp et al., 2013)598. As CO_2 concentrations continue to increase along with other GHGs, pH will decrease while sea temperature will increase, reaching 1.7°C and a decrease of 0.2 pH units (by 2100 under RCP4.5) relative to the pre-industrial period. These changes are likely to continue given the negative correlation of temperature and pH. Experimental manipulation of CO_2, temperature and consequently acidification indicate that these impacts will continue to increase in size and scale as CO_2 and SST continue to increase in tandem (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013)599. While many risks have been defined through laboratory and mesocosm experiments, there is a growing list of impacts from the field (medium confidence) that include community-scale impacts on bacterial assemblages and processes (Endres et al., 2014)600, coccolithophores (K.J.S. Meier et al., 2014)601, pteropods and polar foodwebs (Bednaršek et al., 2012, 2014)602, phytoplankton (Moy et al., 2009; Riebesell et al., 2013; Richier et al., 2014)603, benthic ecosystems (Hall-Spencer et al., 2008; Linares et al., 2015)604, seagrass (Garrard et al., 2014)605, and macroalgae (Webster et al., 2013; Ordonez et al., 2014)606, as well as excavating sponges, endolithic microalgae and reef-building corals (Dove et al., 2013; Reyes-Nivia et al., 2013; Fang et al., 2014)607, and coral reefs (Box 3.4; Fabricius et al., 2011; Allen et al., 2017)608. Some ecosystems, such as those from bathyal areas (i.e., 200–3000 m below the surface), are likely to undergo very large reductions in pH by the year 2100 (0.29 to 0.37 pH units), yet evidence of how deep-water ecosystems will respond is currently limited despite the potential planetary importance of these areas (low to medium confidence) (Hughes and Narayanaswamy, 2013; Sweetman et al., 2017)609. Oxygen levels in the ocean are maintained by a series of processes including ocean mixing, photosynthesis, respiration and solubility (Boyd et al., 2014, 2015; Pörtner et al., 2014; Breitburg et al., 2018)610. Concentrations of oxygen in the ocean are declining (high confidence) owing to three main factors related to climate change: (i) heat-related stratification of the water column (less ventilation and mixing), (ii) reduced oxygen solubility as ocean temperature increases, and (iii) impacts of warming on biological processes that produce or consume oxygen such as photosynthesis and respiration (high confidence) (Bopp et al., 2013; Pörtner et al., 2014; Altieri and Gedan, 2015; Deutsch et al., 2015; Schmidtko et al., 2017; Shepherd et al., 2017; Breitburg et al., 2018)611. Further, a range of processes (Section 3.4.11) are acting synergistically, including factors not related to climate change, such as runoff and coastal eutrophication (e.g., from coastal farming and intensive aquaculture). These changes can lead to increased phytoplankton productivity as a result of the increased concentration of dissolved nutrients. Increased supply of organic carbon molecules from coastal run-off can also increase the metabolic activity of coastal microbial communities (Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015)612. Deep sea areas are likely to experience some of the greatest challenges, as abyssal seafloor habitats in areas of deep-water formation are projected to experience decreased water column oxygen concentrations by as much as 0.03 mL L–1 by 2100 (Levin and Le Bris, 2015; Sweetman et al., 2017)613. The number of 'dead zones' (areas where oxygenated waters have been replaced by hypoxic conditions) has been growing strongly since the 1990s (Diaz and Rosenberg, 2008; Altieri and Gedan, 2015; Schmidtko et al., 2017)614. While attribution can be difficult because of the complexity of the processes involved, both related and unrelated to climate change, some impacts associated to deoxygenation (low-medium confidence) include the expansion of oxygen minimum zones (OMZ) (Turner et al., 2008; Carstensen et al., 2014; Acharya and Panigrahi, 2016; Lachkar et al., 2018)615, physiological impacts (Pörtner et al., 2014)616, and mortality and/or displacement of oxygen dependent organisms such as fish (Hamukuaya et al., 1998; Thronson and Quigg, 2008; Jacinto, 2011)617 and invertebrates (Hobbs and Mcdonald, 2010; Bednaršek et al., 2016; Seibel, 2016; Altieri et al., 2017)618. In addition, deoxygenation interacts with ocean acidification to present substantial separate and combined challenges for fisheries and aquaculture (medium confidence) (Hamukuaya et al., 1998; Bakun et al., 2015; Rodrigues et al., 2015; Feely et al., 2016; S. Li et al., 2016; Asiedu et al., 2017a; Clements and Chopin, 2017; Clements et al., 2017; Breitburg et al., 2018)619. Deoxygenation is expected to have greater impacts as ocean warming and acidification increase (high confidence), with impacts being larger and more numerous than today (e.g., greater challenges for aquaculture and fisheries from hypoxia), and as the number of hypoxic areas continues to increase. Risks from deoxygenation are virtually certain to increase as warming continues, although our understanding of risks at 1.5°C versus 2°C is incomplete (medium confidence). Reducing coastal pollution, and consequently the penetration of organic carbon into deep benthic habitats, is expected to reduce the loss of oxygen in coastal waters and hypoxic areas in general (high confidence) (Breitburg et al., 2018)620. Sea ice is a persistent feature of the planet's polar regions (Polyak et al., 2010)621 and is central to marine ecosystems, people (e.g., food, culture and livelihoods) and industries (e.g., fishing, tourism, oil and gas, and shipping). Summer sea ice in the Arctic, however, has been retreating rapidly in recent decades (Section

3.3.8), with an assessment of the literature revealing that a fundamental transformation is occurring in polar organisms and ecosystems, driven by climate change (high confidence) (Larsen et al., 2014)622. These changes are strongly affecting people in the Arctic who have close relationships with sea ice and associated ecosystems, and these people are facing major adaptation challenges as a result of sea level rise, coastal erosion, the accelerated thawing of permafrost, changing ecosystems and resources, and many other issues (Ford, 2012; Ford et al., 2015)623. There is considerable and compelling evidence that a further increase of 0.5°C beyond the present-day average global surface temperature will lead to multiple levels of impact on a variety of organisms, from phytoplankton to marine mammals, with some of the most dramatic changes occurring in the Arctic Ocean and western Antarctic Peninsula (Turner et al., 2014, 2017b; Steinberg et al., 2015; Piñones and Fedorov, 2016)624. The impacts of climate change on sea ice are part of the focus of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), due to be released in 2019, and hence are not covered comprehensively here. However, there is a range of responses to the loss of sea ice that are occurring and which increase at 1.5°C and further so with 2°C of global warming. Some of these changes are described briefly here. Photosynthetic communities, such macroalgae, phytoplankton and microalgae dwelling on the underside of floating sea ice are changing, owing to increased temperatures, light and nutrient levels. As sea ice retreats, mixing of the water column increases, and photosynthesis have increased access to seasonally high levels of solar radiation (medium confidence) (Dalpadado et al., 2014; W.N. Meier et al., 2014)625. These changes are expected to stimulate fisheries productivity in high-latitude regions by mid-century (high confidence) (Cheung et al., 2009, 2010, 2016b; Lam et al., 2014)626, with evidence that this is already happening for several high-latitude fisheries in the Northern Hemisphere, such as the Bering Sea, although these 'positive' impacts may be relatively short-lived (Hollowed and Sundby, 2014; Sundby et al., 2016)627. In addition to the impact of climate change on fisheries via impacts on net primary productivity (NPP), there are also direct effects of temperature on fish, which may in turn have a range of impacts (Pörtner et al., 2014)628. Sea ice in Antarctica is undergoing changes that exceed those seen in the Arctic (Maksym et al., 2011; Reid et al., 2015)629, with increases in sea ice coverage in the western Ross Sea being accompanied by strong decreases in the Bellingshausen and Amundsen Seas (Hobbs et al., 2016)630. While Antarctica is not permanently populated, the ramifications of changes to the productivity of vast regions, such as the Southern Ocean, have substantial implications for ocean foodwebs and fisheries globally. Mean sea level is increasing (Section 3.3.9), with substantial impacts already being felt by coastal ecosystems and communities (Wong et al., 2014)631 (high confidence). These changes are interacting with other factors, such as strengthening storms, which together are driving larger storm surges, infrastructure damage, erosion and habitat loss (Church et al., 2013; Stocker et al., 2013)632. Coastal wetland ecosystems, such as mangroves, sea grasses and salt marshes are under pressure from rising sea level (medium confidence) (Section 3.4.5; Di Nitto et al., 2014; Ellison, 2014; Lovelock et al., 2015; Mills et al., 2016; Nicholls et al., 2018)633, as well as from a wide range of other risks and impacts unrelated to climate change, with the ongoing loss of wetlands recently estimated at approximately 1% per annum across a large number of countries (Blankespoor et al., 2014; Alongi, 2015)634. While some ecosystems (e.g., mangroves) may be able to shift shoreward as sea levels increase, coastal development (e.g., buildings, seawalls and agriculture) often interrupts shoreward shifts, as well as reducing sediment supplies down some rivers (e.g., dams) due to coastal development (Di Nitto et al., 2014; Lovelock et al., 2015)635. Responses to sea level rise challenges for ocean and coastal systems include reducing the impact of other stresses, such as those arising from tourism, fishing, coastal development, reduced sediment supply and unsustainable aquaculture/agriculture, in order to build ecological resilience (Hossain et al., 2015; Sutton-Grier and Moore, 2016; Asiedu et al., 2017a)636. The available literature largely concludes that these impacts will intensify under a 1.5°C warmer world but will be even higher at 2°C, especially when considered in the context of changes occurring beyond the end of the current century. In some cases, restoration of coastal habitats and ecosystems may be a cost-effective way of responding to changes arising from increasing levels of exposure to rising sea levels, intensifying storms, coastal inundation and salinization (Section 3.4.5 and Box 3.5; Arkema et al., 2013)637, although limitations of these strategies have been identified (e.g., Lovelock et al., 2015; Weatherdon et al., 2016)638. A comprehensive discussion of risk and adaptation options for all natural and human systems is not possible in the context and length of this report, and hence the intention here is to illustrate key risks and adaptation options for ocean ecosystems and sectors. This assessment builds on the recent expert consensus of Gattuso et al. (2015)639 by assessing new literature from 2015–2017 and adjusting the levels of risk from climate change in the light of literature since 2014. The original expert group's assessment (Supplementary Material 3.SM.3.2) was used as input for this new assessment, which focuses on the implications of global warming of 1.5°C as compared to 2°C of global warming. A discussion of potential adaptation options is also provided, the details of which will be further explored in later chapters of this special report. The section draws on the extensive analysis and literature presented in the Supplementary Material of this report (3.SM.3.2, 3.SM.3.3) and has a summary in Figures 3.18 and 3.20 which outline the added relative risks of climate change. Marine organisms ('ecosystem engineers'), such as seagrass, kelp, oysters, salt marsh species, mangroves and corals, build physical structures or frameworks (i.e., sea grass meadows, kelp forests, oyster reefs, salt marshes, mangrove forests and coral reefs) which form the habitat for a large number of species (Gutiérrez et al., 2012)640. These organisms in turn provide food, livelihoods, cultural significance, and services such as coastal protection to human communities (Bell et al., 2011, 2018; Cinner et al., 2012; Arkema et al., 2013; Nurse et al., 2014; Wong et al., 2014; Barbier, 2015; Bell and Taylor, 2015; Hoegh-Guldberg et al., 2015; Mycoo, 2017; Pecl et al., 2017)641. Risks of climate change impacts for seagrass and mangrove ecosystems were recently assessed by an expert group led by Short et al. (2016)642. Impacts of climate change were assessed to be similar across a range of submerged and emerged plants. Submerged plants such as sea grasses were affected mostly by temperature extremes (Arias-Ortiz et al., 2018)643 and indirectly by turbidity, while emergent communities such as mangroves and salt marshes were most susceptible to sea level variability and temperature extremes, which is consistent with other evidence (Di Nitto et al., 2014; Lovelock et al., 2015; Sierra-Correa and Cantera Kintz, 2015; Osorio et al., 2016; Sasmito et al., 2016)644, especially in the context of human activities that reduce sediment supply (Lovelock et al., 2015)645 or interrupt the shoreward movement of mangroves through the construction of coastal infrastructure. This in turn leads to 'coastal squeeze' where ecosystems are trapped between changing ocean conditions and coastal infrastructure (Mills et al., 2016)646. Projections of the future distribution of seagrasses suggest a poleward shift, which raises concerns that low-latitude seagrass communities may contract as a result of increasing stress levels (Valle et al., 2014)647. Climate change (e.g., sea level rise, heat stress, storms) presents risks for coastal ecosystems such as seagrass (high confidence) and reef-building corals (very high confidence) (Figure 3.18, Supplementary Material 3.SM.3.2), with evidence of increasing concern since AR5 and the conclusion that tropical corals may be even more vulnerable to climate change than indicated in assessments made in 2014 (Hoegh-Guldberg et al., 2014; Gattuso et al., 2015)648. The current assessment also considered the heatwave-related loss of 50% of shallow-water corals across hundreds of kilometres of the world's largest continuous coral reef system, the Great Barrier Reef. These large-scale impacts, plus the observation of back-to-back bleaching events on the Great Barrier Reef (predicted two decades ago, Hoegh-Guldberg, 1999)649 and arriving sooner than predicted (Hughes et al., 2017b, 2018)650, suggest that the research community may have underestimated climate risks for coral reefs (Figure 3.18). The general assessment of climate risks for mangroves prior to this special report was that they face greater risks from deforestation and unsustainable coastal development than from climate change (Alongi, 2008; Hoegh-Guldberg et al., 2014; Gattuso et al., 2015)651. Recent large-scale die-offs (Duke et al., 2017; Lovelock et al., 2017)652, however, suggest that risks from climate change may have been underestimated for mangroves as well. With the events of the last past three years in mind, risks are now considered to be undetectable to moderate (i.e., moderate risks now start at 1.3°C as opposed to 1.8°C; medium confidence). Consequently, when average global warming reaches 1.3°C above pre-industrial levels, the risk of climate change to mangroves are projected to be moderate (Figure 3.18) while tropical coral reefs will have reached a high level of risk as increasingly damage from heat stress since the early 1980s. At global warming of 1.8°C above pre-industrial levels, seagrasses are projected to reach moderate to high levels of risk, driven by damage from sea level rise, erosion, extreme temperatures, and storms, while risks to mangroves from climate change are projected to remain moderate (e.g., not keeping up with sea level rise and more frequent heat stress mortality) although there is low certainty as to when or if this important ecosystem is likely to transition to higher levels of additional risk from climate change (Figure 3.18). Warm water (tropical) coral reefs are projected to reach a very high risk of impact at 1.2°C (Figure 3.18), with most available evidence suggesting that coral-dominated ecosystems will be non-existent at this temperature or higher (high confidence). At this point, coral abundance will be near zero at many locations and storms will contribute to 'flattening' the three-dimensional structure of reefs without recovery, as already observed for some coral reefs (Alvarez-Filip et al., 2009)653. The impacts of warming and acidification, are expected to undermine the ability of tropical coral reefs to provide habitat for thousand of species, which together provide a range of ecosystem services (e.g., food, livelihoods, coastal protection, cultural services) that are important for millions of people (high confidence) (Burke et al., 2011)654. Strategies for reducing the impact of climate change on framework organisms include reducing stresses not directly related to climate change (e.g., coastal pollution, overfishing and destructive coastal development) in order to increase their ecological resilience in the face of accelerating climate change impacts (World Bank, 2013; Ellison, 2014; Anthony et al., 2015; Sierra-Correa and Cantera Kintz, 2015; Kroon et al., 2016; O'Leary et al., 2017)655, as well as protecting locations where organisms may be more robust (Palumbi et al., 2014)656 or less exposed to climate change (Bongaerts et al., 2010; van Hooidonk et al., 2013; Beyer et al., 2018)657. This might involve cooler areas due to upwelling, or involve deep-water locations that experience less extreme conditions and impacts. Given the potential value of such locations for promoting the survival of coral communities under climate change, efforts to prevent their loss resulting from other stresses are important (Bongaerts et al., 2010, 2017; Chollet et al., 2010, 2014; Chollett and Mumby, 2013; Fine et al., 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015; Beyer et al., 2018)658. A full understanding of the role of refugia in reducing the loss of ecosystems has yet to be developed (low to medium confidence). There is also interest in ex situ conservation approaches involving the restoration of corals via aquaculture (Shaish et al., 2008; Rinkevich, 2014)659 or the use of 'assisted evolution' to help corals adapt to changing sea temperatures (van Oppen et al., 2015, 2017)660, although there are numerous challenges that must be surpassed if these approaches are to be cost-effective responses to preserving coral reefs under rapid climate change (low confidence) (Hoegh-Guldberg, 2012, 2014a; Bayraktarov et al., 2016)661. High levels of adaptation are expected to be required to prevent impacts on food security and livelihoods in coastal populations (medium confidence). Integrating coastal infrastructure with changing ecosystems such as mangroves, seagrasses and salt marsh, may offer adaptation strategies as they shift shoreward as sea levels rise (high confidence) (Shearman et al., 2013; Lovelock et al., 2015; Sasmito et al., 2016)662. For this reason, habitat for mangroves can be strongly affected by human actions such as building dams which reduce the sediment supply and hence the ability of mangroves to escape 'drowning' as sea level rises (Lovelock et al., 2015)663. In addition, integrated coastal zone management should recognize the importance and economic expediency of using natural ecosystems such as mangroves and tropical coral reefs to protect coastal human communities (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Elliff and Silva, 2017)664. Adaptation options include developing alternative livelihoods and food sources, ecosystem-based management/adaptation such as ecosystem restoration, and constructing coastal infrastructure that reduces the impacts of rising seas and intensifying storms (Rinkevich, 2015; Weatherdon et al., 2016; Asiedu et al., 2017a; Feller et al., 2017)665. Clearly, these options need to be carefully assessed in terms of feasibility, cost and scalability, as well as in the light of the coastal ecosystems involved (Bayraktarov et al., 2016)666. Ocean foodwebs are vast interconnected systems that transfer solar energy and nutrients from phytoplankton to higher trophic levels, including apex predators and commercially important species such as tuna. Here, we consider four representative groups of marine organisms which are important within foodwebs across the ocean, and which illustrate the impacts and ramifications of 1.5°C or higher levels of warming. The first group of organisms, pteropods, are small pelagic molluscs that suspension feed and produce a calcium carbonate shell. They are highly abundant in temperate and polar waters where they are an important link in the foodweb between phytoplankton and a range of other organisms including fish, whales and birds. The second group, bivalve molluscs (e.g., clams, oysters and mussels), are filter-feeding invertebrates. These invertebrate organisms underpin important fisheries and aquaculture industries, from polar to tropical regions, and are important food sources for a range of organisms including humans. The third group of organisms considered here is a globally significant group of invertebrates known as euphausiid crustaceans (krill), which are a key food source for many marine organisms and hence a major link between primary producers and higher trophic levels (e.g., fish, mammals and sea birds). Antarctic krill, Euphausia superba, are among the most abundant species in terms of mass and are consequently an essential component of polar foodwebs (Atkinson et al., 2009)667. The last group, fin fishes, is vitally important components of ocean foodwebs, contribute to the income of coastal communities, industries and nations, and are important to the foodsecurity and livelihood of hundreds of millions of people globally (FAO, 2016)668. Further background for this section is provided in Supplementary Material 3.SM.3.2. There is a moderate risk to ocean foodwebs under present-day conditions (medium to high confidence) (Figure 3.18). Changing water chemistry and temperature are already affecting the ability of pteropods to produce their shells, swim and survive (Bednaršek et al., 2016)669. Shell dissolution, for example, has increased by 19–26% in both nearshore and offshore populations since the pre-industrial period (Feely et al., 2016)670. There is considerable concern as to whether these organisms are declining further, especially given the central importance in ocean foodwebs (David et al., 2017)671. Reviewing the literature reveals that pteropods are projected to face high risks of impact at average global temperatures 1.5°C above pre-industrial levels and increasing risks of impacts at 2°C (medium confidence). As GMST increases by 1.5°C and more, the risk of impacts from ocean warming and acidification are expected to be moderate to high, except in the case of bivalves (mid-latitudes) where the risks of impacts are projected to be high to very high (Figure 3.18). Ocean warming and acidification are already affecting the life history stages of bivalve molluscs (e.g., Asplund et al., 2014; Mackenzie et al., 2014; Waldbusser et al., 2014; Zittier et al., 2015; Shi et al., 2016; Velez et al., 2016; Q. Wang et al., 2016; Castillo et al., 2017; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017)672. Impacts on adult bivalves include decreased growth, increased respiration and reduced calcification, whereas larval stages tend to show greater developmental abnormalities and increased mortality after exposure to these conditions (medium to high confidence) (Q. Wang et al., 2016; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017)673. Risks are expected to accumulate at higher temperatures for bivalve molluscs, with very high risks expected at 1.8°C of warming or more. This general pattern applies to low-latitude fin fish, which are expected to experience moderate to high risks of impact at 1.5°C of global warming (medium confidence), and very high risks at 1.8°C at low latitudes (medium confidence) (Figure 3.18). Large-scale changes to foodweb structure are occurring in all oceans. For example, recent levels of sea ice loss in the Antarctic (Notz and Stroeve, 2016; Turner et al., 2017b)674 translate into a loss of habitat and hence reduced abundance of krill (Piñones and Fedorov, 2016)675, with negative ramifications for the seabirds and whales which feed on krill (Croxall, 1992; Trathan and Hill, 2016)676 (low-medium confidence). Other influences, such as high rates of ocean acidification coupled with shoaling of the aragonite saturation horizon, are likely to also play key roles (Kawaguchi et al., 2013; Piñones and Fedorov, 2016)677. As with many risks associated with impacts at the ecosystem scale, most adaptation options focus on the management of stresses unrelated to climate change but resulting from human activities, such as pollution and habitat destruction. Reducing these stresses will be important in efforts to maintain important foodweb components. Fisheries management at local to regional scales will be important in reducing stress on foodwebs, such as those discussed here, and in helping communities and industries adapt to changing foodweb structures and resources (see further discussion of fisheries per se below; Section 3.4.6.3). One strategy is to maintain larger population levels of fished species in order to provide more resilient stocks in the face of challenges that are increasingly driven by climate change (Green et al., 2014; Bell and Taylor, 2015)678. The ocean provides important services, including the regulation of atmospheric composition via gas exchange across the boundary between ocean and atmosphere, and the storage of carbon in vegetation and soils associated with ecosystems such as mangroves, salt marshes and coastal peatlands. These services involve a series of physicochemical processes which are influenced by ocean chemistry, circulation, biology, temperature and biogeochemical components, as well as by factors other than climate (Boyd, 2015)679. The ocean is also a net sink for CO2 (another important service), absorbing approximately 30% of human emissions from the burning of fossil fuels and modification of land use (IPCC, 2013)680. Carbon uptake by the ocean is decreasing (Iida et al., 2015)681, and there is increasing concern from observations and models regarding the associated changes to carbon uptake by the ocean (Sections 3.3.7 and 3.3.8; Rahmstorf et al., 2015b)682. Biological components of carbon uptake by the ocean are also changing, with observations of changing net primary productivity (NPP) in equatorial and coastal upwelling systems (medium confidence) (Lluch-Cota et al., 2014; Sydeman et al., 2014; Bakun et al., 2015)683, as well as subtropical gyre systems (low confidence) (Signorini et al., 2015)684. There is general agreement that NPP will decline as ocean warming and acidification increase (medium confidence) (Bopp et al., 2013; Boyd et al., 2014; Pörtner et al., 2014; Boyd, 2015)685. Projected risks of impacts from reductions in carbon uptake, coastal protection and services contributing to coral reef recreation suggest a transition from moderate to high risks at 1.5°C and higher (low confidence). At 2°C, risks of impacts associated with changes to carbon uptake are high, while the risks associated with reduced coastal protection and recreation on tropical coral reefs are high, especially given the vulnerability of this ecosystem type, and others (e.g., seagrass and mangroves), to climate change (medium confidence) (Figure 3.18). Coastal protection is a service provided by natural barriers such as mangroves, seagrass meadows, coral reefs, and other coastal ecosystems, and it is important for protecting human communities and infrastructure against the impacts associated with rising sea levels, waves and intensifying storms (high confidence) (Gutiérrez et al., 2012; Kennedy et al., 2013; Ferrario et al., 2014; Barbier, 2015; Cooper et al., 2016; Hauer et al., 2016; Narayan et al., 2016)686. Both natural and human coastal protection have been the potential to reduce these impacts (Fu and Song, 2017)687. Tropical coral reefs, for example, provide effective protection by dissipating about 97% of wave energy, with 86% of the energy being dissipated by reef crests alone (Ferrario et al., 2014; Narayan et al., 2016)688. Mangroves similarly play an important role in coastal protection, as well as providing resources for coastal communities, but they are already under moderate risk of not keeping up with sea level rise due to climate change and to contributing factors, such as reduced sediment supply or obstacles to shoreward shifts (Saunders et al., 2014; Lovelock et al., 2015)689. This implies that coastal areas currently protected by mangroves may experience growing risks over time. Tourism is one of the largest industries globally (Rosselló-Nadal, 2014; Markham et al., 2016; Spalding et al., 2017)690. A substantial part of the global tourist industry is associated with tropical coastal regions and islands, where tropical coral reefs and related ecosystems play important roles (Section 3.4.9.1) (medium confidence). Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries, particularly small island developing states (SIDS) (Section 3.4.9.1, Box 3.5; Weatherdon et al., 2016; Spalding et al., 2017)691. The direct relationship between increasing global temperatures, intensifying storms, elevated thermal stress, and the loss of tropical coral reefs has raised concern about the risks of climate change for local economies and industries based on tropical coral reefs. Risks to coral recreational services from climate change are considered here, as well as in Box 3.5, Section 3.4.9 and Supplementary Material 3.SM.3.2. Adaptations to the broad global changes in carbon uptake by the ocean are limited and are discussed later in this report with respect to changes in NPP and implications for fishing industries. These adaptation options are broad and indirect, and the only other solution at large scale is to reduce the entry of CO2 into the ocean. Strategies for adapting to reduced coastal protection involve (a) avoidance of vulnerable areas and hazards, (b) managed retreat from threatened locations, and/or (c) accommodation of impacts and loss of services (Bell, 2012; André et al., 2016; Cooper et al., 2016; Mills et al., 2016; Raabe and Stumpf, 2016; Fu and Song, 2017)692. Within these broad options, there are some strategies that involve direct human intervention, such as coastal hardening and the construction of seawalls and artificial reefs (Rinkevich, 2014, 2015; André et al., 2016; Cooper et al., 2016; Narayan et al., 2016)693, while others exploit opportunities for increasing coastal protection by involving naturally occurring oyster banks, coral reefs, mangroves, seagrass and other ecosystems (UNEP-WCMC, 2006; Scyphers et al., 2011; Zhang et al., 2012; Ferrario et al., 2014; Cooper et al., 2016)694. Natural ecosystems, when healthy, also have the ability to repair themselves after being damaged, which sets them apart from coastal hardening and other human structures that require constant maintenance (Barbier, 2015; Elliff and Silva, 2017)695. In general, recognizing and restoring coastal ecosystems may be more cost-effective than installing human structures, in that creating and maintaining structures is typically expensive (Temmerman et al., 2013; Mycoo, 2017)696. Recent studies have increasingly stressed the need for coastal protection to be considered within the context of coastal land management, including protecting and ensuring that coastal ecosystems are able to undergo shifts in their distribution and abundance as climate change occurs (Clausen and Clausen, 2014; Martínez et al., 2014; Cui et al., 2015; André et al., 2016; Mills et al., 2016)697. Facilitating these changes will 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 associated ecosystem responses and values (Bell, 2012; Mills et al., 2016)698. 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)699 with a widening appreciation of the role of natural ecosystems as an alternative to hardened coastal structures (Cooper et al., 2016)700. Adaptation options for tropical coral reef recreation include: (i) protecting and improving biodiversity and ecological function by minimizing the impact of stresses unrelated to climate change (e.g., pollution and overfishing), (ii) ensuring fair and equitable access to the economic opportunities associated with recreational activities, and (iv) seeking and protecting supplies of water for tourism, industry and agriculture alongside community needs. Warm-water coral reefs face very high risks (Figure 3.18) from climate change. A world in which global warming is restricted to 1.5°C above pre-industrial levels would be a better place for coral reefs than that of a 2°C warmer world, in which coral reefs would mostly disappear (Donner et al., 2005; Hoegh-Guldberg, 1999; Schleussner et al., 2016b; van Hooidonk et al., 2016; Frieler et al., 2017; Hughes et al., 2017a)704. Even with warming up until today (GMST for decade 2006–2015: 0.87°C; Chapter 1), a substantial proportion of coral reefs have experienced large-scale mortalities that have led to much reduced coral populations (Hoegh-Guldberg et al., 2014)705. In the last three years alone (2016–2018), large coral reef systems such as the Great Barrier Reef (Australia) have lost as much as 50% of their shallow water corals (Hughes et al., 2017b)706. Coral-dominated reefs are found along coastlines between latitudes 30°S and 30°N, where they provide habitat for over a million species (Reaka-Kudla, 1997)707 and food, income, coastal protection, cultural context and many other services for millions of people in tropical coastal areas (Burke et al., 2011; Cinner et al., 2012; Kennedy et al., 2013; Pendleton et al., 2016)708. Ultimately, coral reefs are underpinned by a mutualistic symbiosis between reef-building corals and dinoflagellates from the genus Symbiodinium (Hoegh-Guldberg et al., 2017)709. Warm-water coral reefs are found down to depths of 150 m and are dependent on light, making them distinct from the cold deep-water reef systems that extend down to depths of 2000 m or more. The difficulty in accessing deep-water reefs also means that the literature on the impacts of climate change on these systems is very limited by comparison to those on warm-water coral reefs (Hoegh-Guldberg et al., 2017)710. Consequently, this Box focuses on the impacts of climate change on warm-water (tropical) coral reefs, particularly with respect to their prospects under average global surface temperatures of 1.5°C and 2°C above the pre-industrial period. The distribution and abundance of coral reefs has decreased by approximately 50% over the past 30 years (Gardner et al., 2003; Bruno and Selig, 2007; De'ath et al., 2012)711 as a result of pollution, storms, overfishing and unsustainable coastal development (Burke et al., 2011; Halpern et al., 2015; Cheal et al., 2017)712. More recently, climate change (i.e., heat stress; Hoegh-Guldberg, 1999; Baker et al., 2008; Spalding and Brown, 2015; Hughes et al., 2017b)713 has emerged as the greatest threat to coral reefs, with temperatures of just 1°C above the long-term summer maximum for an area (reference period 1985–1993) over 4–6 weeks being enough to cause mass coral bleaching (loss of the symbionts) and mortality (very high confidence) (WGII AR5, Box 18-2; Cramer et al., 2014)714. Ocean warming and acidification can also slow growth and calcification, making corals less competitive compared to other benthic organisms such as macroalgae or seaweeds (Dove et al., 2013; Reyes-Nivia et al., 2013, 2014)715. As corals disappear, so do fish and many other reef-dependent species, which directly impacts industries such as tourism and fisheries, as well as the livelihoods for many, often disadvantaged, coastal people (Wilson et al., 2006; Graham, 2014; Graham et al., 2015; Cinner et al., 2016; Pendleton et al., 2016)716(Pendleton et al., 2016; Cinner et al., 2016)717. These impacts are exacerbated by increasingly intense storms (Section 3.3.6), which physically destroy coral communities and hence reefs (Cheal et al., 2017)718, and by ocean acidification (Sections 3.3.10 and 3.4.4.5), which can weaken coral skeletons, contribute to disease, and slow the recovery of coral communities after mortality events (low to medium confidence) (Gardner et al., 2005; Dove et al., 2013; Kennedy et al., 2013; Webster et al., 2013; Hoegh-Guldberg, 2014b; Anthony, 2016)719. Ocean acidification also leads to enhanced activity by decalcifying organisms such as excavating sponges (Kline et al., 2012; Dove et al., 2013; Fang et al., 2013, 2014; Reyes-Nivia et al., 2013)720. The predictions of back-to-back bleaching events (Hoegh-Guldberg, 1999)721 have become reality in the summers of 2016–2017 (e.g., Hughes et al., 2018)722, as have projections of declining coral abundance (high confidence). Models have also become increasingly capable and are currently predicting the large-scale loss of coral reefs by mid-century under even low-emissions scenarios (Hoegh-Guldberg, 1999; Donner et al., 2005; Donner, 2009; van Hooidonk and Huber, 2012; Frieler et al., 2013; Hoegh-Guldberg et al., 2014; van Hooidonk et al., 2016)723. Even achieving emission reduction targets consistent with the ambitious goal of 1.5°C of global warming under the Paris Agreement will result in the further loss of 70–90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2°C or more above the pre-industrial period (Frieler et al., 2013; Hoegh-Guldberg, 2014b; Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b; Hughes et al., 2017a)724. The assumptions underpinning these assessments are considered to be highly conservative. In some cases, 'optimistic' assumptions in models include rapid thermal adaptation by corals of 0.2°C–1°C per decade (Donner et al., 2005)725 or 0.4°C per decade (Schleussner et al., 2016b)726, as well as very rapid recovery rates from impacts (e.g., five years in the case of Schleussner et al., 2016b)727. Adaptation to climate change at these high rates, has not been documented, and recovery from mass mortality tends to take much longer (>15 years; Baker et al., 2008)728. Probability analysis also indicates that the underlying increases in sea temperatures that drive coral bleaching and mortality are 25% less likely under 1.5°C when compared to 2°C (King et al., 2017)729. Spatial differences between the rates of heating suggest the possibility of temporary climate refugia (Caldeira, 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015; Keppel and Kavousi, 2015)730, which may play an important role in terms of the regeneration of coral reefs, especially if these refuges are protected from non-climate stresses. Locations at higher latitudes are warming more slowly than those in the tropics, leading to the suggestion that coral reefs will migrate to higher latitudes. The potential for reef-building corals, which may also be valuable in terms of the role of limited refugia and coral reef structures but will have low biodiversity (high confidence) when compared to present-day tropical reefs (Kersting et al., 2017)731. Similarly, deep-water (30–150 m) or mesophotic coral reefs (Bongaerts et al., 2010; Holstein et al., 2016)732 may play an important role because they experience less extreme (i.e., heat and storms) to some extent, although the ability of these ecosystems to assist in repopulating damaged shallow water areas may be limited (Bongaerts et al., 2017)733. Given the sensitivity of corals to heat stress, even short periods of overshoot (i.e., decades) are expected to be extremely damaging to coral reefs. Losing 70–90% of today's coral reefs, however, will remove resources and increase poverty levels across the world's tropical coastlines, highlighting the key issue of equity for the millions of people that depend on these valuable ecosystems (Cross-Chapter Box 6; Spalding et al., 2014; Halpern et al., 2015)734. Anticipating these challenges to food and livelihoods for coastal communities will become increasingly important, as will adaptation options, such as the diversification of livelihoods and the development of new sustainable industries, to reduce the dependency of coastal communities on threatened ecosystems such as coral reefs (Cinner et al., 2012, 2016; Pendleton et al., 2016)735. At the same time, coastal communities will need to pre-empt changes to other services provided by coral reefs such as coastal protection (Kennedy et al., 2013; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014; Gattuso et al., 2015)736. Other threats and challenges to coastal living, such as sea level rise, will amplify challenges from declining coral reefs, specially for SIDS and low-lying tropical nations. Given the scale and cost of these interventions, implementing them earlier rather than later would be expedient. Sea level rise (SLR) is accelerating in response to climate change (Section 3.3.9; Church et al., 2013)737 and will produce significant impacts (high confidence). In this section, impacts and projections of SLR are reported at global and city scales (Sections 3.4.5.1 and 3.4.5.2) and for coastal systems (Sections 3.4.5.3 to 3.4.5.6). For some sectors, there is a lack of precise evidence of change at 1.5°C and 2°C of global warming. Adaptation to sea level rise is discussed in Section 3.4.5.7. Sea level rise (SLR) and other oceanic climate changes are already resulting in salinization, flooding, and erosion and in the future are projected to affect human and ecological systems, including health, heritage, freshwater availability, biodiversity, agriculture, fisheries and other services, with different impacts seen worldwide (high confidence). Owing to the commitment to SLR, there is an overlapping uncertainty in projections at 1.5°C and 2°C (Schleussner et al., 2016b; Sanderson et al., 2017; Goodwin et al., 2018; Mengel et al., 2018; Nicholls et al., 2018; Rasmussen et al., 2018)738 and about 0.1 m difference in global mean sea level (GMSL) rise between 1.5°C and 2°C worlds in the year 2100 (Section 3.3.9, Table 3.3). Exposure and impacts at 1.5°C and 2°C differ at different time horizons (Schleussner et al., 2016b; Brown et al., 2018a, b; Nicholls et al., 2018; Rasmussen et al., 2018)739. However, these are distinct from impacts associated with higher levels of temperature (e.g., 4°C or more, as discussed in Brown et al., 2018a)740 over centennial scales. The benefits of climate change mitigation reinforce findings of earlier IPCC reports (e.g., Wong et al., 2014)741. Table 3.3 shows the land and people exposed to SLR (assuming there is no adaptation or protection at all) using the Dynamic Interactive Vulnerability Assessment (DIVA) model (extracted from Brown et al., 2018a742 and Goodwin et al., 2018)743; see also Supplementary Material 3.SM, Table 3.SM.4). Thus, exposure increases even with temperature stabilization. The exposed land area is projected to at least double by 2300 using a RCP8.5 scenario compared with a mitigation scenario (Brown et al., 2018a)744. In the 21st century, land area exposed to sea level rise (assuming there is no adaptation or protection at all) is projected to be at least an order of magnitude larger than the cumulative land loss due to submergence (which takes into account defences) (Brown et al., 2016, 2018a)745 regardless of the SLR scenario applied. Slower rates of rise due to climate change mitigation may provide a greater opportunity for adaptation (medium confidence), which could substantially reduce impacts. In agreement with the assessment in WGII AR5 Section 5.4.3.1 (Wong et al., 2014)746, climate change mitigation may reduce or delay coastal exposure and impacts (very high confidence). Adaptation has the potential to substantially reduce risk through a portfolio of available options (Sections 5.4.3.1 and 5.5 of Wong et al., 2014; Sections 6.4.2.3 and 6.6 of Nicholls et al., 2007)747. At 1.5°C in 2100, 31–69 million people (2010 population values) worldwide are projected to be exposed to flooding, assuming no adaptation or protection at all, compared with 32–79 million people (2010 population values) at 2°C in 2100 (Supplementary Material 3.SM, Table 3.SM.4; Rasmussen et al., 2018)748. As a result, up to 10.4 million more people would be exposed to sea level rise at 2°C compared with 1.5°C in 2100 (medium confidence). With a 1.5°C stabilization scenario in 2100, 62.7 million people per year are at risk from flooding, with this value increasing to 137.6 million people per year in 2300 (50th percentile average across SSP1–5, no socio-economic change after 2100). These projections assume that no upgrade to current protection levels occurs (Nicholls et al., 2018)749. The number of people at risk increases by approximately 18% in 2030 if a 2°C scenario is used and by 266% in 2300 if an RCP8.5 scenario is considered (Nicholls et al., 2018)750. Through prescribed IPCC Special Report on Emissions Scenarios (SRES) SLR scenarios, Arnell et al. (2016)751 also found that the number of people exposed to flooding increased substantially at warming levels higher than 2°C, assuming no adaptation beyond current protection levels. Adaptation is expected to increase in the second half of the 21st century. Coastal flooding is projected to cost thousands of billions of USD annually, with damage costs under constant protection estimated at 0.3–5.0% of global gross domestic product (GDP) in 2100 under an RCP2.6 scenario (Hinkel et al., 2014)752. Risks are projected to be highest in South and Southeast Asia, assuming there is no upgrade to current protection levels, for all levels of climate warming (Arnell et al., 2016; Brown et al., 2016)753. Countries with at least 50 million people exposed to SLR (assuming no adaptation or protection at all) based on a 1,280 Pg C emissions scenario (approximately a 1.5°C temperature rise above today's level) include China, Bangladesh, Egypt, India, Indonesia, Japan, Philippines, United States and Vietnam (Clark et al., 2016)754. Rasmussen et al. (2018)755 and Brown et al. (2018a)756 project that similar countries would have high exposure to SLR in the 21st century using 1.5°C and 2°C scenarios. Thus, there is high confidence that SLR will have significant impacts worldwide in this century and beyond. Assessment of the impacts of SLR in cities are difficult to record because multiple drivers of change are involved. There are differences between ongoing and planned adaptation to SLR and extreme water levels in some cities (Araos et al., 2016; Nicholls et al., 2018)757, whilst other cities have yet to prepare for these impacts (high confidence) (see Section 3.4.8 and Cross-Chapter Box 9 in Chapter 4). There are limited observations and analyses of how cities will cope with higher and/or multi-centennial SLR, with the exception of Amsterdam, New York and London (Nicholls et al., 2018)758. Coastal urban areas are projected to see more extreme water levels due to rising sea levels, which may lead to increased flooding and damage of infrastructure from extreme events (unless adaptation is undertaken), plus salinization of groundwater. These impacts may be enhanced through localized subsidence (Wong et al., 2014)759, which causes greater relative SLR. At least 136 megacities (port cities with a population greater than 1 million in 2005) are at risk from flooding due to SLR (with magnitudes of rise possible under 1.5°C or 2°C in the 21st century, as indicated in Section 3.3.9) unless further adaptation is undertaken (Hanson et al., 2011; Hallegatte et al., 2013)760. Many of these cities are located in South and Southeast Asia (Hallegatte et al., 2013; Cazenave and Cozannet, 2014; Clark et al., 2016; Jevrejeva et al., 2016)761. Jevrejeva et al. (2016)762 projected that more than 90% of global coastlines could experience SLR greater than 0.2 m with 2°C of warming by 2040 (RCP8.5). However, for scenarios where 2°C is stabilized or occurs later in time, this figure is likely to differ because of the commitment to SLR. Raising existing dikes helps protect against SLR, substantially reducing risks, although other forms of adaptation exist. By 2300, dike heights under a non-mitigation scenario (RCP8.5) could be more than 2 m higher (on average for 136 megacities) than under climate change mitigation scenarios at 1.5°C or 2°C (Nicholls et al., 2018)763. This is because sea level commits coastal cities to long-term adaptation (high confidence). Qualitative physical observations of SLR (and other stresses) include the drowning of parts of low-lying islands, land degradation due to saltwater intrusion in Kiribati and Tuvalu (Wairiu, 2017)764, and shoreline change in French Polynesia (Yates et al., 2013)765, Tuvalu (Kench et al., 2015, 2018)766 and Hawaii (Romine et al., 2013)767. Observations, models and other evidence indicate that unconstrained Pacific atolls have kept pace with SLR, with little reduction in size or net gain in land (Kench et al., 2015, 2018; McLean and Kench, 2015; Beetham et al., 2017)768. Whilst islands are highly vulnerable to SLR (high confidence), they are also reactive to change. Small islands are impacted by multiple climatic stressors, with SLR being a more important stressor to some islands than others (Sections 3.4.10, 4.3.5.6, 5.2.1, 5.5.3.3, Boxes 3.5, 4.3 and 5.3). Observed adaptation to multiple drivers of coastal change, including SLR, includes retreat (migration), accommodation and defence. Migration (internal and international) has always been important on small islands (Farbotko and Lazrus, 2012; Weir et al., 2017)769, with changing environmental and weather conditions being just one factor in the choice to migrate (Sections 3.4.10, 4.3.5.6 and 5.3.2; Campbell and Warrick, 2014)770. Whilst flooding may result in migration or relocation, for example in Vunidogoloa, Fiji (McNamara and Des Combes, 2015); Gharbaoui and Blocher, 2016)771 and the Solomon Islands (Albert et al., 2017)772, in situ adaptation may be tried or preferred, for example stilted housing or raised floors in Tubigon, Bohol, Philippines (Jamero et al., 2017)773, raised roads and floors in Batasan and Ubay, Philippines (Jamero et al., 2018)774, and raised platforms for falaw in Leang, Federated States of Micronesia (Nunn et al., 2017)775. Protective features, such as seawalls or beach nourishment, are observed to locally reduce erosion and flood risk but can have other detrimental implications (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014; AR5 Section 29.6.2)776. There is a lack of precise, quantitative studies of projected impacts of SLR at 1.5°C and 2°C. Small islands are projected to be at risk and very sensitive to coastal climate change and other stressors (high confidence) (Nurse et al., 2014; Benjamin and Thomas, 2016; Ourbak and Magnan, 2017; Brown et al., 2018a; Nicholls et al., 2018;777 AR5 Sections 29.3 and 29.4), such as oceanic warming, SLR (resulting in salinization, flooding and erosion), cyclones and mass coral bleaching and mortality (Section 3.4.4, Boxes 3.4 and 3.5). These can have significant socio-economic and ecological implications, such as on health, agriculture and water resources, which in turn have impacts on livelihoods (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014)778. Combinations of drivers causing adverse impacts are important. For example, Storlazzi et al. (2018)779 found that the impacts of SLR and wave-induced flooding (within a temperature horizon equivalent of 1.5°C), could affect freshwater availability on Roi-Namur, Marshall Islands, but is also dependent on other extreme weather events. Freshwater resources may also be affected by a 0.40 m rise in sea level (which may be experienced with a 1.5°C warming) in other Pacific atolls (Terry and Chui, 2012)780. Whilst SLR is a major hazard for atolls, islands reaching higher elevations are also threatened given that there is often a lack of infrastructure located near the coast (high confidence) (Kumar and Taylor, 2015; Nicholls et al., 2018)781. Tens of thousands of people on small islands are exposed to SLR (Rasmussen et al., 2018)782. Giardino et al. (2018)783 found that hard defence structures on the island of Ebeye in the Marshall Islands were effective in reducing damage due to SLR at 1.5°C and 2°C. Additionally, damage was also reduced under mitigation scenarios compared with non-mitigation scenarios. In Jamaica and St Lucia, SLR and extreme sea levels are projected to threaten transport system infrastructure at 1.5°C unless further adaptation is undertaken (Monioudi et al., 2018)784. Slower rates of SLR will provide a greater opportunity for adaptation to be successful (medium confidence). There may not be substantial enough on islands with a very low mean elevation. Migration and/or relocation may be an adaptation option (Section 3.4.10). Thomas and Benjamin (2017)785 highlight three areas of concern in the context of loss and damage at 1.5°C: a lack of data, gaps in financial assessments, and a lack of targeted policies or mechanisms to address these issues (Cross-Chapter Box 12 in Chapter 5). Small islands are projected to remain vulnerable to SLR (high confidence). Observations of SLR and human influence are felt through salinization, which leads to mixing in deltas and estuaries, aquifers, leading to flooding (also enhanced by precipitation and river discharge), land degradation and erosion. Salinization is projected to impact freshwater sources and pose risks to ecosystems and human systems (Section 5.4; Wong et al., 2014)786. For instance, in the Delaware River estuary on the east coast of the USA, upward trends of salinity (measured since the 1900s), accounting for the effects of streamflow and seasonal variations, have been detected and SLR is a potential cause (Ross et al., 2015)787. Z. Yang et al. (2015)788 found that future climate scenarios for the USA (A1B 1.6°C and B1 2°C in the 2040s) had a greater effect on salinity intrusion than future land-use/land-cover change in the Snohomish River estuary in Washington state (USA). This resulted in a shift in the salinity both upstream and downstream in low flow conditions. Projecting impacts in deltas needs an understanding of both fluvial discharge and SLR, making projections complex because the drivers operate on different temporal and spatial scales (Zaman et al., 2017; Brown et al., 2018b)789. The mean annual flood depth when 1.5°C is first projected to be reached in the Ganges-Brahmaputra delta may be less than the most extreme annual flood depth seen today, taking into account SLR, surges, tides, bathymetry and local river flows (Brown et al., 2018b)790. Further, increased river salinity and saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C of warming (Zaman et al., 2017)791. Salinization could impact agriculture and food security (Cross-Chapter Box 6 in this chapter). For 1.5°C or 2°C stabilization conditions in 2200 or 2300 plus surges, a minimum of 44% of the Bangladeshi Ganges-Brahmaputra, Indian Bengal, Indian Mahanadi and Ghanese Volta delta land area (without defences) would be exposed unless sedimentation occurs (Brown et al., 2018b)792. Other deltas are similarly vulnerable. SLR is only one factor affecting deltas, and assessment of numerous geophysical and anthropogenic drivers of geomorphic change is important (Tessler et al., 2016)793. For example, dike building to reduce flooding and dam building (Gupta et al., 2012)794 restricts sediment movement and deposition, leading to enhanced subsidence, which can occur at a greater rate than SLR (Auerbach et al., 2015; Takagi et al., 2016)795. Although dikes remain essential for reducing flood risk today, promoting sedimentation is an advisable strategy (Brown et al., 2018b)796 which may involve nature-based solutions. Transformative decisions regarding the extent of sediment restoration may need to be considered at 1.5°C and 2°C (Brown et al., 2018b)797. Thus, in a 1.5°C or 2°C warmer world, deltas, which are home to millions of people, are expected to be highly threatened from SLR and localized subsidence (high confidence). Observations indicate that wetlands, such as saltmarshes and mangrove forests, are disrupted by changing conditions (Sections 3.4.4.8; Wong et al., 2014; Lovelock et al., 2015)798, such as total sediment supply and flux (Ganju et al., 2017)800, but at times they can cope with SLR (Kirwan et al., 2016)799 (Kirwan et al., 2016)800. For example, saltmarshes in Connecticut and New York, USA, measured from 1900 to 2012, have accreted with SLR but have lost marsh surface relative to tidal datums, leading to increased marsh flooding and further accretion (Hill and Anisfeld, 2015)799. This change stimulated marsh carbon storage and aided climate change mitigation. Salinization may lead to shifts in wetland communities and their ecosystem functions (Herbert et al., 2015)800. Some projections of wetland change, with magnitudes of rise possible, but not necessarily rates or timing) of SLR analogous to 1.5°C and 2°C of global warming, indicate a net loss of wetlands in the 21st century (e.g., Blankespoor et al., 2014; Cui et al., 2015; Arnell et al., 2016; Crosby et al., 2016)801, whilst others report a net gain with wetland transgression (e.g., Raabe and Stumpf, 2016)802 in the Gulf of Mexico). However, the feedback between wetlands and sea level is complex, with parameters such as lack of accommodation space restricting inland migration, or sediment supply and feedbacks between plant growth and geomorphology (Kirwan and Megonigal, 2013; Ellison, 2014; Martínez et al., 2014; Spencer et al., 2016)803 still being explored. Reducing global warming from 2°C to 1.5°C will deliver long-term benefits, with natural sedimentation rates more likely keep up with SLR. It remains unclear how wetlands will respond and under what conditions (including other climate parameters) to a global temperature rise of 1.5°C and 2°C. There may be potential to aid and benefit climate change mitigation and adaptation (medium confidence) (Sections 4.3.2.2 and 4.3.2.3). Numerous impacts have not been quantified at 1.5°C or 2°C but remain important. Studies of these impacts not mentioned above (Section 3.4.5.4). These include impacts identified in WGII AR5 (AR5 – Section 5.4 of Wong et al., 2014)804, such as beaches, barriers, sand dunes, rocky coasts, aquifers, lagoons and coastal ecosystems (for the last system, see Section 3.4.4.12). For example, SLR potentially affects erosion and accretion, and therefore sediment movement, instigating shoreline change (Section 5.4.2.1 of Wong et al., 2014)805, which could affect land-based ecosystems. Global observations indicate no overall clear effect of SLR on shoreline change (Le Cozannet et al., 2014)806, as it is highly site specific (e.g., Romine et al., 2013)807. Information and geological constraints reduce shoreline movement, causing coastal squeeze. In Japan, for example, SLR is projected to cause beach losses under an RCP2.6 scenario, which will increase under RCP8.5 (Udo and Takeda, 2017)808. Further, compound flooding (the combined risk of flooding from multiple sources) has increased significantly over the past century in major coastal cities (Wahl et al., 2015)809 and is likely to increase with further development and SLR at 1.5°C and 2°C unless adaptation is undertaken. Thus, overall SLR will have a range of adverse effects on coastal zones (medium confidence). Adaptation to coastal change from SLR and other drivers is occurring today (high confidence) (see Cross-Chapter Box 9 in Chapter 4), including migration, ecosystem-based adaptation, raising infrastructure and defences, salt-tolerant food production, early warning systems, insurance and education (Section 5.4.2.1 of Wong et al., 2014)810. Climate change mitigation will reduce the rate of SLR this century, decreasing the need for extensive and, in places, immediate adaptation. Adaptation will reduce impacts in human settings (high confidence) (Hinkel et al., 2014; Wong et al., 2014)811, although there is less certainty for natural ecosystems (Sections 4.3.2 and 4.3.3). With rising seas, ecosystem-based adaptation (e.g., restoring mangroves) and protection against their transitions (Saunders et al., 2014)812. Options for responding to these challenges include reducing the impact of other stresses such as those arising from tourism, fishing, coastal development and unsustainable aquaculture/agriculture. In some cases, restoration of coastal habitats and ecosystems can be a cost-effective way of responding to changes arising from increasing levels of exposure from rising sea levels, changes in storm conditions, coastal inundation and salinization (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Spalding et al., 2014; Elliff and Silva, 2017)813. Since AR5, planned and autonomous adaptation and forward planning have become more widespread (Araos et al., 2016; Nicholls et al., 2018)814, but continued efforts are required as many localities are in the early stages of adapting or are not adapting at all (Cross-Chapter Box 9 in Chapter 4; Araos et al., 2016)815. This is region and sub-sector specific, and also linked to non-climatic factors (Ford et al., 2015; Araos et al., 2016; Lesnikowski et al., 2016)816. Adaptation pathways (e.g., Ranger et al., 2013; Barnett et al., 2014; Rosenzweig and Solecki, 2014; Buurman and Babovic, 2016)817 assist long-term planning but are not widespread practices despite knowledge of long-term risks (Section 4.2.2). Furthermore, human retreat and migration are increasingly being considered as an adaptation response (Hauer et al., 2016; Geisler and Currens, 2017)818, with a growing emphasis on green adaptation. There are few studies on the adaptation limits to SLR where transformation change may be required (AR5 Section 5.5 of Wong et al., 2014819; Nicholls et al., 2015820). Sea level rise poses a long-term threat (Section 3.3.9), and adaptation will remain essential at the centennial scale under 1.5°C and 2°C of warming (high confidence). Climate scenario Impact factor, assuming there is no adaptation or protection at all (50th, [5th-95th percentiles]) Year 2050 2100 2200 2300 1.5°C Temperature rise wrt 1850–1900 (°C) 1.71 (1.44–2.16) 1.60 (1.26–2.33) 1.41 (1.15–2.10) 1.32 (1.12–1.81) SLR (m) wrt 1986–2005 0.20 (0.14–0.29) 0.40 (0.26–0.62) 0.73 (0.47–1.25) 1.00 (0.59–1.55) Land exposed (x103 km2) 574 [558–597] 620 [575–669] 666 [595–772] 702 [666–853] People exposed, SSP1–5 (millions) 127.9–139.0 [123.4–134.0, 134.5–146.4] 102.7–153.5 [94.8–140.7, 102.7–153.5] — 133.8–207.1 [112.3–169.6, 165.2–263.4]* 2°C Temperature rise wrt 1850–1900 (° C) 1.76 (1.51–2.16) 2.03 (1.72–2.64) 1.90 (1.66–2.57) 1.80 (1.60–2.20) SLR (m) wrt 1986-2005 0.20 (0.14–0.29) 0.46 (0.30–0.69) 0.90 (0.58–1.50) 1.26 (0.74–1.90) Land exposed (x103 km2) 575 [558–598] 637 [585–686] 705 [618–827] 767 [642–937] People exposed, SSP1–5 (millions) 128.1–139.2 [123.6–134.2, 134.7–146.6] 105.5–158.1 [97.0–144.1, 118.1–179.0] — 148.3–233.0 [120.3–183.4, 186.4–301.8]* Global warming of 1.5°C is expected to prove challenging for small island developing states (SIDS) that are already experiencing impacts associated with climate change (high confidence). At 1.5°C, compounding impacts from interactions between climate drivers may contribute to the loss of, or change in, critical natural and human systems (medium to high confidence). There are a number of reduced risks at 1.5°C versus 2°C, particularly when coupled with adaptation efforts (medium to high confidence). Changing climate hazards for SIDS at 1.5°C Mean surface temperature is projected to increase in SIDS at 1.5°C of global warming (high confidence). The Caribbean region will experience 0.5°C–1.5°C of warming compared to a 1971–2000 baseline, with the strongest warming occurring over larger land masses (Taylor et al., 2018)823. Under the Representative Concentration Pathway (RCP)2.6 scenario, the western tropical Pacific is projected to experience warming of 0.5°C–1.7°C relative to 1961–1990. Extreme temperatures will also increase, with potential for elevated impacts as a result of comparably small natural variability (Reyer et al., 2017a)824. Compared to the 1971–2000 baseline, up to 50% of the year is projected to be under warm spell conditions in the Caribbean at 1.5°C, with a further increase of up to 70 days at 2°C (Taylor et al., 2018)825. Changes in precipitation patterns, freshwater availability and drought sensitivity differ among small island regions (medium to high confidence). Some western Pacific islands and those in the northern Indian Ocean may see increased freshwater availability, while islands in most other regions are projected to see a substantial decline (Holding et al., 2016; Karnauskas et al., 2016)826. For several SIDS, approximately 25% of the overall freshwater stress projected under 2°C at 2030 could be avoided by limiting global warming to 1.5°C (Karnauskas et al., 2018)827. In accordance with an overall drying trend, an increasing drought risk is projected for Caribbean SIDS (Lehner et al., 2017)828, and moderate to extreme drought conditions are projected to be about 9% longer on average at 2°C versus 1.5°C for islands in this region (Taylor et al., 2018)829. Projected changes in the ocean system at higher warming targets (Section 3.4.4), including potential changes in circulation (Section 3.3.7) and increases in both surface temperatures (Section 3.3.7) and ocean acidification (Section 3.3.10), suggest increasing risks for SIDS associated with warming levels close to and exceeding 1.5°C. Differences in global sea level between 1.5°C and 2°C depend on the time scale considered and are projected to fully materialize only after 2100 (Section 3.3.9). Projected changes in regional sea level are similarly time dependent, but generally found to be above the global average for tropical regions including small islands (Kopp et al., 2014; Jevrejeva et al., 2016)830. Threats related to sea level rise (SLR) for SIDS, for example from salinization, flooding, permanent inundation, erosion and pressure on ecosystems, will therefore persist well beyond the 21st century even under 1.5°C of warming (Section 3.4.5.3; Nicholls et al., 2018)831. Prolonged interannual sea level inundations may increase throughout the tropical Pacific with ongoing warming and in the advent of an increased frequency of extreme La Niña events, exacerbating coastal impacts of projected global mean SLR (Widlansky et al., 2015)832. Changes to the frequency of extreme El Niño and La Niña events may also increase the frequency of droughts and floods in South Pacific islands (Box 4.2, Section 3.5.2; Cai et al., 2012)833. Extreme precipitation in small island regions is often linked to tropical storms and contributes to the climate hazard (Khouakhi et al., 2017)834. Similarly, extreme sea levels for small islands, particularly in the Caribbean, are linked to tropical cyclone occurrence (Khouakhi and Villarini, 2017)835. Under a 1.5°C stabilization scenario, there is a projected decrease in the frequency of weaker tropical storms and an increase in the number of intense cyclones (Section 3.3.6; Wehner et al., 2018a)836. There are not enough studies to assess differences in tropical cyclone statistics for 1.5°C versus 2°C (Section 3.3.6). There are considerable differences in the adaptation responses to tropical cyclones across SIDS (Cross-Chapter Box 11 in Chapter 4). Impacts on key natural and human systems Projected increases in aridity and decreases in freshwater availability at 1.5°C of warming, along with additional risks from SLR and increased wave-induced run-up, might leave several atoll islands uninhabitable (Storlazzi et al., 2015; Gosling and Arnell, 2016)837. Changes in the availability and quality of freshwater, linked to a combination of changes to climate drivers, may adversely impact SIDS' economies (White and Falkland, 2010; Terry and Chui, 2012; Holding and Allen, 2015; Donk et al., 2018)838. Growth-rate projections based on temperature impacts alone indicate robust negative impacts on gross domestic product (GDP) per capita growth for SIDS (Sections 3.4.7.1, 3.4.9.1 and 3.5.4.9; Pretis et al., 2018)839. These impacts would be reduced considerably under 1.5°C but may be increased by escalating risks from climate-related extreme weather events and SLR (Sections 3.4.5.3, 3.4.9.4 and 3.5.3) Marine systems and associated livelihoods in SIDS face higher risks at 2°C compared to 1.5°C (medium to high confidence). Mass coral bleaching and mortality are projected to increase because of interactions between rising ocean temperatures, ocean acidification, and destructive waves from intensifying storms (Section 3.4.4 and 5.2.3, Box 3.4). At 1.5°C, approximately 70–90% of global coral reefs are projected to be at risk of long-term degradation due to coral bleaching, with these values increasing to 99% at 2°C (Frieler et al., 2013; Schleussner et al., 2016b)840. Higher temperatures are also related to an increase in coral disease development, leading to coral degradation (Maynard et al., 2015)841. For marine fisheries, limiting warming to 1.5°C decreases the risk of species extinction and declines in maximum catch potential, particularly for small islands in tropical oceans (Cheung et al., 2016a)842. Long-term risks of coastal flooding and impacts on populations, infrastructure and assets are projected to increase with higher levels of warming (high confidence). Tropical regions including small islands are expected to experience the largest increases in coastal flooding frequency, with the frequency of extreme water-level events in small islands projected to double by 2050 (Vitousek et al., 2017)843. Wave-driven coastal flooding risks for reef-lined islands may increase as a result of coral reef degradation and SLR (Quataert et al., 2015)844. Exposure to coastal hazards is particularly high for SIDS, with a significant share of population, infrastructure and assets at risk (Sections 3.4.5.3 and 3.4.9; Scott et al., 2012; Kumar and Taylor, 2015; Rhiney, 2015; Byers et al., 2018845). Limiting warming to 1.5°C instead of 2°C would spare the inundation of lands currently home to 60,000 individuals in SIDS by 2150 (Rasmussen et al., 2018)846. However, such estimates do not consider shoreline response (Section 3.4.5) or adaptation. Risks of impacts across sectors are projected to be higher at 1.5°C compared to the present, and will further increase at 2°C (medium to high confidence). Projections indicate that at 1.5°C there will be increased incidents of internal migration and displacement (Sections 3.5.5, 4.3.6 and 5.2.2; Albert et al., 2017)847, limited capacity to assess loss and damage (Thomas and Benjamin, 2017)848 and substantial increases in the risk to critical transportation infrastructure from marine inundation (Monioudi et al., 2018)849. The difference between 1.5°C and 2°C might exceed limits for normal thermoregulation of livestock animals and result in persistent heat stress for livestock animals in SIDS (Lallo et al., 2018)850. At 1.5°C, limits to adaptation will be reached for several key impacts in SIDS, resulting in residual impacts, as well as loss and damage (Section 1.1.1, Cross-Chapter Box 12 in Chapter 5). Limiting temperature increase to 1.5°C versus 2°C is expected to reduce a number of risks, particularly when coupled with adaptation efforts that take into account sustainable development (Section 3.4.2 and 5.6.3.1, Box 4.3 and 5.3, Mycoo, 2017; Thomas and Benjamin, 2017)851. Region-specific pathways for SIDS exist to address climate change (Section 5.6.3.1, Boxes 4.6 and 5.3, Cross-Chapter Box 11 in Chapter 4). Quantifying the observed impacts of climate change on food security and food production systems requires assumptions about the many non-climate variables that interact with climate change variables. Implementing specific strategies can partly or greatly alleviate the climate change impacts on these systems (Wei et al., 2017)852, whilst the degree of compensation is mainly dependent on the geographical area and crop type (Rose et al., 2016)853. Despite these uncertainties, recent studies confirm that observed climate change has already affected crop suitability in many areas, resulting in changes in the production levels of the main agricultural crops. These impacts are evident in many areas of the world, ranging from Asia (C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016)854 to America (Cho and McCarl, 2017)855 and Europe (Ramirez-Cabral et al., 2016)856, and they particularly affect the typical local crops cultivated in specific climate conditions (e.g., Mediterranean crops like olive and grapevine, Moriondo et al., 2013a, b)857. Temperature and precipitation trends have reduced crop production and yields, with the most negative impacts being on wheat and maize (Lobell et al., 2011)858, whilst the effects on rice and soybean yields are less clear and may be positive or negative (Kim et al., 2013; van Oort and Zwart, 2018)859. Warming has resulted in positive effects on crop yield in some high-latitude areas (Jaggard et al., 2007; Supit et al., 2010; Gregory and Marshall, 2012; C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016; Daliakopoulos et al., 2017)860, and may make it possible to have more than one harvest per year (B. Chen et al., 2014; Sun et al., 2015)861. Climate variability has been found to explain more than 60% of the of maize, rice, wheat and soybean yield variations in the main global breadbaskets areas (Ray et al., 2015)862, with the percentage varying according to crop type and scale (Moore and Lobell, 2015; Kent et al., 2017)863. Climate trends also explain changes in the length of the growing season, with greater modifications found in the northern high-latitude areas (Qian et al., 2010; Mueller et al., 2015)864. The rise in tropospheric ozone has already reduced yields of wheat, rice, maize and soybean by 3–16% globally (Van Dingenen et al., 2009)865. In some studies, increases in atmospheric CO2 concentrations were found to increase yields by enhancing radiation and water use efficiencies (Elliott et al., 2014; Durand et al., 2018)866. In open-top chamber experiments with a combination of elevated CO2 and 1.5°C of warming, maize and potato yields were observed to increase by 45.7% and 11%, respectively (Singh et al., 2013; Abebe et al., 2016)867. However, observations of trends in actual crop yields indicate that reductions as a result of climate change remain more common than crop yield increases, despite increased atmospheric CO2 concentrations (Porter et al., 2014)868. For instance, McGrath and Lobell (2013)869 indicated that production stimulation at increased atmospheric CO2 concentrations was mostly driven by differences in climate and crop species, whilst yield variability due to elevated CO2 was only about 50–70% of the variability due to climate. Importantly, the faster growth rates induced by elevated CO2 have been found to coincide with lower protein content in several important C3 cereal grains (Myers et al., 2014)870, although this may not always be the case for C4 grains, such as sorghum, under drought conditions (De Souza et al., 2015)871. Elevated CO2 concentrations of 568–590 ppm (a range that corresponds approximately to RCP6 in the 2080s and hence a warming of 2.3°C–3.3°C (van Vuuren et al., 2011a872, AR5 WGI Table 12.2) alone reduced the protein, micronutrient and B vitamin content of the 18 rice cultivars grown most widely in Southeast Asia, where it is a staple food source, by an amount sufficient to create nutrition-related health risks for 600 million people (Zhu et al., 2018)873. Overall, the effects of increased CO2 concentrations alone during the 21st century are therefore expected to have a negative impact on global food security (medium confidence). Crop yields in the future will also be affected by projected changes in temperature and precipitation. Studies of major cereals showed that maize and wheat yields begin to decline with 1°C–2°C of local warming and under nitrogen stress conditions at low latitudes (high confidence) (Porter et al., 2014; Rosenzweig et al., 2014)874. A few studies since AR5 have focused on the impacts on cropping systems for scenarios where the global mean temperature increase is within 1.5°C. Schleussner et al. (2016b)875 projected that constraining warming to 1.5°C rather than 2°C would avoid significant risks of declining tropical crop yield in West Africa, Southeast Asia, and Central and South America. Ricke et al. (2016)876 highlighted that cropland stability declines rapidly between 1°C and 3°C of warming, whilst Bassu et al. (2014)877 found that an increase in air temperature negatively influences the modelled maize yield response by –0.5 t ha−1°C–1 and Challinor et al. (2014)878 reported similar effect for tropical regions. Niang et al. (2014)879 projected significantly lower risks to crop productivity in Africa at 1.5°C compared to 2°C of warming. Lana et al. (2017)880 indicated that the impact of temperature increases on crop failure of maize hybrids would be much greater as temperatures increase by 2°C compared to 1.5°C (high confidence). J. Huang et al. (2017)881 found that limiting warming to 1.5°C compared to 2°C would reduce maize yield losses over drylands. Although Rosenzweig et al. (2017, 2018)882 did not find a clear distinction between yield declines or increases in some breadbasket regions between the two temperature levels, they generally did find projections of decreasing yields in breadbasket regions when the effects of CO2 fertilization were excluded. Iizumi et al. (2017)883 found smaller reductions in maize and soybean yields at 1.5°C than at 2°C of projected warming, higher rice production at 2°C than at 1.5°C, and no clear differences for wheat on a global mean basis. These results are largely consistent with those of other studies (Faye et al., 2018; Ruane et al., 2018)884. In the western Sahel and southern Africa, moving from 1.5°C to 2°C of warming has been projected to result in a further reduction of the suitability of maize, sorghum and cocoa cropping areas and yield losses, especially for C3 crops, with rainfall change only partially compensating these impacts (Läderach et al., 2013; World Bank, 2013; Sultan and Gaetani, 2016)885. A significant reduction has been projected for the global production of wheat (by 6.0 ± 2.9%), rice (by 3.2 ± 3.7%), maize (by 7.4 ± 4.5%), and soybean, (by 3.1%) for each degree Celsius increase in global mean temperature (Asseng et al., 2015; C. Zhao et al., 2017)886. Similarly, Li et al. (2017)887 indicated a significant reduction in rice yields for each degree Celsius increase, by about 10.3%, in the greater Mekong subregion (medium confidence; Cross-Chapter Box 6: Food Security in this chapter). Large rice and maize yield losses are to be expected in China, owing to climate extremes (medium confidence) (Wei et al., 2017; Zhang et al., 2017)888. While not often considered, crop production is also negatively affected by the increase in both direct and indirect climate extremes. Direct extremes include changes in rainfall extremes (Rosenzweig et al., 2014)889, increases

Increasing global temperature poses large risks to food security globally and regionally, especially in low-latitude areas (medium confidence) (Cheung et al., 2010; Rosenzweig et al., 2013; Porter et al., 2014; Rosenzweig and Hillel, 2015; Lam et al., 2016)943, with warming of 2°C projected to result in a greater reduction in global crop yields and global nutrition than warming of 1.5°C (high confidence) (Section 3.4.6), owing to the combined effects of changes in temperature, precipitation and extreme weather events, as well as increasing CO_2 concentrations. Climate change can exacerbate malnutrition by reducing nutrient availability and the quality of food products (medium confidence) (Cramer et al., 2014; Zhu et al., 2018)944. Generally, vulnerability to decreases in water and food availability is projected to be reduced at 1.5°C versus 2°C (Cheung et al., 2016a; Betts et al., 2018)945, especially in regions such as the African Sahel, the Mediterranean, central Europe, the Amazon, and western and southern Africa (medium confidence) (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018)946. Rosenzweig et al. (2018)947 and Ruane et al. (2018)948 reported that the higher CO_2 concentrations associated with 2°C as compared to those at 1.5°C of global warming are projected to drive positive effects in some regions. Production can also benefit from warming in higher latitudes, with more fertile soils, favouring crops, and grassland production, in contrast to the situation at low latitudes (Section 3.4.6), and similar benefits could arise for high-latitude fisheries production (high confidence) (Section 3.4.6.3). Studies exploring regional climate change risks on crop production are strongly influenced by the use of different regional climate change projections and by the assumed strength of CO_2 fertilization effects (Section 3.6), which are uncertain. For C3 crops, theoretically advantageous CO_2 fertilization effects may not be realized in the field; further, they are often accompanied by losses in protein and nutrient content of crops (Section 3.6), and hence these projected benefits may not be realized. In addition, some micronutrients such as iron and zinc will accumulate less and be less available in food (Myers et al., 2014)949. Together, the impacts on protein availability may bring as many as 150 million people into protein deficiency by 2050 (Medek et al., 2017)950. However, short-term benefits could arise for high-latitude fisheries production as waters warm, sea ice contracts and primary productivity increases under climate change (high confidence) (Section 3.4.6.3; Cheung et al., 2010; Hollowed and Sundby, 2014; Lam et al., 2016; Sundby et al., 2016; Weatherdon et al., 2016)951. Factors affecting the projections of food security include variability in regional climate projections, climate change mitigation (where land use is involved; see Section 3.6 and Cross-Chapter Box 7 in this chapter) and biological responses (medium confidence) (Section 3.4.6.1; McGrath and Lobell, 2013; Elliott et al., 2014; Pörtner et al., 2014; Durand et al., 2018)952, extreme events such as droughts and floods (high confidence) (Sections 3.4.6.1, 3.4.6.2; Rosenzweig et al., 2014; Wei et al., 2017)953, financial volatility (Kannan et al., 2000; Ghosh, 2010; Naylor and Falcon, 2010; HLPE, 2011)954, and the distributions of pests and disease (Jiao et al., 2014; van Bruggen et al., 2015)955. Changes in temperature and precipitation are projected to increase global food prices by 3–84% by 2050 (IPCC, 2013)956. Differences in price impacts of climate change are accompanied by differences in land-use change (Nelson et al., 2014b)957, energy policies and food trade (Mueller et al., 2011; Wright, 2011; Roberts and Schlenker, 2013)958. Fisheries and aquatic production systems (aquaculture) face similar challenges to those of crop and livestock sectors (Section 3.4.6.3; Asiedu et al., 2017a, b; Utete et al., 2018)959. Human influences on food security include demography, patterns of food waste, diet shifts, incomes and prices, storage, health status, trade patterns, conflict, and access to land and governmental or other assistance (Chapters 4 and 5). Across all these systems, the efficiency of adaptation strategies is uncertain because it is strongly linked with future economic and trade environments and their response to changing food availability (medium confidence) (Lobell et al., 2011; von Lampe et al., 2014; d'Amour et al., 2016960; Wei et al., 2017)961. Climate change impacts on food security can be reduced through adaptation (Hasegawa et al., 2014)962. While climate change is projected to decrease agricultural yield, the consequences could be reduced substantially at 1.5°C versus 2°C with appropriate investment (high confidence) (Neumann et al., 2010; Muller, 2011; Roudier et al., 2011)963, awareness-raising to help inform farmers of new technologies for maintaining yield, and strong adaptation strategies and policies that develop sustainable agricultural choices (Sections 4.3.2 and 4.5.3). In this regard, initiatives such as 'climate-smart' food production and distribution systems may assist via technologies and adaptation strategies for food systems (Lipper et al., 2014; Martinez-Baron et al., 2018; Whitfield et al., 2018)964, as well as helping meet mitigation goals (Harvey et al., 2014)965. K.R. Smith et al. (2014)966 concluded that climate change will exacerbate current levels of childhood undernutrition and stunting through reduced food availability. As well, climate change can drive undernutrition-related childhood mortality, and increase disability-adjusted life years lost, with the largest risks in Asia and Africa (Supplementary Material 3.SM, Table 3.SM.12; Ishida et al., 2014; Hasegawa et al., 2016; Springmann et al., 2016)967. Studies comparing the health risks associated with reduced food security at 1.5°C and 2°C concluded that risks would be higher and the globally undernourished population larger at 2°C (Hales et al., 2014; Ishida et al., 2014; Hasegawa et al., 2016)968. Climate change impacts on dietary and weight-related risk factors are projected to increase mortality, owing to global reductions in food availability and consumption of fruit, vegetables and red meat (Springmann et al., 2016)969. Further, temperature increases are projected to reduce the protein and micronutrient content of major cereal crops, which is expected to further affect food and nutritional security (Myers et al., 2017; Zhu et al., 2018)970. Strategies for improving food security often do so in complex settings such as the Mekong River basin in Southeast Asia. The Mekong is a major food bowl (Smajgl et al., 2015)971 but is also a climate change hotspot (de Sherbinin, 2014; Lebel et al., 2014)972. This area is also a useful illustration of the complexity of adaptation choices and actions in a 1.5°C warmer world. Climate projections include increased annual average temperatures and precipitation in the Mekong (Zhang et al., 2017)973, as well as increased flooding and related disaster risks (T.F. Smith et al., 2013; Ling et al., 2015; Zhang et al., 2016)974. Sea level rise and saline intrusion are ongoing risks to agricultural systems in this area by reducing soil fertility and limiting the crop productivity (Renaud et al., 2015)975. The main climate impacts in the Mekong are expected to be on ecosystem health, through salinity intrusion, biomass reduction and biodiversity losses (Le Dang et al., 2013; Smajgl et al., 2015)976; agricultural productivity and food security (Smajgl et al., 2015)977; livelihoods such as fishing and farming (D. Wu et al., 2013)978; and disaster risk (D. Wu et al., 2013; Hoang et al., 2016)979, with implications for human mortality and economic and infrastructure losses. Adaptation imperatives and costs in the Mekong will be higher under higher temperatures and associated impacts on agriculture and aquaculture, hazard exposure, and infrastructure. Adaptation measures to meet food security include greater investment in crop diversification and integrated agriculture–aquaculture practices (Renaud et al., 2015)980, improvement of water-use technologies (e.g., irrigation, pond capacity improvement and rainwater harvesting), soil management, crop diversification, and strengthening allied sectors such as livestock rearing and aquaculture (ICEM, 2013)981. Ecosystem-based approaches, such as integrated water resources management, demonstrate successes in mainstreaming adaptation into existing strategies (Sebesvari et al., 2017)982. However, some of these adaptive strategies can have negative impacts that deepen the divide between land-wealthy and land-poor farmers (Chapman et al., 2016)983. Construction of high dikes, for example, has enabled triple-cropping, which benefits land-wealthy farmers but leads to increasing debt for land-poor farmers (Chapman and Darby, 2016)984. Institutional innovation has happened through the Mekong River Commission (MRC), which is an intergovernmental body between Cambodia, Lao PDR, Thailand and Viet Nam that was established in 1995. The MRC has facilitated impact assessment studies, regional capacity building and local project implementation (Schipper et al., 2010)985, although the mainstreaming of adaptation into development policies has lagged behind needs (Gass et al., 2011)986. Existing adaptation interventions can be strengthened through greater flexibility of institutions dealing with land-use planning and agricultural production, improved monitoring of saline intrusion, and the installation of early warning systems that can be accessed by the local authorities or farmers (Renaud et al., 2015; Hoang et al., 2016; Tran et al., 2018)987. It is critical to identify and invest in synergistic strategies from an ensemble of infrastructural options (e.g., building dikes); soft adaptation measures (e.g., land-use change) (Smajgl et al., 2015; Hoang et al., 2018)988; combinations of top-down government-led (e.g., relocation) and bottom-up household strategies (e.g., increasing house height) (Ling et al., 2015)989; and community-based adaptation initiatives that merge scientific knowledge with local solutions (Gustafson et al., 2016, 2018; Tran et al., 2018)990. Special attention needs to be given to strengthening social safety nets and livelihood assets whilst ensuring that adaptation plans are mainstreamed into broader development goals (Sok and Yu, 2015; Kim et al., 2017)991. The combination of environmental, social and economic pressures on people in the Mekong River basin highlights the complexity of climate change impacts and adaptation in this region, as well as the fact that costs are projected to be much lower at 1.5°C than 2°C of global warming. Climate change adversely affects human health by increasing exposure and vulnerability to climate-related stresses, and decreasing the capacity of health systems to manage changes in the magnitude and pattern of climate-sensitive health outcomes (Cramer et al., 2014; Hales et al., 2014)992. Changing weather patterns are associated with shifts in the geographic range, seasonality and transmission intensity of selected climate-sensitive infectious diseases (e.g., Semenza and Menne, 2009)993, and increasing morbidity and mortality are associated with extreme weather and climate events (e.g., K.R. Smith et al., 2014)994. Health detection and attribution studies conducted since AR5 have provided evidence, using multistep attribution, that climate change is negatively affecting adverse health outcomes associated with heatwaves, Lyme disease in Canada, and Vibrio emergence in northern Europe (Mitchell, 2016; Mitchell et al., 2016; Ebi et al., 2017)995. The IPCC AR5 concluded there is high to very high confidence that climate change will lead to greater risks of injuries, disease and death, owing to more intense heatwaves and fires, increased risks of undernutrition, and consequences of reduced labour productivity in vulnerable populations (K.R. Smith et al., 2014)996. The projected risks to human health of warming of 1.5°C and 2°C, based on studies of temperature-related morbidity and mortality, air quality and vector borne diseases assessed in and since AR5, are summarized in Supplementary Material 3.SM, Tables 3.SM.8, 3.SM.9 and 3.SM.10 (based on Ebi et al., 2018)997. Other climate-sensitive health outcomes, such as diarrheal diseases, mental health issues and the full range of sources of poor air quality, were not considered because of the lack of projections of how risks could change at 1.5°C and 2°C. Few projections were available for specific temperatures above pre-industrial levels; Supplementary Material 3.SM, Table 3.SM.7 provides the conversions used to translate risks projected for particular time slices to those for specific temperature changes (Ebi et al., 2018)998. Temperature-related morbidity and mortality: The magnitude of projected heat-related morbidity and mortality is greater at 2°C than at 1.5°C of global warming (very high confidence)(Doyon et al., 2008; Jackson et al., 2010; Hanna et al., 2011; Huang et al., 2012; Petkova et al., 2013; Hajat et al., 2014; Hales et al., 2014; Honda et al., 2014; Vardoulakis et al., 2014; Garland et al., 2015; Huynen and Martens, 2015; Li et al., 2015; Schwartz et al., 2015; L. Wang et al., 2015; Guo et al., 2016; T. Li et al., 2016; Chung et al., 2017; Kendrovski et al., 2017; Mishra et al., 2017; Arnell et al., 2018; Mitchell et al., 2018b)999. The number of people exposed to heat events is projected to be greater at 2°C than at 1.5°C (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018)1000. The extent to which morbidity and mortality are projected to increase varies by region, presumably because of differences in acclimatization, population vulnerability, the built environment, access to air conditioning and other factors (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018)1001. Populations at highest risk include older adults, children, women, those with chronic diseases, and people taking certain medications (very high confidence). Assuming adaptation takes place reduces the projected magnitude of risks (Hales et al., 2014; Huynen and Martens, 2015; T. Li et al., 2016)1002. In some regions, cold-related mortality is projected to decrease with increasing temperatures, although increases in heat-related mortality generally are projected to outweigh any reductions in cold-related mortality with warmer winters, with the heat-related risks increasing with greater degrees of warming (Huang et al., 2012; Hajat et al., 2014; Vardoulakis et al., 2014; Gasparrini et al., 2015; Huynen and Martens, 2015; Schwartz et al., 2015)1003. Occupational health: Higher ambient temperatures and humidity levels place additional stress on individuals engaging in physical activity. Safe work activity and worker productivity during the hottest months of the year would be increasingly compromised with additional climate change (medium confidence) (Dunne et al., 2013; Kjellstrom et al., 2013, 2018; Sheffield et al., 2013; Habibi Mohraz et al., 2016)1004. Patterns of change may be complex; for example, at 1.5°C, there could be about a 20% reduction in areas experiencing severe heat stress in East Asia, compared to significant increases in low latitudes at 2°C (Lee and Min, 2018)1005. The costs of preventing workplace heat-related illnesses through worker breaks suggest that the difference in economic loss between 1.5°C and 2°C could be approximately 0.3% of global gross domestic product (GDP) in 2100 (Takakura et al., 2017)1006. In China, taking into account population growth and employment structure, high temperature subsidies for employees working on extremely hot days are projected to increase from 38.6 billion yuan yr–1 in 1979–2005 to 250 billion yuan yr–1 in the 2030s (about 1.5°C) (Zhao et al., 2016)1007. Air quality: Because ozone formation is temperature dependent, projections focusing only on temperature increase generally conclude that ozone-related mortality will increase with additional warming, with the risks higher at 2°C than at 1.5°C (high confidence) (Supplementary Material 3.SM, Table 3.SM.9; Heal et al., 2013; Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016; Dionisio et al., 2017; J.Y. Lee et al., 2017)1008. Reductions in precursor emissions would reduce future ozone concentrations and associated mortality. Mortality associated with exposure to particulate matter could increase or decrease in the future, depending on climate projections and emissions assumptions (Supplementary Material 3.SM, Table 3.SM.8; Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016)1009. Malaria: Recent projections of the potential impacts of climate change on malaria globally and for Asia, Africa, and South America (Supplementary Material 3.SM, Table 3.SM.10) confirm that weather and climate are among the drivers of the geographic range, intensity of transmission, and seasonality of malaria, and that the relationships are not necessarily linear, resulting in complex patterns of changes in risk with additional warming (very high confidence) (Ren et al., 2016; Song et al., 2016; Semakula et al., 2017)1010. Projections suggest that the burden of malaria could increase with climate change because of a greater geographic range of the Anopheles vector, longer season, and/or increase in the number of people at risk, with larger burdens at higher levels of warming, but with regionally variable patterns (medium to high confidence). Vector populations are projected to shift with climate change, with expansions and reductions depending on the degree of local warming, the ecology of the mosquito vector, and other factors (Ren et al., 2016)1011. Aedes (mosquito vector for dengue fever, chikungunya, yellow fever and Zika virus): Projections of the geographic distribution of Aedes aegypti and Ae. albopictus (principal vectors) or of the prevalence of dengue fever generally conclude that there will be an increase in the number of mosquitos and a larger geographic range at 2°C than at 1.5°C, and they suggest that more individuals will be at risk of dengue fever, with regional differences (high confidence) (Fischer et al., 2011, 2013; Colón-González et al., 2013, 2018; Bouzid et al., 2014; Ogden et al., 2014a; Mweya et al., 2016)1012. The risks increase with greater warming. Projections suggest that climate change is projected to expand the geographic range of chikungunya, with greater expansions occurring at higher degrees of warming (Tjaden et al., 2017)1013. Other vector-borne diseases: Increased warming in North America and Europe could result in geographic expansions of regions (latitudinally and altitudinally) climatically suitable for West Nile virus transmission, particularly along the current edges of its transmission areas, and extension of the transmission season, with the magnitude and pattern of changes varying by location and level of warming (Semenza et al., 2016)1014. Most projections conclude that climate change could expand the geographic range and seasonality of Lyme and other tick-borne diseases in parts of North America and Europe (Ogden et al., 2014b; Levi et al., 2015)1015. The projected changes are larger with greater warming and under higher greenhouse gas emissions pathways. Projections of the impacts of climate change on leishmaniosis and Chagas disease indicate that climate change could increase or decrease future health burdens, with greater impacts occurring at higher degrees of warming (González et al., 2014; Ceccarelli and Rabinovich, 2015)1016. In summary, warming of 2°C poses greater risks to human health than warming of 1.5°C, often with the risks varying regionally, with a few exceptions (high confidence). There is very high confidence that each additional unit of warming could increase heat-related morbidity and mortality, and that adaptation would reduce the magnitude of impacts. There is high confidence that ozone-related mortality could increase if precursor emissions remain the same, and that higher temperatures could affect the transmission of some infectious diseases, with increases and decreases projected depending on the disease (e.g., malaria, dengue fever, West Nile virus and Lyme disease), region and degree of temperature change. There is new literature on urban climate change and its differential impacts on and risks for infrastructure sectors – energy, water, transport and buildings – and vulnerable populations, including those living in informal settlements (UCCRN, 2018)1017. However, there is limited literature on the risks of warming of 1.5°C and 2°C in urban areas. Heat-related extreme events (Matthews et al., 2017)1018, variability in precipitation (Yu et al., 2018)1019 and sea level rise can directly affect urban areas (Section 3.4.5, Bader et al., 2018; Dawson et al., 2018)1020. Indirect risks may arise from interactions between urban and natural systems. Future warming and urban expansion could lead to more extreme heat stress (Argüeso et al., 2015; Suzuki-Parker et al., 2015)1021. At 1.5°C of warming, twice as many megacities (such as Lagos, Nigeria and Shanghai, China) could become heat stressed, exposing more than 350 million more people to deadly heat by 2050 under midrange population growth. Without considering adaptation options, such as cooling from more reflective roofs, and overall characteristics of urban agglomerations in terms of land use, zoning and building codes (UCCRN, 2018)1022, Karachi (Pakistan) and Kolkata (India) could experience conditions equivalent to the deadly 2015 heatwaves on an annual basis under 2°C of warming (Akbari et al., 2009; Oleson et al., 2010; Matthews et al., 2017)1023. Warming of 2°C is expected to increase the risks of heatwaves in China's urban agglomerations (Yu et al., 2018)1024. Stabilizing at 1.5°C of warming instead of 2°C could decrease mortality related to extreme temperatures in key European cities, assuming no adaptation and constant vulnerability (Jacob et al., 2018; Mitchell et al., 2018a)1025. Holding temperature change to below 2°C but taking urban heat islands (UHI) into consideration, projections indicate that there could be a substantial increase in the occurrence of deadly heatwaves in cities. The urban impacts of these heatwaves are expected to be similar at 1.5°C and 2°C and substantially larger than under the present climate (Matthews et al., 2017; Yu et al., 2018)1026. Increases in the intensity of UHI could exacerbate warming of urban areas, with projections ranging from a 6% decrease to a 30% increase for a doubling of CO_2 (McCarthy et al., 2010)1027. Increases in population and city size, in the context of a warmer climate, are projected to increase UHI (Georgescu et al., 2012; Argüeso et al., 2014; Conlon et al., 2016; Kusaka et al., 2016; Grossman-Clarke et al., 2017)1028. For extreme heat events, an additional 0.5°C of warming implies a shift from the upper bounds of observed natural variability to a new global climate regime (Schleussner et al., 2016b)1029, with distinct implications for the urban poor (Revi et al., 2014; Jean-Baptiste et al., 2018; UCCRN, 2018)1030. Adverse impacts of extreme events could arise in tropical coastal areas of Africa, South America and Southeast Asia (Schleussner et al., 2016b)1031. These urban coastal areas in the tropics are particularly at risk given their large informal settlements and other vulnerable urban populations, as well as vulnerable assets, including businesses and critical urban infrastructure (energy, water, transport and buildings) (McGranahan et al., 2007; Hallegatte et al., 2013; Revi et al., 2014; UCCRN, 2018)1032. Mediterranean water stress is projected to increase from 9% at 1.5°C to 17% at 2°C compared to values in 1986–2005 period. Regional dry spells are projected to expand from 7% at 1.5°C to 11% at 2°C for the same reference period. Sea level rise is expected to be lower at 1.5°C than 2°C, lowering risks for coastal metropolitan agglomerations (Schleussner et al., 2016b)1033. Climate models are better at projecting implications of greenhouse gas forcing on physical systems than at assessing differential risks associated with achieving a specific temperature target (James et al., 2017)1034. These challenges in managing risks are amplified when combined with the scale of urban areas and assumptions about socio-economic pathways (Krey et al., 2012; Kamei et al., 2016; Yu et al., 2016; Jiang and Neill, 2017)1035. In summary, in the absence of adaptation, in most cases, warming of 2°C poses greater risks to urban areas than warming of 1.5°C, depending on the vulnerability of the location (coastal or non-coastal) (high confidence), businesses, infrastructure sectors (energy, water and transport), levels of poverty, and the mix of formal and informal settlements. Climate change could affect tourism, energy systems and transportation through direct impacts on operations (e.g., sea level rise) and through impacts on supply and demand, with the risks varying significantly with geographic region, season and time. Projected risks also depend on assumptions with respect to population growth, the rate and pattern of urbanization, and investments in infrastructure. Table 3.SM.11 in Supplementary Material 3.SM summarizes the cited publications. The implications of climate change for the global tourism sector are far-reaching and are impacting sector investments, destination assets (environment and cultural), operational and transportation costs, and tourist demand patterns (Scott et al., 2016a; Scott and Gössling, 2018)1036. Since AR5, observed impacts on tourism markets and destination communities continue to be not well analysed, despite the many analogue conditions (e.g., heatwaves, major hurricanes, wild fires, reduced snow pack, coastal erosion and coral reef bleaching) that are anticipated to occur more frequently with climate change. There is some evidence that observed impacts on tourism assets, such as environmental and cultural heritage, are leading to the development of 'last chance to see' tourism markets, where travellers visit destinations before they are substantially degraded by climate change impacts or to view the impacts of climate change on landscapes (Lemelin et al., 2012; Stewart et al., 2016; Piggott-McKellar and McNamara, 2017)1037. There is limited research on the differential risks of a 1.5° versus 2°C temperature increase and resultant environmental and socio-economic impacts in the tourism sector. The translation of these changes in climate resources for tourism into projections of tourism demand remains geographically limited to Europe. Based on analyses of tourist comfort, summer and spring /autumn tourism in much of western Europe may be favoured by 1.5°C of warming, but with negative effects projected for Spain and Cyprus (decreases of 8% and 2%, respectively, in overnight stays) and most coastal regions of the Mediterranean (Jacob et al., 2018)1038. Similar geographic patterns of potential tourism gains (central and northern Europe) and reduced summer favourability (Mediterranean countries) are projected under 2°C (Grillakis et al., 2016)1039. Considering potential changes in natural snow only, winter overnight stays at 1.5°C are projected to decline by 1–2% in Austria, Italy and Slovakia, with an additional 1.9 million overnight stays lost under 2°C of warming (Jacob et al., 2018)1040. Using an econometric analysis of the relationship between regional tourism demand and climate conditions, Ciscar et al. (2014)1041 projected that a 2°C warmer world would reduce European tourism by 5% (€15 billion yr–1), with losses of up to 11% (€6 billion yr–1) for southern Europe and a potential gain of €0.5 billion yr–1 in the UK. There is growing evidence that the magnitude of projected impacts is temperature dependent and that sector risks could be much greater with higher temperature increases and resultant environmental and socio-economic impacts (Markham et al., 2016; Scott et al., 2016a; Jones, 2017; Steiger et al., 2017)1042. Studies from 27 countries consistently project substantially decreased reliability of ski areas that are dependent on natural snow, increased snowmaking requirements and investment in snowmaking systems, shortened and more variable ski seasons, a contraction in the number of operating ski areas, altered competitiveness among and within regional ski markets, and subsequent impacts on employment and the value of vacation properties (Steiger et al., 2017)1043. Studies that omit snowmaking do not reflect the operating realities of most ski areas and overestimate impacts at 1.5°C–2°C. In all regional markets, the extent and timing of these impacts depend on the magnitude of climate change and the types of adaptive responses by the ski industry, skiers and destination communities. The decline in the number of former Olympic Winter Games host locations that could remain climatically reliable for future Olympic and Paralympic Winter Games has been projected to be much greater under scenarios warmer than 2°C (Scott et al., 2015; Jacob et al., 2018)1044. The tourism sector is also affected by climate-induced changes in environmental assets critical for tourism, including biodiversity, beaches, glaciers and other features important for environmental and cultural heritage. Limited analyses of projected risks associated with 1.5°C versus 2°C are available (Section 3.4.4.12). A global analysis of sea level rise (SLR) risk to 720 UNESCO Cultural World Heritage sites projected that about 47 sites might be affected under 1°C of warming, with this number increasing to 110 and 136 sites under 2°C and 3°C, respectively (Marzeion and Levermann, 2014)1045. Similar risks to vast worldwide coastal tourism infrastructure and beach assets remain unquantified for most major tourism destinations and small island developing states (SIDS) that economically depend on coastal tourism. One exception is the projection that an eventual 1 m SLR could partially or fully inundate 29% of 900 coastal resorts in 19 Caribbean countries, with a substantially higher proportion (49–60%) vulnerable to associated coastal erosion (Scott and Verkoeyen, 2017)1046. A major barrier to understanding the risks of climate change for tourism, from the destination community scale to the global scale, has been the lack of integrated sectoral assessments that analyse the full range of potential compounding impacts and their interactions with other major drivers of tourism (Rosselló-Nadal, 2014; Scott et al., 2016b)1047. When applied to 181 countries, a global vulnerability index including 27 indicators found that countries with the lowest risk are located in western and northern Europe, central Asia, Canada and New Zealand, while the highest sector risks are projected for Africa, the Middle East, South Asia and SIDS in the Caribbean, Indian and Pacific Oceans (Scott and Gössling, 2018)1048. Countries with the highest risks and where tourism represents a significant proportion of the national economy (i.e., more than 15% of GDP) include many SIDS and least developed countries. Sectoral climate change risk also aligns strongly with regions where tourism growth is projected to be the strongest over the coming decades, including sub-Saharan Africa and South Asia, pointing to an important potential barrier to tourism development. The transnational implications of these impacts on the highly interconnected global tourism sector and the contribution of tourism to achieving the 2030 sustainable development goals (SDGs) remain important uncertainties. In summary, climate is an important factor influencing the geography and seasonality of tourism demand and spending globally (very high confidence). Increasing temperatures are projected to directly impact climate-dependent tourism markets, including sun, beach and snow sports tourism, with lesser risks for other tourism markets that are less climate sensitive (high confidence). The degradation or loss of beach and coral reef assets is expected to increase risks for coastal tourism, particularly in subtropical and tropical regions (high confidence). Climate change is projected to lead to an increased demand for air conditioning in most tropical and subtropical regions (Arent et al., 2014; Hong and Kim, 2015)1049 (high confidence). Increasing temperatures will decrease the thermal efficiency of fossil, nuclear, biomass and solar power generation technologies, as well as buildings and other infrastructure (Arent et al., 2014)1050. For example, in Ethiopia, capital expenditures through 2050 might either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario (Block and Strzepek, 2012)1051. Impacts on energy systems can affect gross domestic product (GDP). The economic damage in the United States from climate change is estimated to be, on average, roughly 1.2% cost of GDP per year per 1°C increase under RCP8.5 (Hsiang et al., 2017)1052. Projections of GDP indicate that negative impacts of energy demand associated with space heating and cooling in 2100 will be greatest (median: –0.94% change in GDP) under 4°C (RCP8.5) compared with under 1.5°C (median: –0.05%), depending on the socio-economic conditions (Park et al., 2018)1053. Additionally, projected total energy demands for heating and cooling at the global scale do not change much with increases in global mean surface temperature (GMST) of up to 2°C. A high degree of variability is projected between regions (Arnell et al., 2018)1054. Evidence for the impact of climate change on energy systems since AR5 is limited. Globally, gross hydropower potential is projected to increase (by 2.4% under RCP2.6 and by 6.3% under RCP8.5 for the 2080s), with the most growth expected in Central Africa, Asia, India and northern high latitudes (van Vliet et al., 2016)1055. Byers et al. (2018)1056 found that energy impacts at 2°C increase, including more cooling degree days, especially in tropical regions, as well as increased hydro-climatic risk to thermal and hydropower plants predominantly in Europe, North America, South and Southeast Asia and southeast Brazil. Donk et al. (2018)1057 assessed future climate impacts on hydropower in Suriname and projected a decrease of approximately 40% in power capacity for a global temperature increase in the range of 1.5°C. At minimum and maximum increases in global mean temperature of 1.35°C and 2°C, the overall stream flow in Florida, USA is projected to increase by an average of 21%, with pronounced seasonal variations, resulting in increases in power generation in winter (+72%) and autumn (+15%) and decreases in summer (–14%; Chilkoti et al., 2017)1058. Greater changes are projected at higher temperature increases. In a reference scenario with global mean temperatures rising by 1.7°C from 2005 to 2050, U.S. electricity demand in 2050 was 1.6–6.5% higher than in a control scenario with constant temperatures (McFarland et al., 2015)1059. Decreased electricity generation of –15% is projected for Brazil starting in 2040, with values expected to decline to –28% later in the century (de Queiroz et al., 2016)1060. In large parts of Europe, electricity demand is projected to decrease, mainly owing to reduced heating demand (Jacob et al., 2018)1061. In Europe, no major differences in large-scale wind energy resources or in inter- or intra-annual variability are projected for 2016–2035 under RCP8.5 and RCP4.5 (Carvalho et al., 2017)1062. However, in 2046–2100, wind energy density is projected to decrease in eastern Europe (–30%) and increase in Baltic regions (+30%). Intra-annual variability is expected to increase in northern Europe and decrease in southern Europe. Under RCP4.5 and RCP8.5, the annual energy yield of European wind farms as a whole, as projected to be installed by 2050, will remain stable (±5 yield for all climate models). However, wind farm yields are projected to undergo changes of up to 15% in magnitude at country and local scales and of 5% at the regional scale (Tobin et al., 2015, 2016)1063. Hosking et al. (2018)1064 assessed wind power generation over Europe for 1.5°C of warming and found the potential for wind energy to be greater than previously assumed in northern Europe. Additionally, Tobin et al. (2018)1065 assessed impacts under 1.5°C and 2°C of warming on wind, solar photovoltaic and thermoelectric power generation across Europe. These authors found that photovoltaic and wind power might be reduced by up to 10%, and hydropower and thermoelectric generation might decrease by up to 20%, with impacts being limited at 1.5°C of warming but increasing as temperature increases (Tobin et al., 2018)1066. Road, air, rail, shipping and pipeline transportation can be impacted directly or indirectly by weather and climate, including increases in precipitation and temperature; extreme weather events (flooding and storms); SLR; and incidence of freeze–thaw cycles (Arent et al., 2014)1067. Much of the published research on the risks of climate change for the transportation sector has been qualitative. The limited new research since AR5 supports the notion that increases in global temperatures will impact the transportation sector. Warming is projected to result in increased numbers of days of ice-free navigation and a longer shipping season in cold regions, thus affecting shipping and reducing transportation costs (Arent et al., 2014)1068. In the North Sea Route, large-scale commercial shipping might not be possible until 2030 for bulk shipping and until 2050 for container shipping under RCP8.5. A 0.05% increase in mean temperature is projected from an increase in short-lived pollutants, as well as elevated CO_2 and non-CO_2 emissions, associated with additional economic growth enabled by the North Sea Route. (Yumashev et al., 2017)1069. Open water vessel transit has the potential to double by mid-century, with a two to four month longer season (Melia et al., 2016)1070. Multiple drivers and embedded social processes influence the magnitude and pattern of livelihoods and poverty, as well as the changing structure of communities related to migration, displacement and conflict (Adger et al., 2014)1071. In AR5, evidence of a climate change signal was limited, with more evidence of impacts of climate change on the places where indigenous people live and use traditional ecological knowledge (Olsson et al., 2014)1072. At approximately 1.5°C of global warming (2030), climate change is expected to be a poverty multiplier that makes poor people poorer and increases the poverty head count (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017)1073. Poor people might be heavily affected by climate change even when impacts on the rest of population are limited. Climate change alone could force more than 3 million to 16 million people into

2.5°C of warming (medium confidence). Impacts from fluvial flooding (related to RFCs 2, 3 and 4) depend on the frequency and intensity of the events, as well as the extent of exposure and vulnerability of society (i.e., socio-economic conditions and the effect of non-climate stressors). Moderate risks posed by 1.5°C of warming are expected to continue to increase with higher levels of warming (Sections 3.3.5 and 3.4.2), with projected risks being threefold the current risk in economic damages due to flooding in 19 countries for warming of 2°C, indicating a transition to high risk at this level (medium confidence). Because few studies have assessed the potential to adapt to these risks, there was insufficient evidence to locate a transition to very high risk (purple). Climate-change induced sea level rise (SLR) and associated coastal flooding (related to RFCs 2, 3 and 4) have been detectable and attributable since approximately 1970 (Slangen et al., 2016)1114, during which time temperatures have risen by 0.3°C (medium confidence) (Section 3.3.9). Analysis suggests that impacts could be more widespread in sensitive systems such as small islands (high confidence) (Section 3.4.5.3) and increasingly widespread by the 2070s (Brown et al., 2018a) as temperatures rise from 1.5°C to 2°C1115, even when adaptation measures are considered, suggesting a transition to high risk (Section 3.4.5). With 2.5°C of warming, adaptation limits are expected to be exceeded in sensitive areas, and hence a transition to very high risk is projected. Additionally, at this temperature, sea level rise could have adverse effects for centuries, posing significant risk to low-lying areas (high confidence) (Sections 3.4.5.7 and 3.5.2). Heat-related morbidity and mortality (related to RFCs 2, 3 and 4), detection and attribution studies show heat-related mortality in some locations increasing with climate change (high confidence) (Section 3.4.7; Ebi et al., 2017)1116. The projected risks of heat-related morbidity and mortality are generally higher under warming of 2°C than 1.5°C (high confidence), with projections of greater exposure to high ambient temperatures and increased morbidity and mortality (Section 3.4.7). Risk levels will depend on the rate of warming and the (related) level of adaptation, so a transition in risk from moderate (yellow) to high (red) is located between 1°C and 3°C (medium confidence). For tourism (related to RFCs 3 and 4), changing weather patterns, extreme weather and climate events, and sea level rise are affecting many – but not all – global tourism investments, as well as environmental and cultural destination assets (Section 3.4.4.12), with 'last chance to see' tourism markets developing based on observed impacts on environmental and cultural heritage (Section 3.4.9.1), indicating a transition from undetectable to moderate risk between 0°C and 1.5°C of warming (high confidence). Based on limited analyses, risks to the tourism sector are projected to be larger at 2°C than at 1.5°C, with impacts on climate-sensitive sun, beach and snow sports tourism markets being greatest. The degradation or loss of coral reef systems is expected to increase the risks to coastal tourism in subtropical and tropical regions. A transition in risk from moderate to high levels of added risk from climate change is projected to occur between 1.5°C and 3°C (medium confidence). Climate change is already having large scale impacts on ecosystems, human health and agriculture, which is making it much more difficult to reach goals to eradicate poverty and hunger, and to protect health and life on land (Sections 5.1 and 5.2.1 in Chapter 5), suggesting a transition from undetectable to moderate risk for present-day global warming of 1°C (medium confidence). Based on the limited analyses available, there is evidence and agreement that the risks to sustainable development are considerably less at 1.5°C than 2°C (Section 5.2.2), including impacts on poverty and food security. It is easier to achieve many of the sustainable development goals (SDGs) at 1.5°C, suggesting that a transition to higher risk will not begin yet at this level. At 2°C and higher levels of warming (e.g., RCP8.5), however, there are high risks of failure to meet SDGs such as eradicating poverty and hunger, providing safe water, reducing inequity and protecting ecosystems, and these risks are projected to become severe and widespread if warming increases further to about 3°C (medium confidence) (Section 5.2.3). Disclosure statement: The selection of elements depicted in Figures 3.18 and 3.20 is not intended to be fully comprehensive and does not necessarily include all elements for which new literature is available, nor does it necessarily include all elements which are of particular interest to decision-makers. Oppenheimer et al. (2014, AR5 WGII Chapter 19)1118 provided a framework that aggregates projected risks from global mean temperature change into five categories identified as 'Reasons for Concern'. Risks are classified as moderate, high or very high and coloured yellow, red or purple, respectively, in Figure 19.4 of that chapter (AR5 WGII Chapter 19 for details and findings). The framework's conceptual basis and the risk judgements made by Oppenheimer et al. (2014)1119 were recently reviewed, and most judgements were confirmed in the light of more recent literature (O'Neill et al., 2017)1120. The approach of Oppenheimer et al. (2014)1121 was adopted, with updates to the aggregation of risk informed by the most recent literature, for the analysis of avoided impacts at 1.5°C compared to 2°C of global warming presented in this section. The regional economic benefits that could be obtained by limiting the global temperature increase to 1.5°C of warming, rather than 2°C or higher levels, are discussed in Section 3.5.3 in the light of the five RFCs explored in Section 3.5.2. Climate change hotspots that could be avoided or reduced by achieving the 1.5°C global warming target are summarized in Section 3.5.4. The section concludes with a discussion of regional tipping points that could be avoided at 1.5°C compared to higher degrees of global warming (Section 3.5.5). An update of the accrual of RFCs with global warming, as assessed in WGII AR5, is provided in the following sections, which leads into an update of relevant literature published since AR5. The new literature is used to confirm the levels of global warming at which risks are considered to increase from undetectable to moderate, from moderate to high, and from high to very high. Figure 3.21 modifies Figure 19.4 from AR5 WGII, and the following text in this subsection provides justification for the modifications. O'Neill et al. (2017)1122 presented a very similar assessment to that of WGII AR5, but with further discussion of the potential to create 'embers' specific to socio-economic scenarios in the future. There is insufficient literature to do this at present, so the original, simple approach has been used here. As the focus of the present assessment is on the consequences of global warming of 1.5°C–2°C above the pre-industrial period, no assessment of global warming of 3°C or more is included in the figure (i.e., analysis is discontinued at 2.5°C). WGII AR5 Chapter 19 found that some unique and threatened systems are at risk from climate change at current temperatures, with increasing numbers of systems at potential risk of severe consequences at global warming of 1.6°C above pre-industrial levels. It was also observed that many species and ecosystems have a limited ability to adapt to the very large risks associated with warming of 2.6°C or more, particularly Arctic sea ice and coral reef systems (high confidence). In the AR5 analysis, a transition from white to yellow indicated that the onset of moderate risk was located below present-day global temperatures (medium confidence); a transition from yellow to red indicated that the onset of high risk was located at 1.6°C, and a transition from red to purple indicated that the onset of very high risk was located at about 2.6°C. This WGII AR5 analysis already implied that there would be a significant reduction in risks to unique and threatened systems if warming were limited to 1.5°C compared with 2°C. Since AR5, evidence of present-day impacts in these systems has continued to grow (Sections 3.4.2, 3.4.4 and 3.4. 5), whilst new evidence has also accumulated for reduced risks at 1.5°C compared to 2°C of warming in Arctic ecosystems (Section 3.3.9), coral reefs (Section 3.4.4) and some other unique ecosystems (Section 3.4.3), as well as for biodiversity. Several lines of evidence since AR5 has provided a closer focus on the comparative levels of risk to coral reefs at 1.5°C versus 2°C of global warming. As assessed in Section 3.4.4 and Box 3.4, reaching 2°C will increase the frequency of mass coral bleaching and mortality to a point at which it will result in the total loss of coral reefs from the world's tropical and subtropical regions. Restricting overall warming to 1.5°C will still see a downward trend in average coral cover (70–90% decline by mid-century) but will prevent the total loss of coral reefs projected with warming of 2°C (Frieler et al., 2013)1123. The remaining reefs at 1.5°C will also benefit from increasingly stable ocean conditions by the mid-to-late 21st century. Limiting global warming to 1.5°C during the course of the century may, therefore, open the window for many ecosystems to adapt or reassort geographically. This indicates a transition in risk in this system from high to very high (high confidence) at 1.5°C of warming and contributes to a lowering of the transition from high to very high in this RFC1 compared to in AR5. Further details of these risks are described in Figure 3.18. Substantial losses in Arctic Ocean summer ice were projected in WGI AR5 for global warming of 1.6°C, with a nearly ice-free Arctic Ocean being projected for global warming of more than 2.6°C. Since AR5, the importance of a threshold between 1°C and 2°C has been further emphasized in the literature, with sea ice projected to persist throughout the year for a global warming of less than 1.5°C, yet chances of an ice-free Arctic during summer being high at 2°C of warming (Section 3.3.8). Less of the permafrost in the Arctic is projected to thaw under 1.5°C of warming (17–44%) compared with under 2°C (28–53%) (Section 3.3.5.2; Chadburn et al., 2017)1124, which is expected to reduce risks to both social and ecological systems in the Arctic. This indicates a transition in risk in this system from high to very high between 1.5°C and 2°C of warming and contributes to a lowering of the transition from high to very high in this RFC1 compared to in AR5. AR5 identified a large number of threatened systems, including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems. These include Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succulent Karoo areas of South Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, impacts accrue with greater warming and impacts at 2°C are expected to be greater than those at 1.5°C (medium confidence). One study since AR5 has shown that constraining global warming to 1.5°C would maintain the functioning of prairie pothole ecosystems in North America in terms of their productivity and biodiversity, whilst warming of 2°C would not do so (Johnson et al., 2016)1125. The large proportion of insects projected to lose over half their range at 2°C of warming (25%) compared to at 1.5°C (9%) also suggests a significant loss of functionality in these threatened systems at 2°C of warming, owing to the critical role of insects in nutrient cycling, pollination, detritivory and other important ecosystem processes (Section 3.4.3). Unique and threatened systems in small island states and in systems fed by glacier meltwater were also considered to contribute to this RFC in AR5, but there is little new information about these systems that pertains to 1.5°C or 2°C of global warming. Taken together, the evidence suggests that the transition from high to very high risk in unique and threatened systems occurs at a lower level of warming, between 1.5°C and 2°C (high confidence), than in AR5, where this transition was located at 2.6°C. The transition from moderate to high risk relocates very slightly from 1.6°C to 1.5°C (high confidence). There is also high confidence in the location of the transition from low to moderate risk below present-day global temperatures. Reduced risks in terms of the likelihood of occurrence of extreme weather events are discussed in this sub-subsection for 1.5°C as compared to 2°C of global warming, for those extreme events where evidence is currently available based on the assessments of Section 3.3. AR5 assigned a moderate level of risk from extreme weather events at recent temperatures (1986–2005) owing to the attribution of heat and precipitation extremes to climate change, and a transition to high levels beginning below 1.6°C of global warming based on the magnitude, likelihood and timing of projected changes in risk associated with extreme events, indicating more severe and widespread impacts. The AR5 analysis already suggested a significant benefit of limiting warming to 1.5°C, as doing so might keep risks closer to the moderate level. New literature since AR5 has provided greater confidence in a reduced level of risks due to extreme weather events at 1.5°C versus 2°C of warming for some types of extremes (Section 3.3 and below; Figure 3.21). Temperature: It is expected that further increases in the number of warm days/nights and decreases in the number of cold days/nights, and an increase in the overall temperature of hot and cold extremes would occur under 1.5°C of global warming relative to pre-industrial levels (high confidence) compared to under the present-day climate (1°C of warming), with further changes occurring towards 2°C of global warming (Section 3.3). As assessed in Sections 3.3.1 and 3.3.2, impacts of 0.5°C of global warming can be identified for temperature extremes at global scales, based on observations and the analysis of climate models. At 2°C of global warming, it is likely that temperature increases of more than 2°C would occur over most land regions in terms of extreme temperatures (up to 4°C–6°C depending on region and considered extreme index) (Section 3.3.2, Table 3.2). Regional increases in temperature extremes can be robustly limited if global warming is constrained to 1.5°C, with regional warmings of up to 3°C–4.5°C (Section 3.3.2, Table 3.2). Benefits obtained from this general reduction in extremes depend to a large extent on whether the lower range of increases in extremes at 1.5°C is sufficient for critical thresholds to be exceeded, within the context of wide-ranging aspects such as crop yields, human health and the sustainability of ecosystems. Heavy precipitation: AR5 assessed trends in heavy precipitation for land regions where observational coverage was sufficient for assessment. It concluded with medium confidence that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century, for a global warming of approximately 0.5°C (Section 3.3.3). A recent observation-based study likewise showed that a 0.5°C increase in global mean temperature has had a detectable effect on changes in precipitation extremes at the global scale (Schleussner et al., 2017)1126, thus suggesting that there would be detectable differences in heavy precipitation at 1.5°C and 2°C of global warming. These results are consistent with analyses of climate projections, although they also highlight a large amount of regional variation in the sensitivity of changes in heavy precipitation (Section 3.3.3). Droughts: When considering the difference between precipitation and evaporation (P–E) as a function of global temperature changes, the subtropics generally display an overall trend towards drying, whilst the northern high latitudes display a robust response towards increased wetting (Section 3.3.4, Figure 3.12). Limiting global mean temperature increase to 1.5°C as opposed to 2°C could substantially reduce the risk of reduced regional water availability in some regions (Section 3.3.4). Regions that are projected to benefit most robustly from restricted warming include the Mediterranean and southern Africa (Section 3.3.4). Fire: Increasing evidence that anthropogenic climate change has already caused significant increases in fire area globally (Section 3.4.3) is in line with projected fire risks. These risks are projected to increase further under 1.5°C of global warming relative to the present day (Section 3.4.3). Under 1.2°C of global warming, fire frequency has been estimated to increase by over 37.8% of global land areas, compared to 61.9% of global land areas under 3.5°C of warming. For in-depth discussion and uncertainty estimates, see Meehl et al. (2007), Moritz et al. (2012) and Romero-Lankao et al. (2014)1127. Regarding extreme weather events (RFC2), the transition from moderate to high risk is located between 1°C and 1.5°C of global warming (Figure 3.21), which is very similar to the AR5 assessment but is assessed with greater confidence (medium confidence). The impact literature contains little information about the potential for human society to adapt to extreme weather events, and hence it has not been possible to locate the transition from high to very high risk within the context of assessing impacts at 1.5°C and 2°C of global warming. There is thus low confidence in the level at which global warming could lead to very high risks associated with extreme weather events in the context of this report. Risks due to climatic change are unevenly distributed and are generally greater at lower latitudes and for disadvantaged people and communities in countries at all levels of development. AR5 located the transition from undetectable to moderate risk below recent temperatures, owing to the detection and attribution of regionally differentiated changes in crop yields (medium to high confidence; Figure 3.20), and new literature has continued to confirm this finding. Based on the assessment of risks to regional crop production and water resources, AR5 located the transition from moderate to high risk between 1.6°C and 2.6°C above pre-industrial levels. Cross-Chapter Box 6 in this chapter highlights that at 2°C of warming, new literature shows that risks of food shortage are projected to emerge in the African Sahel, the Mediterranean, central Europe, the Amazon, and western and southern Africa, and that these are much larger than the corresponding risks at 1.5°C. This suggests a transition from moderate to high risk of regionally differentiated impacts between 1.5°C and 2°C above pre-industrial levels for food security (medium confidence) (Figure 3.20). Reduction in the availability of water resources at 2°C is projected to be greater than 1.5°C of global warming, although changes in socio-economics could have a greater influence (Section 3.4.2), with larger risks in the Mediterranean (Box 3.2); estimates of the magnitude of the risks remain similar to those cited in AR5. Globally, millions of people may be at risk from sea level rise (SLR) during the 21st century (Hinkel et al., 2014; Hauer et al., 2016)1128, particularly if adaptation is limited. At 2°C of warming, more than 90% of global coastlines are projected to experience SLR greater than 0.2 m, suggesting regional differences in the risks of coastal flooding. Regionally differentiated multi-sector risks are already apparent at 1.5°C of warming, being more prevalent where vulnerable people live, predominantly in South Asia (mostly Pakistan, India and China), but these risks are projected to spread to sub-Saharan Africa, the Middle East and East Asia as temperature rises, with the world's poorest people disproportionately impacted at 2°C of warming (Byers et al., 2018)1129. The hydrological impacts of climate change in Europe are projected to increase in spatial extent and intensity across increasing global warming levels of 1.5°C, 2°C and 3°C (Donnelly et al., 2017)1130. Taken together, a transition from moderate to high risk is now located between 1.5°C and 2°C above pre-industrial levels, based on the assessment of risks to food security, water resources, drought, heat exposure and coastal submergence (high confidence; Figure 3.21). Oppenheimer et al. (2014)1131 explained the inclusion of non-economic metrics related to impacts on ecosystems and species at the global level, in addition to economic metrics in global aggregate impacts. The degradation of ecosystem services by climate change and ocean acidification have generally been excluded from previous global aggregate economic analyses. Global economic impacts: WGII AR5 found that overall global aggregate impacts become moderate at 1°C–2°C of warming, and the transition to moderate risk levels was therefore located at 1.6°C above pre-industrial levels. This was based on the assessment of literature using model simulations which indicated that the global aggregate economic impact will become significantly negative between 1°C and 2°C of warming (medium confidence), whilst there will be a further increase in the magnitude and likelihood of aggregate economic risks at 3°C of warming (low confidence). Since AR5, three studies have emerged using two entirely different approaches which indicate that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5°C. The study by Warren et al. (2018c)1132 used the integrated assessment model PAGE09 to estimate that avoided global economic damages of 22% (10–26%) accrue from constraining warming to 1.5°C rather than 2°C, 90% (77–93%) from 1.5°C rather than 3.66°C, and 87% (74–91%) from 2°C rather than 3.66°C. In the second study, Pretis et al. (2018)1133 identified several regions where economic damages are projected to be greater at 2°C compared to 1.5°C of warming, further estimating that projected damages at 1.5°C remain similar to today's levels of economic damage. The third study, by M. Burke et al. (2018)1134 used an empirical, statistical approach and found that limiting warming to 1.5°C instead of 2°C would save 1.5–2.0% of the gross world product (GWP) by mid-century and 3.5% of the GWP by end-of-century (see Figure 2A in M. Burke et al., 2018)1135. Based on a 3% discount rate, this corresponds to 8.1–11.6 trillion USD and 38.5 trillion USD in avoided damages by mid- and end-of-century, respectively, agreeing closely with the estimate by Warren et al. (2018c)1136 of 15 trillion USD. Under the no-policy baseline scenario, temperature rises by 3.66°C by 2100, resulting in a global gross domestic product (GDP) loss of 2.6% (5–95% percentile range 0.5–8.2%), compared with 0.3% (0.1–0.5%) by 2100 under the 1.5°C scenario and 0.5% (0.1–1.0%) in the 2°C scenario. Limiting warming to 1.5°C rather than 2°C by 2060 has also been estimated to result in co-benefits of 0.5–0.6% of the world GDP, owing to reductions in air pollution (Shindell et al., 2018)1137, which is similar to the avoided damages identified for the USA (Box 3.6). Two studies focusing only on the USA found that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5°C. Hsiang et al. (2017)1138 found a mean difference of 0.35% GDP (range 0.2–0.65%), while Yohe (2017)1139 identified a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree. Further, the avoided risks compared to a no-policy baseline are greater in the 1.5°C case (4%, range 2–7%) compared to the 2°C case (3.5%, range 1.8–6.5%). These analyses suggest that the point at which global aggregates of economic impacts become negative is below 2°C (medium confidence), and that there is a possibility that it is below 1.5°C of warming. Oppenheimer et al. (2014)1140 noted that the global aggregated damages associated with large-scale singular events has not been explored, and reviews of integrated modelling exercises have indicated a potential underestimation of global aggregate damages due to the lack of consideration of the potential for these events in many studies. Since AR5, further analyses of the potential economic consequences of triggering these large-scale singular events have indicated a two to eight fold larger economic impact associated with warming of 3°C than estimated in most previous analyses, with the extent of increase depending on the number of events incorporated. Lemoine and Traeger (2016)1141 included only three known singular events whereas Y. Cai et al. (2016)1142 included five. Biome shifts, species range loss, increased risks of species extinction and risks of loss of ecosystem functioning and services: 13% (range 8–20%) of Earth's land area is projected to undergo biome shifts at 2°C of warming compared to approximately 7% at 1.5°C (medium confidence) (Section 3.4.3; Warszawski et al., 2013)1143, implying a halving of biome transformations. Overall levels of species loss at 2°C of warming are similar to values found in previous studies for plants and vertebrates (Warren et al., 2013, 2018a)1144, but insects have been found to be more sensitive to climate change, with 18% (6–35%) projected to lose over half their range at 2°C of warming compared to 6% (1–18%) under 1.5°C of warming, corresponding to a difference of 66% (Section 3.4.3). The critical role of insects in ecosystem functioning therefore suggests that there are also larger risks to global ecosystem functioning at 2°C than at 1.5°C, as their range losses are considered to be an increased risk of extinction (Section 3.4.3.3). Since AR5, new literature has concluded that declines in marine fish stocks and fisheries are lower under 1.5°C–2°C of global warming relative to pre-industrial levels compared to under higher warming scenarios (Section 3.4.6), especially in tropical and polar systems. In AR5, the transition from undetectable to moderate impacts was considered to occur between 1.6°C and 2.6°C of global warming reflecting impacts on the economy and on biodiversity globally, whereas high risks were associated with 3.6°C of warming to reflect the high risks to biodiversity and accelerated effects on the global economy. New evidence suggests moderate impacts on the global aggregate economy and global biodiversity by 1.5°C of warming, suggesting a lowering of the temperature level for the transition to moderate risk to 1.5°C (Figure 3.21). Further, recent literature points to higher risks than previously assessed for the global aggregate economy and global biodiversity by 2°C of global warming, implying that the transition to high risk level is located between 1.5°C and 2.5°C of warming (Figure 3.21), as opposed to at 3.6°C as previously assessed (medium confidence). Large-scale singular events are components of the global Earth system that are thought to hold the risk of reaching critical tipping points under climate change, and that can result in or be associated with major shifts in the climate system. These components include: • the cryosphere: West Antarctic ice sheet, Greenland ice sheet • the thermohaline circulation: slowdown of the Atlantic Meridional Overturning Circulation (AMOC) • the El Niño–Southern Oscillation (ENSO) as a global mode of climate variability • role of the Southern Ocean in the global carbon cycle AR5 assessed that the risks associated with these events become moderate between 0.6°C and 1.6°C above pre-industrial levels, based on early warning signs, and that risk was expected to become high between 1.6°C and 4.6°C based on the potential for commitment to large irreversible sea level rise from the melting of land-based ice sheets (low to medium confidence). The increase in risk between 1.6°C and 2.6°C above pre-industrial levels was assessed to be disproportionately large. New findings since AR5 are described in detail below. Greenland and West Antarctic ice sheets and marine ice sheet instability (MISI): Various feedbacks between the Greenland ice sheet and the wider climate system, most notably those related to the dependence of ice melt on albedo and surface elevation, make irreversible loss of the ice sheet a possibility. Church et al. (2013)1145 assessed this threshold to be at 2°C of warming or higher levels relative to pre-industrial temperature. Robinson et al. (2012)1146 found a range for this threshold of 0.8°C–3.2°C (95% confidence). The threshold of global temperature increase that may initiate irreversible loss of the West Antarctic ice sheet and marine ice sheet instability (MISI) is estimated to lie between 1.5°C and 2°C. The time scale for eventual loss of the ice varies between millennia and tens of millennia and assumes constant surface temperature forcing during this period. If temperature were to decline subsequently the ice sheets might regrow, although the amount of cooling required is likely to be highly dependent on the duration and rate of the previous retreat. The magnitude of global sea level rise that could occur over the next two centuries under 1.5°C–2°C of global warming is estimated to be in the order of several tenths of a metre according to most studies (low confidence) (Schewe et al., 2011; Church et al., 2013; Levermann et al., 2014; Marzeion and Levermann, 2014; Fürst et al., 2015; Golledge et al., 2015)1147, although a smaller number of investigations (Joughin et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016)1148 project increases of 1–2 m. This body of evidence suggests that the temperature range of 1.5°C–2°C may be regarded as representing moderate risk, in that it may trigger MISI in Antarctica or irreversible loss of the Greenland ice sheet and it may be associated with sea level rise by as much as 1–2 m over a period of two centuries. Thermohaline circulation (slowdown of AMOC): It is more likely than not that the AMOC has been weakening in recent decades, given the detection of cooling of surface waters in the North Atlantic and evidence that the Gulf Stream has slowed since the late 1950s (Rahmstorf et al., 2015b; Srokosz and Bryden, 2015; Caesar et al., 2018)1149. There is limited evidence linking the recent weakening of the AMOC to anthropogenic warming (Caesar et al., 2018)1150. It is very likely that the AMOC will weaken over the 21st century. Best estimates and ranges for the reduction based on CMIP5 simulations are 11% (1–24%) in RCP2.6 and 34% (12–54%) in RCP8.5 (AR5). There is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5°C versus 2°C of global warming, or of a shutdown of the AMOC at these global temperature thresholds. Associated risks are classified as low to moderate. El Niño–Southern Oscillation (ENSO): Extreme El Niño events are associated with significant warming of the usually cold eastern Pacific Ocean, and they occur about once every 20 years (Cai et al., 2015)1151. Such events reorganize the distribution of regions of organized convection and affect weather patterns across the globe. Recent research indicates that the frequency of extreme El Niño events increases linearly with the global mean temperature, and that the number of such events might double (one event every ten years) under 1.5°C of global warming (G. Wang et al., 2017)1152. This pattern is projected to persist for a century after stabilization at 1.5°C, thereby challenging the limits to adaptation, and thus indicates high risk even at the 1.5°C threshold. La Niña event (the opposite or balancing event to El Niño) frequency is projected to remain similar to that of the present day under 1.5°C–2°C of global warming. Role of the Southern Ocean in the global carbon cycle: The critical role of the Southern Ocean as a net sink of carbon might decline under global warming, and assessing this effect under 1.5°C compared to 2°C of global warming is a priority. Changes in ocean chemistry (e.g., oxygen content and ocean acidification), especially those associated with the deep sea, and the associated concerns (Section 3.3.10). For large-scale singular events (RFC5), moderate risk is now located at 1°C of warming and high risk is located at 2.5°C (Figure 3.21), as opposed to at 1.6°C (moderate risk) and around 4°C (high risk) in AR5, because of new observations and models of the West Antarctic ice sheet (medium confidence), which suggest that the ice sheet may be in the early stages of marine ice sheet instability (MISI). Very high risk is assessed as lying above 5°C because the growing literature on process-based projections of the West Antarctic ice sheet predominantly supports the AR5 assessment of an MISI contribution of several additional tenths of a metre by 2100. This section reviews recent literature that has estimated the economic benefits of constraining global warming to 1.5°C compared to 2°C. The focus here is on evidence pertaining to specific regions, rather than on global aggregated benefits (Section 3.5.2.4). At 2°C of global warming, lower economic growth is projected for many countries than at 1.5C of global warming, with low-income countries projected to experience the greatest losses (low to medium confidence) (M. Burke et al., 2018; Pretis et al., 2018)1153. A critical issue for developing countries in particular is that advantages in some sectors are projected to be offset by increasing mitigation costs (Rogelj et al., 2013; M. Burke et al., 2018)1154, with food production being a key factor. That is, although restraining the global temperature increase to 2°C is projected to reduce crop losses under climate change relative to higher levels of warming, the associated mitigation costs may increase the risk of hunger in low-income countries (low confidence) (Hasegawa et al., 2016)1155. It is likely that the even more stringent mitigation measures required to restrict global warming to 1.5°C (Rogelj et al., 2013)1156 will further increase these mitigation costs and impacts. International trade in food might be a key response measure for alleviating hunger in developing countries under 1.5°C and 2°C stabilization scenarios (IFPRI, 2018)1157. Although warming is projected to be the highest in the Northern Hemisphere under 1.5°C or 2°C of global warming, regions in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth (low to medium confidence) (Gallup et al., 1999; M. Burke et al., 2015; Pretis et al., 2018)1158. Despite the uncertainties associated with climate change projections and econometrics (e.g., M. Burke et al., 2018)1159, it is more likely than not that there will be large differences in economic growth under 1.5°C and 2°C of global warming for developing versus developed countries (M. Burke et al., 2018; Pretis et al., 2018)1160. Statistically significant reductions in gross domestic product (GDP) per capita growth are projected across much of the African continent, Southeast Asia, India, Brazil and Mexico (low to medium confidence). Countries in the western parts of tropical Africa are projected to benefit most from restricting global warming to 1.5°C, as opposed to 2°C, in terms of future economic growth (Pretis et al., 2018)1161. An important reason why developed countries in the tropics and subtropics are projected to benefit substantially from restricting global warming to 1.5°C is that present-day temperatures in these regions are above the threshold thought to be optimal for economic production (M. Burke et al., 2015b, 2018)1162. The world's largest economies are also projected to benefit from restricting warming to 1.5°C as opposed to 2°C (medium confidence), with the likelihood of such benefits being estimated at 76%, 85% and 81% for the USA, China and Japan, respectively (M. Burke et al., 2018)1163. Two studies focusing only on the USA found that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5°C. Yohe (2017)1164 found a mean difference of 0.35% GDP (range 0.2–0.65%), while Hsiang et al. (2017)1165 identified a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree. Overall, no statistically significant changes in GDP are projected to occur over most of the developed world under 1.5°C of global warming in comparison to present-day conditions, but under 2°C of global warming GDP are projected to be generally negative (low confidence) (Pretis et al., 2018)1166. A caveat to the analyses of Pretis et al. (2018)1167 and M. Burke et al. (2018)1168 is that the effects of sea level rise were not included in the estimations of damages or future economic growth, implying a potential underestimation of the benefits of limiting warming to 1.5°C for the case where significant sea level rise is avoided at 1.5°C but not at 2°C. This subsection integrates Sections 3.3 and 3.4 in terms of climate-change-induced hotspots that occur through interactions across the physical climate system, ecosystems and socio-economic human systems, with a focus on the extent to which risks can be avoided or reduced by achieving the 1.5°C global warming goal (as opposed to the 2°C goal). Findings are summarized in Table 3.6. Ice-free Arctic Ocean summers are very likely at levels of global warming higher than 2°C (Notz and Stroeve, 2016; Rosenblum and Eisenman, 2016; Screen and Williamson, 2017; Niederdrenk and Notz, 2018)1169. Some studies even indicate that the entire Arctic Ocean summer period will become ice free under 2°C of global warming, whilst others more conservatively estimate this probability to be in the order of 50% (Section 3.3.8; Sanderson et al., 2017)1170. The probability of ice-free Arctic in September at 1.5°C of global warming is low and substantially lower than for the case of 2°C of global warming (high confidence) (Section 3.3.8; Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018)1171. There is, however, a single study that questions the validity of the 1.5°C threshold in terms of maintaining summer Arctic Ocean sea ice (Niederdrenk and Notz, 2018)1172. In contrast to summer, little ice is projected to be lost during winter for either 1.5°C or 2°C of global warming (medium confidence) (Niederdrenk and Notz, 2018)1173. The losses in sea ice at 1.5°C and 2°C of warming will result in habitat losses for organisms such as seals, polar bears, whales and sea birds (e.g., Larsen et al., 2014)1174. There is high agreement and robust evidence that photosynthetic species will change because of sea ice retreat and related changes in temperature and radiation (Section 3.4.4.7), and this is very likely to benefit fisheries productivity in the Northern Hemisphere spring bloom system (Section 3.4.4.7). In some Arctic land regions, the warming of cold extremes and the increase in annual minimum temperature at 1.5°C are stronger than the global mean temperature increase by a factor of two to three, meaning 3°C–4.5°C of regional warming at 1.5°C of global warming (e.g., northern Europe in Supplementary Material 3.SM, Figure 3.SM.5 see also Section 3.3.2 and Seneviratne et al., 2016)1175. Over much of the Arctic, a further increase of 0.5°C in the global mean temperature, from 1.5°C to 2°C, may lead to further temperature increases of 2°C–2.5°C (Figure 3.3). As a consequence, biome (major ecosystem type) shifts are likely in the Arctic, with increases in fire frequency, degradation of permafrost, and tree cover likely to occur at 1.5°C of warming and further amplification of these changes expected under 2°C of global warming (e.g., Gerten et al., 2013; Bring et al., 2016)1176. Rather than being a hotspot for crop production under climate change, the Arctic is rather a region where increased crop production is projected to increase the potential for the Arctic (W.N. Meier et al., 2014)1177 with these impacts larger at 2°C than at 1.5°C of warming (Lenner et al., 2016). Alpine regions are generally regarded as climate change hotspots given that rich biodiversity has evolved in their cold and harsh climate, but with many species consequently being vulnerable to increasing temperatures. Under regional warming, alpine species have been found to migrate upwards on mountain slopes (Reasoner and Tinner, 2009)1178, an adaptation response that is obviously limited by mountain height and habitability. Moreover, many of the world's alpine regions are important from a water security perspective through associated glacier melt, snow melt and river flow (see Section 3.3.5.2 for a discussion of these aspects). Projected biome shifts are likely to be severe in alpine regions already at 1.5°C of warming and to increase further at 2°C (Gerten et al., 2013, Figure 1b)1179; B. Chen et al., 2014)1180. Southeast Asia is a region highly vulnerable to increased flooding in the context of sea level rise (Arnell et al., 2016; Brown et al., 2016, 2018a)1181. Risks from increased flooding are projected to rise from 1.5°C to 2°C of warming (medium confidence), with substantial increases projected beyond 2°C (Arnell et al., 2016)1182. Southeast Asia displays statistically significant differences in projected changes in heavy precipitation, runoff and high flows at 1.5°C versus 2°C of warming, with stronger increases occurring at 2°C (Section 3.3; Wartenburger et al., 2017; Döll et al., 2018; Seneviratne et al., 2018c)1183; thus, this region is considered a hotspot in terms of increases in heavy precipitation between these two global temperature levels (medium confidence) (Schleussner et al., 2016b; Seneviratne et al., 2016)1184. For Southeast Asia, 2°C of warming by 2040 could lead to a decline by one-third in per capita crop production associated with general decreases in crop yields (Nelson et al., 2010)1185. However, under 1.5°C of warming, significant risks for crop yield reduction in the region are avoided (Schleussner et al., 2016b)1186. These changes pose significant risks for poor people in both rural regions and urban areas of Southeast Asia (Section 3.4.10.1), with these risks being larger at 2°C of global warming than at 1.5°C (medium confidence). The Mediterranean is regarded as a climate change hotspot, both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature increase (e.g., Seneviratne et al., 2016)1187 and in terms of robust increases in the probability of occurrence of extreme droughts at 2°C vs 1.5°C global warming (Section 3.3.4). Low river flows are projected to decrease in the Mediterranean under 1.5°C of global warming (Marx et al., 2018)1188, with associated significant decreases in high flows and floods (Thober et al., 2018)1189, largely in response to reduced precipitation. The median reduction in annual runoff is projected to almost double from about 9% (likely range 4.5–15.5%) at 1.5°C to 17% (likely range 8–25%) at 2°C (Schleussner et al., 2016b)1190. Similar results were found by Döll et al. (2018)1191. Overall, there is high confidence that strong increases in dryness and decreases in water availability in the Mediterranean and southern Europe would occur from 1.5°C to 2°C of global warming. Sea level rise is expected to be lower for 1.5°C versus 2°C, lowering risks for coastal metropolitan agglomerations. The risks (assuming current adaptation) related to water deficit in the Mediterranean are high for global warming of 2°C but could be substantially reduced if global warming is limited to 1.5°C (Section 3.3.4; Guiot and Cramer, 2016; Schleussner et al., 2016b; Donnelly et al., 2017)1192. West Africa and the Sahel are likely to experience increases in the number of hot nights and longer and more frequent heatwaves even if the global temperature increase is constrained to 1.5°C, with further increases expected at 2°C of global warming and beyond (e.g., Weber et al., 2018)1193. Moreover, daily rainfall intensity and runoff is expected to increase (low confidence) towards 2°C and higher levels of global warming (Schleussner et al., 2016b; Weber et al., 2018)1194, with these changes also being relatively large compared to the projected changes at 1.5°C of warming. Moreover, increased risks are projected in terms of drought, particularly for the pre-monsoon season (Sylla et al., 2015)1195, with both rural and urban populations affected, and more so at 2°C of global warming as opposed to 1.5°C (Liu et al., 2018)1196. Based on a World Bank (2013)1197 study for sub-Saharan Africa, a 1.5°C warming by 2030 might reduce the present maize cropping areas by 40%, rendering these areas no longer suitable for current cultivars. Substantial negative impacts are also projected for sorghum suitability in the western Sahel (Läderach et al., 2013; Sultan and Gaetani, 2016)1198. An increase in warming to 2°C by 2040 would result in further yield losses and damages to crops (i.e., maize, sorghum, wheat, millet, groundnut and cassava). Schleussner et al. (2016b)1199 found consistently reduced impacts on crop yield for West Africa under 1.5°C compared to 2°C of warming. There is medium confidence that vulnerabilities to water and food security in the African Sahel will be higher at 2°C compared to 1.5°C of global warming (Cheung et al., 2016a; Betts et al., 2018)1200, and at 2°C these vulnerabilities are expected to be worse (high evidence) (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018)1201. Under global warming of more than 2°C, the western Sahel might experience the strongest drying and experience serious food security issues (Ahmed et al., 2015; Parkes et al., 2018)1202. The southern African region is projected to be a climate change hotspot in terms of both hot extremes (Figures 3.5 and 3.6) and drying (Figure 3.12). Indeed, temperatures have been rising in the subtropical regions of southern Africa at approximately twice the global rate over the last five decades (Engelbrecht et al., 2015)1203. Associated elevated warming of the regional land-based hot extremes has occurred (Section 3.3; Seneviratne et al., 2016)1204. Increases in the number of hot nights, as well as longer and more frequent heatwaves, are projected even if the global temperature increase is constrained to 1.5°C (high confidence), with further increases expected at 2°C of global warming and beyond (high confidence) (Weber et al., 2018)1205. Moreover, the region is likely to be generally drier with reduced water availability under low mitigation (Niang et al., 2014; Engelbrecht et al., 2015; Karl et al., 2015; James et al., 2017)1206, with this particular risk being prominent under 2°C of global warming and even under 1.5°C (Gerten et al., 2013)1207. Risks are significantly reduced, however, under 1.5°C of global warming compared to under higher levels (Schleussner et al., 2016b)1208. There are consistent and statistically significant increases in projected risks of increased meteorological drought in southern Africa at 2°C versus 1.5°C of warming (medium confidence). Despite the general rainfall reductions projected for southern Africa, daily rainfall intensities are expected to increase over much of the region (medium confidence), and increasingly so with higher levels of global warming (Section 3.3.3). There is medium confidence that livestock in southern Africa will experience increased water stress under both 1.5°C and 2°C of global warming, with negative economic consequences (e.g., Boone et al., 2018)1209. The region is also projected to experience reduced maize, sorghum and cocoa cropping area suitability, as well as yield losses under 1.5°C of warming, with further decreases occurring towards 2°C of warming (World Bank, 2013)1210. Generally, there is high confidence that vulnerability to decreases in water and food availability is reduced at 1.5°C versus 2°C for southern Africa (Betts et al., 2018)1211, whilst at 2°C these are expected to be higher (high confidence) (Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018)1212. Worldwide, the largest increases in the number of hot days are projected to occur in the tropics (Figure 3.7). Moreover, the largest differences in the number of hot days for 1.5°C versus 2°C of global warming are projected to occur in the tropics (Mahlstein et al., 2011)1213. In tropical Africa, increases in the number of hot nights, as well as longer and more frequent heatwaves, are projected under 1.5°C of global warming, with further increases expected under 2°C of global warming (Weber et al., 2018)1214. Impact studies for major tropical cereals reveal that yields of maize and sorghum begin to decline with 1°C to 2°C of local warming in the tropics. Schleussner et al. (2016b)1215 project that constraining warming to 1.5°C rather than 2°C would avoid significant risks of tropical crop yield declines in West Africa, Southeast Asia, and Central and South America. There is limited evidence and thus low confidence that these changes may result in significant population displacement from the tropics to the subtropics (e.g., Hsiang and Sobel, 2016)1216. It is widely recognized that small islands are very sensitive to climate change impacts such as sea level rise, oceanic warming, heavy precipitation, cyclones and coral bleaching (high confidence) (Nurse et al., 2014; Ourbak and Magnan, 2017)1217. Even at 1.5°C of global warming, the compounding impacts of changes in rainfall, temperature, tropical cyclones and sea level are likely to be significant across multiple natural and human systems. There are potential benefits to small island developing states (SIDS) from avoided risks at 1.5°C versus 2°C, especially when coupled with adaptation efforts. In terms of sea level rise, by 2150, roughly 60,000 fewer people living in SIDS will be exposed in a 1.5°C world than in a 2°C world (Rasmussen et al., 2018)1218. Constraining global warming to 1.5°C may significantly reduce water stress (by about 25%) compared to the projected water stress at 2°C, for example in the Caribbean region (Karnauskas et al., 2018)1219, and may enhance the ability of SIDS to adapt (Benjamin and Thomas, 2016)1220. Up to 50% of the year is projected to be very warm in the Caribbean at 1.5°C, with a further increase by up to 70 days at 2°C versus 1.5°C (Taylor et al., 2018)1221. By limiting warming to 1.5°C instead of 2°C in 2050, risks of coastal flooding (measured as the flood amplification factors for 100-year flood events) are reduced by 20–80% for SIDS (Rasmussen et al., 2018)1222. A case study of Jamaica with lessons for other Caribbean SIDS demonstrated that the difference between 1.5°C and 2°C is likely to challenge livestock thermoregulation, resulting in persistent heat stress for livestock (Lallo et al., 2018)1223. The Fynbos and succulent Karoo biomes of South Africa are threatened systems that were assessed in AR5. Similar shrublands exist in the semi-arid regions of other continents, with the Sonora-Mojave creosotebush-white bursage desert scrub ecosystem in the USA being a prime example. Impacts accrue across these systems with greater warming, with impacts at 2°C likely to be greater than those at 1.5°C (medium confidence). Under 2°C of global warming, regional warming in drylands is projected to be 3.2°C–4°C, and under 1.5°C of global warming, mean warming in drylands is projected to still be about 3°C. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters (high confidence). The Fynbos biome is projected to lose about 20%, 45% and 80% of its current suitable climate area relative to its present-day area under 1°C, 2°C and 3°C of warming, respectively (Engelbrecht and Engelbrecht, 2016)1224, demonstrating the value of climate change mitigation in protecting this rich centre of biodiversity. Region and/or Phenomenon Warming of 1.5°C or less Warming of 1.5°C–2°C Warming of 2°C–3°C Arctic sea ice Arctic summer sea ice is likely to be maintained Habitat losses for organisms such as polar bears, whales, seals and sea birds Benefits for Arctic fisheries The risk of an ice-free Arctic in summer is about 50% or higher Habitat losses for organisms such as polar bears, whales, seals and sea birds may be critical if summers are ice free Benefits for Arctic fisheries The Arctic is very likely to be ice free in summer Critical habitat losses for organisms such as polar bears, whales, seals and sea birds Benefits for Arctic fisheries Arctic land regions Cold extremes warm by a factor of 2–3, reaching up to 4.5°C (high confidence) Biome shifts in the tundra and permafrost deterioration are likely Cold extremes warm by as much as 8°C (high confidence) Larger intrusions of trees and shrubs in the tundra than under 1.5°C of warming are likely; larger but constrained losses in permafrost are likely Drastic regional warming is very likely A collapse in permafrost may occur (low confidence); a drastic biome shift from tundra to boreal forest is possible (low confidence) Alpine regions Severe shifts in biomes are likely Even more severe shifts are likely Collapse in alpine ecosystems is likely Southeast Asia Risks for increased flooding related to sea level rise Increases in heavy precipitation events Significant risks of crop yield reductions are avoided Higher risks of increased flooding related to sea level rise (medium confidence) Stronger increases in heavy precipitation events (medium confidence) One-third decline in per capita crop production (medium confidence) Substantial increases in risks related to flooding from sea level rise Substantial increase in heavy precipitation and high-flow events Substantial reductions in crop yield Mediterranean Increase in probability of extreme drought (medium confidence) Medium confidence in reduction in runoff of about 9% (likely range 4.5–15.5%) Risk of water deficit (medium confidence) Robust increase in probability of extreme drought (medium confidence) Medium confidence in further reductions (about 17%) in runoff (likely range 8–28%) Higher risks of water deficit (medium confidence) Robust and large increases in extreme drought. Substantial reductions in precipitation and in runoff (medium confidence) Very high risks of water deficit (medium confidence) West Africa and the Sahel Increases in the number of hot nights and longer and more frequent heatwaves are likely Reduced maize and sorghum production is likely, with area suitable for maize production reduced by as much as 40% Increased risks of undernutrition Further increases in number of hot nights and longer and more frequent heatwaves are likely Negative impacts on maize and sorghum production likely larger than at 1.5°C; medium confidence that vulnerabilities to food security in the African Sahel will be higher at 2°C compared to 1.5°C Higher risks of undernutrition Substantial increases in the number of hot nights and heatwave duration and frequency (very likely) Negative impacts on crop yield may result in major regional food insecurities (medium confidence) High risks of undernutrition Southern Africa Reductions in water availability (medium confidence) Increases in number of hot nights and longer and more frequent heatwaves (high confidence) High risks of increased mortality from heatwaves High risk of undernutrition in communities dependent on dryland agriculture and livestock Larger reductions in rainfall and water availability (medium confidence) Further increases in number of hot nights and longer and more frequent heatwaves (high confidence), associated increases in risks of increased mortality from heatwaves compared to 1.5°C of warming (high confidence) Higher risks of undernutrition in communities dependent on dryland agriculture and livestock Large reductions in rainfall and water availability (medium confidence) Drastic increases in the number of hot nights, hot days and heatwaves (high confidence) Very high risks of increased mortality from heatwaves Very high risks of undernutrition in communities dependent on dryland agriculture and livestock Tropics Increases in the number of hot days and hot nights as well as longer and more frequent heatwaves (high confidence) Risks to tropical crop yields in West Africa, Southeast Asia and Central and South America are significantly less than under 2°C of warming The largest increase in hot days under 2°C compared to 1.5°C is projected for the tropics. Risks to tropical crop yields in West Africa, Southeast Asia and Central and South America could be extensive Oppressive temperatures and accumulated heatwave duration very likely to directly impact human health, mortality and productivity Substantial reductions in crop yield very likely Small islands Land of 60,000 less people exposed by 2150 on SIDS compared to impacts under 2°C of global warming Risks for coastal flooding reduced by 20–80% for SIDS compared to 2°C of global warming Freshwater stress reduced by 25% Increase in the number of warm days for SIDS in the tropics Persistent heat stress in cattle avoided Loss of 70–90% of coral reefs Tens of thousands of people displaced owing to inundation of SIDSHigh risks for coastal floodingFreshwater stress reduced by 25% compared to 2°C of global warming Freshwater stress from projected aridity Further increase of about 70 warm days per year Persistent heat stress in cattle in SIDS Loss of most coral reefs and weaker remaining structures owing to ocean acidification Substantial and widespread impacts through inundation of SIDS, coastal flooding, freshwater stress, persistent heat stress and loss of most coral reefs (very likely) Fynbos biome About 30% of suitable climate area lost (medium confidence) Increased losses (about 45%) of suitable climate area (medium confidence) Up to 80% of suitable climate area lost (medium confidence) Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, an analysis is provided of how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming, whereas tipping points in the global climate system, referred to as large-scale singular events, were already discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7. Collins et al. (2013)1225 discussed the loss of Arctic sea ice in the context of potential tipping points. Climate models have been used to assess whether a bifurcation exists that would lead to the irreversible loss of Arctic sea ice (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012)1226 and to test whether the summer sea ice extent can recover after it has been lost (Schröder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011)1227. These studies did not find evidence of bifurcation or indicate that sea ice returns within a few years of its loss, leading Collins et al. (2013)1228 to conclude that there is little evidence for a tipping point in the transition from perennial to seasonal ice cover. No evidence has been found for irreversibility or tipping points, suggesting that year-round sea ice will return given a suitable climate (medium confidence) (Schröder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011)1229. Tree growth in tundra-dominated landscapes is strongly constrained by the number of days with mean air temperature above 0°C. A potential tipping point exists where the number of days below 0°C decreases to the extent that the tree fraction increases significantly. Tundra-dominated landscapes have warmed more than the global average over the last century (Settele et al., 2014)1230, with associated increases in fires and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016)1231. These processes facilitate conditions for woody species establishment in tundra areas, and for the eventual transition of the tundra to boreal forest. The number of investigations into how the tree fraction may respond in the Arctic to different degrees of global warming is limited, and studies generally indicate that substantial increases will likely occur gradually (e.g., Lenton et al., 2008)1232. Abrupt changes are only plausible at levels of warming significantly higher than 2°C (low confidence) and would occur in conjunction with a collapse in permafrost (Drijfhout et al., 2015)1233. Widespread thawing of permafrost potentially makes a large carbon store (estimated to be twice the size of the atmospheric store; Dolman et al., 2010)1234 vulnerable to decomposition, which could lead to further increases in atmospheric carbon dioxide and methane and hence to further global warming. This feedback loop between warming and the release of greenhouse gas from thawing tundra represents a potential tipping point. However, the carbon released to the atmosphere from thawing permafrost is projected to be restricted to 0.09–0.19 Gt C yr–1 at 2°C of global warming and to 0.08–0.16 Gt C yr–1 at 1.5°C (E.J. Burke et al., 2018)1235, which does not indicate a tipping point (medium confidence). At higher degrees of global warming, in the order of 3°C, a different type of tipping point in permafrost may be reached. A single model projection (Drijfhout et al., 2015)1236 suggested that higher temperatures may induce a smaller ice fraction in soils in the tundra, leading to more rapidly warming soils and a positive feedback mechanism that results in permafrost collapse (low confidence). The disparity between the multi-millennial time scales of soil carbon accumulation and potentially rapid decomposition in a warming climate implies that the loss of this carbon to the atmosphere would be essentially irreversible (Collins et al., 2013)1237. At a fundamental level, the pressure gradient between the Indian Ocean and Asian continent determines the strength of the Asian monsoon. As land masses warm faster than the oceans, a general strengthening of this gradient, and hence of monsoons, may be expected under global warming (e.g., Lenton et al., 2008)1238. Additional factors such as changes in albedo induced by aerosols and snow-cover change may also affect temperature gradients and consequently pressure gradients and the strength of the monsoon. In fact, it has been estimated that an increase of the regional land mass albedo to 0.5 over India would represent a tipping point resulting in the collapse of the monsoon system (Lenton et al., 2008)1239. The overall impacts of the various types of radiative forcing under different emissions scenarios are more subtle, with a weakening of the monsoon north of about 25°N in East Asia but a strengthening south of this latitude projected by Jiang and Tian (2013)1240 under high and modest emissions scenarios. Increases in the intensity of monsoon precipitation are likely under low mitigation (AR5). Given that scenarios of 1.5°C or 2°C of global warming would include a substantially smaller radiative forcing than those assessed in the study by Jiang and Tian (2013)1241, there is low confidence regarding changes in monsoons at these low global warming levels, as well as regarding the differences between responses at 1.5°C versus 2°C of warming. Earlier work has identified 3°C of global warming as the tipping point leading to a significant strengthening of the West African monsoon and subsequent wettening (and greening) of the Sahel and Sahara (Lenton et al., 2008)1242. AR5 (Niang et al., 2014)1243, as well as more recent research through the Coordinated Regional Downscaling Experiment for Africa (CORDEX–AFRICA), provides a more uncertain view, however, in terms of the rainfall futures of the Sahel under low mitigation futures. Even if a wetter Sahel should materialize under 3°C of global warming (low confidence), it should be noted that there would be significant offsets in the form of strong regional warming and related adverse impacts on crop yield, livestock mortality and human health under such low mitigation futures (Engelbrecht et al., 2015; Sylla et al., 2016; Weber et al., 2018)1244. A large portion of rainfall over the world's largest rainforests is recirculated (e.g., Lenton et al., 2008)1245, which raises the concern that deforestation may trigger a threshold in reduced forest cover, leading to pronounced forest dieback. For the Amazon, this deforestation threshold has been estimated to be 40% (Nobre et al., 2016)1246. Global warming of 3°C–4°C may also, independent of deforestation, represent a tipping point that results in a significant dieback of the Amazon forest, with a key forcing mechanism being stronger El Niño events bringing more frequent droughts to the region (Nobre et al., 2016)1247. Increased fire frequencies under global warming may interact with and accelerate deforestation, particularly during periods of El Niño-induced droughts (Lenton et al., 2008; Nobre et al., 2016)1248. Global warming of 3°C is projected to reduce the extent of tropical rainforest in Central America, with biomass being reduced by about 40%, which can lead to a large replacement of rainforest by savanna and grassland (Lyra et al., 2017)1249. Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016)1250 and observational constraints (Cox et al., 2013)1251 suggest that pronounced rainforest dieback may only be triggered at 3°C–4°C (medium confidence), although pronounced biomass losses may occur at 1.5°C– 2°C of global warming. Boreal forests are likely to experience stronger local warming than the global average (WGII AR5; Collins et al., 2013)1252. Increased disturbance from fire, pests and heat-related mortality may affect, in particular, the southern boundary of boreal forests (medium confidence) (Gauthier et al., 2015)1253, with these impacts accruing with greater warming and thus impacts at 2°C would be expected to be greater than those at 1.5°C (medium confidence). A tipping point for significant dieback of the boreal forests is thought to exist, where increased tree mortality would result in the creation of large regions of open woodlands and grasslands, which would favour further regional warming and increased fire frequencies, thus inducing a powerful positive feedback mechanism (Lenton et al., 2008; Lenton, 2012)1254. This tipping point has been estimated to exist between 3°C and 4°C of global warming (low confidence) (Lucht et al., 2006; Kriegler et al., 2009)1255, but given the complexities of the various forcing mechanisms and feedback processes involved, this is thought to be an uncertain estimate. Increases in ambient temperature are linearly related to hospitalizations and deaths once specific thresholds are exceeded (so there is not a tipping point per se). It is plausible that coping strategies will not be in place for many regions, with potentially significant impacts on communities with low adaptive capacity, effectively representing the occurrence of a local/regional tipping point. In fact, even if global warming is restricted to below 2°C, there could be a substantial increase in the occurrence of deadly heatwaves in cities if urban heat island effects are considered, with impacts being similar at 1.5°C and 2°C but substantially larger than under the present climate (Matthews et al., 2017)1256. At 1.5°C of warming, twice as many megacities (such as Lagos, Nigeria, and Shanghai, China) than at present are likely to become heat stressed, potentially exposing more than 350 million more people to deadly heat stress by 2050. At 2°C of warming, Karachi (Pakistan) and Kolkata (India) could experience conditions equivalent to their deadly 2015 heatwaves on an annual basis (medium confidence). These statistics imply a tipping point in the extent and scale of heatwave impacts. However, these projections do not integrate adaptation to projected warming, for instance cooling that could be achieved with more reflective roofs and urban surfaces in general (Akbari et al., 2009; Oleson et al., 2010)1257. A large number of studies have consistently indicated that maize crop yield will be negatively affected under increased global warming, with negative impacts being higher at 2°C of warming than at 1.5°C (e.g., Niang et al., 2014; Schleussner et al., 2016b; J. Huang et al., 2017; Iizumi et al., 2017)1258. Under 2°C of global warming, losses of 8–14% are projected in global maize production (Bassu et al., 2014)1259. Under global warming of more than 2°C, regional losses are projected to be about 20% if they co-occur with reductions in rainfall (Lana et al., 2017)1260. These changes may be classified as incremental rather than representing a tipping point. Large-scale reductions in maize crop yield, including the potential collapse of this crop in some regions, may exist under 3°C or more of global warming (low confidence) (e.g., Thornton et al., 2011)1261. The potential impacts of climate change on livestock (Section 3.4.6), in particular the direct impacts through increased heat stress, have been less well studied than impacts on crop yield, especially from the perspective of critical thresholds being exceeded. A case study from Jamaica revealed that the difference in heat stress for livestock between 1.5°C and 2°C of warming is likely to exceed the limits for normal thermoregulation and result in persistent heat stress for these animals (Lallo et al., 2018)1262. It is plausible that this finding holds for livestock production in both tropical and subtropical regions more generally (medium confidence) (Section 3.4.6). Under 3°C of global warming, significant reductions in the areas suitable for livestock production could occur (low confidence), owing to strong increases in regional temperatures in the tropics and subtropics (high confidence). Thus, regional tipping points in the viability of livestock production may well exist, but little evidence quantifying such changes exists. Tipping point Warming of 1.5°C or less Warming of 1.5°C–2°C Warming of up to 3°C Arctic sea ice Arctic summer sea ice is likely to be maintained Sea ice changes reversible under suitable climate restoration The risk of an ice-free Arctic in summer is about 50% or higher Sea ice changes reversible under suitable climate restoration Arctic is very likely to be ice free in summer Sea ice changes reversible under suitable climate restoration Tundra Decrease in number of growing degree days below 0°CAbrupt increases in tree cover are unlikely Further decreases in number of growing degree days below 0°C Abrupt increased in tree cover are unlikely Potential for an abrupt increase in tree fraction (low confidence) Permafrost 17–44% reduction in permafrost Approximately 2 million km2 more permafrost maintained than under 2°C of global warming (medium confidence) Irreversible loss of stored carbon 28–53% reduction in permafrost Irreversible loss of stored carbon Potential for permafrost collapse (low confidence) Asian monsoon Low confidence in projected changes Low confidence in projected changes Increases in the intensity of monsoon precipitation likely West African monsoon and the Sahel Uncertain changes; unlikely that a tipping point is reached Uncertain changes; unlikely that tipping point is reached Strengthening of monsoon with wettening and greening of the Sahel and Sahara (low confidence) Negative associated impacts through increases in extreme temperature events Rainforests Reduced biomass, deforestation and fire increases pose uncertain risks to forest dieback Larger biomass reductions than under 1.5°C of warming; deforestation and fire increases pose uncertain risk to forest dieback Reduced extent of tropical rainforest in Central America and large replacement of rainforest by savanna and grassland Potential tipping point leading to pronounced forest dieback (medium confidence) Boreal forests Increased tree mortality at southern boundary of boreal forest (medium confidence) Further increases in tree mortality at southern boundary of boreal forest (medium confidence) Potential tipping point at 3°C–4°C for significant dieback of boreal forest (low confidence) Heatwaves, unprecedented heat and human health Substantial increase in occurrence of potentially deadly heatwaves (likely)More than 350 million more people exposed to deadly heat by 2050 under a midrange population growth scenario (likely) Substantial increase in potentially deadly heatwaves (likely)Annual occurrence of heatwaves similar to the deadly 2015 heatwaves in India and Pakistan (medium confidence) Substantial increase in potentially deadly heatwaves very likely Agricultural systems: key staple crops Global maize crop reductions of about 10% Larger reductions in maize crop production than under 1.5°C of about 15% Drastic reductions in maize crop globally and in Africa (high confidence) Potential tipping point for collapse of maize crop in some regions (low confidence) Livestock in the tropics and subtropics Increased heat stress Onset of persistent heat stress (medium confidence) Persistent heat stress likely Balancing the costs and benefits of mitigation is challenging because estimating the value of climate change damages depends on multiple parameters whose appropriate values have been debated for decades (for example, the appropriate value of the discount rate) or that are very difficult to quantify (for example, the value of non-market impacts; the economic effects of losses in ecosystem services; and the potential for adaptation, which is dependent on the rate and timing of climate change and on the socio-economic content). See Cross-Chapter Box 5 in Chapter 2 for the definition of the social cost of carbon and for a discussion of the economics of 1.5°C-consistent pathways and the social cost of carbon, including the impacts of inequality on the social cost of carbon. Global economic damages of climate change are projected to be smaller under warming of 1.5°C than 2°C in 2100 (Warren et al., 2018c)1263. The mean net present value of the costs of damages from warming in 2100 for 1.5°C and. 2°C (including costs associated with climate change-induced market and non-market impacts, impacts due to sea level rise, and impacts associated with large-scale discontinuities) are $54 and $69 trillion, respectively, relative to 1961–1990. Values of the social cost of carbon vary when tipping points are included. The social cost of carbon in the default setting of the Dynamic Integrated Climate-Economy (DICE) model increases from $15 tCO_2^{-1} to $116 (range 50–166) tCO_2^{-1} when large-scale singularities or 'tipping elements' are incorporated (Y. Cai et al., 2016; Lemoine and Traeger, 2016)1264. Lemoine and Traeger (2016)1265 included optimization calculations that minimize welfare impacts resulting from the combination of climate change risks and climate change mitigation costs, showing that welfare is minimized if warming is limited to 1.5°C. These calculations excluded the large health co-benefits that accrue when greenhouse gas emissions are reduced (Section 3.4.7.1; Shindell et al., 2018)1266. The economic damages of climate change in the USA are projected to be large (Hsiang et al., 2017; Yohe, 2017)1267. Hsiang et al. (2017)1268 shows that the USA stand to lose -0.1 to 1.7% of the Gross Domestic Product (GDP) at 1.5°C warming. Yohe (2017)1269 calculated transient temperature trajectories from a linear relationship with contemporaneous cumulative emissions under a median no-policy baseline trajectory that brings global emissions to roughly 93 $GtCO_2$ yr^{-1} by the end of the century (Fawcett et al., 2015)1270, with 1.75°C per 1000 $GtCO_2$ as the median estimate. Associated aggregate economic damages in decadal increments through the year 2100 are estimated in terms of the percentage loss of GDP at the median, 5th percentile and 95th percentile transient temperature (Hsiang et al., 2017)1271. The results for the baseline no-policy case indicate that economic damages along median temperature change and median damages (median-median) reach 4.5% of GDP by 2100, with an uncertainty range of 2.5% and 8.5% resulting from different combinations of temperature change and damages. Avoided damages from achieving a 1.5°C temperature limit along the median-median case are nearly 4% (range 2–7%) by 2100. Avoided damages from achieving a 2°C temperature limit are only 3.5% (range 1.8–6.5%). Avoided damages from achieving 1.5°C versus 2°C are modest at about 0.35% (range 0.20–0.65%) by 2100. The values of achieving the two temperature limits do not diverge significantly until 2040, when their difference tracks between 0.05 and 0.13%; the differences between the two temperature targets begin to diverge substantially in the second half of the century.