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Box 3.2 (continued)

5 million in 1960 to 22 million in 2008). Koutroulis et al. (2016) reported that only 6% out of the total 18% decrease in water availability projected for Crete under 2°C of global warming at the end of the 21st century would be due to decreased precipitation, with the remaining 12% due to an increase in evapotranspiration. This study and others like it confirm an important risk of extreme drought conditions for the Middle East under 1.5°C of global warming (Jacob et al., 2018), with risks being even higher in continental locations than on islands; these projections are consistent with current observed changes (Section 3.3.4; Greve et al., 2014). Risks of drying in the Mediterranean region could be substantially reduced if global warming is limited to 1.5°C compared to 2°C or higher levels of warming (Section 3.4.3; Guiot and Cramer, 2016). Higher warming levels may induce high levels of vulnerability exacerbated by large changes in demography.

3.3.5 Runoff and Fluvial Flooding

3.3.5.1 Observed and attributed changes in runoff and river flooding

There has been progress since AR5 in identifying historical changes in streamflow and continental runoff. Using the available streamflow data, Dai (2016) showed that long-term (1948–2012) flow trends are statistically significant only for 27.5% of the world's 200 major rivers, with negative trends outnumbering the positive ones. Although streamflow trends are mostly not statistically significant, they are consistent with observed regional precipitation changes. From 1950 to 2012, precipitation and runoff have increased over southeastern South America, central and northern Australia, the central and northeastern United States, central and northern Europe, and most of Russia, and they have decreased over most of Africa, East and South Asia, eastern coastal Australia, the southeastern and northwestern United States, western and eastern Canada, the Mediterranean region and some regions of Brazil (Dai, 2016).

A large part of the observed regional trends in streamflow and runoff might have resulted from internal multi-decadal and multi-year climate variations, especially the Pacific decadal variability (PDV), the Atlantic Multi-Decadal Oscillation (AMO) and the El Niño–Southern Oscillation (ENSO), although the effect of anthropogenic greenhouse gases and aerosols could also be important (Hidalgo et al., 2009; Gu and Adler, 2013, 2015; Chiew et al., 2014; Luo et al., 2016; Gudmundsson et al., 2017). Additionally, other human activities can influence the hydrological cycle, such as land-use/land-cover change, modifications in river morphology and water table depth, construction and operation of hydropower plants, dikes and weirs, wetland drainage, and agricultural practices such as water withdrawal for irrigation. All of these activities can also have a large impact on runoff at the river basin scale, although there is less agreement over their influence on global mean runoff (Gerten et al., 2008; Sterling et al., 2012; Hall et al., 2014; Betts et al., 2015; Arheimer et al., 2017). Some studies suggest that increases in global runoff resulting from changes in land cover or land use (predominantly deforestation) are counterbalanced by decreases resulting from irrigation (Gerten et al., 2008; Sterling et al., 2012). Likewise, forest and grassland fires can modify the hydrological response at the watershed scale when the burned area is significant (Versini et al., 2013; Springer et al., 2015; Wine and Cadol, 2016).

Few studies have explored observed changes in extreme streamflow and river flooding since the IPCC AR5. Mallakpour and Villarini (2015) analysed changes of flood magnitude and frequency in the central United States by considering stream gauge daily records with at least 50 years of data ending no earlier than 2011. They showed that flood frequency has increased, whereas there was limited evidence of a decrease in flood magnitude in this region. Stevens et al. (2016) found a rise in the number of reported floods in the United Kingdom during the period 1884–2013, with flood events appearing more frequently towards the end of the 20th century. A peak was identified in 2012, when annual rainfall was the second highest in over 100 years. Do et al. (2017) computed the trends in annual maximum daily streamflow data across the globe over the 1966–2005 period. They found decreasing trends for a large number of stations in western North America and Australia, and increasing trends in parts of Europe, eastern North America, parts of South America, and southern Africa.

In summary, streamflow trends since 1950 are not statistically significant in most of the world's largest rivers (*high confidence*), while flood frequency and extreme streamflow have increased in some regions (*high confidence*).

3.3.5.2 Projected changes in runoff and river flooding at 1.5°C versus 2°C of global warming

Global-scale assessments of projected changes in freshwater systems generally suggest that areas with either positive or negative changes in mean annual streamflow are smaller for 1.5°C than for 2°C of global warming (Betts et al., 2018; Döll et al., 2018). Döll et al. (2018) found that only 11% of the global land area (excluding Greenland and Antarctica) shows a statistically significantly larger hazard at 2°C than at 1.5°C. Significant decreases are found for 13% of the global land area for both global warming levels, while significant increases are projected to occur for 21% of the global land area at 1.5°C, and rise to between 26% (Döll et al., 2018) and approximately 50% (Betts et al., 2018) at 2°C.

At the regional scale, projected runoff changes generally follow the spatial extent of projected changes in precipitation (see Section 3.3.3). Emerging literature includes runoff projections for different warming levels. For 2°C of global warming, an increase in runoff is projected for much of the high northern latitudes, Southeast Asia, East Africa, northeastern Europe, India, and parts of, Austria, China, Hungary, Norway, Sweden, the northwest Balkans and Sahel (Schleussner et al., 2016b; Donnelly et al., 2017; Döll et al., 2018; Zhai et al., 2018). Additionally, decreases are projected in the Mediterranean region, southern Australia, Central America, and central and southern South

America (Schleussner et al., 2016b; Donnelly et al., 2017; Döll et al., 2018). Differences between 1.5°C and 2°C would be most prominent in the Mediterranean, where the median reduction in annual runoff is expected to be about 9% (likely range 4.5–15.5%) at 1.5°C, while at 2°C of warming runoff could decrease by 17% (likely range 8–25%) (Schleussner et al., 2016b). Consistent with these projections, Döll et al. (2018) found that statistically insignificant changes in the mean annual streamflow around the Mediterranean region became significant when the global warming scenario was changed from 1.5°C to 2°C, with decreases of 10–30% between these two warming levels. Donnelly et al. (2017) found an intense decrease in runoff along both the Iberian and Balkan coasts with an increase in warming level.

Basin-scale projections of river runoff at different warming levels are available for many regions. Betts et al. (2018) assessed runoff changes in 21 of the world's major river basins at 1.5°C and 2°C of global warming (Figure 3.15). They found a general tendency towards increased runoff, except in the Amazon, Orange, Danube and Guadiana basins where the range of projections indicate decreased mean flows (Figure 3.13). In the case of the Amazon, mean flows are projected to decline by up to 25% at 2°C global warming (Betts et al., 2018). Gosling et al. (2017) analysed the impact of global warming of 1°C, 2°C and 3°C above pre-industrial levels on river runoff at the catchment scale, focusing on eight major rivers in different continents: Upper Amazon, Darling, Ganges, Lena, Upper Mississippi, Upper Niger, Rhine and Tagus. Their results show that the sign and magnitude of change with global warming for the Upper Amazon, Darling, Ganges, Upper Niger and Upper Mississippi is unclear, while the Rhine and Tagus may experience decreases in projected runoff and the Lena may experience increases. Donnelly et al. (2017) analysed the mean flow response to different warming levels for six major European rivers: Glomma, Wisla, Lule, Ebro, Rhine and Danube. Consistent with the increases in mean runoff projected for large parts of northern Europe, the Glomma, Wisla and Lule rivers could experience increased discharges with global warming while discharges from the Ebro could decrease, in part due to a decrease in runoff in southern Europe. In the case of the Rhine and Danube rivers, Donnelly et al. (2017) did not find clear results. Mean annual runoff of the Yiluo River catchment in northern China is projected to decrease by 22% at 1.5°C and by 21% at 2°C, while the mean annual runoff for the Beijiang River catchment in southern China is projected to increase by less than 1% at 1.5°C and 3% at 2°C in comparison to the studied baseline period (L. Liu et al., 2017).

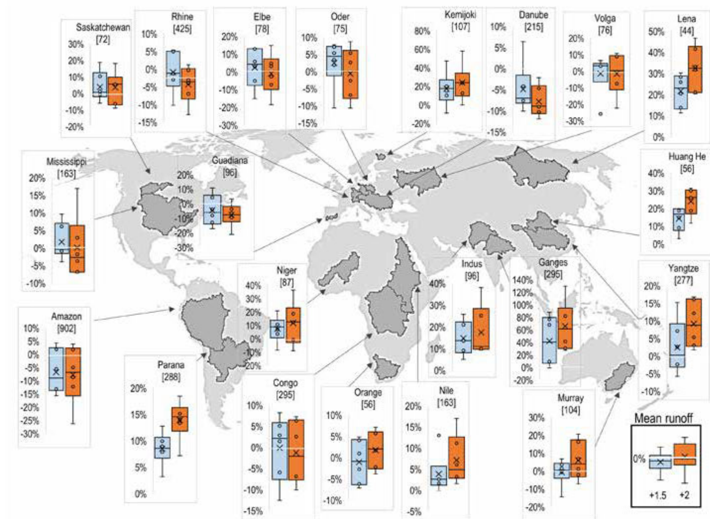

Figure 3.15 | Runoff changes in twenty-one of the world's major river basins at 1.5°C (blue) and 2°C (orange) of global warming, simulated by the Joint UK Land Environment Simulator (JULES) ecosystem–hydrology model under the ensemble of six climate projections. Boxes show the 25th and 75th percentile changes, whiskers show the range, circles show the four projections that do not define the ends of the range, and crosses show the ensemble means. Numbers in square brackets show the ensemble-mean flow in the baseline (millimetres of rain equivalent) (Source: Betts et al., 2018).

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Chen et al. (2017) assessed the future changes in water resources in the Upper Yangtze River basin for the same warming levels and found a slight decrease in the annual discharge at 1.5°C but a slight increase at 2°C. Montroull et al. (2018) studied the hydrological impacts of the main rivers (Paraguay, Paraná, Iguazú and Uruguay) in La Plata basin in South America under 1.5°C and 2°C of global warming and for two emissions scenarios. The Uruguay basin shows increases in streamflow for all scenarios/warming targets except for the combination of RCP8.5/1.5°C of warming. The increase is approximately 15% above the 1981–2000 reference period for 2°C of global warming and the RCP4.5 scenario. For the other three rivers the sign of the change in mean streamflow depends strongly on the RCP and GCM used.

Marx et al. (2018) analysed how hydrological low flows in Europe are affected under different global warming levels (1.5°C, 2°C and 3°C). The Alpine region showed the strongest low flow increase, from 22% at 1.5°C to 30% at 2°C, because of the relatively large snow melt contribution, while in the Mediterranean low flows are expected to decrease because of the decreases in annual precipitation projected for that region. Döll et al. (2018) found that extreme low flows in the tropical Amazon, Congo and Indonesian basins could decrease by 10% at 1.5°C, whereas they could increase by 30% in the southwestern part of Russia under the same warming level. At 2°C, projected increases in extreme low flows are exacerbated in the higher northern latitudes and in eastern Africa, India and Southeast Asia, while projected decreases intensify in the Amazon basin, western United States, central Canada, and southern and western Europe, although not in the Congo basin or Indonesia, where models show less agreement.

Recent analyses of projections in river flooding and extreme runoff and flows are available for different global warming levels. At the global scale, Alfieri et al. (2017) assessed the frequency and magnitude of river floods and their impacts under 1.5°C, 2°C and 4°C global warming scenarios. They found that flood events with an occurrence interval longer than the return period of present-day flood protections are projected to increase in all continents under all considered warming levels, leading to a widespread increment in the flood hazard. Döll et al. (2018) found that high flows are projected to increase significantly on 11% and 21% of the global land area at 1.5°C and 2°C, respectively. Significantly increased high flows are expected to occur in South and Southeast Asia and Central Africa at 1.5°C, with this effect intensifying and including parts of South America at 2°C.

Regarding the continental scale, Donnelly et al. (2017) and Thober et al. (2018) explored climate change impacts on European high flows and/or floods under 1.5°C, 2°C and 3°C of global warming. Thober et al. (2018) identified the Mediterranean region as a hotspot of change, with significant decreases in high flows of –11% and –13% at 1.5°C and 2°C, respectively, mainly resulting from reduced precipitation (Box 3.2). In northern regions, high flows are projected to rise by 1% and 5% at 1.5°C and 2°C, respectively, owing to increasing precipitation, although floods could decrease by 6% in both scenarios because of less snowmelt. Donnelly et al. (2017) found that high runoff levels could rise in intensity, robustness and spatial extent over large parts of continental Europe with an increasing warming level. At 2°C, flood magnitudes are expected to increase significantly in Europe south of 60°N, except for some regions (Bulgaria, Poland and southern Spain); in contrast, they are projected to decrease at higher latitudes (e.g., in most of Finland, northwestern Russia and northern Sweden), with the exception of southern Sweden and some coastal areas in Norway where flood magnitudes may increase (Roudier et al., 2016). At the basin scale, Mohammed et al. (2017) found that floods are projected to be more frequent and flood magnitudes greater at 2°C than at 1.5°C in the Brahmaputra River in Bangladesh. In coastal regions, increases in heavy precipitation associated with tropical cyclones (Section 3.3.6) combined with increased sea levels (Section 3.3.9) may lead to increased flooding (Section 3.4.5).

In summary, there is *medium confidence* that global warming of 2°C above the pre-industrial period would lead to an expansion of the area with significant increases in runoff, as well as the area affected by flood hazard, compared to conditions at 1.5°C of global warming. A global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium confidence*) and to an increase in flood hazard in some regions (*medium confidence*) compared to present-day conditions.

3.3.6 Tropical Cyclones and Extratropical Storms

Most recent studies on observed trends in the attributes of tropical cyclones have focused on the satellite era starting in 1979 (Rienecker et al., 2011), but the study of observed trends is complicated by the heterogeneity of constantly advancing remote sensing techniques and instrumentation during this period (e.g., Landsea, 2006; Walsh et al., 2016). Numerous studies leading up to and after AR5 have reported a decreasing trend in the global number of tropical cyclones and/or the globally accumulated cyclonic energy (Emanuel, 2005; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Klotzbach and Landsea, 2015; Walsh et al., 2016). A theoretical physical basis for such a decrease to occur under global warming was recently provided by Kang and Elsner (2015). However, using a relatively short (20 year) and relatively homogeneous remotely sensed record, Klotzbach (2006) reported no significant trends in global cyclonic activity, consistent with more recent findings of Holland and Bruyère (2014). Such contradictions, in combination with the fact that the almost four-decade-long period of remotely sensed observations remains relatively short to distinguish anthropogenically induced trends from decadal and multi-decadal variability, implies that there is only *low confidence* regarding changes in global tropical cyclone numbers under global warming over the last four decades.

Studies in the detection of trends in the occurrence of very intense tropical cyclones (category 4 and 5 hurricanes on the Saffir-Simpson scale) over recent decades have yielded contradicting results. Most studies have reported increases in these systems (Emanuel, 2005; Webster et al., 2005; Klotzbach, 2006; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Walsh et al., 2016), in particular for the North Atlantic, North Indian and South Indian Ocean basins (e.g., Singh et al., 2000; Singh, 2010; Kossin et al., 2013; Holland and Bruyère, 2014; Walsh et al., 2016). In the North Indian Ocean over the Arabian Sea, an increase in the frequency of extremely severe cyclonic storms has been reported and attributed to anthropogenic warming (Murakami et al., 2017). However, to the east over the Bay of Bengal, tropical cyclones and severe tropical cyclones have exhibited decreasing trends over

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the period 1961–2010, although the ratio between severe tropical cyclones and all tropical cyclones is increasing (Mohapatra et al., 2017). Moreover, studies that have used more homogeneous records, but were consequently limited to rather short periods of 20 to 25 years, have reported no statistically significant trends or decreases in the global number of these systems (Kamahori et al., 2006; Klotzbach and Landsea, 2015). Likewise, CMIP5 model simulations of the historical period have not produced anthropogenically induced trends in very intense tropical cyclones (Bender et al., 2010; Knutson et al., 2010, 2013; Camargo, 2013; Christensen et al., 2013), consistent with the findings of Klotzbach and Landsea (2015). There is consequently *low confidence* in the conclusion that the number of very intense cyclones is increasing globally.

General circulation model (GCM) projections of the changing attributes of tropical cyclones under high levels of greenhouse gas forcing (3°C to 4°C of global warming) consistently indicate decreases in the global number of tropical cyclones (Knutson et al., 2010, 2015; Sugi and Yoshimura, 2012; Christensen et al., 2013; Yoshida et al., 2017). A smaller number of studies based on statistical downscaling methodologies contradict these findings, however, and indicate increases in the global number of tropical cyclones under climate change (Emanuel, 2017). Most studies also indicate increases in the global number of very intense tropical cyclones under high levels of global warming (Knutson et al., 2015; Sugi et al., 2017), consistent with dynamic theory (Kang and Elsner, 2015), although a few studies contradict this finding (e.g., Yoshida et al., 2017). Hence, it is assessed that under 3°C to 4°C of warming that the global number of tropical cyclones would decrease whilst the number of very intense cyclones would increase (*medium confidence*).

To date, only two studies have directly explored the changing tropical cyclone attributes under 1.5°C versus 2°C of global warming. Using a high resolution global atmospheric model, Wehner et al. (2018a) concluded that the differences in tropical cyclone statistics under 1.5°C versus 2°C stabilization scenarios, as defined by the HAPPI protocols (Mitchell et al., 2017) are small. Consistent with the majority of studies performed for higher degrees of global warming, the total number of tropical cyclones is projected to decrease under global warming, whilst the most intense (categories 4 and 5) cyclones are projected to occur more frequently. These very intense storms are projected to be associated with higher peak wind speeds and lower central pressures under 2°C versus 1.5°C of global warming. The accumulated cyclonic energy is projected to decrease globally from 1.5°C to 2°C, in association with a decrease in the global number of tropical cyclones under progressively higher levels of global warming. It is also noted that heavy rainfall associated with tropical cyclones was assessed in the IPCC SREX as *likely* to increase under increasing global warming (Seneviratne et al., 2012). Two recent articles suggest that there is *high confidence* that the current level of global warming (i.e., about 1°C, see Section 3.3.1) increased the heavy precipitation associated with the 2017 Hurricane Harvey by about 15% or more (Risser and Wehner, 2017; van Oldenborgh et al., 2017). Hence, it can be inferred, under the assumption of linear dynamics, that further increases in heavy precipitation would occur under 1.5°C, 2°C and higher levels of global warming (*medium confidence*). Using a high resolution regional climate model, Muthige et al. (2018) explored the effects of different degrees of global warming on tropical cyclones over the southwest Indian Ocean, using transient simulations that downscaled a number of RCP8.5 GCM projections. Decreases in tropical cyclone frequencies are projected under both 1.5°C and 2°C of global warming. The decreases in cyclone frequencies under 2°C of global warming are somewhat larger than under 1.5°C, but no further decreases are projected under 3°C. This suggests that 2°C of warming, at least in these downscaling simulations, represents a type of stabilization level in terms of tropical cyclone formation over the southwest Indian Ocean and landfall over southern Africa (Muthige et al., 2018). There is thus *limited evidence* that the global number of tropical cyclones will be lower under 2°C compared to 1.5°C of global warming, but with an increase in the number of very intense cyclones (*low confidence*).

The global response of the mid-latitude atmospheric circulation to 1.5°C and 2°C of warming was investigated using the HAPPI ensemble with a focus on the winter season (Li et al., 2018). Under 1.5°C of global warming a weakening of storm activity over North America, an equatorward shift of the North Pacific jet exit and an equatorward intensification of the South Pacific jet are projected. Under an additional 0.5°C of warming a poleward shift of the North Atlantic jet exit and an intensification on the flanks of the Southern Hemisphere storm track are projected to become more pronounced. The weakening of the Mediterranean storm track that is projected under low mitigation emerges in the 2°C warmer world (Li et al., 2018). AR5 assessed that under high greenhouse gas forcing (3°C or 4°C of global warming) there is *low confidence* in projections of poleward shifts of the Northern Hemisphere storm tracks, while there is *high confidence* that there would be a small poleward shift of the Southern Hemisphere storm tracks (Stocker et al., 2013). In the context of this report, the assessment is that there is *limited evidence* and *low confidence* in whether any projected signal for higher levels of warming would be clearly manifested under 2°C of global warming.

3.3.7 Ocean Circulation and Temperature

It is *virtually certain* that the temperature of the upper layers of the ocean (0–700 m in depth) has been increasing, and that the global mean for sea surface temperature (SST) has been changing at a rate just behind that of GMST. The surfaces of three ocean basins has warmed over the period 1950–2016 (by 0.11°C, 0.07°C and 0.05°C per decade for the Indian, Atlantic and Pacific Oceans, respectively; Hoegh-Guldberg et al., 2014), with the greatest changes occurring at the highest latitudes. Isotherms (i.e., lines of equal temperature) of sea surface temperature (SST) are shifting to higher latitudes at rates of up to 40 km per year (Burrows et al., 2014; García Molinos et al., 2015). Long-term patterns of variability make detecting signals due to climate change complex, although the recent acceleration of changes to the temperature of the surface layers of the ocean has made the climate signal more distinct (Hoegh-Guldberg et al., 2014). There is also evidence of significant increases in the frequency of marine heatwaves in the observational record (Oliver et al., 2018), consistent with changes in mean ocean temperatures (*high confidence*). Increasing climate extremes in the ocean are associated with the general rise in global average surface temperature, as well as more intense patterns of climate variability (e.g., climate change intensification of ENSO) (Section 3.5.2.5). Increased heat in the upper layers of the ocean is

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also driving more intense storms and greater rates of inundation in some regions, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas (Section 3.3.6).

Increasing land–sea temperature gradients have the potential to strengthen upwelling systems associated with the eastern boundary currents (Benguela, Canary, Humboldt and Californian Currents; Bakun, 1990). Observed trends support the conclusion that a general strengthening of longshore winds has occurred (Sydeman et al., 2014), but the implications of trends detected in upwelling currents themselves are unclear (Lluch-Cota et al., 2014). Projections of the scale of changes between 1°C and 1.5°C of global warming and between 1.5°C and 2°C are only informed by the changes during the past increase in GMST of 0.5°C (*low confidence*). However, evidence from GCM projections of future climate change indicates that a general strengthening of the Benguela, Canary and Humboldt upwelling systems under enhanced anthropogenic forcing (D. Wang et al., 2015) is projected to occur (*medium confidence*). This strengthening is projected to be stronger at higher latitudes. In fact, evidence from regional climate modelling is supportive of an increase in long-shore winds at higher latitudes, whereas long-shore winds may decrease at lower latitudes as a consequence of the poleward displacement of the subtropical highs under climate change (Christensen et al., 2007; Engelbrecht et al., 2009).

It is more likely than not that the Atlantic Meridional Overturning Circulation (AMOC) has been weakening in recent decades, given the detection of the 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). There is only *limited evidence* linking the current anomalously weak state of AMOC to anthropogenic warming (Caesar et al., 2018). It is *very likely* that the AMOC will weaken over the 21st century. The 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.

3.3.8 Sea Ice

Summer sea ice in the Arctic has been retreating rapidly in recent decades. During the period 1997 to 2014, for example, the monthly mean sea ice extent during September (summer) decreased on average by 130,000 km² per year (Serreze and Stroeve, 2015). This is about four times as fast as the September sea ice loss during the period 1979 to 1996. Sea ice thickness has also decreased substantially, with an estimated decrease in ice thickness of more than 50% in the central Arctic (Lindsay and Schweiger, 2015). Sea ice coverage and thickness also decrease in CMIP5 simulations of the recent past, and are projected to decrease in the future (Collins et al., 2013). However, the modelled sea ice loss in most CMIP5 models is much smaller than observed losses. Compared to observations, the simulations are less sensitive to both global mean temperature rise (Rosenblum and Eisenman, 2017) and anthropogenic CO_2 emissions (Notz and Stroeve, 2016). This mismatch between the observed and modelled sensitivity of Arctic sea ice implies that the multi-model-mean responses of future sea ice evolution probably underestimates the sea ice loss for a given amount of global warming. To address this issue, studies estimating the future evolution of Arctic sea ice tend to bias correct the model simulations based on the observed evolution of Arctic sea ice in response to global warming. Based on such bias correction, pre-AR5 and post-AR5 studies generally agree that for 1.5°C of global warming relative to pre-industrial levels, the Arctic Ocean will maintain a sea ice cover throughout summer in most years (Collins et al., 2013; Notz and Stroeve, 2016; Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Sigmond et al., 2018). For 2°C of global warming, chances of a sea ice-free Arctic during summer are substantially higher (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Screen et al., 2018; Sigmond et al., 2018). Model simulations suggest that there will be at least one sea ice-free Arctic[5] summer after approximately 10 years of stabilized warming at 2°C, as compared to one sea ice-free summer after 100 years of stabilized warming at 1.5°C above pre-industrial temperatures (Jahn, 2018; Screen et al., 2018; Sigmond et al., 2018). For a specific given year under stabilized warming of 2°C, studies based on large ensembles of simulations with a single model estimate the likelihood of ice-free conditions as 35% without a bias correction of the underlying model (Sanderson et al., 2017; Jahn, 2018); as between 10% and >99% depending on the observational record used to correct the sensitivity of sea ice decline to global warming in the underlying model (Niederdrenk and Notz, 2018); and as 19% based on a procedure to correct for biases in the climatological sea ice coverage in the underlying model (Sigmond et al., 2018). The uncertainty of the first year of the occurrence of an ice-free Arctic Ocean arising from internal variability is estimated to be about 20 years (Notz, 2015; Jahn et al., 2016).

The more recent estimates of the warming necessary to produce an ice-free Arctic Ocean during summer are lower than the ones given in AR5 (about 2.6°C–3.1°C of global warming relative to pre-industrial levels or 1.6°C–2.1°C relative to present-day conditions), which were similar to the estimate of 3°C of global warming relative to pre-industrial levels (or 2°C relative to present-day conditions) by Mahlstein and Knutti (2012) based on bias-corrected CMIP3 models. Rosenblum and Eisenman (2016) explained why the sensitivity estimated by Mahlstein and Knutti (2012) might be too low, estimating instead that September sea ice in the Arctic would disappear at 2°C of global warming relative to pre-industrial levels (or about 1°C relative to present-day conditions), in line with the other recent estimates. Notz and Stroeve (2016) used the observed correlation between September sea ice extent and cumulative CO_2 emissions to estimate that the Arctic Ocean would become nearly free of sea ice during September with a further 1000 Gt of emissions, which also implies a sea ice loss at about 2°C of global warming. Some of the uncertainty in these numbers stems from the possible impact of aerosols (Gagne et al., 2017) and of volcanic forcing (Rosenblum and Eisenman, 2016). During winter, little Arctic sea ice is projected to be lost for either 1.5°C or 2°C of global warming (Niederdrenk and Notz, 2018).

[5] Ice free is defined for the Special Report as when the sea ice extent is less than 106 km². Ice coverage less than this is considered to be equivalent to an ice-free Arctic Ocean for practical purposes in all recent studies.

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A substantial number of pre-AR5 studies found that there is no indication of hysteresis behaviour of Arctic sea ice under decreasing temperatures following a possible overshoot of a long-term temperature target (Holland et al., 2006; Schröder and Connolley, 2007; Armour et al., 2011; Sedláček et al., 2011; Tietsche et al., 2011; Boucher et al., 2012; Ridley et al., 2012). In particular, the relationship between Arctic sea ice coverage and GMST was found to be indistinguishable between a warming scenario and a cooling scenario. These results have been confirmed by post-AR5 studies (Li et al., 2013; Jahn, 2018), which implies *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea ice coverage.

In the Antarctic, sea ice shows regionally contrasting trends, such as a strong decrease in sea ice coverage near the Antarctic peninsula but increased sea ice coverage in the Amundsen Sea (Hobbs et al., 2016). Averaged over these contrasting regional trends, there has been a slow long-term increase in overall sea ice coverage in the Southern Ocean, although with comparably low ice coverage from September 2016 onwards. Collins et al. (2013) assessed *low confidence* in Antarctic sea ice projections because of the wide range of model projections and an inability of almost all models to reproduce observations such as the seasonal cycle, interannual variability and the long-term slow increase. No existing studies have robustly assessed the possible future evolution of Antarctic sea ice under low-warming scenarios.

In summary, the probability of a sea-ice-free Arctic Ocean during summer is substantially higher at 2°C compared to 1.5°C of global warming relative to pre-industrial levels, and there is *medium confidence* that there will be at least one sea ice-free Arctic summer after about 10 years of stabilized warming at 2°C, while about 100 years are required at 1.5°C. There is *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea ice coverage with regrowth on decadal time scales.

3.3.9 Sea Level

Sea level varies over a wide range of temporal and spatial scales, which can be divided into three broad categories. These are global mean sea level (GMSL), regional variation about this mean, and the occurrence of sea-level extremes associated with storm surges and tides. GMSL has been rising since the late 19th century from the low rates of change that characterized the previous two millennia (Church et al., 2013). Slowing in the reported rate over the last two decades (Cazenave et al., 2014) may be attributable to instrumental drift in the observing satellite system (Watson et al., 2015) and increased volcanic activity (Fasullo et al., 2016). Accounting for the former results in rates (1993 to mid-2014) between 2.6 and 2.9 mm yr^{-1} (Watson et al., 2015). The relative contributions from thermal expansion, glacier and ice-sheet mass loss, and freshwater storage on land are relatively well understood (Church et al., 2013; Watson et al., 2015) and their attribution is dominated by anthropogenic forcing since 1970 (15 ± 55% before 1950, 69 ± 31% after 1970) (Slangen et al., 2016).

There has been a significant advance in the literature since AR5, which has included the development of semi-empirical models (SEMs) into a broader emulation-based approach (Kopp et al., 2014; Mengel et al., 2016; Nauels et al., 2017) that is partially based on the results from more detailed, process-based modelling Church et al. (2013) assigned *low confidence* to SEMs because these models assume that the relation between climate forcing and GMSL is the same in the past (calibration) and future (projection). Probable future changes in the relative contributions of thermal expansion, glaciers and (in particular) ice sheets invalidate this assumption. However, recent emulation-based studies overcame this shortcoming by considering individual GMSL contributors separately, and they are therefore employed in this assessment. In this subsection, the process-based literature of individual contributors to GMSL is considered for scenarios close to 1.5°C and 2°C of global warming before emulation-based approaches are assessed.

A limited number of processes-based studies are relevant to GMSL in 1.5°C and 2°C worlds. Marzeion et al. (2018) used a global glacier model with temperature-scaled scenarios based on RCP2.6 to investigate the difference between 1.5°C and 2°C of global warming and found little difference between scenarios in the glacier contribution to GMSL for the year 2100 (54–97 mm relative to present-day levels for 1.5°C and 63–112 mm for 2°C, using a 90% confidence interval). This arises because glacier melt during the remainder of the century is dominated by the response to warming from pre-industrial to present-day levels, which is in turn a reflection of the slow response times of glaciers. Fürst et al. (2015) made projections of the Greenland ice sheet's contribution to GMSL using an ice-flow model forced by the regional climate model Modèle Atmosphérique Régional (MAR; considered by Church et al. (2013) to be the 'most realistic' such model). They projected an RCP2.6 range of 24–60 mm (1 standard deviation) by the end of the century (relative to the year 2000 and consistent with the assessment of Church et al. (2013); however, their projections do not allow the difference between 1.5°C and 2°C worlds to be evaluated.

The Antarctic ice sheet can contribute both positively, through increases in outflow (solid ice lost directly to the ocean), and negatively, through increases in snowfall (owing to the increased moisture-bearing capacity of a warmer atmosphere), to future GMSL rise. Frieler et al. (2015) suggested a range of 3.5–8.7% $°C^{-1}$ for this effect, which is consistent with AR5. Observations from the Amundsen Sea sector of Antarctica suggest an increase in outflow (Mouginot et al., 2014) over recent decades associated with grounding line retreat (Rignot et al., 2014) and the influx of relatively warm Circumpolar Deepwater (Jacobs et al., 2011). Literature on the attribution of these changes to anthropogenic forcing is still in its infancy (Goddard et al., 2017; Turner et al., 2017a). RCP2.6-based projections of Antarctic outflow (Levermann et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016, who include snowfall changes) are consistent with the AR5 assessment of Church et al. (2013) for end-of-century GMSL for RCP2.6, and do not support substantial additional GMSL rise by Marine Ice Sheet Instability or associated instabilities (see Section 3.6). While agreement is relatively good, concerns about the numerical fidelity of these models still exist, and this may affect the quality of their projections (Drouet et al., 2013; Durand and Pattyn, 2015). An assessment of Antarctic contributions beyond the end of the century, in particular related to the Marine Ice Sheet Instability, can be found in Section 3.6.

While some literature on process-based projections of GMSL for the period up to 2100 is available, it is insufficient for distinguishing

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between emissions scenarios associated with 1.5°C and 2°C warmer worlds. This literature is, however, consistent with the assessment by Church et al. (2013) of a *likely* range of 0.28–0.61 m in 2100 (relative to 1986–2005), suggesting that the AR5 assessment is still appropriate.

Recent emulation-based studies show convergence towards this AR5 assessment (Table 3.1) and offer the advantage of allowing a comparison between 1.5°C and 2°C warmer worlds. Table 3.1 features a compilation of recent emulation-based and SEM studies.

Table 3.1 | Compilation of recent projections for sea level at 2100 (in cm) for Representative Concentration Pathway (RCP)2.6, and 1.5°C and 2°C scenarios. Upper and lower limits are shown for the 17-84% and 5-95% confidence intervals quoted in the original papers.

Study	Baseline	RCP2.6		1.5°C		2°C	
		67%	90%	67%	90%	67%	90%
AR5	1986–2005	28–61					
Kopp et al. (2014)	2000	37–65	29–82				
Jevrejeva et al. (2016)	1986–2005		29–58				
Kopp et al. (2016)	2000	28–51	24–61				
Mengel et al. (2016)	1986–2005	28–56					
Nauels et al. (2017)	1986–2005	35–56					
Goodwin et al. (2017)	1986–2005		31–59 45–70 45–72				
Schaeffer et al. (2012)	2000		52–96		54–99		56–105
Schleussner et al. (2016b)	2000			26–53		36–65	
Bittermann et al. (2017)	2000				29–46		39–61
Jackson et al. (2018)	1986–2005			30–58 40–77	20–67 28–93	35–64 47–93	24–74 32–117
Sanderson et al. (2017)					50–80		60–90
Nicholls et al. (2018)	1986–2005				24–54		31–65
Rasmussen et al. (2018)	2000			35–64	28–82	39–76	28–96
Goodwin et al. (2018)	1986–2005				26–62		30–69

There is little consensus between the reported ranges of GMSL rise (Table 3.1). Projections vary in the range 0.26–0.77 m and 0.35–0.93 m for 1.5°C and 2°C respectively for the 17–84% confidence interval (0.20–0.99 m and 0.24–1.17 m for the 5–95% confidence interval). There is, however, *medium agreement* that GMSL in 2100 would be 0.04–0.16 m higher in a 2°C warmer world compared to a 1.5°C warmer world based on the 17–84% confidence interval (0.00–0.24 m based on 5–95% confidence interval) with a value of around 0.1 m. There is *medium confidence* in this assessment because of issues associated with projections of the Antarctic contribution to GMSL that are employed in emulation-based studies (see above) and the issues previously identified with SEMs (Church et al., 2013).

Translating projections of GMSL to the scale of coastlines and islands requires two further steps. The first step accounts for regional changes associated with changing water and ice loads (such as Earth's gravitational field and rotation, and vertical land movement), as well as spatial differences in ocean heat uptake and circulation. The second step maps regional sea level to changes in the return periods of particular flood events to account for effects not included in global climate models, such as tides, storm surges, and wave setup and runup. Kopp et al. (2014) presented a framework to do this and gave an example application for nine sites located in the US, Japan, northern Europe and Chile. Of these sites, seven (all except those in northern Europe) were found to experience at least a quadrupling in the number of years in the 21st century with 1-in-100-year floods under RCP2.6 compared to under no future sea level rise. Rasmussen et al. (2018) used this approach to investigate the difference between 1.5°C and 2°C warmer worlds up to 2200. They found that the reduction in the frequency of 1-in-100-year floods in a 1.5°C compared to a 2°C warmer world would be greatest in the eastern USA and Europe, with ESL event frequency amplification being reduced by about a half and with smaller reductions for small island developing states (SIDS). This last result contrasts with the finding of Vitousek et al. (2017) that regions with low variability in extreme water levels (such as SIDS in the tropics) are particularly sensitive to GMSL rise, such that a doubling of frequency may be expected for even small (0.1–0.2 m) rises. Schleussner et al. (2011) emulated the AMOC based on a subset of CMIP-class climate models. When forced using global temperatures appropriate for the CP3-PD scenario (1°C of warming in 2100 relative to 2000 or about 2°C of warming relative to pre-industrial) the emulation suggests an 11% median reduction in AMOC strength at 2100 (relative to 2000) with an associated 0.04 m dynamic sea level rise along the New York City coastline.

In summary, there is *medium confidence* that GMSL rise will be about 0.1 m (within a 0.00–0.20 m range based on 17–84% confidence-interval projections) less by the end of the 21st century in a 1.5°C compared to a 2°C warmer world. Projections for 1.5°C and 2°C global warming cover the ranges 0.2–0.8 m and 0.3–1.00 m relative to 1986–2005, respectively (*medium confidence*). Sea level rise beyond 2100 is discussed in Section 3.6; however, recent literature strongly supports the assessment by Church et al. (2013) that sea level rise will continue well beyond 2100 (*high confidence*).

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Box 3.3 | Lessons from Past Warm Climate Episodes

Climate projections and associated risk assessments for a future warmer world are based on climate model simulations. However, Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models do not include all existing Earth system feedbacks and may therefore underestimate both rates and extents of changes (Knutti and Sedláček, 2012). Evidence from natural archives of three moderately warmer (1.5°C–2°C) climate episodes in Earth's past help to assess such long-term feedbacks (Fischer et al., 2018).

While evidence over the last 2000 years and during the Last Glacial Maximum (LGM) was discussed in detail in the IPCC Fifth Assessment Report (Masson-Delmotte et al., 2013), the climate system response during past warm intervals was the focus of a recent review paper (Fischer et al., 2018) summarized in this Box. Examples of past warmer conditions with essentially modern physical geography include the Holocene Thermal Maximum (HTM; broadly defined as about 10–5 kyr before present (BP), where present is defined as 1950), the Last Interglacial (LIG; about 129–116 kyr BP) and the Mid Pliocene Warm Period (MPWP; 3.3–3.0 Myr BP).

Changes in insolation forcing during the HTM (Marcott et al., 2013) and the LIG (Hoffman et al., 2017) led to a global temperature up to 1°C higher than that in the pre-industrial period (1850–1900); high-latitude warming was 2°C–4°C (Capron et al., 2017), while temperature in the tropics changed little (Marcott et al., 2013). Both HTM and LIG experienced atmospheric CO_2 levels similar to pre-industrial conditions (Masson-Delmotte et al. 2013). During the MPWP, the most recent time period when CO_2 concentrations were similar to present-day levels, the global temperature was >1°C and Arctic temperatures about 8°C warmer than pre-industrial (Brigham-Grette et al., 2013).

Although imperfect as analogues for the future, these regional changes can inform risk assessments such as the potential for crossing irreversible thresholds or amplifying anthropogenic changes (Box 3.3, Figure 1). For example, HTM and LIG greenhouse gas (GHG) concentrations show no evidence of runaway greenhouse gas releases under limited global warming. Transient releases of CO_2 and CH_4 may follow permafrost melting, but these occurrences may be compensated by peat growth over longer time scales (Yu et al., 2010). Warming may release CO_2 by enhancing soil respiration, counteracting CO_2 fertilization of plant growth (Frank et al., 2010). Evidence of a collapse of the Atlantic Meridional Overturning Circulation (AMOC) during these past events of limited global warming could not be found (Galaasen et al., 2014).

The distribution of ecosystems and biomes (major ecosystem types) changed significantly during past warming events, both in the ocean and on land. For example, some tropical and temperate forests retreated because of increased aridity, while savannas expanded (Dowsett et al., 2016). Further, poleward shifts of marine and terrestrial ecosystems, upward shifts in alpine regions, and reorganizations of marine productivity during past warming events are recorded in natural archives (Williams et al., 2009; Haywood et al., 2016). Finally, past warming events are associated with partial sea ice loss in the Arctic. The limited amount of data collected so far on Antarctic sea ice precludes firm conclusions about Southern Hemisphere sea ice losses (de Vernal et al., 2013).

Reconstructed global sea level rise of 6–9 m during the LIG and possibly >6 m during the MPWP requires a retreat of either the Greenland or Antarctic ice sheets or both (Dutton et al., 2015). While ice sheet and climate models suggest a substantial retreat of the West Antarctic ice sheet (WAIS) and parts of the East Antarctic ice sheet (DeConto and Pollard, 2016) during these periods, direct observational evidence is still lacking. Evidence for ice retreat in Greenland is stronger, although a complete collapse of the Greenland ice sheet during the LIG can be excluded (Dutton et al., 2015). Rates of past sea level rises under modest warming were similar to or up to two times larger than rises observed over the past two decades (Kopp et al., 2013). Given the long time scales required to reach equilibrium in a warmer world, sea level rise will likely continue for millennia even if warming is limited to 2°C.

Finally, temperature reconstructions from these past warm intervals suggest that current climate models underestimate regional warming at high latitudes (polar amplification) and long-term (multi-millennial) global warming. None of these past warm climate episodes involved the high rate of change in atmospheric CO_2 and temperatures that we are experiencing today (Fischer et al., 2018).

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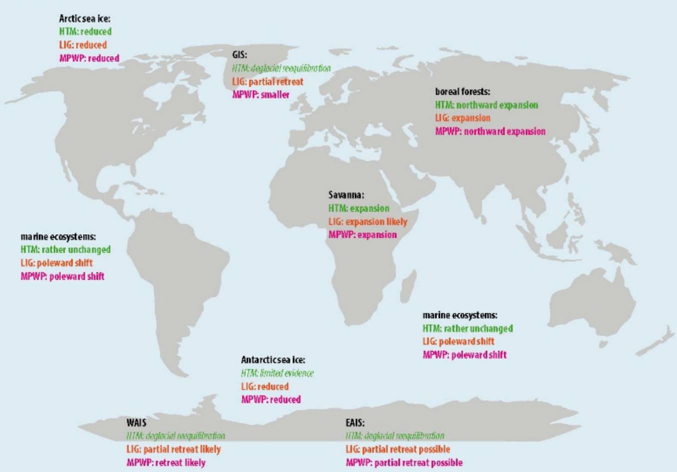
Box 3.3 (continued)



Box 3.3, Figure 1 | Impacts and responses of components of the Earth System. Summary of typical changes found for warmer periods in the paleorecord, as discussed by Fischer et al (2018). All statements are relative to pre-industrial conditions. Statements in italics indicate that no conclusions can be drawn for the future. Note that significant spatial variability and uncertainty exists in the assessment of each component, and this figure therefore should not be referred to without reading the publication in detail. HTM: Holocene Thermal Maximum, LIG: Last Interglacial, MPWP: Mid Pliocene Warm Period. (Adapted from Fischer et al., 2018).

3.3.10 Ocean Chemistry

Ocean chemistry includes pH, salinity, oxygen, CO_2, and a range of other ions and gases, which are in turn affected by precipitation, evaporation, storms, river runoff, coastal erosion, up-welling, ice formation, and the activities of organisms and ecosystems (Stocker et al., 2013). Ocean chemistry is changing alongside increasing global temperature, with impacts projected at 1.5°C and, more so, at 2°C of global warming (Doney et al., 2014) (*medium to high confidence*). Projected changes in the upper layers of the ocean include altered pH, oxygen content and sea level. Despite its many component processes, ocean chemistry has been relatively stable for long periods of time prior to the industrial period (Hönisch et al., 2012). Ocean chemistry is changing under the influence of human activities and rising greenhouse gases (*virtually certain*; Rhein et al., 2013; Stocker et al., 2013). About 30% of CO_2 emitted by human activities, for example, has been absorbed by the upper layers of the ocean, where it has combined with water to produce a dilute acid that dissociates and drives ocean acidification (*high confidence*) (Cao et al., 2007; Stocker et al., 2013). Ocean pH has decreased by 0.1 pH units since the pre-industrial period, a shift that is unprecedented in the last 65 Ma (*high confidence*) (Ridgwell and Schmidt, 2010) or even 300 Ma of Earth's history (*medium confidence*) (Hönisch et al., 2012).

Ocean acidification is a result of increasing CO_2 in the atmosphere (*very high confidence*) and is most pronounced where temperatures are lowest (e.g., polar regions) or where CO_2-rich water is brought to the ocean surface by upwelling (Feely et al., 2008). Acidification can also be influenced by effluents from natural or disturbed coastal land use (Salisbury et al., 2008), plankton blooms (Cai et al., 2011), and the atmospheric deposition of acidic materials (Omstedt et al., 2015). These sources may not be directly attributable to climate change, but they may amplify the impacts of ocean acidification (Bates and Peters, 2007; Duarte et al., 2013). Ocean acidification also influences the ionic composition of seawater by changing the organic and inorganic speciation of trace metals (e.g., 20-fold increases in free ion

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concentrations of metals such as aluminium) – with changes expected to have impacts although they are currently poorly documented and understood (*low confidence*) (Stockdale et al., 2016).

Oxygen varies regionally and with depth; it is highest in polar regions and lowest in the eastern basins of the Atlantic and Pacific Oceans and in the northern Indian Ocean (Doney et al., 2014; Karstensen et al., 2015; Schmidtko et al., 2017). Increasing surface water temperatures have reduced oxygen in the ocean by 2% since 1960, with other variables such as ocean acidification, sea level rise, precipitation, wind and storm patterns playing roles (Schmidtko et al., 2017). Changes to ocean mixing and metabolic rates, due to increased temperature and greater supply of organic carbon to deep areas, has increased the frequency of 'dead zones', areas where oxygen levels are so low that they no longer support oxygen dependent life (Diaz and Rosenberg, 2008). The changes are complex and include both climate change and other variables (Altieri and Gedan, 2015), and are increasing in tropical as well as temperate regions (Altieri et al., 2017).

Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e., precipitation versus evaporation). Some regions, such as northern oceans and the Arctic, have decreased in salinity, owing to melting glaciers and ice sheets, while others have increased in salinity, owing to higher sea surface temperatures and evaporation (Durack et al., 2012). These changes in salinity (i.e., density) are also potentially contributing to large-scale changes in water movement (Section 3.3.8).

3.3.11 Global Synthesis

Table 3.2 features a summary of the assessments of global and regional climate changes and associated hazards described in this chapter, based on the existing literature. For more details about observation and attribution in ocean and cryosphere systems, please refer to the upcoming IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) due to be released in 2019.

Table 3.2 | Summary of assessments of global and regional climate changes and associated hazards. Confidence and likelihood statements are quoted from the relevant chapter text and are omitted where no assessment was made, in which case the IPCC Fifth Assessment Report (AR5) assessment is given where available. GMST: global mean surface temperature, AMOC: Atlantic Meridional Overturning Circulation, GMSL: global mean sea level.

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present-day versus pre-industrial)	Projected change at 1.5°C of global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C of global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C of global warming
GMST anomaly	GMST anomalies were 0.87°C (±0.10°C *likely* range) above pre-industrial (1850–1900) values in the 2006–2015 decade, with a recent warming of about 0.2°C (±0.10°C) per decade (*high confidence*) [Chapter 1]	The observed 0.87°C GMST increase in the 2006–2015 decade compared to pre-industrial (1850–1900) conditions was mostly human-induced (*high confidence*) Human-induced warming reached about 1°C (±0.2°C *likely* range) above pre-industrial levels in 2017 [Chapter 1]	1.5°C	2°C	0.5°C
Temperature extremes	Overall decrease in the number of cold days and nights and overall increase in the number of warm days and nights at the global scale on land (*very likely*) Continental-scale increase in intensity and frequency of hot days and nights, and decrease in intensity and frequency of cold days and nights, in North America, Europe and Australia (*very likely*) Increases in frequency or duration of warm spell lengths in large parts of Europe, Asia and Australia (*high confidence* (*likely*)), as well as at the global scale (*medium confidence*) [Section 3.3.2]	Anthropogenic forcing has contributed to the observed changes in frequency and intensity of daily temperature extremes on the global scale since the mid-20th century (*very likely*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights (*very likely*) Warming of temperature extremes highest over land, including many inhabited regions (*high confidence*), with increases of up to 3°C in the mid-latitude warm season and up to 4.5°C in the high-latitude cold season (*high confidence*) Largest increase in frequency of unusually hot extremes in tropical regions (*high confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights (*very likely*) Warming of temperature extremes highest over land, including many inhabited regions (*high confidence*), with increases of up to 4°C in the mid-latitude warm season and up to 6°C in the high-latitude cold season (*high confidence*) Largest increase in frequency of unusually hot extremes in tropical regions (*high confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights (*high confidence*) Global-scale increase in length of warm spells and decrease in length of cold spells (*high confidence*) Strongest increase in frequency for the rarest and most extreme events (*high confidence*) Particularly large increases in hot extremes in inhabited regions (*high confidence*) [Section 3.3.2]

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Table 3.2 (continued)

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present-day versus pre-industrial)	Projected change at 1.5°C of global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C of global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C of global warming
Heavy precipitation	More areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation (*likely*) [Section 3.3.3]	Human influence contributed to the global-scale tendency towards increases in the frequency, intensity and/or amount of heavy precipitation events (*medium confidence*) [Section 3.3.3; AR5 Chapter 10 (Bindoff et al., 2013a)]	Increases in frequency, intensity and/or amount heavy precipitation when averaged over global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Increases in frequency, intensity and/or amount heavy precipitation when averaged over global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Higher frequency, intensity and/or amount of heavy precipitation when averaged over global land, with positive trends in several regions (*medium confidence*) Several regions are projected to experience increases in heavy precipitation at 2°C versus 1.5°C (*medium confidence*), in particular in high-latitude and mountainous regions, as well as in eastern Asia and eastern North America (*medium confidence*) [Section 3.3.3]
Drought and dryness	*High confidence* in dryness trends in some regions, especially drying in the Mediterranean region (including southern Europe, northern Africa and the Near East) *Low confidence* in drought and dryness trends at the global scale [Section 3.3.4]	*Medium confidence* in attribution of drying trends in southern Europe (Mediterranean region) *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied [Section 3.3.4]	*Medium confidence* in drying trends in the Mediterranean region *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but substantial variability in signals depending on considered indices or climate model (*medium confidence*) [Section 3.3.4]	*Medium confidence* in drying trends in the Mediterranean region and Southern Africa *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but substantial variability in signals depending on considered indices or climate model (*medium confidence*). [Section 3.3.4]	*Medium confidence* in stronger drying trends in the Mediterranean region and Southern Africa *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on the dryness index definition applied [Section 3.3.4]
Runoff and river flooding	Streamflow trends mostly not statistically significant (*high confidence*) Increase in flood frequency and extreme streamflow in some regions (*high confidence*) [Section 3.3.5]	Not assessed in this report	Expansion of the global land area with a significant increase in runoff (*medium confidence*) Increase in flood hazard in some regions (*medium confidence*) [Section 3.3.5]	Expansion of the global land area with a significant increase in runoff (*medium confidence*) Increase in flood hazard in some regions (*medium confidence*) [Section 3.3.5]	Expansion of the global land area with significant increase in runoff (*medium confidence*) Expansion in the area affected by flood hazard (*medium confidence*) [Section 3.3.5]
Tropical and extra-tropical cyclones	*Low confidence* in the robustness of observed changes [Section 3.3.6]	Not meaningful to assess given *low confidence* in changes, due to large interannual variability, heterogeneity of the observational record and contradictory findings regarding trends in the observational record	Increases in heavy precipitation associated with tropical cyclones (*medium confidence*)	Further increases in heavy precipitation associated with tropical cyclones (*medium confidence*)	Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). Limited evidence that the global number of tropical cyclones will be lower under 2°C of global warming compared to under 1.5°C of warming, but an increase in the number of very intense cyclones (*low confidence*)

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Table 3.2 (continued)

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present-day versus pre-industrial)	Projected change at 1.5°C of global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C of global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C of global warming
Ocean circulation and temperature	Observed warming of the upper ocean, with slightly lower rates than global warming (*virtually certain*) Increased occurrence of marine heatwaves (*high confidence*) AMOC has been weakening over recent decades (*more likely than not*) [Section 3.3.7]	*Limited evidence* attributing the weakening of AMOC in recent decades to anthropogenic forcing [Section 3.3.7]	Further increases in ocean temperatures, including more frequent marine heatwaves (*high confidence*) AMOC will weaken over the 21st century and substantially so under high levels (more than 2°C) of global warming (*very likely*) [Section 3.3.7]		
Sea ice	Continuing the trends reported in AR5, the annual Arctic sea ice extent decreased over the period 1979–2012. The rate of this decrease was *very likely* between 3.5 and 4.1% per decade (0.45 to 0.51 million km² per decade) [AR5 Chapter 4 (Vaughan et al., 2013)]	Anthropogenic forcings are *very likely* to have contributed to Arctic sea ice loss since 1979 [AR5 Chapter 10 (Bindoff et al., 2013a)]	At least one sea-ice-free Arctic summer after about 100 years of stabilized warming (*medium confidence*) [Section 3.3.8] Intermediate temperature overshoot has no long-term consequences for Arctic sea ice cover (*high confidence*) [3.3.8]	At least one sea-ice-free Arctic summer after about 10 years of stabilized warming (*medium confidence*) [Section 3.3.8]	Probability of sea-ice-free Arctic summer greatly reduced at 1.5°C versus 2°C of global warming (*medium confidence*) [Section 3.3.8]
Sea level	It is *likely* that the rate of GMSL rise has continued to increase since the early 20th century, with estimates that range from 0.000 [–0.002 to 0.002] mm yr⁻² to 0.013 [0.007 to 0.019] mm yr⁻² [AR5 Chapter 13 (Church et al., 2013)]	It is very *likely* that there is a substantial contribution from anthropogenic forcings to the global mean sea level rise since the 1970s [AR5 Chapter 10 (Bindoff et al., 2013a)]	Not assessed in this report	Not assessed in this report	GMSL rise will be about 0.1 m (0.00–0.20 m) less at 1.5°C versus 2°C global warming (*medium confidence*) [Section 3.3.9]
Ocean chemistry	Ocean acidification due to increased CO_2 has resulted in a 0.1 pH unit decrease since the pre-industrial period, which is unprecedented in the last 65 Ma (*high confidence*) [Section 3.3.10]	The oceanic uptake of anthropogenic CO_2 has resulted in acidification of surface waters (*very high confidence*). [Section 3.3.10]	Ocean chemistry is changing with global temperature increases, with impacts projected at 1.5°C and, more so, at 2°C of warming (*high confidence*) [Section 3.3.10]		

3.4 Observed Impacts and Projected Risks in Natural and Human Systems

3.4.1 Introduction

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). 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

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to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) 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). 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). 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).

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.

3.4.2 Freshwater Resources (Quantity and Quality)

3.4.2.1 Water availability

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). UNESCO (2011) 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), as well as green water, water quality and environmental flow requirements (J. Liu et al., 2017). 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., 2015; Mehran et al., 2015). 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).

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).

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). Assuming a constant population in the models used in his study, Gerten et al. (2013) 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). 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). 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).

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). Hanasaki et al. (2013) 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) highlighted the importance of water

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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). 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). 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).

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), 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). Greece, Spain and Bulgaria are projected to have the largest reduction at 2°C of warming (Tobin et al., 2018).

Fricko et al. (2016) 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.

3.4.2.2 Extreme hydrological events (floods and droughts)

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). 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).

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). AR5 concluded that there was *low confidence* in the attribution of global changes in droughts (Bindoff et al., 2013b). 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).

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). 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). Alfieri et al. (2017) 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) reported that the projected changes are not homogeneously distributed across the world land surface. Alfieri et al. (2018) 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) 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) 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) 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.

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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). 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). Under the SSP2 population scenario, Arnell et al. (2018) 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) 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) also suggested that more urban populations would be exposed to severe droughts at 1.5°C 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), 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) .

Alfieri et al. (2018) 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) 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) 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.

3.4.2.3 Groundwater

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).

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).

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).

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). 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).

Portmann et al. (2013) 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).

3.4.2.4 Water quality

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). 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).

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). 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). 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

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Zwolsman, 2010; Hosseini et al., 2017). 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). 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). 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). Under the same warming scenarios, Trang et al. (2017) 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).

3.4.2.5 Soil erosion and sediment load

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). As the number of studies on climate change impacts on soil erosion has increased where rainfall is an important driver (Lu et al., 2013), studies have increasingly considered other factors, such as rainfall intensity (e.g., Shi and Wang, 2015; Li and Fang, 2016), snow melt, and change in vegetation cover resulting from temperature rise (Potemkina and Potemkin, 2015), as well as crop management practices (Mullan et al., 2012). 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).

While the number of published studies of climate change impacts on soil erosion have increased globally since 2000 (Li and Fang, 2016), 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). 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). 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).

3.4.3 Terrestrial and Wetland Ecosystems

3.4.3.1 Biome shifts

Latitudinal and elevational shifts of biomes (major ecosystem types) in boreal, temperate and tropical regions have been detected (Settele et al., 2014) and new studies confirm these changes (e.g., shrub encroachment on tundra; Larsen et al., 2014). 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).

An ensemble of seven Dynamic Vegetation Models driven by projected climates from 19 alternative general circulation models (GCMs) (Warszawski et al., 2013) 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) 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) 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).

3.4.3.2 Changes in phenology

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). The rates of change are particularly high in the Arctic zone owing to the stronger local warming (Oberbauer et al., 2013), whereas phenology in tropical forests appears to be more responsive to moisture stress (Zhou et al., 2014). 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), in the dates of egg laying and migration in birds (newly reported in China; Wu and Shi, 2016), in the emergence dates of butterflies (Roy et al., 2015), 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).

The potential for decoupling species–species interactions owing to differing phenological responses to climate change is well established (Settele et al., 2014), for example for plants and their insect pollinators (Willmer, 2012; Scaven and Rafferty, 2013). 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). 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

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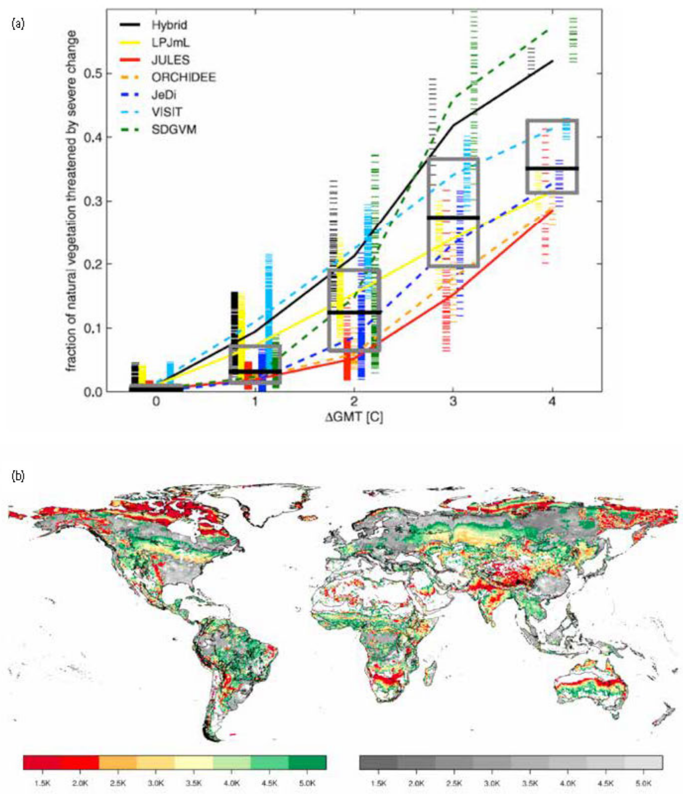

Figure 3.16 | (a) Fraction of global natural vegetation (including managed forests) at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems, models, global climate change models and Representative Concentration Pathways (RCPs). The colours represent the different ecosystem models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the temperature for a given year is the average over a 30-year window centred on that year. The boxes span the 25th and 75th percentiles across the entire ensemble. The short, horizontal stripes represent individual (annual) data points, the curves connect the mean value per ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation composition changes. Source: (Warszawski et al., 2013) (b) Threshold level of global temperature anomaly above pre-industrial levels that leads to significant local changes in terrestrial ecosystems. Regions with severe (coloured) or moderate (greyish) ecosystem transformation; delineation refers to the 90 biogeographic regions. All values denote changes found in >50% of the simulations. Source: (Gerten et al., 2013). Regions coloured in dark red are projected to undergo severe transformation under a global warming of 1.5°C while those coloured in light red do so at 2°C; other colours are used when there is no severe transformation unless global warming exceeds 2°C.

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could alter community structure in temperate forests (Roberts et al., 2015). 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). This phenological plasticity is not always adaptive and must be interpreted cautiously (Duputié et al., 2015), 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).

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.

3.4.3.3 Changes in species range, abundance and extinction

AR5 (Settele et al., 2014) concluded that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming: approximately 17 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). Further, a recent meta-analysis of 27 studies concerning a total of 976 species (Wiens, 2016) 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) 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).

Warren et al. (2013) 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). 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) (*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). 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). 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).

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). There is also the potential for highly invasive species to become established in new areas as the climate changes (Murphy and Romanuk, 2014), but there is no literature that quantifies this possibility for 1.5°C of global warming.

Pecl et al. (2017) 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). 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). 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) 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). A link between very high levels of range loss and greatly increased extinction risk may be inferred (Urban, 2015). 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*).

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3.4.3.4 Changes in ecosystem function, biomass and carbon stocks

Working Group II of AR5 (Settele et al., 2014) 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). 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). These losses are expected to contribute to a decrease in the terrestrial carbon sink. Anderegg et al. (2015) 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). In boreal peatlands, for example, increased temperature may diminish carbon storage and compromise the stability of the peat (Dieleman et al., 2016). In addition, J. Yang et al. (2015) 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). Soil can also be a key compartment for substantial carbon sequestration (Lal, 2014; Minasny et al., 2017), depending on the net biome productivity and the soil quality (Bispo et al., 2017).

AR5 assessed that large uncertainty remains regarding the land carbon cycle behaviour of the future (Ciais et al., 2013), with most, but not all, CMIP5 models simulating continued terrestrial carbon uptake under all four RCP scenarios (Jones et al., 2013). Disagreement between models outweighs differences between scenarios even up to the year 2100 (Hewitt et al., 2016; Lovenduski and Bonan, 2017). Increased atmospheric CO_2 concentrations are expected to drive further increases in the land carbon sink (Ciais et al., 2013; Schimel et al., 2015), which could persist for centuries (Pugh et al., 2016). 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). Climate change may accelerate plant uptake of carbon (Gang et al., 2015) but also increase the rate of decomposition (Todd-Brown et al., 2014; Koven et al., 2015; Crowther et al., 2016). Ahlström et al. (2012) 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). Friend et al. (2014) 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). 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) projected a robust increase in the net primary productivity (NPP) of temperate forests. However, Ahlström et al. (2012) 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). This projection is supported by findings by Sakalli et al. (2017) 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) 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). 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). 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).

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*).

3.4.3.5 Regional and ecosystem-specific risks

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*).

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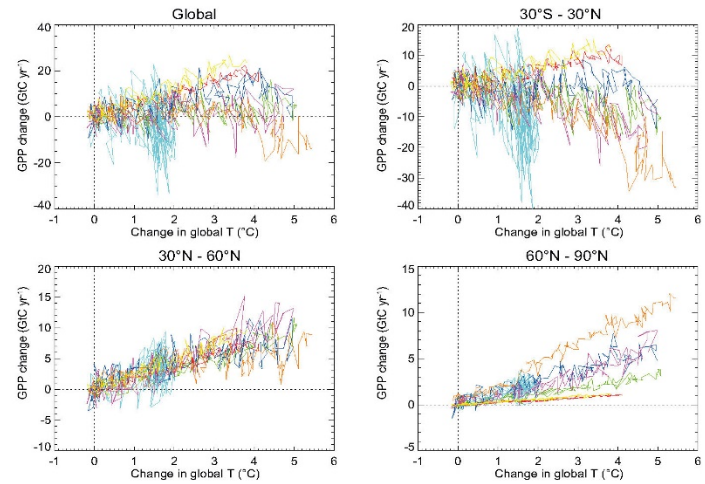

Figure 3.17 | The response of terrestrial productivity (gross primary productivity, GPP) to climate change, globally (top left) and for three latitudinal regions: 30°S–30°N; 30–60°N and 60–90°N. Data come from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (http://cmip-pcmdi.llnl.gov/cmip5/). Seven Earth System Models were used: Norwegian Earth System Model (NorESM-ME, yellow); Community Earth System Model (CESM, red); Institute Pierre Simon Laplace (IPLS)-CM5-LR (dark blue); Geophysical Fluid Dynamics Laboratory (GFDL, pale blue); Max Plank Institute-Earth System Model (MPI-ESM, pink); Hadley Centre New Global Environmental Model 2-Earth System (HadGEM2-ES, orange); and Canadian Earth System Model 2 (CanESM2, green). Differences in GPP between model simulations with ('1pctCO_2') and without ('esmfixclim1') the effects of climate change are shown. Data are plotted against the global mean temperature increase above pre-industrial levels from simulations with a 1% per year increase in CO_2 ('1pctCO_2').

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). 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). 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). Observational constraints suggest that stabilization at 1.5°C of warming would avoid the thawing of approximately 1.5 to 2.5 million km^2 of permafrost (*medium confidence*) compared with stabilization at 2°C (Chadburn et al., 2017), but the time scale for release of thawed carbon as CO_2 or CH_4 should be many centuries (Burke et al., 2017). 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). Aalto et al. (2017) 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), 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). 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). 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). 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), 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

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approximately 3.5°C.[6] The values in Table 26-1 in a recent paper by Romero-Lankao et al. (2014) 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), but this threshold may move under elevated CO_2 (Good et al., 2011). Future changes in rainfall, especially dry season length, will determine responses of the Amazon forest (Good et al., 2013). The forest may be especially vulnerable to combined pressure from multiple stressors, namely changes in climate and continued anthropogenic disturbance (Borma et al., 2013; Nobre et al., 2016). Modelling (Huntingford et al., 2013) and observational constraints (Cox et al., 2013) suggest that large-scale forest dieback is less likely than suggested under early coupled modelling studies (Cox et al., 2000; Jones et al., 2009). Nobre et al. (2016) 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). 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). 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). Further, Guiot and Cramer (2016) 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). 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). Regarding Central America, Lyra et al. (2017) 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). 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). 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). When drained, this carbon is released to the atmosphere. At least 15% of peatlands have drained, mostly in Europe and Southeast Asia, and are responsible for 5% of human derived CO_2 emissions (Green and Page, 2017). Moreover, in the Congo basin (Dargie et al., 2017) and in the Amazonian basin (Draper et al., 2014), 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). 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). Settele et al. (2014) 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) 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).

3.4.3.6 Summary of implications for ecosystem services

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.

3.4.4 Ocean Ecosystems

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). Together with local stresses (Halpern et al., 2015), 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

[6] The approximate temperatures are derived from Figure 10.5a in Meehl et al. (2007), which indicates an ensemble average projection of 0.7°C or 3°C above 1980–1999 temperatures, which were already 0.5°C above pre-industrial values.

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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.

3.4.4.1 Observed impacts

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). 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).

3.4.4.2 Warming and stratification of the surface ocean

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). 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), 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). 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). 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) 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).

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). 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., 2016). 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). 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), 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).

3.4.4.3 Storms and coastal runoff

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). 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). 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) and tropical coral reefs (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017). 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, 2016; AR5, Table 5.1).

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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). 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) 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). 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).

3.4.4.4 Ocean circulation

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) and a lack of records that match the long-term nature of these changes in many cases (Lluch-Cota et al., 2014). An assessment of the literature since AR5 (Sydeman et al., 2014), 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), with potentially positive and negative consequences (Bakun et al., 2015).

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), as well as the arrival of novel disease agents (*low-medium confidence*) (Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016). 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). 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). 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).

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). Evidence of a slowdown of AMOC has increased since AR5 (Smeed et al., 2014; Rahmstorf et al., 2015a, b; Kelly et al., 2016), yet a strong causal connection to climate change is missing (*low confidence*) (Section 3.3.7).

3.4.4.5 Ocean acidification

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). 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), 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). 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).

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). 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

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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).

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), coccolithophores (K.J.S. Meier et al., 2014), pteropods and polar foodwebs (Bednaršek et al., 2012, 2014), phytoplankton (Moy et al., 2009; Riebesell et al., 2013; Richier et al., 2014), benthic ecosystems (Hall-Spencer et al., 2008; Linares et al., 2015), seagrass (Garrard et al., 2014), and macroalgae (Webster et al., 2013; Ordonez et al., 2014), as well as excavating sponges, endolithic microalgae and reef-building corals (Dove et al., 2013; Reyes-Nivia et al., 2013; Fang et al., 2014), and coral reefs (Box 3.4; Fabricius et al., 2011; Allen et al., 2017). 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).

3.4.4.6 Deoxygenation

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). 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). 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). 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).

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). 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), physiological impacts (Pörtner et al., 2014), and mortality and/or displacement of oxygen dependent organisms such as fish (Hamukuaya et al., 1998; Thronson and Quigg, 2008; Jacinto, 2011) and invertebrates (Hobbs and Mcdonald, 2010; Bednaršek et al., 2016; Seibel, 2016; Altieri et al., 2017). 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). 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).

3.4.4.7 Loss of sea ice

Sea ice is a persistent feature of the planet's polar regions (Polyak et al., 2010) 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). 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).

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).

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

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the water column increases, and phototrophs have increased access to seasonally high levels of solar radiation (*medium confidence*) (Dalpadado et al., 2014; W.N. Meier et al., 2014). 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), 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). 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). Sea ice in Antarctica is undergoing changes that exceed those seen in the Arctic (Maksym et al., 2011; Reid et al., 2015), 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). 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.

3.4.4.8 Sea level rise

Mean sea level is increasing (Section 3.3.9), with substantial impacts already being felt by coastal ecosystems and communities (Wong et al., 2014) (*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; Blankespoor et al., 2014). 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), 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). 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; Mills et al., 2016).

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). 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), although limitations of these strategies have been identified (e.g., Lovelock et al., 2015; Weatherdon et al., 2016).

3.4.4.9 Projected risks and adaptation options for oceans under global warming of 1.5°C or 2°C above pre-industrial levels

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) 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. 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.

3.4.4.10 Framework organisms (tropical corals, mangroves and seagrass)

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). 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).

Risks of climate change impacts for seagrass and mangrove ecosystems were recently assessed by an expert group led by Short et al. (2016). Impacts of climate change were assessed to be similar across a range of submerged and emerged plants. Submerged plants such as seagrass were affected mostly by temperature extremes (Arias-Ortiz et al., 2018), 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; Sierra-Correa and Cantera Kintz, 2015; Osorio et al., 2016; Sasmito et al., 2016), especially in the context of human activities that reduce sediment supply (Lovelock et al., 2015) or interrupt the shoreward movement of mangroves though the construction of coastal infrastructure. This in turn leads to 'coastal squeeze' where coastal ecosystems are trapped between changing ocean conditions and coastal infrastructure (Mills et al., 2016). 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).

Climate change (e.g., sea level rise, heat stress, storms) presents risk 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

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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). 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) and arriving sooner than predicted (Hughes et al., 2017b, 2018), 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). Recent large-scale die-offs (Duke et al., 2017; Lovelock et al., 2017), 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 examplified by increasing 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 (e.g., damage resulting 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). The impacts of warming, coupled with ocean 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).

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), as well as protecting locations where organisms may be more robust (Palumbi et al., 2014) or less exposed to climate change (Bongaerts et al., 2010; van Hooidonk et al., 2013; Beyer et al., 2018). 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; Chollett 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). 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 (Shafir et al., 2006; Rinkevich, 2014) or the use of 'assisted evolution' to help corals adapt to changing sea temperatures (van Oppen et al., 2015, 2017), 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).

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*). Maintaining the sediment supply to coastal areas would also assist mangroves in keeping pace with sea level rise (Shearman et al., 2013; Lovelock et al., 2015; Sasmito et al., 2016). 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). 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). 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). 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).

3.4.4.11 Ocean foodwebs (pteropods, bivalves, krill and fin fish)

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,

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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). 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). 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). Shell dissolution, for example, has increased by 19–26% in both nearshore and offshore populations since the pre-industrial period (Feely et al., 2016). There is considerable concern as to whether these organisms are declining further, especially given the central importance in ocean foodwebs (David et al., 2017). 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). 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). 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 1.3°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, record levels of sea ice loss in the Antarctic (Notz and Stroeve, 2016; Turner et al., 2017b) translate into a loss of habitat and hence reduced abundance of krill (Piñones and Fedorov, 2016), with negative ramifications for the seabirds and whales which feed on krill (Croxall, 1992; Trathan and Hill, 2016) (*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). 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 foodweb organisms, 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).

3.4.4.12 Key ecosystem services (e.g., carbon uptake, coastal protection, and tropical coral reef recreation)

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). The ocean is also a net sink for CO_2 (another important service), absorbing approximately 30% of human emissions from the burning of fossil fuels and modification of land use (IPCC, 2013). Carbon uptake by the ocean is decreasing (Iida et al., 2015), and there is increasing concern from observations and models regarding associated changes to ocean circulation (Sections 3.3.7 and 3.4.4., Rahmstorf et al., 2015b);. 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), as well as subtropical gyre systems (*low confidence*) (Signorini et al., 2015). 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).

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 (*high confidence*), 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, larger 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). Both natural and human coastal

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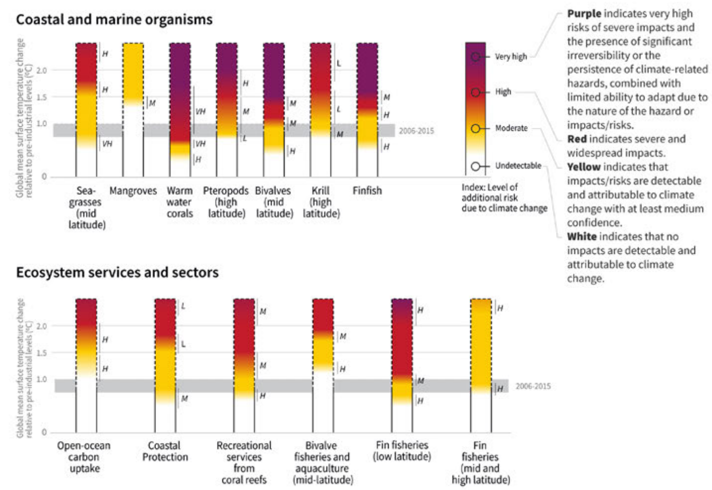
protection have the potential to reduce these impacts (Fu and Song, 2017). Tropical coral reefs, for example, provide effective protection by dissipating about 97% of wave energy, with 86% of the energy being dissipated by reef crests alone (Ferrario et al., 2014; Narayan et al., 2016). Mangroves similarly 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). This implies that coastal areas currently protected by mangroves may experience growing risks over time.

Risks for specific marine and coastal organisms, ecosystems and sectors

The key elements are presented here as a function of the risk level assessed between 1.5 and 2°C (Average global sea surface temperature).



Confidence level for transition: *L*=Low, *M*=Medium, *H*=High and *VH*=Very high

Figure 3.18 | Summary of additional risks of impacts from ocean warming (and associated climate change factors such ocean acidification) for a range of ocean organisms, ecosystems and sectors at 1.0°C, 1.5°C and 2.0°C of warming of the average sea surface temperature (SST) relative to the pre-industrial period. The grey bar represents the range of GMST for the most recent decade: 2006–2015. The assessment of changing risk levels and associated confidence were primarily derived from the expert judgement of Gattuso et al. (2015) and the lead authors and relevant contributing authors of Chapter 3 (SR1.5), while additional input was received from the many reviewers of the ocean systems section of SR1.5. Notes: (i) The analysis shown here is not intended to be comprehensive. The examples of organisms, ecosystems and sectors included here are intended to illustrate the scale, types and projection of risks for representative natural and human ocean systems. (ii) The evaluation of risks by experts did not consider genetic adaptation, acclimatization or human risk reduction strategies (mitigation and societal adaptation). (iii) As discussed elsewhere (Sections 3.3.10 and 3.4.4.5, Box 3.4; Gattuso et al., 2015), ocean acidification is also having impacts on organisms and ecosystems as carbon dioxide increases in the atmosphere. These changes are part of the responses reported here, although partitioning the effects of the two drivers is difficult at this point in time and hence was not attempted. (iv) Confidence levels for location of transition points between levels of risk (L = low, M = moderate, H = high and VH = very high) are assessed and presented here as in the accompanying study by Gattuso et al. (2015). Three transitions in risk were possible: W–Y (white to yellow), Y–R (yellow to red), and R–P (red to purple), with the colours corresponding to the level of additional risk posed by climate change. The confidence levels for these transitions were assessed, based on level of agreement and extent of evidence, and appear as letters associated with each transition (see key in diagram).

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Tourism is one of the largest industries globally (Rosselló-Nadal, 2014; Markham et al., 2016; Spalding et al., 2017). 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). 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 reef 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 CO_2 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). 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), 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). 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). 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).

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). 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). In this regard, the interactions between climate change, sea level rise and coastal disasters are increasingly being informed by models (Bosello and De Cian, 2014) with a widening appreciation of the role of natural ecosystems as an alternative to hardened coastal structures (Cooper et al., 2016). 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 adequate levels of coastal protection by supporting and repairing ecosystems that protect coastal regions, (iii) 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.

Box 3.4 | Warm-Water (Tropical) Coral Reefs in a 1.5°C Warmer World

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 et al., 2014; Schleussner et al., 2016b; van Hooidonk et al., 2016; Frieler et al., 2017; Hughes et al., 2017a). 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 lead to much reduced coral populations (Hoegh-Guldberg et al., 2014). 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).

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) 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). Ultimately, coral reefs are underpinned by a mutualistic symbiosis between reef-building corals and dinoflagellates from the genus *Symbiodinium* (Hoegh-Guldberg et al., 2017). 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). 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.

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Box 3.4 (continued)

The distribution and abundance of coral reefs has decreased by approximately 50% over the past 30 years (Gardner et al., 2005; Bruno and Selig, 2007; De'ath et al., 2012) as a result of pollution, storms, overfishing and unsustainable coastal development (Burke et al., 2011; Halpern et al., 2015; Cheal et al., 2017). More recently, climate change (i.e., heat stress; Hoegh-Guldberg, 1999; Baker et al., 2008; Spalding and Brown, 2015; Hughes et al., 2017b) 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). 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). 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). These impacts are exacerbated by increasingly intense storms (Section 3.3.6), which physically destroy coral communities and hence reefs (Cheal et al., 2017), 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). 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, 2014).

The predictions of back-to-back bleaching events (Hoegh-Guldberg, 1999) have become the reality in the summers of 2016–2017 (e.g., Hughes et al., 2017b), 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). Even achieving emissions 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).

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) or 0.4°C per decade (Schleussner et al., 2016b), as well as very rapid recovery rates from impacts (e.g., five years in the case of Schleussner et al., 2016b). 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). 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). 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), which may play an important role in terms of the regeneration of coral reefs, especially if these refuges are protected from risks unrelated to climate change. Locations at higher latitudes are reporting the arrival of reef-building corals, which may 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). Similarly, deep-water (30–150 m) or mesophotic coral reefs (Bongaerts et al., 2010; Holstein et al., 2016) may play an important role because they avoid shallow water extremes (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).

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). 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). 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). 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.

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3.4.5 Coastal and Low-Lying Areas, and Sea Level Rise

Sea level rise (SLR) is accelerating in response to climate change (Section 3.3.9; Church et al., 2013) 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 SLR is discussed in Section 3.4.5.7.

3.4.5.1 Global / sub-global scale

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) 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). However, these are distinct from impacts associated with higher increases in temperature (e.g., 4°C or more, as discussed in Brown et al., 2018a) over centennial scales. The benefits of climate change mitigation reinforce findings of earlier IPCC reports (e.g., Wong et al., 2014).

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., 2018a and Goodwin et al., 2018; 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). 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) 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), 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). 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). 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, range across SSP1–5, no socio-economic change after 2100). These projections assume that no upgrade to current protection levels occurs (Nicholls et al., 2018). 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). Through prescribed IPCC Special Report on Emissions Scenarios (SRES) SLR scenarios, Arnell et al. (2016) 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. Additionally, impacts increased 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). 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). 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). Rasmussen et al. (2018) and Brown et al. (2018a) 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.

3.4.5.2 Cities

Observations of the impacts of SLR in cities are difficult to record because multiple drivers of change are involved. There are observations of ongoing and planned adaptation to SLR and extreme water levels in some cities (Araos et al., 2016; Nicholls et al., 2018), 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).

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), 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). 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). Jevrejeva et al. (2016) projected that more than 90% of global coastlines could experience SLR greater than 0.2 m with 2°C

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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). Thus, rising sea levels commit coastal cities to long-term adaptation (*high confidence*).

3.4.5.3 Small islands

Qualitative physical observations of SLR (and other stresses) include inundation of parts of low-lying islands, land degradation due to saltwater intrusion in Kiribati and Tuvalu (Wairiu, 2017), and shoreline change in French Polynesia (Yates et al., 2013), Tuvalu (Kench et al., 2015, 2018) and Hawaii (Romine et al., 2013). 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). 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), 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). Whilst flooding may result in migration or relocation, for example in Vunidogoloa, Fiji (McNamara and Des Combes, 2015; Gharbaoui and Blocher, 2016) and the Solomon Islands (Albert et al., 2017), in situ adaptation may be tried or preferred, for example stilted housing or raised floors in Tubigon, Bohol, Philippines (Jamero et al., 2017), raised roads and floors in Batasan and Ubay, Philippines (Jamero et al., 2018), and raised platforms for faluw in Leang, Federated States of Micronesia (Nunn et al., 2017). Protective features, such as seawalls or beach nourishment, are observed to locally reduce erosion and flood risk but can have other adverse implications (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014; AR5 Section 29.6.22).

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; Rasmussen et al., 2018; 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 impacts 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). Combinations of drivers causing adverse impacts are important. For example, Storlazzi et al. (2018) 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). Whilst SLR is a major hazard for atolls, islands reaching higher elevations are also threatened given that there is often a lot of infrastructure located near the coast (*high confidence*) (Kumar and Taylor, 2015; Nicholls et al., 2018). Tens of thousands of people on small islands are exposed to SLR (Rasmussen et al., 2018). Giardino et al. (2018) 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). Slower rates of SLR will provide a greater opportunity for adaptation to be successful (*medium confidence*), but this 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) 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*).

3.4.5.4 Deltas and estuaries

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). 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).

Z. Yang et al. (2015) 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). 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). Further, increased river salinity and saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C of warming (Zaman et al., 2017). 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

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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). 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., 2018). For example, dike building to reduce flooding and dam building (Gupta et al., 2012) 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). Although dikes remain essential for reducing flood risk today, promoting sedimentation is an advisable strategy (Brown et al., 2018b) which may involve nature-based solutions. Transformative decisions regarding the extent of sediment restrictive infrastructure may need to be considered over centennial scales (Brown et al., 2018b). 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*).

3.4.5.5 Wetlands

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), such as total water levels and sediment availability. 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). 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). Some projections of wetland change, with magnitudes (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), whilst others report a net gain with wetland transgression (e.g., Raabe and Stumpf, 2016 in the Gulf of Mexico). However, the feedback between wetlands and sea level is complex, with parameters such as a 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) 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. However, they have great potential to aid and benefit climate change mitigation and adaptation (*medium confidence*) (Sections 4.3.2.2 and 4.3.2.3).

3.4.5.6 Other coastal settings

Numerous impacts have not been quantified at 1.5°C or 2°C but remain important. This includes systems identified in WGII AR5 (AR5 – Section 5.4 of Wong et al., 2014), 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), which could affect land-based ecosystems. Global observations indicate no overall clear effect of SLR on shoreline change (Le Cozannet et al., 2014), as it is highly site specific (e.g., Romine et al., 2013). Infrastructure 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 worsen under RCP8.5 (Udo and Takeda, 2017). 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) 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 wide range of adverse effects on coastal zones (*medium confidence*).

3.4.5.7 Adapting to coastal change

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). 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), although there is less certainty for natural ecosystems (Sections 4.3.2 and 4.3.3.3). While some ecosystems (e.g., mangroves) may be able to move shoreward as sea levels increase, coastal development (e.g., coastal building, seawalls and agriculture) often interrupt these transitions (Saunders et al., 2014). 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).

Since AR5, planned and autonomous adaptation and forward planning have become more widespread (Araos et al., 2016; Nicholls et al., 2018), 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). 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). Adaptation pathways (e.g., Ranger et al., 2013; Barnett et al., 2014; Rosenzweig and Solecki, 2014; Buurman and Babovic, 2016) 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), 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., 2014; Nicholls et al., 2015). 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*).

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Table 3.3 | Land and people exposed to sea level rise (SLR), assuming no protection at all. Extracted from Brown et al. (2018a) and Goodwin et al. (2018). SSP: Shared Socio-Economic Pathway; wrt: with respect to; *: Population held constant at 2100 level.

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]*

Box 3.5 | Small Island Developing States (SIDS)

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). 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). 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).

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). 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). In accordance with an overall drying trend, an increasing drought risk is projected for Caribbean SIDS (Lehner et al., 2017), 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).

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). 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). Prolonged interannual sea level inundations may increase throughout the tropical Pacific with ongoing warming and in the advent of an

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Box 3.5 (continued)

increased frequency of extreme La Niña events, exacerbating coastal impacts of projected global mean SLR (Widlansky et al., 2015). 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).

Extreme precipitation in small island regions is often linked to tropical storms and contributes to the climate hazard (Khouakhi et al., 2017). Similarly, extreme sea levels for small islands, particularly in the Caribbean, are linked to tropical cyclone occurrence (Khouakhi and Villarini, 2017). 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). 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). 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). 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). 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). Higher temperatures are also related to an increase in coral disease development, leading to coral degradation (Maynard et al., 2015). 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).

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). Wave-driven coastal flooding risks for reef-lined islands may increase as a result of coral reef degradation and SLR (Quataert et al., 2015). 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., 2018). 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). 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), limited capacity to assess loss and damage (Thomas and Benjamin, 2017) and substantial increases in the risk to critical transportation infrastructure from marine inundation (Monioudi et al., 2018). 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).

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). 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).

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3.4.6 Food, Nutrition Security and Food Production Systems (Including Fisheries and Aquaculture)

3.4.6.1 Crop production

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), whilst the degree of compensation is mainly dependent on the geographical area and crop type (Rose et al., 2016). 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) to America (Cho and McCarl, 2017) and Europe (Ramirez-Cabral et al., 2016), 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).

Temperature and precipitation trends have reduced crop production and yields, with the most negative impacts being on wheat and maize (Lobell et al., 2011), 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). 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), and may make it possible to have more than one harvest per year (B. Chen et al., 2014; Sun et al., 2015). 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), with the percentage varying according to crop type and scale (Moore and Lobell, 2015; Kent et al., 2017). 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).

The rise in tropospheric ozone has already reduced yields of wheat, rice, maize and soybean by 3–16% globally (Van Dingenen et al., 2009). In some studies, increases in atmospheric CO_2 concentrations were found to increase yields by enhancing radiation and water use efficiencies (Elliott et al., 2014; Durand et al., 2018). In open-top chamber experiments with a combination of elevated CO_2 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). 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 CO_2 concentrations (Porter et al., 2014). For instance, McGrath and Lobell (2013) indicated that production stimulation at increased atmospheric CO_2 concentrations was mostly driven by differences in climate and crop species, whilst yield variability due to elevated CO_2 was only about 50–70% of the variability due to climate. Importantly, the faster growth rates induced by elevated CO_2 have been found to coincide with lower protein content in several important C3 cereal grains (Myers et al., 2014), although this may not always be the case for C4 grains, such as sorghum, under drought conditions (De Souza et al., 2015). Elevated CO_2 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., 2011a, 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). Overall, the effects of increased CO_2 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). 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) 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) highlighted that cropland stability declines rapidly between 1°C and 3°C of warming, whilst Bassu et al. (2014) 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) reported similar effect for tropical regions. Niang et al. (2014) projected significantly lower risks to crop productivity in Africa at 1.5°C compared to 2°C of warming. Lana et al. (2017) 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) 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) 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 CO_2 fertilization were excluded. Iizumi et al. (2017) 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). 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).

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). Similarly, Li et al. (2017) 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).

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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), increases in hot nights (Welch et al., 2010; Okada et al., 2011), extremely high daytime temperatures (Schlenker and Roberts, 2009; Jiao et al., 2016; Lesk et al., 2016), drought (Jiao et al., 2016; Lesk et al., 2016), heat stress (Deryng et al., 2014, Betts et al., 2018), flooding (Betts et al., 2018; Byers et al., 2018), and chilling damage (Jiao et al., 2016), while indirect effects include the spread of pests and diseases (Jiao et al., 2014; van Bruggen et al., 2015), which can also have detrimental effects on cropping systems.

Taken together, the findings of studies on the effects of changes in temperature, precipitation, CO_2 concentration and extreme weather events indicate that a global warming of 2°C is projected to result in a greater reduction in global crop yields and global nutrition than global warming of 1.5°C (*high confidence*; Section 3.6).

3.4.6.2 Livestock production

Studies of climate change impacts on livestock production are few in number. Climate change is expected to directly affect yield quantity and quality (Notenbaert et al., 2017), as well as indirectly impacting the livestock sector through feed quality changes and spread of pests and diseases (Kipling et al., 2016) (*high confidence*). Increased warming and its extremes are expected to cause changes in physiological processes in livestock (i.e., thermal distress, sweating and high respiratory rates) (Mortola and Frappell, 2000) and to have detrimental effects on animal feeding, growth rates (André et al., 2011; Renaudeau et al., 2011; Collier and Gebremedhin, 2015) and reproduction (De Rensis et al., 2015). Wall et al. (2010) observed reduced milk yields and increased cow mortality as the result of heat stress on dairy cow production over some UK regions.

Further, a reduction in water supply might increase cattle water demand (Masike and Urich, 2008). Generally, heat stress can be responsible for domestic animal mortality increase and economic losses (Vitali et al., 2009), affecting a wide range of reproductive parameters (e.g., embryonic development and reproductive efficiency in pigs, Barati et al., 2008; ovarian follicle development and ovulation in horses, Mortensen et al., 2009). Much attention has also been dedicated to ruminant diseases (e.g., liver fluke, Fox et al., 2011; blue-tongue virus, Guis et al., 2012; foot-and-mouth disease (FMD), Brito et al. (2017); and zoonotic diseases, Njeru et al., 2016; Simulundu et al., 2017).

Climate change impacts on livestock are expected to increase. In temperate climates, warming is expected to lengthen the forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Similarly, a decrease in forage quality is expected for both natural grassland in France (Graux et al., 2013) and sown pastures in Australia (Perring et al., 2010). Water resource availability for livestock is expected to decrease owing to increased runoff and reduced groundwater resources. Increased temperature will likely induce changes in river discharge and the amount of water in basins, leading human and livestock populations to experience water stress, especially in the driest areas (i.e., sub-Saharan Africa and South Asia) (*medium confidence*) (Palmer et al., 2008). Elevated temperatures are also expected to increase methane production (Knapp et al., 2014; M.A. Lee et al., 2017). Globally, a decline in livestock of 7–10% is expected at about 2°C of warming, with associated economic losses between $9.7 and $12.6 billion (Boone et al., 2018).

3.4.6.3 Fisheries and aquaculture production

Global fisheries and aquaculture contribute a total of 88.6 and 59.8 million tonnes of fish and other products annually (FAO, 2016), and play important roles in the food security of a large number of countries (McClanahan et al., 2015; Pauly and Charles, 2015) as well as being essential for meeting the protein demand of a growing global population (Cinner et al., 2012, 2016; FAO, 2016; Pendleton et al., 2016). A steady increase in the risks associated with bivalve fisheries and aquaculture at mid-latitudes is coincident with increases in temperature, ocean acidification, introduced species, disease and other drivers (Lacoue-Labarthe et al., 2016; Clements and Chopin, 2017; Clements et al., 2017; Parker et al., 2017). Sea level rise and storm intensification pose a risk to hatcheries and other infrastructure (Callaway et al., 2012; Weatherdon et al., 2016), whilst others risks are associated with the invasion of parasites and pathogens (Asplund et al., 2014; Castillo et al., 2017). Specific human strategies have reduced these risks, which are expected to be moderate under RCP2.6 and very high under RCP8.5 (Gattuso et al., 2015). The risks related to climate change for fin fish (Section 3.4.4) are producing a number of challenges for small-scale fisheries (e.g., Kittinger, 2013; Pauly and Charles, 2015; Bell et al., 2018). Recent literature from 2015 to 2017 has described growing threats from rapid shifts in the biogeography of key species (Poloczanska et al., 2013, 2016; Burrows et al., 2014; García Molinos et al., 2015) and the ongoing rapid degradation of key ecosystems such as coral reefs, seagrass and mangroves (Section 3.4.4, Box 3.4). The acceleration of these changes, coupled with non-climate stresses (e.g., pollution, overfishing and unsustainable coastal development), are driving many small-scale fisheries well below the sustainable harvesting levels required to maintain these resources as a source of food (McClanahan et al., 2009, 2015; Cheung et al., 2010; Pendleton et al., 2016). As a result, future scenarios surrounding climate change and global population growth increasingly project shortages of fish protein for many regions, such as the Pacific Ocean (Bell et al., 2013, 2018) and Indian Ocean (McClanahan et al., 2015). Mitigation of these risks involves marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Kittinger, 2013; McClanahan et al., 2015; Song and Chuenpagdee, 2015; Weatherdon et al., 2016). Other threats concern the increasing incidence of alien species and diseases (Kittinger et al., 2013; Weatherdon et al., 2016).

Risks of impacts related to climate change on low-latitude small-scale fin fisheries are moderate today but are expected to reach very high levels by 1.1°C of global warming. Projections for mid- to high-latitude fisheries include increases in fishery productivity in some cases (Cheung et al., 2013; Hollowed et al., 2013; Lam et al., 2014; FAO, 2016). These projections are associated with the biogeographical shift of species towards higher latitudes (Fossheim et al., 2015), which brings benefits as well as challenges (e.g., increased production yet a greater risk of disease and invasive species; *low confidence*). Factors underpinning

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the expansion of fisheries production to high-latitude locations include warming, increased light levels and mixing due to retreating sea ice (Cheung et al., 2009), which result in substantial increases in primary productivity and fish harvesting in the North Pacific and North Atlantic (Hollowed and Sundby, 2014).

Present-day risks for mid-latitude bivalve fisheries and aquaculture become undetectible up to 1.1°C of global warming, moderate at 1.3°C, and moderate to high up to 1.9°C (Figure 3.18). For instance, Cheung et al. (2016a), simulating the loss in fishery productivity at 1.5°C, 2°C and 3.5°C above the pre-industrial period, found that the potential global catch for marine fisheries will *likely* decrease by more than three million metric tonnes for each degree of warming. Low-latitude fin-fish fisheries have higher risks of impacts, with risks being moderate under present-day conditions and becoming high above 0.9°C and very high at 2°C of global warming. High-latitude fisheries are undergoing major transformations, and while production is increasing, present-day risk is moderate and is projected to remain moderate at 1.5°C and 2°C (Figure 3.18).

Adaptation measures can be applied to shellfish, large pelagic fish resources and biodiversity, and they include options such as protecting reproductive stages and brood stocks from periods of high ocean acidification (OA), stock selection for high tolerance to OA (*high confidence*) (Ekstrom et al., 2015; Rodrigues et al., 2015; Handisyde et al., 2016; Lee, 2016; Weatherdon et al., 2016; Clements and Chopin, 2017), redistribution of highly migratory resources (e.g., Pacific tuna) (*high confidence*), governance instruments such as international fisheries agreements (Lehodey et al., 2015; Matear et al., 2015), protection and regeneration of reef habitats, reduction of coral reef stresses, and development of alternative livelihoods (e.g., aquaculture; Bell et al., 2013, 2018).

Cross-Chapter Box 6 | Food Security

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Climate change influences food and nutritional security through its effects on food availability, quality, access and distribution (Paterson and Lima, 2010; Thornton et al., 2014; FAO, 2016). More than 815 million people were undernourished in 2016, and 11% of the world's population has experienced recent decreases in food security, with higher percentages in Africa (20%), southern Asia (14.4%) and the Caribbean (17.7%) (FAO et al., 2017). Overall, food security is expected to be reduced at 2°C of global warming compared to 1.5°C, owing to projected impacts of climate change and extreme weather on yields, crop nutrient content, livestock, fisheries and aquaculture and land use (cover type and management) (Sections 3.4.3.6, 3.4.4.12 and 3.4.6), (*high confidence*). The effects of climate change on crop yield, cultivation area, presence of pests, food price and supplies are projected to have major implications for sustainable development, poverty eradication, inequality and the ability of the international community to meet the United Nations sustainable development goals (SDGs; Cross-Chapter Box 4 in Chapter 1).

Goal 2 of the SDGs is to end hunger, achieve food security, improve nutrition and promote sustainable agriculture by 2030. This goal builds on the first millennium development goal (MDG-1) which focused on eradicating extreme poverty and hunger, through efforts that reduced the proportion of undernourished people in low- and middle-income countries from 23.3% in 1990 to 12.9% in 2015. Climate change threatens the capacity to achieve SDG 2 and could reverse the progress made already. Food security and agriculture are also critical to other aspects of sustainable development, including poverty eradication (SDG 1), health and well-being (SDG 3), clean water (SDG 6), decent work (SDG 8), and the protection of ecosystems on land (SDG 14) and in water (SDG 15) (UN, 2015, 2017; Pérez-Escamilla, 2017).

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), 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). 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), 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).

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Cross-Chapter Box 6 (continued)

Rosenzweig et al. (2018) and Ruane et al. (2018) 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). Together, the impacts on protein availability may bring as many as 150 million people into protein deficiency by 2050 (Medek et al., 2017). 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).

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), 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), financial volatility (Kannan et al., 2000; Ghosh, 2010; Naylor and Falcon, 2010; HLPE, 2011), and the distributions of pests and disease (Jiao et al., 2014; van Bruggen et al., 2015). Changes in temperature and precipitation are projected to increase global food prices by 3–84% by 2050 (IPCC, 2013). Differences in price impacts of climate change are accompanied by differences in land-use change (Nelson et al., 2014b), energy policies and food trade (Mueller et al., 2011; Wright, 2011; Roberts and Schlenker, 2013). 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). 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., 2016; Wei et al., 2017).

Climate change impacts on food security can be reduced through adaptation (Hasegawa et al., 2014). 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), 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), as well as helping meet mitigation goals (Harvey et al., 2014).

K.R. Smith et al. (2014) 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). 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). 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). 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).

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) but is also a climate change hotspot (de Sherbinin, 2014; Lebel et al., 2014). 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), as well as increased flooding and related disaster risks (T.F. Smith et al., 2013; Ling et al., 2015; Zhang et al., 2016). 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). 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); agricultural productivity and food security (Smajgl et al., 2015); livelihoods such as fishing and farming (D. Wu et al., 2013); and disaster risk (D. Wu et al., 2013; Hoang et al., 2016), with implications for human mortality and economic and infrastructure losses.

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Cross-Chapter Box 6 (continued)

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), 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). Ecosystem-based approaches, such as integrated water resources management, demonstrate successes in mainstreaming adaptation into existing strategies (Sebesvari et al., 2017). 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). 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).

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), although the mainstreaming of adaptation into development policies has lagged behind needs (Gass et al., 2011). 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). 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); combinations of top-down government-led (e.g., relocation) and bottom-up household strategies (e.g., increasing house height) (Ling et al., 2015); and community-based adaptation initiatives that merge scientific knowledge with local solutions (Gustafson et al., 2016, 2018; Tran et al., 2018). 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). 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.

3.4.7 Human Health

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). 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), and increasing morbidity and mortality are associated with extreme weather and climate events (e.g., K.R. Smith et al., 2014). 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). 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).

3.4.7.1 Projected risk at 1.5°C and 2°C of global warming

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). 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).

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). 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). 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). Populations at highest risk include older adults, children,

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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).

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).

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). 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). 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). 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).

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). 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).

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). 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).

***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). 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).

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). 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). 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).

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.

3.4.8 Urban Areas

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). 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), variability in precipitation (Yu et al., 2018) and sea level rise can directly affect urban areas (Section 3.4.5, Bader et al., 2018; Dawson et al., 2018). Indirect risks may arise from interactions between urban and natural systems.

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Future warming and urban expansion could lead to more extreme heat stress (Argüeso et al., 2015; Suzuki-Parker et al., 2015). 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), 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). Warming of 2°C is expected to increase the risks of heatwaves in China's urban agglomerations (Yu et al., 2018). 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). 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). 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). 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).

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), with distinct implications for the urban poor (Revi et al., 2014; Jean-Baptiste et al., 2018; UCCRN, 2018). Adverse impacts of extreme events could arise in tropical coastal areas of Africa, South America and Southeast Asia (Schleussner et al., 2016b). 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). 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).

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). 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).

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.

3.4.9 Key Economic Sectors and Services

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.

3.4.9.1 Tourism

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). 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).

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). 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). 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). Using an econometric analysis of the relationship between regional tourism demand and climate conditions, Ciscar et al. (2014) 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

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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). 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). 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).

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). 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).

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). 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). 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*).

3.4.9.2 Energy systems

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) (*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). 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).

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). 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). 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).

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). Byers et al. (2018) 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) 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). 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). Decreased electricity generation of –15% is projected for Brazil starting in 2040, with values expected to decline to –28% later in the

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century (de Queiroz et al., 2016). In large parts of Europe, electricity demand is projected to decrease, mainly owing to reduced heating demand (Jacob et al., 2018).

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). 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). Hosking et al. (2018) 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) 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).

3.4.9.3 Transportation

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). 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). 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). Open water vessel transit has the potential to double by mid-century, with a two to four month longer season (Melia et al., 2016).

3.4.10 Livelihoods and Poverty, and the Changing Structure of Communities

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). 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).

3.4.10.1 Livelihoods and poverty

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). 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 extreme poverty, mostly through impacts on agriculture and food prices (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Unmitigated warming could reshape the global economy later in the century by reducing average global incomes and widening global income inequality (Burke et al., 2015b). The most severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia.

3.4.10.2 The changing structure of communities: migration, displacement and conflict

Migration: In AR5, the potential impacts of climate change on migration and displacement were identified as an emerging risk (Oppenheimer et al., 2014). The social, economic and environmental factors underlying migration are complex and varied; therefore, detecting the effect of observed climate change or assessing its possible magnitude with any degree of confidence is challenging (Cramer et al., 2014).

No studies have specifically explored the difference in risks between 1.5°C and 2°C of warming on human migration. The literature consistently highlights the complexity of migration decisions and the difficulties in attributing causation (e.g., Nicholson, 2014; Baldwin and Fornalé, 2017; Bettini, 2017; Constable, 2017; Islam and Shamsuddoha, 2017; Suckall et al., 2017). The studies on migration that have most closely explored the probable impacts of 1.5°C and 2°C have mainly focused on the direct effects of temperature and precipitation anomalies on migration or the indirect effects of these climatic changes through changing agriculture yield and livelihood sources (Mueller et al., 2014; Piguet and Laczko, 2014; Mastrorillo et al., 2016; Sudmeier-Rieux et al., 2017).

Temperature has had a positive and statistically significant effect on outmigration over recent decades in 163 countries, but only for agriculture-dependent countries (R. Cai et al., 2016). A 1°C increase in average temperature in the International Migration Database of the Organisation for Economic Co-operation and Development (OECD) was associated with a 1.9% increase in bilateral migration flows from 142 sending countries and 19 receiving countries, and an additional millimetre of average annual precipitation was associated with an increase in migration by 0.5% (Backhaus et al., 2015). In another study, an increase in precipitation anomalies from the long-term mean, was strongly associated with an increase in outmigration, whereas no significant effects of temperature anomalies were reported (Coniglio and Pesce, 2015).

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Internal and international migration have always been important for small islands (Farbotko and Lazrus, 2012; Weir et al., 2017). There is rarely a single cause for migration (Constable, 2017). Numerous factors are important, including work, education, quality of life, family ties, access to resources, and development (Bedarff and Jakobeit, 2017; Speelman et al., 2017; Nicholls et al., 2018). Depending on the situation, changing weather, climate or environmental conditions might each be a factor in the choice to migrate (Campbell and Warrick, 2014).

Displacement: At 2°C of warming, there is a potential for significant population displacement concentrated in the tropics (Hsiang and Sobel, 2016). Tropical populations may have to move distances greater than 1000 km if global mean temperature rises by 2°C from 2011–2030 to the end of the century. A disproportionately rapid evacuation from the tropics could lead to a concentration of population in tropical margins and the subtropics, where population densities could increase by 300% or more (Hsiang and Sobel, 2016).

Conflict: A recent study has called for caution in relating conflict to climate change, owing to sampling bias (Adams et al., 2018). Insufficient consideration of the multiple drivers of conflict often leads to inconsistent associations being reported between climate change and conflict (e.g., Hsiang et al., 2013; Hsiang and Burke, 2014; Buhaug, 2015, 2016; Carleton and Hsiang, 2016; Carleton et al., 2016). There also are inconsistent relationships between climate change, migration and conflict (e.g., Theisen et al., 2013; Buhaug et al., 2014; Selby, 2014; Christiansen, 2016; Brzoska and Fröhlich, 2016; Burrows and Kinney, 2016; Reyer et al., 2017c; Waha et al., 2017). Across world regions and from the international to micro level, the relationship between drought and conflict is weak under most circumstances (Buhaug, 2016; von Uexkull et al., 2016). However, drought significantly increases the likelihood of sustained conflict for particularly vulnerable nations or groups, owing to the dependence of their livelihood on agriculture. This is particularly relevant for groups in the least developed countries (von Uexkull et al., 2016), in sub-Saharan Africa (Serdeczny et al., 2016; Almer et al., 2017) and in the Middle East (Waha et al., 2017). Hsiang et al. (2013) reported causal evidence and convergence across studies that climate change is linked to human conflicts across all major regions of the world, and across a range of spatial and temporal scales. A 1°C increase in temperature or more extreme rainfall increases the frequency of intergroup conflicts by 14% (Hsiang et al., 2013). If the world warms by 2°C–4°C by 2050, rates of human conflict could increase. Some causal associations between violent conflict and socio-political instability were reported from local to global scales and from hour to millennium time frames (Hsiang and Burke, 2014). A temperature increase of one standard deviation increased the risk of interpersonal conflict by 2.4% and intergroup conflict by 11.3% (Burke et al., 2015a). Armed-conflict risks and climate-related disasters are both relatively common in ethnically fractionalized countries, indicating that there is no clear signal that environmental disasters directly trigger armed conflicts (Schleussner et al., 2016a).

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

3.4.11 Interacting and Cascading Risks

The literature on compound as well as interacting and cascading risks at warming of 1.5°C and 2°C is limited. Spatially compound risks, often referred to as hotspots, involve multiple hazards from different sectors overlapping in location (Piontek et al., 2014). Global exposures were assessed for 14 impact indicators, covering water, energy and land sectors, from changes including drought intensity and water stress index, cooling demand change and heatwave exposure, habitat degradation, and crop yields using an ensemble of climate and impact models (Byers et al., 2018). Exposures are projected to approximately double between 1.5°C and 2°C, and the land area affected by climate risks is expected to increase as warming progresses. For populations vulnerable to poverty, the exposure to climate risks in multiple sectors could be an order of magnitude greater (8–32 fold) in the high poverty and inequality scenarios (SSP3; 765–1,220 million) compared to under sustainable socio-economic development (SSP1; 23–85 million). Asian and African regions are projected to experience 85–95% of global exposure, with 91–98% of the exposed and vulnerable population (depending on SSP/GMT combination), approximately half of which are in South Asia. Figure 3.19 shows that moderate and large multi-sector impacts are prevalent at 1.5°C where vulnerable people live, predominantly in South Asia (mostly Pakistan, India and China), but that impacts spread to sub-Saharan Africa, the Middle East and East Asia at higher levels of warming. Beyond 2°C and at higher risk thresholds, the world's poorest populations are expected to be disproportionately impacted, particularly in cases (SSP3) of great inequality in Africa and southern Asia. Table 3.4 shows the number of exposed and vulnerable people at 1.5°C and 2°C of warming, with 3°C shown for context, for selected multi-sector risks.

3.4.12 Summary of Projected Risks at 1.5°C and 2°C of Global Warming

The information presented in Section 3.4 is summarized below in Table 3.5, which illustrates the growing evidence of increasing risks across a broad range of natural and human systems at 1.5°C and 2°C of global warming.

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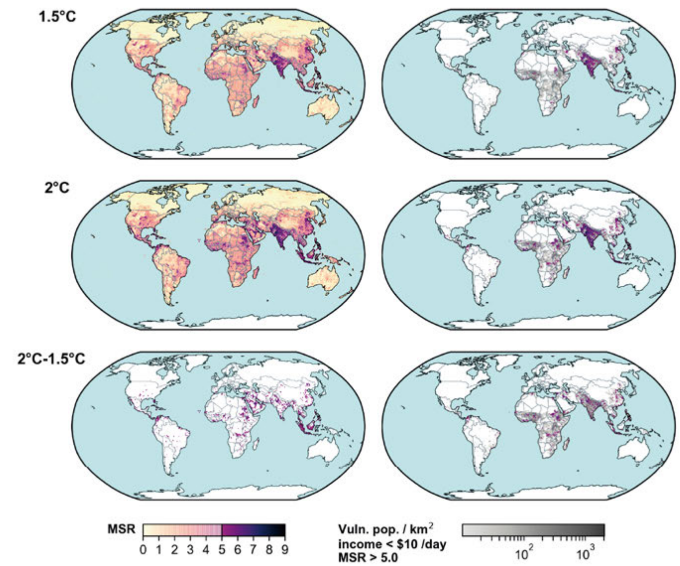

Figure 3.19 | Multi-sector risk maps for 1.5°C (top), 2°C (middle), and locations where 2°C brings impacts not experienced at 1.5°C (2°C–1.5°C; bottom). The maps in the left column show the full range of the multi-sector risk (MSR) score (0–9), with scores ≤5.0 shown with a transparency gradient and scores >5.0 shown with a colour gradient. Score must be >4.0 to be considered 'multi-sector'. The maps in the right column overlay the 2050 vulnerable populations (low income) under Shared Socio-Economic Pathway (SSP)2 (greyscale) with the multi-sector risk score >5.0 (colour gradient), thus indicating the concentrations of exposed and vulnerable populations to risks in multiple sectors. Source: Byers et al. (2018).

Table 3.4 | Number of exposed and vulnerable people at 1.5°C, 2°C, and 3°C for selected multi-sector risks under shared socioeconomic pathways (SSPs). Source: Byers et al., 2018

SSP2 (SSP1 to SSP3 range), millions	1.5°C		2°C		3°C	
Indicator	Exposed	Exposed and vulnerable	Exposed	Exposed and vulnerable	Exposed	Exposed and vulnerable
Water stress index	3340 (3032–3584)	496 (103–1159)	3658 (3080–3969)	586 (115–1347)	3920 (3202–4271)	662 (146–1480)
Heatwave event exposure	3960 (3546–4508)	1187 (410–2372)	5986 (5417–6710)	1581 (506–3218)	7909 (7286–8640)	1707 (537–3575)
Hydroclimate risk to power production	334 (326–337)	30 (6–76)	385 (374–389)	38 (9–94)	742 (725–739)	72 (16–177)
Crop yield change	35 (32–36)	8 (2–20)	362 (330–396)	81 (24–178)	1817 (1666–1992)	406 (118–854)
Habitat degradation	91 (92–112)	10 (4–31)	680 (314–706)	102 (23–234)	1357 (809–1501)	248 (75–572)
Multi-sector exposure						
Two indicators	1129 (1019–1250)	203 (42–487)	2726 (2132–2945)	562 (117–1220)	3500 (3212–3864)	707 (212–1545)
Three indicators	66 (66–68)	7 (0.9–19)	422 (297–447)	54 (8–138)	1472 (1177–1574)	237 (48–538)
Four indicators	5 (0.3–5.7)	0.3 (0–1.2)	11 (5–14)	0.5 (0–2)	258 (104–280)	33 (4–86)

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Table 3.5 | Summary of projected risks to natural and human systems at 1.5°C and 2°C of global warming, and of the potential to adapt to these risks. Table summarizes the chapter text and with references supporting table entries found in the main chapter text. Risk magnitude is provided either as assessed levels of risk (very high: vh, high: h, medium: m, or low: l) or as quantitative examples of risk levels taken from the literature. Further compilations of quantified levels of risk taken from the literature may be found Tables 3.SM1-5 in the Supplementary Material. Similarly, potential to adapt is assessed from the literature by expert judgement as either high (h), medium (m), or low (l). Confidence in each assessed level/quantification of risk, or in each assessed adaptation potential, is indicated as very high (VH), high (H), medium (M), or low (L). Note that the use of l, m, h and vh here is distinct from the use of L, M, H and VH in Figures 3.18, 3.20 and 3.21.

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to 2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Freshwater	Precipitation, temperature, snowmelt	Water Stress	Around half compared to the risks at 2°C[1]	Additional 8% of the world population in 2000 exposed to new or aggravated water scarcity[1]	Up to 100% increase	M		Europe, Australia, southern Africa		3	l	l	M
		Fluvial flood	100% increase in the population affected compared to the impact simulated over the baseline period 1976–2005[2]	170% increase in the population affected compared to the impact simulated over the baseline period 1976–2005[2]	70% increase	M	USA, Asia, Europe		Africa, Oceania	2	l/m	l/m	M
		Drought	350.2 ± 158.8 million, changes in urban population exposure to severe drought at the globe scale[3]	410.7 ± 213.5 million, changes in urban population exposure to severe drought at the globe scale[3]	60.5 ± 84.1 million (±84.1 based on the SSP1 scenario) (based on PDSI estimate)	M	Central Europe, southern Europe, Mediterranean, West Africa, East and West Asia, Southeast Asia (based on PDSI estimate[3])			2	l/m	l/m	L
Terrestrial ecosystems	Temperature, precipitation	Species range loss	6% insects, 4% vertebrates, 8% plants, lose >50% range[4]	18% insects, 8% vertebrates, 16% plants lose >50% range[4]	Double or triple	M		Amazon, Europe, southern Africa		1,4	m	l	H
		Loss of ecosystem functioning and services	m	h		M				4			
		Shifts of biomes (major ecosystem types)	About 7% transformed[5]	13% (range 8–20%) transformed[5]	About double	M		Arctic, Tibet, Himalayas, South Africa, Australia		4			
	Heat and cold stress, warming, precipitation drought	Wildfire	h	h	Increased risk	M	Canada, USA and Mediterranean	Mediterranean	Central and South America, Australia, Russia, China, Africa	1, 2, 4, 5	l	l	M

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Table 3.5 (continued)

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Ocean	Warming and stratification of the surface ocean	Loss of framework species (coral reefs)	vh	vh	Greater rate of loss: from 70–90% loss at 1.5°C to 99% loss at 2°C and above	H/very H	Tropical/ subtropical countries	Tropical/ subtropical countries	Southern Red Sea, Somalia, Yemen, deep water coral reefs	1,2	h	l	H
		Loss of framework species (seagrass)	m	h	Increase in risk	M	Tropical/ subtropical countries	Tropical/ subtropical countries	Southern Red Sea, Somalia, Yemen, Myanmar	1,2	m	l	M/H
		Loss of framework species (mangroves)	m	m	Uncertain and depends on other human activities	M/H	Tropical/ subtropical countries	Tropical/ subtropical countries	Southern Red Sea, Somalia, Yemen, Myanmar	1,3	m	l	L/M
		Disruption of marine foodwebs	h	vh	Large increase in risk	M	Global	Global	Deep sea	4	m	l	M/H
		Range migration of marine species and ecosystems	m	h	Large increase in risk	H	Global	Global	Deep sea	1	m	l	H
		Loss of fin fish and fisheries	h	h/vh	Large increase in risk	H	Global	Global	Deep sea, up-welling systems	4	m	m/l	M/H
	Ocean acidification and elevated sea temperatures	Loss of coastal ecosystems and protection	m	h	Increase in risk	M	Low-latitude tropical/ subtropical countries	Low-latitude tropical/subtropi-cal countries	Most regions – risks not well defined	1	m	m/l	M
		Loss of bivalves and bivalve fisheries	m/h	h/vh	Large increase in risk	H	Temperate countries with upwelling	Temperate countries with upwelling	Most regions – risks not well defined	4	m/h	l/m	M/H
		Changes to physiology and ecology of marine species	l/m	m	Increase in risk	H	Global	Global	Most regions – risks not well defined	4	l	l	M/H
	Reduced bulk ocean circulation and de-oxygenation	Increased hypoxic dead zones	l	l/m	Large increase in risk	L/M	Temperate countries with upwelling	Temperate countries with upwelling	Deep sea	4	m	l	M
		Changes to upwelling productivity	l	m	Increase in risk	L/M	Most upwelling regions	Most upwelling regions	Some upwelling systems	4	l	l	M

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Table 3.5 (continued)

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Ocean	Intensified storms, precipitation plus sea level rise	Loss of coastal ecosystems	h	h/vh	Large increase in risk	H	Tropical/ subtropical countries	Tropical/ subtropical countries		1, 4	m	l	M
		Inundation and destruction of human/coastal infrastructure and livelihoods	h	h/vh	Large increase in risk	H	Global	Global		1, 5	m/h	m	M/L
	Loss of sea ice	Loss of habitat	h	vh	Large increase in risk	H	Polar regions	Polar regions		1	l	very l	H
		Increased productivity but changing fisheries	l/m	m/h	Large increase in risk	very H	Polar regions	Polar regions		1, 4	l	m/l	H
Coastal	Sea level rise, increased storminess	Area exposed (assuming no defences)	562–575th km² when 1.5°C first reached[6,7,8]	590–613th km² when 2°C first reached[6,7,8]	Increasing; 25–38th km² when temperatures are first reached, 10–17th km² in 2100 increasing to 16–230th km² in 2300[6,7,8]	M/H (dependent on population datasets)	Asia, small islands	Asia, small islands	Small islands	2, 3	m	m	M
		Population exposed (assuming no defences)	128–143 million when 1.5°C first reached	141–151 million when 2°C first reached	Increasing; 13–8 million when temperatures are first reached, 0–6 million people in 2100, increasing to 35–95 million people in 2300[8]	M/H (dependent on population datasets)	Asia, small islands	Asia, small islands	Small islands	2, 3	m	m	M
		People at risk accounting for defences (modelled in 1995)	2–28 million people yr⁻¹ if defences are not upgraded from the modelled 1995 baseline[9]	15–53 million people yr⁻¹ if defences are not upgraded from the modelled 1995 baseline[9]	Increasing with time, but highly dependent on adaptation[9]	M/H (dependent on adaptation)	Asia, small islands, potentially African nations	Asia, small islands	Small islands	2, 3, 4	m	m	M

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Table 3.5 (continued)

Sector	Physical climate change drivers	Nature of risk	Global risks at 1.5°C of global warming above pre-industrial	Global risks at 2°C of global warming above pre-industrial	Change in risk when moving from 1.5°C to 2°C of warming	Confidence in risk statements	Regions where risks are particularly high with 2°C of global warming	Regions where the change in risk when moving from 1.5°C to2°C are particularly high	Regions with little or no information	RFC*	Adaptation potential at 1.5°C	Adaptation potential at 2°C	Confidence in assigning adaptation potential
Food security and food production systems	Heat and cold stress, warming, precipitation, drought	Changes in ecosystem production	m/h	h	Large increase	M/H	Global	North America, Central and South America, Mediterranean basin, South Africa, Australia, Asia		2, 4, 5	h	m/h	M/H
	Heat and cold stress, warming, precipitation drought#	Shift and composition change of biomes (major ecosystem types)	m/h	h	Moderate increase	L/M	Global	Global, tropical areas, Mediterranean	Africa, Asia	1, 2, 3, 4	l/m	l	L/M
Human health	Temperature	Heat-related morbidity and mortality	m	m/h	Risk increased	VH	All regions at risk	All regions	Africa	2, 3, 4	h	h	H
		Occupational heat stress	m	m/h	Risk increased	M	Tropical regions	Tropical regions	Africa	2, 3, 4	h	m	M
	Air quality	Ozone-related mortality	m (if precursor emissions remain the same)	m/h (if precursor emissions remain the same)	Risk increased	H	High income and emerging economies	High income and emerging economies	Africa, parts of Asia	2, 3, 4	l	l	M
	Temperature, precipitation	Undernutrition	m	m/h	Risk increased	H	Low-income countries in Africa and Asia	Low-income countries in Africa and Asia	Small islands	2, 3, 4	m	l	M
Key economic sectors	Temperature	Tourism (sun, beach, and snow sports)	m/h	h	Risk increased	VH	Coastal tourism, particularly in subtropical and tropical regions	Coastal tourism, particularly in subtropical and tropical regions	Africa	1, 2, 3	m	l	H

*RFC: 1 = unique and threatened systems, 2 = extreme events, 3 = unequal distribution of impacts, 4 = global aggregate impacts (economic + biodiversity), 5 = large-scale singular events.

PDSI-based drought estimates tend to overestimate drought impacts (see Section 3.3.4); hence projections with other drought indices may differ. Further quantifications may be found in Table 3.SM.1

[1] Gerten et al., 2013; [2] Alfieri et al., 2017; [3] Liu et al., 2018; [4] Warren et al., 2018a; [5] Warzawski et al., 2013; [6] Brown et al., 2018a; [7] Rasmussen et al., 2018; [8] Yokoki et al., 2018; [9] Nicholls et al., 2018.

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3.4.13 Synthesis of Key Elements of Risk

Some elements of the assessment in Section 3.4 were synthesized into Figure 3.18 and 3.20, indicating the overall risk for a representative set of natural and human systems from increases in global mean surface temperature (GMST) and anthropogenic climate change. The elements included are supported by a substantive enough body of literature providing at least *medium confidence* in the assessment. The format for Figures 3.18 and 3.20 match that of Figure 19.4 of WGII AR5 Chapter 19 (Oppenheimer et al., 2014) indicating the levels of additional risk as colours: undetectable (white) to moderate (detected and attributed; yellow), from moderate to high (severe and widespread; red), and from high to very high (purple), the last of which indicates significant irreversibility or persistence of climate-related hazards combined with a much reduced capacity to adapt. Regarding the transition from undetectable to moderate, the impact literature assessed in AR5 focused on describing and quantifying linkages between weather and climate patterns and impact outcomes, with limited detection and attribution to anthropogenic climate change (Cramer et al., 2014). A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) confirmed that the impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of those impacts related to precipitation is only weakly evident or absent. Moreover, there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016).

The current synthesis is complementary to the synthesis in Section 3.5.2 that categorizes risks into 'Reasons for Concern' (RFCs), as described in Oppenheimer et al. (2014). Each element, or burning ember, presented here (Figures 3.18, 3.20) maps to one or more RFCs (Figure 3.21). It should be emphasized that risks to the elements assessed here are only a subset of the full range of risks that contribute to the RFCs. Figures 3.18 and 3.20 are not intended to replace the RFCs but rather to indicate how risks to particular elements of the Earth system accrue with global warming, through the visual burning embers format, with a focus on levels of warming of 1.5°C and 2°C. Key evidence assessed in earlier parts of this chapter is summarized to indicate the transition points between the levels of risk. In this regard, the assessed confidence in assigning the transitions between risk levels are as follows: L=Low, M=Medium, H=High, and VH=Very high levels of confidence. A detailed account of the procedures involved is provided in the Supplementary Material (3.SM.3.2 and 3.SM.3.3).

In terrestrial ecosystems (feeding into RFC1 and RFC4), detection and attribution studies show that impacts of climate change on terrestrial ecosystems began to take place over the past few decades, indicating a transition from no risk (white areas in Figure 3.20) to moderate risk below recent temperatures (*high confidence*) (Section 3.4.3). Risks to unique and threatened terrestrial ecosystems are generally projected to be higher under warming of 2°C compared to 1.5°C (Section 3.5.2.1), while at the global scale severe and widespread risks are projected to occur by 2°C of warming. These risks are associated with biome shifts and species range losses (Sections 3.4.3 and 3.5.2.4); however, because many systems and species are projected to be unable to adapt to levels of warming below 2°C, the transition to high risk (red areas in Figure 3.20) is located below 2°C (*high confidence*). With 3°C of warming, however, biome shifts and species range losses are expected to escalate to very high levels, and the systems are projected to have very little capacity to adapt (Figure 3.20) (*high confidence*) (Section 3.4.3).

In the Arctic (related to RFC1), the increased rate of summer sea ice melt was detected and attributed to climate change by the year 2000 (corresponding to warming of 0.7°C), indicating moderate risk. At 1.5°C of warming an ice-free Arctic Ocean is considered *unlikely*, whilst by 2°C of warming it is considered *likely* and this unique ecosystem is projected to be unable to adapt. Hence, a transition from high to very high risk is expected between 1.5°C and 2°C of warming.

For warm-water coral reefs, there is *high confidence* in the transitions between risk levels, especially in the growing impacts in the transition of warming from non-detectable (0.2°C to 0.4°C), and then successively higher levels risk until high and very high levels of risks by 1.2°C (Section 3.4.4 and Box 3.4). This assessment 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, as well as losses at other sites globally. The major increase in the size and loss of coral reefs over the past three years, plus sequential mass coral bleaching and mortality events on the Great Barrier Reef, (Hoegh-Guldberg, 1999; Hughes et al., 2017b, 2018), have reinforced the scale of climate-change related risks to coral reefs. General assessments of climate-related risks for mangroves prior to this special report concluded 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). Recent climate-related die-offs (Duke et al., 2017; Lovelock et al., 2017), however, suggest that climate change risks may have been underestimated for mangroves as well, and risks have thus been assessed as undetectable to moderate, with the transition now starting at 1.3°C as opposed to 1.8°C as assessed in 2015 (Gattuso et al., 2015). Risks of impacts related to climate change on small-scale fisheries at low latitudes, many of which are dependent on ecosystems such as coral reefs and mangroves, are moderate today but are expected to reach high levels of risk around 0.9°C–1.1°C (*high confidence*) (Section 3.4.4.10).

The transition from undetectable to moderate risk (related to RFCs 3 and 4), shown as white to yellow in Figure 3.20, is based on AR5 WGII Chapter 7, which indicated with *high confidence* that climate change impacts on crop yields have been detected and attributed to climate change, and the current assessment has provided further evidence to confirm this (Section 3.4.6). Impacts have been detected in the tropics (AR5 WGII Chapters 7 and 18), and regional risks are projected to become high in some regions by 1.5°C of warming, and in many regions by 2.5°C, indicating a transition from moderate to high risk between 1.5°C and 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

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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), 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°C, 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 3.5.2.5).

For 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). 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*).

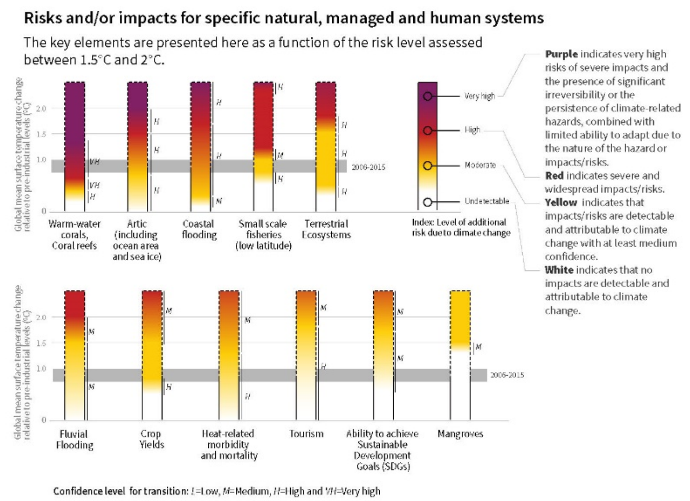

Figure 3.20 | The dependence of risks and/or impacts associated with selected elements of human and natural systems on the level of climate change, adapted from Figure 3.21 and from AR5 WGII Chapter 19, Figure 19.4, and highlighting the nature of this dependence between 0°C and 2°C warming above pre-industrial levels. The selection of impacts and risks to natural, managed and human systems is illustrative and is not intended to be fully comprehensive. Following the approach used in AR5, literature was used to make expert judgements to assess the levels of global warming at which levels of impact and/or risk are undetectable (white), moderate (yellow), high (red) or very high (purple). The colour scheme thus indicates the additional risks due to climate change. The transition from red to purple, introduced for the first time in AR4, is defined by a very high risk of severe impacts and the presence of significant irreversibility or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMST. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation independently of development pathway. The levels of risk illustrated reflect the judgements of the authors of Chapter 3 and Gattuso et al. (2015; for three marine elements). The grey bar represents the range of GMST for the most recent decade: 2006–2015.

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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 projcted 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 recent temperatures at 0.5°C of warming (*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 inequality 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 there is a substantive body of literature, nor does it necessarily include all elements which are of particular interest to decision-makers.

3.5 Avoided Impacts and Reduced Risks at 1.5°C Compared with 2°C of Global Warming

3.5.1 Introduction

Oppenheimer et al. (2014, AR5 WGII Chapter 19) 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) were recently reviewed, and most judgements were confirmed in the light of more recent literature (O'Neill et al., 2017). The approach of Oppenheimer et al. (2014) 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 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).

3.5.2 Aggregated Avoided Impacts and Reduced Risks at 1.5°C versus 2°C of Global Warming

A brief summary of the accrual of 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) 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 for global warming of 3°C or more is included in the figure (i.e., analysis is discontinued at 2.5°C).

3.5.2.1 RFC 1 – Unique and threatened systems

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.

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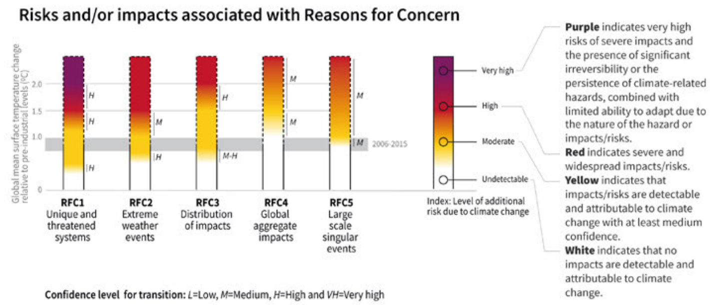

Figure 3.21 | The dependence of risks and/or impacts associated with the Reasons for Concern (RFCs) on the level of climate change, updated and adapted from WGII AR5 Ch 19, Figure 19.4 and highlighting the nature of this dependence between 0°C and 2°C warming above pre-industrial levels. As in the AR5, literature was used to make expert judgements to assess the levels of global warming at which levels of impact and/or risk are undetectable (white), moderate (yellow), high (red) or very high (purple). The colour scheme thus indicates the additional risks due to climate change. The transition from red to purple, introduced for the first time in AR4, is defined by very high risk of severe impacts and the presence of significant irreversibility, or persistence of climate-related hazards combined with a limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMST. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation (RFC 1, 3, 5) independently of development pathway. The rate and timing of impacts were taken into account in assessing RFC 1 and 5. The levels of risk illustrated reflect the judgements of the Ch 3 authors. RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots. RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4 Global aggregate impacts: global monetary damage, global scale degradation and loss of ecosystems and biodiversity. RFC5 Large-scale singular events: are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets. The grey bar represents the range of GMST for the most recent decade: 2006–2015.

New literature 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). 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 (Figure 3.21) in this RFC1 compared to in AR5. Further details of risk transitions for ocean systems are described in Figure 3.18.

Substantial losses of 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), which is expected to reduce risks to both social and ecological systems in the Arctic. This indicates a transition in the 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). 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,

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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.

3.5.2.2 RFC 2 – Extreme weather events

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 risk 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), 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).

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.

3.5.2.3 RFC 3 – Distribution of impacts

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

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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), 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). 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). 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).

3.5.2.4 RFC 4 – Global aggregate impacts

Oppenheimer et al. (2014) 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) 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) 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) 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). 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) 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), 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) found a mean difference of 0.35% GDP (range 0.2–0.65%), while Yohe (2017) 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) 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) included only three known singular events whereas Y. Cai et al. (2016) 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), 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), 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

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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 will be impacts on global ecosystem functioning already at 2°C of warming, whilst species that lose large proportions of their range are considered to be at increased risk of extinction (Section 3.4.3.3). Since AR5, new literature has indicated that impacts on 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, suggesting that the transition to a 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*).

3.5.2.5 RFC 5 – Large-scale singular events

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) assessed this threshold to be at 2°C of warming or higher levels relative to pre-industrial temperature. Robinson et al. (2012) 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 be between 1.5°C and 2°C. The time scale for eventual loss of the ice sheets 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), although a smaller number of investigations (Joughin et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016) 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). There is limited evidence linking the recent weakening of the AMOC to anthropogenic warming (Caesar et al., 2018). 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). 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). 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, are associated concerns (Section 3.3.10).

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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 suggests 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.

3.5.3 Regional Economic Benefit Analysis for the 1.5°C versus 2°C Global Goals

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 1.5°C 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). 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), 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). It is *likely* that the even more stringent mitigation measures required to restrict global warming to 1.5°C (Rogelj et al., 2013) 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).

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., 2018; Pretis et al., 2018). Despite the uncertainties associated with climate change projections and econometrics (e.g., M. Burke et al., 2018), 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). 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). 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).

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 realized estimated at 76%, 85% and 81% for the USA, China and Japan, respectively (M. Burke et al., 2018). 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) found a mean difference of 0.35% GDP (range 0.2–0.65%), while Hsiang et al. (2017) 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 impacts on GDP are projected to be generally negative (*low confidence*) (Pretis et al., 2018).

A caveat to the analyses of Pretis et al. (2018) and M. Burke et al. (2018) 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.

3.5.4 Reducing Hotspots of Change for 1.5°C and 2°C of Global Warming

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.

3.5.4.1 Arctic sea ice

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). 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). The probability of an 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). 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). 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). 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). 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).

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3.5.4.2 Arctic land regions

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 3.3.2.2 and Seneviratne et al., 2016). Moreover, over much of the Arctic, a further increase of 0.5°C in the global surface 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). Rising temperatures, thawing permafrost and changing weather patterns are projected to increasingly impact people, infrastructure and industries in the Arctic (W.N. Meier et al., 2014) with these impacts larger at 2°C than at 1.5°C of warming (*medium confidence*).

3.5.4.3 Alpine regions

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 increases in temperature. Under regional warming, alpine species have been found to migrate upwards on mountain slopes (Reasoner and Tinner, 2009), 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; B. Chen et al., 2014).

3.5.4.4 Southeast Asia

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). 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). 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 3.3.3; Wartenburger et al., 2017; Döll et al., 2018; Seneviratne et al., 2018c); 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). 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). However, under 1.5°C of warming, significant risks for crop yield reduction in the region are avoided (Schleussner et al., 2016b). 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 compared to 1.5°C (*medium confidence*).

3.5.4.5 Southern Europe and the Mediterranean

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) and in terms of 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), with associated significant decreases in high flows and floods (Thober et al., 2018), 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). Similar results were found by Döll et al. (2018). 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 were limited to 1.5°C (Section 3.3.4; Guiot and Cramer, 2016; Schleussner et al., 2016b; Donnelly et al., 2017).

3.5.4.6 West Africa and the Sahel

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). 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), 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), 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). Based on a World Bank (2013) 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). 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) found consistently reduced impacts on crop yield for West Africa under 2°C compared to 1.5°C of global 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), 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). 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).

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3.5.4.7 Southern Africa

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). Associated elevated warming of the regional land-based hot extremes has occurred (Section 3.3; Seneviratne et al., 2016). 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).

Moreover, southern Africa is *likely* to generally become drier with reduced water availability under low mitigation (Niang et al., 2014; Engelbrecht et al., 2015; Karl et al., 2015; James et al., 2017), with this particular risk being prominent under 2°C of global warming and even under 1.5°C (Gerten et al., 2013). Risks are significantly reduced, however, under 1.5°C of global warming compared to under higher levels (Schleussner et al., 2016b). 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. 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). 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). 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), 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).

3.5.4.8 Tropics

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). 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). Impact studies for major tropical cereals reveal that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Schleussner et al. (2016b) 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).

3.5.4.9 Small islands

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). 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). 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), and may enhance the ability of SIDS to adapt (Benjamin and Thomas, 2016). 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). 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). 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).

3.5.4.10 Fynbos and shrub biomes

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), demonstrating the value of climate change mitigation in protecting this rich centre of biodiversity.

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Table 3.6 | Emergence and intensity of climate change hotspots under different degrees of global warming

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*	Critical losses in alpine habitats are *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 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 heatwave duration and frequency to impact substantially on agriculture, livestock and human health and mortality (*high confidence*) 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 SIDS High risks for coastal flooding Freshwater 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*)

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3.5.5 Avoiding Regional Tipping Points by Achieving More Ambitious Global Temperature Goals

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.

3.5.5.1 Arctic sea ice

Collins et al. (2013) 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) 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). 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) 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).

3.5.5.2 Tundra

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), with associated increases in fires and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016). 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). 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).

3.5.5.3 Permafrost

Widespread thawing of permafrost potentially makes a large carbon store (estimated to be twice the size of the atmospheric store; Dolman et al., 2010) vulnerable to decomposition, which 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), 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) 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).

3.5.5.4 Asian monsoon

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). 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). 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) 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), 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.

3.5.5.5 West African monsoon and the Sahel

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). AR5 (Niang et al., 2014), 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*

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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).

3.5.5.6 Rainforests

A large portion of rainfall over the world's largest rainforests is recirculated (e.g., Lenton et al., 2008), 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). 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). 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). 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). Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016) and observational constraints (Cox et al., 2013) 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.

3.5.5.7 Boreal forests

Boreal forests are likely to experience stronger local warming than the global average (WGII AR5; Collins et al., 2013). 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), 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). 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), but given the complexities of the various forcing mechanisms and feedback processes involved, this is thought to be an uncertain estimate.

3.5.5.8 Heatwaves, unprecedented heat and human health

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). 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).

3.5.5.9 Agricultural systems: key staple crops

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). Under 2°C of global warming, losses of 8–14% are projected in global maize production (Bassu et al., 2014). 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). 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).

3.5.5.10 Agricultural systems: livestock in the tropics and subtropics

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). 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.

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Table 3.7 | Summary of enhanced risks in the exceedance of regional tipping points under different global temperature goals.

Tipping point	Warming of 1.5°C or less	Warming of 1.5°C–2°C	Warming of 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°C Abrupt increases in tree cover are *unlikely*	Further decreases in number of growing degree days below 0°C Abrupt increased in tree cover are *unlikely*	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*

Box 3.6 | Economic Damages from Climate Change

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). 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.

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Box 3.6 (continued)

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). Lemoine and Traeger (2016) 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).

The economic damages of climate change in the USA are projected to be large (Hsiang et al., 2017; Yohe, 2017). Hsiang et al. (2017) 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) 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), 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). 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.

3.6 Implications of Different 1.5°C and 2°C Pathways

This section provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C of global warming. Some of these aspects are also addressed in more detail in Cross-Chapter Boxes 7 and 8 in this chapter.

3.6.1 Gradual versus Overshoot in 1.5°C Scenarios

All 1.5°C scenarios from Chapter 2 include some overshoot above 1.5°C of global warming during the 21st century (Chapter 2 and Cross-Chapter Box 8 in this chapter). The level of overshoot may also depend on natural climate variability. An overview of possible outcomes of 1.5°C-consistent mitigation scenarios for changes in the physical climate at the time of overshoot and by 2100 is provided in Cross-Chapter Box 8 on '1.5°C warmer worlds'. Cross-Chapter Box 8 also highlights the implications of overshoots.

3.6.2 Non-CO_2 Implications and Projected Risks of Mitigation Pathways

3.6.2.1 Risks arising from land-use changes in mitigation pathways

In mitigation pathways, land-use change is affected by many different mitigation options. First, mitigation of non-CO_2 emissions from agricultural production can shift agricultural production between regions via trade of agricultural commodities. Second, protection of carbon-rich ecosystems such as tropical forests constrains the area for agricultural expansion. Third, demand-side mitigation measures, such as less consumption of resource-intensive commodities (animal products) or reductions in food waste, reduce pressure on land (Popp et al., 2017; Rogelj et al., 2018). Finally, carbon dioxide removal (CDR) is a key component of most, but not all, mitigation pathways presented in the literature to date which constrain warming to 1.5°C or 2°C. Carbon dioxide removal measures that require land include bioenergy with carbon capture and storage (BECCS), afforestation and reforestation (AR), soil carbon sequestration, direct air capture, biochar and enhanced weathering (see Cross-Chapter Box 7 in this chapter). These potential methods are assessed in Section 4.3.7.

In cost-effective integrated assessment modelling (IAM) pathways recently developed to be consistent with limiting warming to 1.5°C, use of CDR in the form of BECCS and AR are fundamental elements (Chapter 2; Popp et al., 2017; Hirsch et al., 2018; Rogelj et al., 2018; Seneviratne et al., 2018c). The land-use footprint of CDR deployment in 1.5°C-consistent pathways can be substantial (Section 2.3.4, Figure 2.11), even though IAMs predominantly rely on second-generation biomass and assume future productivity increases in agriculture.

A body of literature has explored potential consequences of large-scale use of CDR. In this case, the corresponding land footprint by the end of the century could be extremely large, with estimates including: up to 18% of the land surface being used (Wiltshire and Davies-Barnard, 2015); vast acceleration of the loss of primary forest and natural grassland (Williamson, 2016) leading to increased greenhouse gas emissions (P. Smith et al., 2013, 2015); and potential loss of up to 10% of the current forested lands to biofuels (Yamagata et al., 2018). Other estimates reach 380–700 Mha or 21–64% of current arable cropland (Section 4.3.7). Boysen et al. (2017) found that in a scenario in which emissions reductions were sufficient only to limit warming to 2.5°C,

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use of CDR to further limit warming to 1.7°C would result in the conversion of 1.1–1.5 Gha of land – implying enormous losses of both cropland and natural ecosystems. Newbold et al. (2015) found that biodiversity loss in the Representative Concentration Pathway (RCP)2.6 scenario could be greater than that in RCP4.5 and RCP6, in which there is more climate change but less land-use change. Risks to biodiversity conservation and agricultural production are therefore projected to result from large-scale bioenergy deployment pathways (P. Smith et al., 2013; Tavoni and Socolow, 2013). One study explored an extreme mitigation strategy encouraging biofuel expansion sufficient to limit warming to 1.5°C and found that this would be more disruptive to land use and crop prices than the impacts of a 2°C warmer world which has a larger climate signal and lower mitigation requirement (Ruane et al., 2018). However, it should again be emphasized that many of the pathways explored in Chapter 2 of this report follow strategies that explore how to reduce these issues. Chapter 4 provides an assessment of the land footprint of various CDR technologies (Section 4.3.7).

The degree to which BECCS has these large land-use footprints depends on the source of the bioenergy used and the scale at which BECCS is deployed. Whether there is competition with food production and biodiversity depends on the governance of land use, agricultural intensification, trade, demand for food (in particular meat), feed and timber, and the context of the whole supply chain (Section 4.3.7, Fajardy and Mac Dowell, 2017; Booth, 2018; Sterman et al., 2018).

The more recent literature reviewed in Chapter 2 explores pathways which limit warming to 2°C or below and achieve a balance between sources and sinks of CO_2 by using BECCS that relies on second-generation (or even third-generation) biofuels, changes in diet or more generally, management of food demand, or CDR options such as forest restoration (Chapter 2; Bajželj et al., 2014). Overall, this literature explores how to reduce the issues of competition for land with food production and with natural ecosystems (in particular forests) (Cross-Chapter Box 1 in Chapter 1; van Vuuren et al., 2009; Haberl et al., 2010, 2013; Bajželj et al., 2014; Daioglou et al., 2016; Fajardy and Mac Dowell, 2017).

Some IAMs manage this transition by effectively protecting carbon stored on land and focusing on the conversion of pasture area into both forest area and bioenergy cropland. Some IAMs explore 1.5°C-consistent pathways with demand-side measures such as dietary changes and efficiency gains such as agricultural changes (Sections 2.3.4 and 2.4.4), which lead to a greatly reduced CDR deployment and consequently land-use impacts (van Vuuren et al., 2018). In reality, however, whether this CDR (and bioenergy in general) has large adverse impacts on environmental and societal goals depends in large part on the governance of land use (Section 2.3.4; Obersteiner et al., 2016; Bertram et al., 2018; Humpenöder et al., 2018).

Rates of sequestration of 3.3 GtC ha^{-1} require 970 Mha of afforestation and reforestation (Smith et al., 2015). Humpenöder et al. (2014) estimated that in least-cost pathways afforestation would cover 2800 Mha by the end of the century to constrain warming to 2°C. Hence, the amount of land considered if least-cost mitigation is implemented by afforestation and reforestation could be up to three to five times greater than that required by BECCS, depending on the forest management used. However, not all of the land footprint of CDR is necessarily to be in competition with biodiversity protection. Where reforestation is the restoration of natural ecosystems, it benefits both carbon sequestration and conservation of biodiversity and ecosystem services (Section 4.3.7) and can contribute to the achievement of the Aichi targets under the Convention on Biological Diversity (CBD) (Leadley et al., 2016). However, reforestation is often not defined in this way (Section 4.3.8; Stanturf et al., 2014) and the ability to deliver biodiversity benefits is strongly dependent on the precise nature of the reforestation, which has different interpretations in different contexts and can often include agroforestry rather than restoration of pristine ecosystems (Pistorious and Kiff, 2017). However, 'natural climate solutions', defined as conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands and agricultural lands, are estimated to have the potential to provide 37% of the cost-effective CO_2 mitigation needed by southern Europe and the Mediterranean by 2030 – in order to have a >66% chance of holding warming to below 2°C (Griscom et al., 2017).

Any reductions in agricultural production driven by climate change and/or land management decisions related to CDR may (e.g., Nelson et al., 2014a; Dalin and Rodríguez-Iturbe, 2016) or may not (Muratori et al., 2016) affect food prices. However, these studies did not consider the deployment of second-generation (instead of first-generation) bioenergy crops, for which the land footprint can be much smaller.

Irrespective of any mitigation-related issues, in order for ecosystems to adapt to climate change, land use would also need to be carefully managed to allow biodiversity to disperse to areas that become newly climatically suitable for it (Section 3.4.1) and to protect the areas where the future climate will still remain suitable. This implies a need for considerable expansion of the protected area network (Warren et al., 2018b), either to protect existing natural habitat or to restore it (perhaps through reforestation, see above). At the same time, adaptation to climate change in the agricultural sector (Rippke et al., 2016) can require transformational as well as new approaches to land-use management; in order to meet the rising food demand of a growing human population, it is projected that additional land will need to be brought into production unless there are large increases in agricultural productivity (Tilman et al., 2011). However, future rates of deforestation may be underestimated in the existing literature (Mahowald et al., 2017a), and reforestation may therefore be associated with significant co-benefits if implemented to restore natural ecosystems (*high confidence*).

3.6.2.2 Biophysical feedbacks on regional climate associated with land-use changes

Changes in the biophysical characteristics of the land surface are known to have an impact on local and regional climates through changes in albedo, roughness, evapotranspiration and phenology, which can lead to a change in temperature and precipitation. This includes changes in land use through agricultural expansion/intensification (e.g., Mueller et al., 2016), reforestation/revegetation endeavours (e.g., Feng et al., 2016; Sonntag et al., 2016; Bright et al., 2017) and changes in land management (e.g., Luyssaert et al., 2014; Hirsch et al., 2017) that can

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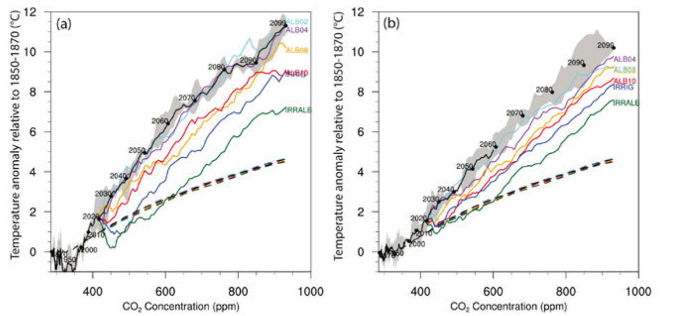

Figure 3.22 | Regional temperature scaling with carbon dioxide (CO_2) concentration (ppm) from 1850 to 2099 for two different regions defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) for central Europe (CEU) (a) and central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TXx) anomaly, and dashed lines correspond to the global mean temperature anomaly, where all temperature anomalies are relative to 1850–1870 and units are degrees Celsius. The black line in all panels denotes the three-member control ensemble mean, with the grey shaded regions corresponding to the ensemble range. The coloured lines represent the three-member ensemble means of the experiments corresponding to albedo +0.02 (cyan), albedo +0.04 (purple), albedo + 0.08 (orange), albedo +0.10 (red), irrigation (blue), and irrigation with albedo +0.10 (green). Adapted from Hirsch et al. (2017).

involve double cropping (e.g., Jeong et al., 2014; Mueller et al., 2015; Seifert and Lobell, 2015), irrigation (e.g., Lobell et al., 2009; Sacks et al., 2009; Cook et al., 2011; Qian et al., 2013; de Vrese et al., 2016; Pryor et al., 2016; Thiery et al., 2017), no-till farming and conservation agriculture (e.g., Lobell et al., 2006; Davin et al., 2014), and wood harvesting (e.g., Lawrence et al., 2012). Hence, the biophysical impacts of land-use changes are an important topic to assess in the context of low-emissions scenarios (e.g., van Vuuren et al., 2011b), in particular for 1.5°C warming levels (see also Cross-Chapter Box 7 in this chapter).

The magnitude of the biophysical impacts is potentially large for temperature extremes. Indeed, changes induced both by modifications in moisture availability and irrigation and by changes in surface albedo tend to be larger (i.e., stronger cooling) for hot extremes than for mean temperatures (e.g., Seneviratne et al., 2013; Davin et al., 2014; Wilhelm et al., 2015; Hirsch et al., 2017; Thiery et al., 2017). The reasons for reduced moisture availability are related to a strong contribution of moisture deficits to the occurrence of hot extremes in mid-latitude regions (Mueller and Seneviratne, 2012; Seneviratne et al., 2013). In the case of surface albedo, cooling associated with higher albedo (e.g., in the case of no-till farming) is more effective at cooling hot days because of the higher incoming solar radiation for these days (Davin et al., 2014). The overall effect of either irrigation or albedo has been found to be at the most in the order of about 1°C–2°C regionally for temperature extremes. This can be particularly important in the context of low-emissions scenarios because the overall effect is in this case of similar magnitude to the response to the greenhouse gas forcing (Figure 3.22; Hirsch et al., 2017; Seneviratne et al., 2018a,c).

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

We note that the biophysical impacts of land use in the context of mitigation pathways constitute an emerging research topic. This topic, as well as the overall role of land-use change in climate change projections and socio-economic pathways, will be addressed in depth in the upcoming IPCC Special Report on Climate Change and Land Use due in 2019.

3.6.2.3 Atmospheric compounds (aerosols and methane)

There are multiple pathways that could be used to limit anthropogenic climate change, and the details of the pathways will influence the impacts of climate change on humans and ecosystems. Anthropogenic-driven changes in aerosols cause important modifications to the global climate (Bindoff et al., 2013a; Boucher et al., 2013b; P. Wu et al., 2013; Sarojini et al., 2016; H. Wang et al., 2016). Enforcement of strict air quality policies may lead to a large decrease in cooling aerosol emissions in the next few decades. These aerosol emission reductions may cause a warming comparable to that resulting from the increase in greenhouse gases by mid-21st century under low CO_2 pathways (Kloster et al., 2009; Acosta Navarro et al., 2017). Further background

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is provided in Sections 2.2.2 and 2.3.1; Cross Chapter Box 1 in Chapter 1). Because aerosol effects on the energy budget are regional, strong regional changes in precipitation from aerosols may occur if aerosol emissions are reduced for air quality reasons or as a co-benefit from switches to sustainable energy sources (H. Wang et al., 2016). Thus, regional impacts, especially on precipitation, are very sensitive to 1.5°C-consistent pathways (Z. Wang et al., 2017).

Pathways which rely heavily on reductions in methane (CH_4) instead of CO_2 will reduce warming in the short term because CH_4 is such a stronger and shorter-lived greenhouse gas than CO_2, but will lead to stronger warming in the long term because of the much longer residence time of CO_2 (Myhre et al., 2013; Pierrehumbert, 2014). In addition, the dominant loss mechanism for CH_4 is atmospheric photo-oxidation. This conversion modifies ozone formation and destruction in the troposphere and stratosphere, therefore modifying the contribution of ozone to radiative forcing, as well as feedbacks on the oxidation rate of methane itself (Myhre et al., 2013). Focusing on pathways and policies which both improve air quality and reduce impacts of climate change can provide multiple co-benefits (Shindell et al., 2017). These pathways are discussed in detail in Sections 4.3.7 and 5.4.1 and in Cross-Chapter Box 12 in Chapter 5.

Atmospheric aerosols and gases can also modify the land and ocean uptake of anthropogenic CO_2; some compounds enhance uptake while others reduce it (Section 2.6.2; Ciais et al., 2013). While CO_2 emissions tend to encourage greater uptake of carbon by the land and the ocean (Ciais et al., 2013), CH_4 emissions can enhance ozone pollution, depending on nitrogen oxides, volatile organic compounds and other organic species concentrations, and ozone pollution tends to reduce land productivity (Myhre et al., 2013; B. Wang et al., 2017). Aside from inhibiting land vegetation productivity, ozone may also alter the CO_2, CH_4 and nitrogen (N_2O) exchange at the land–atmosphere interface and transform the global soil system from a sink to a source of carbon (B. Wang et al., 2017). Aerosols and associated nitrogen-based compounds tend to enhance the uptake of CO_2 in land and ocean systems through deposition of nutrients and modification of climate (Ciais et al., 2013; Mahowald et al., 2017b).

Cross-Chapter Box 7 | Land-Based Carbon Dioxide Removal in Relation to 1.5°C of Global Warming

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Climate and land form a complex system characterized by multiple feedback processes and the potential for non-linear responses to perturbation. Climate determines land cover and the distribution of vegetation, affecting above- and below-ground carbon stocks. At the same time, land cover influences global climate through altered biogeochemical processes (e.g., atmospheric composition and nutrient flow into oceans), and regional climate through changing biogeophysical processes including albedo, hydrology, transpiration and vegetation structure (Forseth, 2010).

Greenhouse gas (GHG) fluxes related to land use are reported in the 'agriculture, forestry and other land use' sector (AFOLU) and comprise about 25% (about 10–12 $GtCO_2eq\ yr^{-1}$) of anthropogenic GHG emissions (P. Smith et al., 2014). Reducing emissions from land use, as well as land-use change, are thus an important component of low-emissions mitigation pathways (Clarke et al., 2014), particularly as land-use emissions can be influenced by human actions such as deforestation, afforestation, fertilization, irrigation, harvesting, and other aspects of cropland, grazing land and livestock management (Paustian et al., 2006; Griscom et al., 2017; Houghton and Nassikas, 2018).

In the IPCC Fifth Assessment Report, the vast majority of scenarios assessed with a 66% or better chance of limiting global warming to 2°C by 2100 included carbon dioxide removal (CDR) – typically about 10 $GtCO_2\ yr^{-1}$ in 2100 or about 200–400 $GtCO_2$ over the course of the century (Smith et al., 2015; van Vuuren et al., 2016). These integrated assessment model (IAM) results were predominately achieved by using bioenergy with carbon capture and storage (BECCS) and/or afforestation and reforestation (AR). Virtually all scenarios that limit either peak or end-of-century warming to 1.5°C also use land-intensive CDR technologies (Rogelj et al., 2015; Holz et al., 2017; Kriegler et al., 2017; Fuss et al., 2018; van Vuuren et al., 2018). Again, AR (Sections 2.3 and 4.3.7) and BECCS (Sections 4.3.2. and 4.3.7) predominate. Other CDR options, such as the application of biochar to soil, soil carbon sequestration, and enhanced weathering (Section 4.3.7) are not yet widely incorporated into IAMs, but their deployment would also necessitate the use of land and/or changes in land management.

Integrated assessment models provide a simplified representation of land use and, with only a few exceptions, do not include biophysical feedback processes (e.g., albedo and evapotranspiration effects) (Kreidenweis et al., 2016) despite the importance of these processes for regional climate, in particular hot extremes (Section 3.6.2.2; Seneviratne et al., 2018c). The extent, location and impacts of large-scale land-use change described by existing IAMs can also be widely divergent, depending on model structure, scenario parameters, modelling objectives and assumptions (including regarding land availability and productivity) (Prestele et

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Cross-Chapter Box 7 (continued)

al., 2016; Alexander et al., 2017; Popp et al., 2017; Seneviratne et al., 2018c). Despite these limitations, IAM scenarios effectively highlight the extent and nature of potential land-use transitions implicit in limiting warming to 1.5°C.

Cross-Chapter Box 7 Table 1 presents a comparison of the five CDR options assessed in this report. This illustrates that if BECCS and AR were to be deployed at a scale of 12 $GtCO_2\ yr^{-1}$ in 2100, for example, they would have a substantial land and water footprint. Whether this footprint would result in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, limit the expansion of agriculture at the expense of natural ecosystems, and increase agriculture productivity (Bonsch et al., 2016; Obersteiner et al., 2016; Bertram et al., 2018; Humpenöder et al., 2018). In comparison, the land and water footprints of enhanced weathering, soil carbon sequestration and biochar application are expected to be far less per $GtCO_2$ sequestered. These options may offer potential co-benefits by providing an additional source of nutrients or by reducing N_2O emissions, but they are also associated with potential side effects. Enhanced weathering would require massive mining activity, and providing feedstock for biochar would require additional land, even though a proportion of the required biomass is expected to come from residues (Woolf et al., 2010; Smith, 2016). For the terrestrial CDR options, permanence and saturation are important considerations, making their viability and long-term contributions to carbon reduction targets uncertain.

The technical, political and social feasibility of scaling up and implementing land-intensive CDR technologies (Cross-Chapter Box 3 in Chapter 1) is recognized to present considerable potential barriers to future deployment (Boucher et al., 2013a; Fuss et al., 2014, 2018; Anderson and Peters, 2016; Vaughan and Gough, 2016; Williamson, 2016; Minx et al., 2017, 2018; Nemet et al., 2018; Strefler et al., 2018; Vaughan et al., 2018). To investigate the implications of restricting CDR options should these barriers prove difficult to overcome, IAM studies (Section 2.3.4) have developed scenarios that limit – either implicitly or explicitly – the use of BECCS and bioenergy (Krey et al., 2014; Bauer et al., 2018; Rogelj et al., 2018) or the use of BECCS and afforestation (Strefler et al., 2018). Alternative strategies to limit future reliance on CDR have also been examined, including increased electrification, agricultural intensification, behavioural change, and dramatic improvements in energy and material efficiency (Bauer et al., 2018; Grubler et al., 2018; van Vuuren et al., 2018). Somewhat counterintuitively, scenarios that seek to limit the deployment of BECCs may result in increased land use, through greater deployment of bioenergy, and afforestation (Chapter 2, Box 2.1; Krey et al., 2014; Krause et al., 2017; Bauer et al., 2018; Rogelj et al., 2018). Scenarios aiming to minimize the total human land footprint (including land for food, energy and climate mitigation) also result in land-use change, for example by increasing agricultural efficiency and dietary change (Grubler et al., 2018).

The impacts of changing land use are highly context, location and scale dependent (Robledo-Abad et al., 2017). The supply of biomass for CDR (e.g., energy crops) has received particular attention. The literature identifies regional examples of where the use of land to produce biofuels might be sustainably increased (Jaiswal et al., 2017), where biomass markets could contribute to the provision of ecosystem services (Dale et al., 2017), and where bioenergy could increase the resilience of production systems and contribute to rural development (Kline et al., 2017). However, studies of global biomass potential provide only limited insight into the local feasibility of supplying large quantities of biomass on a global scale (Slade et al., 2014). Concerns about large-scale use of biomass for CDR include a range of potential consequences including greatly increased demand for freshwater use, increased competition for land, loss of biodiversity and/or impacts on food security (Section 3.6.2.1; Heck et al., 2018). The short- versus long-term carbon impacts of substituting biomass for fossil fuels, which are largely determined by feedstock choice, also remain a source of contention (Schulze et al., 2012; Jonker et al., 2014; Booth, 2018; Sterman et al., 2018).

Afforestation and reforestation can also present trade-offs between biodiversity, carbon sequestration and water use, and these strategies have a higher land footprint per tonne of CO_2 removed (Cunningham, 2015; Naudts et al., 2016; Smith et al., 2018). For example, changing forest management to strategies favouring faster growing species, greater residue extraction and shorter rotations may have a negative impact on biodiversity (de Jong et al., 2014). In contrast, reforestation of degraded land with native trees can have substantial benefits for biodiversity (Section 3.6). Despite these constraints, the potential for increased carbon sequestration through improved land stewardship measures is considered to be substantial (Griscom et al., 2017).

Evaluating the synergies and trade-offs between mitigation and adaptation actions, resulting land and climate impacts, and the myriad issues related to land-use governance will be essential to better understand the future role of CDR technologies. This topic will be addressed further in the IPCC Special Report on Climate Change and Land (SRCCL) due to be published in 2019.

Cross-Chapter Box 7 (continued next page)

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Cross-Chapter Box 7 (continued)

Key messages:

Cost-effective strategies to limit peak or end-of-century warming to 1.5°C all include enhanced GHG removals in the AFOLU sector as part of their portfolio of measures (*high confidence*).

Large-scale deployment of land-based CDR would have far-reaching implications for land and water availability (*high confidence*). This may impact food production, biodiversity and the provision of other ecosystem services (*high confidence*).

The impacts of deploying land-based CDR at large scales can be reduced if a wider portfolio of CDR options is deployed, and if increased mitigation effort focuses on strongly limiting demand for land, energy and material resources, including through lifestyle and dietary changes (*medium confidence*).

Afforestation and reforestation may be associated with significant co-benefits if implemented appropriately, but they feature large land and water footprints if deployed at large scales (*medium confidence*).

Cross-Chapter Box 7, Table 1 | Comparison of land-based carbon removal options.

Sources: [a] assessed ranges by Fuss et al. (2018), see Figures in Section 4.3.7 for full literature range; [b] based on the 2100 estimate for mean potentials by Smith et al (2015). Note that biophysical impacts of land-based CDR options besides albedo changes (e.g., through changes in evapotranspiration related to irrigation or land cover/use type) are not displayed.

Option	Potentials [a]	Cost [a]	Required land [b]	Required water [b]	Impact on nutrients [b]	Impact on albedo [b]	Saturation and permanence [a]
	$GtCO_2\ y^{-1}$	*$\$\ tCO_2^{-1}$*	*$Mha\ GtCO_2^{-1}$*	*$km^3\ GtCO_2^{-1}$*	*$Mt\ N, P, K\ y^{-1}$*	*No units*	*No units*
BECCS	0.5–5	100–200	31–58	60	Variable	Variable; depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g., no-till farming for crops)	Long-term governance of storage; limits on rates of bioenergy production and carbon sequestration
Afforestation & reforestation	0.5–3.6	5–50	80	92	0.5	Negative, or reduced GHG benefit where not negative	Saturation of forests; vulnerable to disturbance; post-AR forest management essential
Enhanced weathering	2–4	50–200	3	0.4	0	0	Saturation of soil; residence time from months to geological timescale
Biochar	0.3–2	30–120	16–100	0	N: 8.2, P: 2.7, K: 19.1	0.08–0.12	Mean residence times between decades to centuries, depending on soil type, management and environmental conditions
Soil carbon sequestration	2.3–5	0–100	0	0	N: 21.8, P: 5.5, K: 4.1	0	Soil sinks saturate and can reverse if poor management practices resume

3.6.3 Implications Beyond the End of the Century

3.6.3.1 Sea ice

Sea ice is often cited as a tipping point in the climate system (Lenton, 2012). Detailed modelling of sea ice (Schröder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011), however, suggests that summer sea ice can return within a few years after its artificial removal for climates in the late 20th and early 21st centuries. Further studies (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) modelled the removal of sea ice by raising CO_2 concentrations and studied subsequent regrowth by lowering CO_2. These studies suggest that changes in Arctic sea ice are neither irreversible nor exhibit bifurcation behaviour. It is therefore plausible that the extent of Arctic sea ice may quickly re-equilibrate to the end-of-century climate under an overshoot scenario.

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3.6.3.2 Sea level

Policy decisions related to anthropogenic climate change will have a profound impact on sea level, not only for the remainder of this century but for many millennia to come (Clark et al., 2016). On these long time scales, 50 m of sea level rise (SLR) is possible (Clark et al., 2016). While it is *virtually certain* that sea level will continue to rise well beyond 2100, the amount of rise depends on future cumulative emissions (Church et al., 2013) as well as their profile over time (Bouttes et al., 2013; Mengel et al., 2018). Marzeion et al. (2018) found that 28–44% of present-day glacier volume is unsustainable in the present-day climate and that it would eventually melt over the course of a few centuries, even if there were no further climate change. Some components of SLR, such as thermal expansion, are only considered reversible on centennial time scales (Bouttes et al., 2013; Zickfeld et al., 2013), while the contribution from ice sheets may not be reversible under any plausible future scenario (see below).

Based on the sensitivities summarized by Levermann et al. (2013), the contributions of thermal expansion (0.20–0.63 m °C^{-1}) and glaciers (0.21 m °C^{-1} but falling at higher degrees of warming mostly because of the depletion of glacier mass, with a possible total loss of about 0.6 m) amount to 0.5–1.2 m and 0.6–1.7 m in 1.5°C and 2°C warmer worlds, respectively. The bulk of SLR on greater than centennial time scales will therefore be caused by contributions from the continental ice sheets of Greenland and Antarctica, whose existence is threatened on multi-millennial time scales.

For Greenland, where melting from the ice sheet's surface is important, a well-documented instability exists where the surface of a thinning ice sheet encounters progressively warmer air temperatures that further promote melting and thinning. A useful indicator associated with this instability is the threshold at which annual mass loss from the ice sheet by surface melt exceeds mass gain by snowfall. Previous estimates put this threshold at about 1.9°C to 5.1°C above pre-industrial temperatures (Gregory and Huybrechts, 2006). More recent analyses, however, suggest that this threshold sits between 0.8°C and 3.2°C, with a best estimate at 1.6°C (Robinson et al., 2012). The continued decline of the ice sheet after this threshold has been passed is highly dependent on the future climate and varies between about 80% loss after 10,000 years to complete loss after as little as 2000 years (contributing about 6 m to SLR). Church et al. (2013) were unable to quantify a *likely* range for this threshold. They assigned *medium confidence* to a range greater than 2°C but less than 4°C, and had *low confidence* in a threshold of about 1°C. There is insufficient new literature to change this assessment.

The Antarctic ice sheet, in contrast, loses the mass gained by snowfall as outflow and subsequent melt to the ocean, either directly from the underside of floating ice shelves or indirectly by the melting of calved icebergs. The long-term existence of this ice sheet will also be affected by a potential instability (the marine ice sheet instability, MISI), which links outflow (or mass loss) from the ice sheet to water depth at the grounding line (i.e., the point at which grounded ice starts to float and becomes an ice shelf) so that retreat into deeper water (the bedrock underlying much of Antarctica slopes downwards towards the centre of the ice sheet) leads to further increases in outflow and promotes yet further retreat (Schoof, 2007). More recently, a variant on this mechanism was postulated in which an ice cliff forms at the grounding line and retreats rapidly though fracture and iceberg calving (DeConto and Pollard, 2016). There is a growing body of evidence (Golledge et al., 2015; DeConto and Pollard, 2016) that large-scale retreat may be avoided in emissions scenarios such as Representative Concentration Pathway (RCP)2.6 but that higher-emissions RCP scenarios could lead to the loss of the West Antarctic ice sheet and sectors in East Antarctica, although the duration (centuries or millennia) and amount of mass loss during such a collapse is highly dependent on model details and no consensus exists yet. Schoof (2007) suggested that retreat may be irreversible, although a rigorous test has yet to be made. In this context, overshoot scenarios, especially of higher magnitude or longer duration, could increase the risk of such irreversible retreat.

Church et al. (2013) noted that the collapse of marine sectors of the Antarctic ice sheet could lead to a global mean sea level (GMSL) rise above the likely range, and that there was *medium confidence* that this additional contribution 'would not exceed several tenths of a metre during the 21st century'.

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

In summary, there is *medium confidence* that a threshold in the long-term GMSL contribution of both the Greenland and Antarctic ice sheets lies around 1.5°C to 2°C of global warming relative to pre-industrial; however, the GMSL associated with these two levels of global warming cannot be differentiated on the basis of the existing literature.

3.6.3.3 Permafrost

The slow rate of permafrost thaw introduces a lag between the transient degradation of near-surface permafrost and contemporary climate, so that the equilibrium response is expected to be 25–38% greater than the transient response simulated in climate models (Slater and Lawrence, 2013). The long-term, equilibrium Arctic permafrost loss to global warming was analysed by Chadburn et al. (2017). They used an empirical relation between recent mean annual air temperatures and the area underlain by permafrost coupled to Coupled Model Intercomparison Project Phase 5 (CMIP5) stabilization projections to 2300 for RCP2.6 and RCP4.5. Their estimate of the sensitivity of permafrost to warming is 2.9–5.0 million km^2 °C^{-1} (1 standard deviation confidence interval), which suggests that stabilizing climate at 1.5°C as opposed to 2°C would reduce the area of eventual permafrost loss by 1.5 to 2.5 million km^2 (stabilizing at 56–83% as opposed to 43–72% of 1960–1990 levels). This work, combined with the assessment of Collins et al. (2013) on the link between global warming and permafrost loss, leads to the assessment that permafrost extent would be appreciably greater in a 1.5°C warmer world compared to in a 2°C warmer world (*low to medium confidence*).

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3.7 Knowledge Gaps

Most scientific literature specific to global warming of 1.5°C is only just emerging. This has led to differences in the amount of information available and gaps across the various sections of this chapter. In general, the number of impact studies that specifically focused on 1.5°C lags behind climate-change projections in general, due in part to the dependence of the former on the latter. There are also insufficient studies focusing on regional changes, impacts and consequences at 1.5°C and 2°C of global warming.

The following gaps have been identified with respect to tools, methodologies and understanding in the current scientific literature specific to Chapter 3. The gaps identified here are not comprehensive but highlight general areas for improved understanding, especially regarding global warming at 1.5°C compared to 2°C and higher levels.

3.7.1 Gaps in Methods and Tools

- Regional and global climate model simulations for low-emissions scenarios such as a 1.5°C warmer world.
- Robust probabilistic models which separate the relatively small signal between 1.5°C versus 2°C from background noise, and which handle the many uncertainties associated with non-linearities, innovations, overshoot, local scales, and latent or lagging responses in climate.
- Projections of risks under a range of climate and development pathways required to understand how development choices affect the magnitude and pattern of risks, and to provide better estimates of the range of uncertainties.
- More complex and integrated socio-ecological models for predicting the response of terrestrial as well as coastal and oceanic ecosystems to climate and models which are more capable of separating climate effects from those associated with human activities.
- Tools for informing local and regional decision-making, especially when the signal is ambiguous at 1.5°C and/or reverses sign at higher levels of global warming.

3.7.2 Gaps in Understanding

3.7.2.1 Earth systems and 1.5°C of global warming

- The cumulative effects of multiple stresses and risks (e.g., increased storm intensity interacting with sea level rise and the effect on coastal people; feedbacks on wetlands due to climate change and human activities).
- Feedbacks associated with changes in land use/cover for low-emissions scenarios, for example feedback from changes in forest cover, food production, biofuel production, bio-energy with carbon capture and storage (BECCS), and associated unquantified biophysical impacts.
- The distinct impacts of different overshoot scenarios, depending on (i) the peak temperature of the overshoot, (ii) the length of the overshoot period, and (iii) the associated rate of change in global temperature over the time period of the overshoot.

3.7.2.2 Physical and chemical characteristics of a 1.5°C warmer world

- Critical thresholds for extreme events (e.g., drought and inundation) between 1.5°C and 2°C of warming for different climate models and projections. All aspects of storm intensity and frequency as a function of climate change, especially for 1.5°C and 2°C warmer worlds, and the impact of changing storminess on storm surges, damage, and coastal flooding at regional and local scales.
- The timing and implications of the release of stored carbon in Arctic permafrost in a 1.5°C warmer world and for climate stabilization by the end of the century.
- Antarctic ice sheet dynamics, global sea level, and links between seasonal and year-long sea ice in both polar regions.

3.7.2.3 Terrestrial and freshwater systems

- The dynamics between climate change, freshwater resources and socio-economic impacts for lower levels of warming.
- How the health of vegetation is likely to change, carbon storage in plant communities and landscapes, and phenomena such as the fertilization effect.
- The risks associated with species' maladaptation in response to climatic changes (e.g., effects of late frosts). Questions associated with issues such as the consequences of species advancing their spring phenology in response to warming, as well as the interaction between climate change, range shifts and local adaptation in a 1.5°C warmer world.
- The biophysical impacts of land use in the context of mitigation pathways.

3.7.2.4 Ocean Systems

- Deep sea processes and risks to deep sea habitats and ecosystems.
- How changes in ocean chemistry in a 1.5°C warmer world, including decreasing ocean oxygen content, ocean acidification and changes in the activity of multiple ion species, will affect natural and human systems.
- How ocean circulation is changing towards 1.5°C and 2°C warmer worlds, including vertical mixing, deep ocean processes, currents, and their impacts on weather patterns at regional to local scales.
- The impacts of changing ocean conditions at 1.5°C and 2°C of warming on foodwebs, disease, invading species, coastal protection, fisheries and human well-being, especially as organisms modify

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their biogeographical ranges within a changing ocean.

- Specific linkages between food security and changing coastal and ocean resources.

3.7.2.5 Human systems

- The impacts of global and regional climate change at 1.5°C on food distribution, nutrition, poverty, tourism, coastal infrastructure and public health, particularly for developing nations.
- Health and well-being risks in the context of socio-economic and climate change at 1.5°C, especially in key areas such as occupational health, air quality and infectious disease.
- Micro-climates at urban/city scales and their associated risks for natural and human systems, within cities and in interaction with surrounding areas. For example, current projections do not integrate adaptation to projected warming by considering cooling that could be achieved through a combination of revised building codes, zoning and land use to build more reflective roofs and urban surfaces that reduce urban heat island effects.
- Implications of climate change at 1.5°C on livelihoods and poverty, as well as on rural communities, indigenous groups and marginalized people.
- The changing levels of risk in terms of extreme events, including storms and heatwaves, especially with respect to people being displaced or having to migrate away from sensitive and exposed systems such as small islands, low-lying coasts and deltas.

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Cross-Chapter Box 8 | 1.5°C Warmer Worlds

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Introduction

The Paris Agreement includes goals of stabilizing global mean surface temperature (GMST) well below 2°C and 1.5°C above pre-industrial levels in the longer term. There are several aspects, however, that remain open regarding what a '1.5°C warmer world' could be like, in terms of mitigation (Chapter 2) and adaptation (Chapter 4), as well as in terms of projected warming and associated regional climate change (Chapter 3), which are overlaid on anticipated and differential vulnerabilities (Chapter 5). **Alternative '1.5°C warmer worlds' resulting from mitigation and adaptation choices, as well as from climate variability (climate 'noise'), can be vastly different,** as highlighted in this Cross-Chapter Box. In addition, the range of models underlying 1.5°C projections can be substantial and needs to be considered.

Key questions[7]:

- **What is a 1.5°C global mean warming, how is it measured, and what temperature increase does it imply for single locations and at specific times?** Global mean surface temperature (GMST) corresponds to the globally averaged temperature of Earth derived from point-scale ground observations or computed in climate models (Chapters 1 and 3). Global mean surface temperature is additionally defined over a given time frame, for example averaged over a month, a year, or multiple decades. Because of climate variability, a climate-based GMST typically needs to be defined over several decades (typically 20 or 30 years; Chapter 3, Section 3.2). Hence, whether or when global warming reaches 1.5°C depends to some extent on the choice of pre-industrial reference period, whether 1.5°C refers to total or human-induced warming, and which variables and coverage are used to define GMST change (Chapter 1). By definition, because GMST is an average in time and space, there will be locations and time periods in which 1.5°C of warming is exceeded, even if the global mean warming is at 1.5°C. In some locations, these differences can be particularly large (Cross-Chapter Box 8, Figure 1).
- **What is the impact of different climate models for projected changes in climate at 1.5°C of global warming?** The range between single model simulations of projected regional changes at 1.5°C GMST increase can be substantial for regional responses (Chapter 3, Section 3.3). For instance, for the warming of cold extremes in a 1.5°C warmer world, some model simulations project a 3°C warming while others project more than 6°C of warming in the Arctic land areas (Cross-Chapter Box 8, Figure 2). For hot temperature extremes in the contiguous United States, the range of model simulations includes temperatures lower than pre-industrial values (–0.3°C) and a warming of 3.5°C (Cross-Chapter Box 8, Figure 2). Some regions display an even larger range (e.g., 1°C–6°C regional warming in hot extremes in central Europe at 1.5°C of warming; Chapter 3, Sections 3.3.1 and 3.3.2). This large spread is due to both modelling uncertainty and internal climate variability. While the range is large, it also highlights risks that can be avoided with near certainty in a 1.5°C warmer world compared to worlds at higher levels of warming (e.g., an 8°C warming of cold extremes in the Arctic is not reached at 1.5°C of global warming in the multimodel ensemble but could happen at 2°C of global warming; Cross-Chapter Box 8, Figure 2). Inferred projected ranges of regional responses (mean value, minimum and maximum) for different mitigation scenarios from Chapter 2 are displayed in Cross-Chapter Box 8, Table 1.
- **What is the impact of emissions pathways with, versus without, an overshoot?** All mitigation pathways projecting less than 1.5°C of global warming over or at the end of the 21st century include some probability of overshooting 1.5°C. These pathways include some periods with warming stronger than 1.5°C in the course of the coming decades and/or some probability of not reaching 1.5°C (Chapter 2, Section 2.2). This is inherent to the difficulty of limiting global warming to 1.5°C, given that we are already very close to this warming level. The implications of overshooting are large for risks to natural and human

[7] Part of this discussion is based on Seneviratne et al (2018b).

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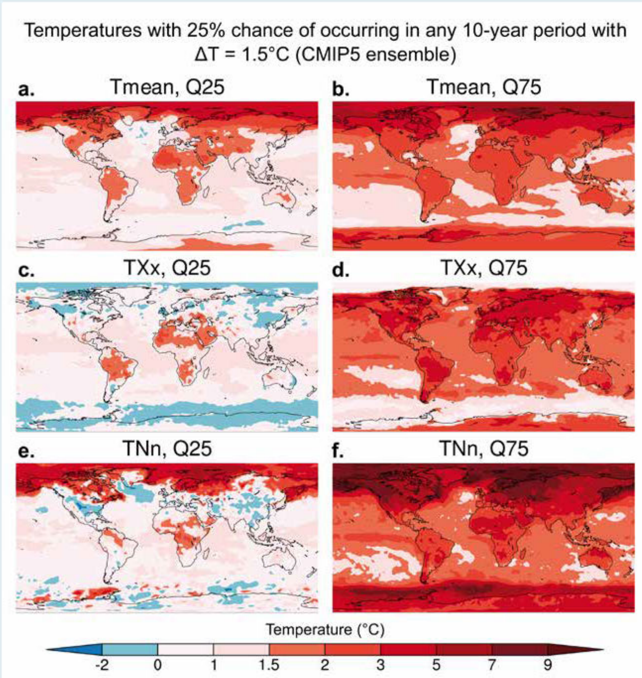
Cross-Chapter Box 8 (continued)



Cross-Chapter Box 8, Figure 1 | Range of projected realized temperatures at 1.5°C of global warming (due to stochastic noise and model-based spread). Temperatures with a 25% chance of occurrence at any location within a 10-year time frame are shown, corresponding to GMST anomalies of 1.5°C (Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel ensemble). The plots display the 25th percentile (Q25, left) and 75th percentile (Q75, right) values of mean temperature (Tmean), yearly maximum daytime temperature (TXx) and yearly minimum night-time temperature (TNn), sampled from all time frames with GMST anomalies of 1.5°C in Representative Concentration Pathway (RCP)8.5 model simulations of the CMIP5 ensemble. From Seneviratne et al. (2018b).

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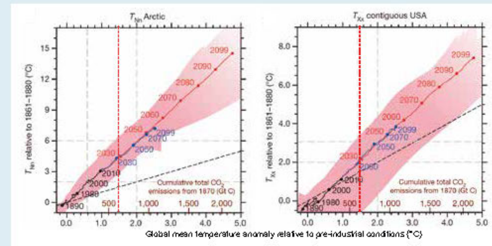
Cross-Chapter Box 8 (continued)



Cross-Chapter Box 8, Figure 2 | Spread of projected multimodel changes in minimum annual night-time temperature (TNn) in Arctic land (left) and in maximum annual daytime temperature (TXx) in the contiguous United States as a function of mean global warming in climate simulations. The multimodel range (due to model spread and internal climate variability) is indicated in red shading (minimum and maximum value based on climate model simulations). The multimodel mean value is displayed with solid red and blue lines for two emissions pathways (blue: Representative Concentration Pathway (RCP)4.5; red: RCP8.5). The dashed red line indicates projections for a 1.5°C warmer world. The dashed black line displays the 1:1 line. The figure is based on Figure 3 of Seneviratne et al. (2016).

systems, especially if the temperature at peak warming is high, because some risks may be long lasting and irreversible, such as the loss of some ecosystems (Chapter 3, Box 3.4). The chronology of emissions pathways and their implied warming is also important for the more slowly evolving parts of the Earth system, such as those associated with sea level rise. In addition, for several types of risks the rate of change may be most relevant (Loarie et al., 2009; LoPresti et al., 2015), with potentially large risks occurring in the case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. On the other hand, if overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate and unprecedented global efforts to mitigate GHGs are required (Cross-Chapter Box 8, Table 1; Chapter 4).

- What is the probability of reaching 1.5°C of global warming if emissions compatible with 1.5°C pathways are followed? Emissions pathways in a 'prospective scenario' (see Chapter 1, Section 1.2.3, and Cross-Chapter Box 1 in Chapter 1 on 'Scenarios and pathways') compatible with 1.5°C of global warming are determined based on their probability of reaching 1.5°C by 2100 (Chapter 2, Section 2.1), given current knowledge of the climate system response. These probabilities cannot be quantified precisely but are typically 50–66% in 1.5°C-consistent pathways (Section 1.2.3). This implies a one-in-two to one-in-three probability that global warming would exceed 1.5°C even under a 1.5°C-consistent pathway, including some possibility that global warming would be substantially over this value (generally about 5–10% probability; see Cross-Chapter Box 8, Table 1 and Seneviratne et al., 2018b). These alternative outcomes need to be factored into the decision-making process. To address this issue, 'adaptive' mitigation scenarios have been proposed in which emissions are continually adjusted to achieve a temperature goal (Millar et al., 2017). The set of dimensions involved in mitigation options (Chapter 4) is complex and need system-wide approaches to be successful. Adaptive scenarios could be facilitated by the global stocktake mechanism established in the Paris Agreement, and thereby transfer the risk of higher-than-expected warming to a risk of faster-than-expected mitigation efforts. However, there are some limits to the feasibility of such approaches because some investments, for example in infrastructure, are long term and also because the actual departure from an aimed pathway will need to be detected against the backdrop of internal climate variability, typically over several decades (Haustein et al., 2017; Seneviratne et al., 2018b). Avoiding impacts that depend on atmospheric composition as well as GMST (Baker et al., 2018) would also require limits on atmospheric CO_2 concentrations in the event of a lower-than-expected GMST response.

- How can the transformation towards a 1.5°C warmer world be implemented? This can be achieved in a variety of ways, such as decarbonizing the economy with an emphasis on demand reductions and sustainable lifestyles, or, alternatively, with an emphasis on large-scale technological solutions, amongst many other options (Chapter 2, Sections 2.3 and 2.4; Chapter 4, Sections 4.1 and 4.4.4). Different portfolios of mitigation measures come with distinct synergies and trade-offs with respect to other societal objectives. Integrated solutions and approaches are required to achieve multiple societal objectives simultaneously (see Chapter 4, Section 4.5.4 for a set of synergies and trade-offs).

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Cross-Chapter Box 8 (continued)

- **What determines risks and opportunities in a 1.5°C warmer world?** The risks to natural, managed and human systems in a 1.5°C warmer world will depend not only on uncertainties in the regional climate that results from this level of warming, but also very strongly on the methods that humanity uses to limit global warming to 1.5°C. This is particularly the case for natural ecosystems and agriculture (see Cross-Chapter Box 7 in this chapter and Chapter 4, Section 4.3.2). The risks to human systems will also depend on the magnitude and effectiveness of policies and measures implemented to increase resilience to the risks of climate change and on development choices over coming decades, which will influence the underlying vulnerabilities and capacities of communities and institutions for responding and adapting.

- **Which aspects are not considered, or only partly considered, in the mitigation scenarios from Chapter 2?** These include biophysical impacts of land use, water constraints on energy infrastructure, and regional implications of choices of specific scenarios for tropospheric aerosol concentrations or the modulation of concentrations of short-lived climate forcers, that is, greenhouse gases (Chapter 3, Section 3.6.3). Such aspects of development pathways need to be factored into comprehensive assessments of the regional implications of mitigation and adaptation measures. On the other hand, some of these aspects are assessed in Chapter 4 as possible options for mitigation and adaptation to a 1.5°C warmer world.

- **Are there commonalities to all alternative 1.5°C warmer worlds?** Human-driven warming linked to CO_2 emissions is nearly irreversible over time frames of 1000 years or more (Matthews and Caldeira, 2008; Solomon et al., 2009). The GSMT of the Earth responds to the cumulative amount of CO_2 emissions. Hence, all 1.5°C stabilization scenarios require both net CO_2 emissions and multi-gas CO_2-forcing-equivalent emissions to be zero at some point (Chapter 2, Section 2.2). This is also the case for stabilization scenarios at higher levels of warming (e.g., at 2°C); the only difference is the projected time at which the net CO_2 budget is zero.

  Hence, a transition to decarbonization of energy use is necessary in all scenarios. It should be noted that **all scenarios of Chapter 2 include approaches for carbon dioxide removal (CDR)** in order to achieve the net zero CO_2 emissions budget. **Most of these use carbon capture and storage (CCS)** in addition to reforestation, although to varying degrees (Chapter 4, Section 4.3.7). Some potential pathways to 1.5°C of warming in 2100 would minimize the need for CDR (Obersteiner et al., 2018; van Vuuren et al., 2018). Taking into account the implementation of CDR, the CO_2-induced warming by 2100 is determined by the difference between the total amount of CO_2 generated (that can be reduced by early decarbonization) and the total amount permanently stored out of the atmosphere, for example by geological sequestration (Chapter 4, Section 4.3.7).

- **What are possible storylines of 'warmer worlds' at 1.5°C versus higher levels of global warming?** Cross-Chapter Box 8, Table 2 features possible storylines based on the scenarios of Chapter 2, the impacts of Chapters 3 and 5, and the options of Chapter 4. These storylines are not intended to be comprehensive of all possible future outcomes. Rather, they are intended as plausible scenarios of alternative warmer worlds, with two storylines that include stabilization at 1.5°C (Scenario 1) or close to 1.5°C (Scenario 2), and one storyline missing this goal and consequently only including reductions of CO_2 emissions and efforts towards stabilization at higher temperatures (Scenario 3).

Summary:

There is no single '1.5°C warmer world'. Impacts can vary strongly for different worlds characterized by a 1.5°C global warming. Important aspects to consider (besides the changes in global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of the increase in global surface temperature at 1.5°C could be achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of regional and subregional risks.

The implications of overshooting are large for risks to natural and human systems, especially if the temperature at peak warming is high, because some risks may be long lasting and irreversible, such as the loss of some ecosystems. In addition, for several types of risks, the rate of change may be most relevant, with potentially large risks occurring in the case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. If overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate and unprecedented global efforts to mitigate GHGs are required.

The time frame for initiating major mitigation measures is essential in order to reach a 1.5°C (or even a 2°C) global stabilization of climate warming (see consistent cumulative CO_2 emissions up to peak warming in Cross-Chapter Box 8, Table 1). If mitigation pathways are not rapidly activated, much more expensive and complex adaptation measures will have to be taken to avoid the impacts of higher levels of global warming on the Earth system.

Cross-Chapter Box 8 (continued next page)

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Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 1 | Different worlds resulting from 1.5°C and 2°C mitigation (prospective) pathways, including 66% (probable) best-case outcome, and 5% worst-case outcome, based on Chapter 2 scenarios and Chapter 3 assessments of changes in regional climate. Note that the pathway characteristics estimates are based on computations with the MAGICC model (Meinshausen et al., 2011) consistent with the set-up used in AR5 WGIII (Clarke et al., 2014), but are uncertain and will be subject to updates and adjust-ments (see Chapter 2 for details). Updated from Seneviratne et al. (2018b).

		B1.5_LOS (below 1.5°C with low overshoot) with 2/3 'probable best-case outcome'[a]	B1.5_LOS (below 1.5°C with low overshoot) with 1/20 'worst-case outcome'[b]	L20 (lower than 2°C) with 2/3 'probable best-case outcome'[a]	L20 (lower than 2°C) with 1/20 'worst-case outcome'[b]
General characteristics of pathway	**Overshoot > 1.5°C in 21st century**[c]	**Yes (51/51)**	**Yes (51/51)**	**Yes (72/72)**	**Yes (72/72)**
	Overshoot > 2°C in 21st century	**No (0/51)**	**Yes (37/51)**	**No (72/72)**	**Yes (72/72)**
	Cumulative CO_2 emissions up to peak warming (relative to 2016)[d] [$GtCO_2$]	610–760	590–750	1150–1460	1130–1470
	Cumulative CO_2 emissions up to 2100 (relative to 2016)[d] [$GtCO_2$]	170–560		1030–1440	
	Global GHG emissions in 2030[d] [$GtCO_2$ y-1]	19–23		31–38	
	Years of global net zero CO_2 emissions[d]	2055–2066		2082–2090	
Possible climate range at peak warming (regional+global)	**Global mean temperature anomaly at peak warming**	**1.7°C (1.66°C–1.72°C)**	**2.05°C (2.00°C–2.09°C)**	**2.11°C (2.05°C–2.17°C)**	**2.67°C (2.59°C–2.76°C)**
	Warming in the Arctic[e] (TNn[f])	4.93°C (4.36, 5.52)	6.02°C (5.12, 6.89)	6.24°C (5.39, 7.21)	7.69°C (6.69, 8.93)
	Warming in Central North America[e] (TXx[g])	2.65°C (1.92, 3.15)	3.11°C (2.37, 3.63)	3.18°C (2.50, 3.71)	4.06°C (3.35, 4.63)
	Warming in Amazon region[e] (TXx)	2.55°C (2.23, 2.83)	3.07°C (2.74, 3.46)	3.16°C (2.84, 3.57)	4.05°C (3.62, 4.46)
	Drying in the Mediterranean region[e,h]	−1.11 (−2.24, −0.41)	−1.28 (−2.44, −0.51)	−1.38 (−2.58, −0.53)	−1.56 (−3.19, −0.67)
	Increase in heavy precipitation events[e] in Southern Asia[i]	9.94% (6.76, 14.00)	11.94% (7.52, 18.86)	12.68% (7.71, 22.39)	19.67% (11.56, 27.24)
Possible climate range in 2100 (regional+global)	**Global mean temperature warming in 2100**	**1.46°C (1.41°C–1.51°C)**	**1.87°C (1.81°C–1.94°C)**	**2.06°C (1.99°C–2.15°C)**	**2.66°C (2.56°C–2.76°C)**
	Warming in the Arctic[j] (TNn)	4.28°C (3.71, 4.77)	5.50°C (4.74, 6.21)	6.08°C (5.20, 6.94)	7.63°C (6.66, 8.90)
	Warming in Central North America[j] (TXx)	2.31°C (1.56, 2.66)	2.83°C (2.03, 3.49)	3.12°C (2.38, 3.67)	4.06°C (3.33, 4.59)
	Warming in Amazon region[j] (TXx)	2.22°C (2.00, 2.45)	2.76°C (2.50, 3.07)	3.10°C (2.75, 3.49)	4.03°C (3.62, 4.45)
	Drying in the Mediterranean region[j]	−0.95 (−1.98, −0.30)	−1.10 (−2.17, −0.51)	−1.26 (−2.43, −0.52)	−1.55 (−3.17, −0.67)
	Increase in heavy precipitation events in Southern Asia[j]	8.38% (4.63, 12.68)	10.34% (6.64, 16.07)	12.02% (7.41, 19.62)	19.72% (11.34, 26.95)

Notes:

a) 66th percentile for global temperature (that is, 66% likelihood of being at or below values)

b) 95th percentile for global temperature (that is, 5% likelihood of being at or above values)

c) All 1.5°C scenarios include a substantial probability of overshooting above 1.5°C global warming before returning to 1.5°C.

d) Interquartile range (25th percentile, q25, and 75th percentile, q75)

e) The regional projections in these rows provide the median and the range [q25, q75] associated with the median global temperature outcomes of the considered mitigation scenarios at peak warming.

f) TNn: Annual minimum night-time temperature

g) TXx: Annual maximum day-time temperature

h) Indicates drying of soil moisture expressed in units of standard deviations of pre-industrial climate (1861–1880) variability (where −1 is dry; −2 is severely dry; and −3 is very severely dry);

i) Rx5day: the annual maximum consecutive 5-day precipitation.

j) As for footnote e, but for the regional responses associated with the median global temperature outcomes of the considered mitigation scenarios in 2100

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Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 2 | Storylines of possible worlds resulting from different mitigation options. The storylines build upon Cross-Chapter Box 8, Table 1 and the assessments of Chapters 1–5. Only a few of the many possible storylines were chosen and they are presented for illustrative purposes.

Scenario 1 [one possible storyline among best-case scenarios]: **Mitigation:** early move to decarbonization, decarbonization designed to minimize land footprint, coordination and rapid action of the world's nations towards 1.5°C goal by 2100 **Internal climate variability:** probable (66%) best-case outcome for global and regional climate responses	**In 2020, strong participation and support for the Paris Agreement and its ambitious goals for reducing CO_2 emissions by an almost unanimous international community led to a time frame for net zero emissions that is compatible with halting global warming at 1.5°C by 2100.** There is strong participation in all major world regions at the national, state and/or city levels. Transport is strongly decarbonized through a shift to electric vehicles, with more cars with electric than combustion engines being sold by 2025 (Chapter 2, Section 2.4.3; Chapter 4, Section 4.3.3). Several industry-sized plants for carbon capture and storage are installed and tested in the 2020s (Chapter 2, Section 2.4.2; Chapter 4, Sections 4.3.4 and 4.3.7). Competition for land between bioenergy cropping, food production, and biodiversity conservation is minimized by sourcing bioenergy for carbon capture and storage from agricultural wastes, algae and kelp farms (Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2). Agriculture is intensified in countries with coordinated planning associated with a drastic decrease in food waste (Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2). This leaves many natural ecosystems relatively intact, supporting continued provision of most ecosystem services, although relocation of species towards higher latitudes and elevations still results in changes in local biodiversity in many regions, particularly in mountain, tropical, coastal and Arctic ecosystems (Chapter 3, Section 3.4.3). Adaptive measures such as the establishment of corridors for the movement of species and parts of ecosystems become a central practice within conservation management (Chapter 3, Section 3.4.3; Chapter 4, Section 4.3.2). The movement of species presents new challenges for resource management as novel ecosystems, as well as pests and disease, increase (Cross-Chapter Box 6 in Chapter 3). Crops are grown on marginal land, no-till agriculture is deployed, and large areas are reforested with native trees (Chapter 2, Section 2.4.4; Chapter 3, Section 3.6.2; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2). Societal preference for healthy diets reduces meat consumption and associated GHG emissions (Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 6 in Chapter 3). By 2100, global mean temperature is on average 0.5°C warmer than it was in 2018 (Chapter 1, Section 1.2.1). Only a minor temperature overshoot occurs during the century (Chapter 2, Section 2.2). In mid-latitudes, frequent hot summers and precipitation events tend to be more intense (Chapter 3, Section 3.3). Coastal communities struggle with increased inundation associated with rising sea levels and more frequent and intense heavy rainfall (Chapter 3, Sections 3.3.2 and 3.3.9; Chapter 4, Section 4.3.2; Chapter 5, Box 5.3 and Section 5.3.2; Cross-Chapter Box 12 in Chapter 5), and some respond by moving, in many cases with consequences for urban areas. In the tropics, in particular in megacities, there are frequent deadly heatwaves whose risks are reduced by proactive adaptation (Chapter 3, Sections 3.3.1 and 3.4.8; Chapter 4, Section 4.3.8), overlaid on a suite of development challenges and limits in disaster risk management (Chapter 4, Section 4.3.3; Chapter 5, Sections 5.2.1 and 5.2.2; Cross-Chapter Box 12 in Chapter 5). Glaciers extent decreases in most mountainous areas (Chapter 3, Sections 3.3.5 and 3.5.4). Reduced Arctic sea ice opens up new shipping lanes and commercial corridors (Chapter 3, Section 3.3.8; Chapter 4, Box 4.3). Small island developing states (SIDS), as well as coastal and low-lying areas, have faced significant changes but have largely persisted in most regions (Chapter 3, Sections 3.3.9 and 3.5.4, Box 3.5). The Mediterranean area becomes drier (Chapter 3, Section 3.3.4 and Box 3.2) and irrigation of crops expands, drawing the water table down in many areas (Chapter 3, Section 3.4.6). The Amazon is reasonably well preserved, through avoided risk of droughts (Chapter 3, Sections 3.3.4 and 3.4.3; Chapter 4, Box 4.3) and reduced deforestation (Chapter 2, Section 2.4.4; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2), and the forest services are working with the pattern observed at the beginning of the 21st century (Chapter 4, Box 4.3). While some climate hazards become more frequent (Chapter 3, Section 3.3), timely adaptation measures help reduce the associated risks for most, although poor and disadvantaged groups continue to experience high climate risks to their livelihoods and well-being (Chapter 5, Section 5.3.1; Cross-Chapter Box 12 in Chapter 5; Chapter 3, Boxes 3.4 and 3.5; Cross-Chapter Box 6 in Chapter 3). Summer sea ice has not completely disappeared from the Arctic (Chapter 3, Section 3.4.4.7) and coral reefs, having been driven to a low level (10–30% of levels in 2018), have partially recovered by 2100 after extensive dieback (Chapter 3, Section 3.4.4.10 and Box 3.4). The Earth system, while warmer, is still recognizable compared to the 2000s, and no major tipping points are reached (Chapter 3, Section 3.5.2.5). Crop yields remain relatively stable (Chapter 3, Section 3.4). Aggregate economic damage of climate change impacts is relatively small, although there are some local losses associated with extreme weather events (Chapter 3, Section 3.5; Chapter 4). Human well-being remains overall similar to that in 2020 (Chapter 5, Section 5.2.2).
Scenario 2 [one possible storyline among mid-case scenarios]: **Mitigation:** delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), overshoot at 2°C, decrease towards 1.5°C afterward, no efforts to minimize the land and water footprints of bioenergy **Internal climate variability:** 10% worst-case outcome (2020s) followed by normal internal climate variability	**The international community continues to largely support the Paris Agreement and agrees in 2020 on reduction targets for CO_2 emissions and time frames for net zero emissions. However, these targets are not ambitious enough to reach stabilization at 2°C of warming, let alone 1.5°C.** In the 2020s, internal climate variability leads to higher warming than projected, in a reverse development to what happened in the so-called 'hiatus' period of the 2000s. Temperatures are regularly above 1.5°C of warming, although radiative forcing is consistent with a warming of 1.2°C or 1.3°C. Deadly heatwaves in major cities (Chicago, Kolkata, Beijing, Karachi, São Paulo), droughts in southern Europe, southern Africa and the Amazon region, and major flooding in Asia, all intensified by the global and regional warming (Chapter 3, Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.4.8; Cross-Chapter Box 11 in Chapter 4), lead to increasing levels of public unrest and political destabilization (Chapter 5, Section 5.2.1). An emergency global summit in 2025 moves to much more ambitious climate targets. Costs for rapidly phasing out fossil fuel use and infrastructure, while rapidly expanding renewables to reduce emissions, are much higher than in Scenario 1, owing to a failure to support economic measures to drive the transition (Chapter 4). Disruptive technologies become crucial to face up to the adaptation measures needed (Chapter 4, Section 4.4.4).

Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 2 *(continued)*

Scenario 2 [one possible storyline among mid-case scenarios]: **Mitigation:** delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), overshoot at 2°C, decrease towards 1.5°C afterward, no efforts to minimize the land and water footprints of bioenergy **Internal climate variability:** 10% worst-case outcome (2020s) followed by normal internal climate variability	Temperature peaks at 2°C of warming by the middle of the century before decreasing again owing to intensive implementation of bioenergy plants with carbon capture and storage (Chapter 2), without efforts to minimize the land and water footprint of bioenergy production (Cross-Chapter Box 7 in Chapter 3). Reaching 2°C of warming for several decades eliminates or severely damages key ecosystems such as coral reefs and tropical forests (Chapter 3, Section 3.4). The elimination of coral reef ecosystems and the deterioration of their calcified frameworks, as well as serious losses of coastal ecosystems such as mangrove forests and seagrass beds (Chapter 3, Boxes 3.4 and 3.5, Sections 3.4.4.10 and 3.4.5), leads to much reduced levels of coastal defence from storms, winds and waves. These changes increase the vulnerability and risks facing communities in tropical and subtropical regions, with consequences for many coastal communities (Cross-Chapter Box 12 in Chapter 5). These impacts are being amplified by steadily rising sea levels (Chapter 3, Section 3.3.9) and intensifying storms (Chapter 3, Section 3.4.4.3). The intensive area required for the production of bioenergy, combined with increasing water stress, puts pressure on food prices (Cross-Chapter Box 6 in Chapter 3), driving elevated rates of food insecurity, hunger and poverty (Chapter 4, Section 4.3.2; Cross-Chapter Box 6 in Chapter 3; Cross-Chapter Box 11 in Chapter 4). Crop yields decline significantly in the tropics, leading to prolonged famines in some African countries (Chapter 3, Section 3.4; Chapter 4, Section 4.3.2). Food trumps environment in terms of importance in most countries, with the result that natural ecosystems decrease in abundance, owing to climate change and land-use change (Cross-Chapter Box 7 in Chapter 3). The ability to implement adaptive action to prevent the loss of ecosystems is hindered under the circumstances and is consequently minimal (Chapter 3, Sections 3.3.6 and 3.4.4.10). Many natural ecosystems, in particular in the Mediterranean, are lost because of the combined effects of climate change and land-use change, and extinction rates increase greatly (Chapter 3, Section 3.4 and Box 3.2). By 2100, warming has decreased but is still stronger than 1.5°C, and the yields of some tropical crops are recovering (Chapter 3, Section 3.4.3). Several of the remaining natural ecosystems experience irreversible climate change-related damages whilst others have been lost to land-use change, with very rapid increases in the rate of species extinctions (Chapter 3, Section 3.4; Cross-Chapter Box 7 in Chapter 3; Cross-Chapter Box 11 in Chapter 4). Migration, forced displacement, and loss of identity are extensive in some countries, reversing some achievements in sustainable development and human security (Chapter 5, Section 5.3.2). Aggregate economic impacts of climate change damage are small, but the loss in ecosystem services creates large economic losses (Chapter 4, Sections 4.3.2 and 4.3.3). The health and well-being of people generally decrease from 2020, while the levels of poverty and disadvantage increase considerably (Chapter 5, Section 5.2.1).
Scenario 3 [one possible storyline among worst-case scenarios]: **Mitigation:** uncoordinated action, major actions late in the 21st century, 3°C of warming in 2100 **Internal climate variability:** unusual (ca. 10%) best-case scenario for one decade, followed by normal internal climate variability	**In 2020, despite past pledges, the international support for the Paris Agreement starts to wane. In the years that follow, CO_2 emissions are reduced at the local and national level but efforts are limited and not always successful.** Radiative forcing increases and, due to chance, the most extreme events tend to happen in less populated regions and thus do not increase global concerns. Nonetheless, there are more frequent heatwaves in several cities and less snow in mountain resorts in the Alps, Rockies and Andes (Chapter 3, Section 3.3). Global warming of 1.5°C is reached by 2030 but no major changes in policies occur. Starting with an intense El Niño–La Niña phase in the 2030s, several catastrophic years occur while global warming starts to approach 2°C. There are major heatwaves on all continents, with deadly consequences in tropical regions and Asian megacities, especially for those ill-equipped for protecting themselves and their communities from the effects of extreme temperatures (Chapter 3, Sections 3.3.1, 3.3.2 and 3.4.8). Droughts occur in regions bordering the Mediterranean Sea, central North America, the Amazon region and southern Australia, some of which are due to natural variability and others to enhanced greenhouse gas forcing (Chapter 3, Section 3.3.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 11 in Chapter 4). Intense flooding occurs in high-latitude and tropical regions, in particular in Asia, following increases in heavy precipitation events (Chapter 3, Section 3.3.3). Major ecosystems (coral reefs, wetlands, forests) are destroyed over that period (Chapter 3, Section 3.4), with massive disruption to local livelihoods (Chapter 5, Section 5.2.2 and Box 5.3; Cross-Chapter Box 12 in Chapter 5). An unprecedented drought leads to large impacts on the Amazon rainforest (Chapter 3, Sections 3.3.4 and 3.4), which is also affected by deforestation (Chapter 2). A hurricane with intense rainfall and associated with high storm surges (Chapter 3, Section 3.3.6) destroys a large part of Miami. A two-year drought in the Great Plains in the USA and a concomitant drought in eastern Europe and Russia decrease global crop production (Chapter 3, Section 3.3.4), resulting in major increases in food prices and eroding food security. Poverty levels increase to a very large scale, and the risk and incidence of starvation increase considerably as food stores dwindle in most countries; human health suffers (Chapter 3, Section 3.4.6.1; Chapter 4, Sections 4.3.2 and 4.4.3; Chapter 5, Section 5.2.1). There are high levels of public unrest and political destabilization due to the increasing climatic pressures, resulting in some countries becoming dysfunctional (Chapter 4, Sections 4.4.1 and 4.4.2). The main countries responsible for the CO_2 emissions design rapidly conceived mitigation plans and try to install plants for carbon capture and storage, in some cases without sufficient prior testing (Chapter 4, Section 4.3.6). Massive investments in renewable energy often happen too late and are uncoordinated, energy prices soar as a result of the high demand and lack of infrastructure. In some cases, demand cannot be met, leading to further delays. Some countries propose to consider sulphate-aerosol based Solar Radiation Modification (SRM) (Chapter 4, Section 4.3.8); however, intensive international negotiations on the topic take substantial time and are inconclusive because of overwhelming concerns about potential impacts on monsoon rainfall and risks in case of termination (Cross-Chapter Box 10 in Chapter 4). Global and regional temperatures continue to increase strongly while mitigation solutions are being developed and implemented.

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Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 2 *(continued)*

Scenario 3 [one possible storyline among worst-case scenarios]: **Mitigation:** uncoordinated action, major actions late in the 21st century, 3°C of warming in 2100 **Internal climate variability:** unusual (ca. 10%) best-case scenario for one decade, followed by normal internal climate variability	Global mean warming reaches 3°C by 2100 but is not yet stabilized despite major decreases in yearly CO_2 emissions, as a net zero CO_2 emissions budget could not yet be achieved and because of the long lifetime of CO_2 concentrations (Chapters 1, 2 and 3). The world as it was in 2020 is no longer recognizable, with decreasing life expectancy, reduced outdoor labour productivity, and lower quality of life in many regions because of too frequent heatwaves and other climate extremes (Chapter 4, Section 4.3.3). Droughts and stress on water resources renders agriculture economically unviable in some regions (Chapter 3, Section 3.4; Chapter 4, Section 4.3.2) and contributes to increases in poverty (Chapter 5, Section 5.2.1; Cross-Chapter Box 12 in Chapter 5). Progress on the sustainable development goals is largely undone and poverty rates reach new highs (Chapter 5, Section 5.2.3). Major conflicts take place (Chapter 3, Section 3.4.9.6; Chapter 5, Section 5.2.1). Almost all ecosystems experience irreversible impacts, species extinction rates are high in all regions, forest fires escalate, and biodiversity strongly decreases, resulting in extensive losses to ecosystem services. These losses exacerbate poverty and reduce quality of life (Chapter 3, Section 3.4; Chapter 4, Section 4.3.2). Life for many indigenous and rural groups becomes untenable in their ancestral lands (Chapter 4, Box 4.3; Cross-Chapter Box 12 in Chapter 5). The retreat of the West Antarctic ice sheet accelerates (Chapter 3, Sections 3.3 and 3.6), leading to more rapid sea level rise (Chapter 3, Section 3.3.9; Chapter 4, Section 4.3.2). Several small island states give up hope of survival in their locations and look to an increasingly fragmented global community for refuge (Chapter 3, Box 3.5; Cross-Chapter Box 12 in Chapter 5). Aggregate economic damages are substantial, owing to the combined effects of climate changes, political instability, and losses of ecosystem services (Chapter 4, Sections 4.4.1 and 4.4.2; Chapter 3, Box 3.6 and Section 3.5.2.4). The general health and well-being of people is substantially reduced compared to the conditions in 2020 and continues to worsen over the following decades (Chapter 5, Section 5.2.3).

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Frequently Asked Questions

FAQ 3.1 | What are the Impacts of 1.5°C and 2°C of Warming?

Summary: *The impacts of climate change are being felt in every inhabited continent and in the oceans. However, they are not spread uniformly across the globe, and different parts of the world experience impacts differently. An average warming of 1.5°C across the whole globe raises the risk of heatwaves and heavy rainfall events, amongst many other potential impacts. Limiting warming to 1.5°C rather than 2°C can help reduce these risks, but the impacts the world experiences will depend on the specific greenhouse gas emissions 'pathway' taken. The consequences of temporarily overshooting 1.5°C of warming and returning to this level later in the century, for example, could be larger than if temperature stabilizes below 1.5°C. The size and duration of an overshoot will also affect future impacts.*

Human activity has warmed the world by about 1°C since pre-industrial times, and the impacts of this warming have already been felt in many parts of the world. This estimate of the increase in global temperature is the average of many thousands of temperature measurements taken over the world's land and oceans. Temperatures are not changing at the same speed everywhere, however: warming is strongest on continents and is particularly strong in the Arctic in the cold season and in mid-latitude regions in the warm season. This is due to self-amplifying mechanisms, for instance due to snow and ice melt reducing the reflectivity of solar radiation at the surface, or soil drying leading to less evaporative cooling in the interior of continents. This means that some parts of the world have already experienced temperatures greater than 1.5°C above pre-industrial levels.

Extra warming on top of the approximately 1°C we have seen so far would amplify the risks and associated impacts, with implications for the world and its inhabitants. This would be the case even if the global warming is held at 1.5°C, just half a degree above where we are now, and would be further amplified at 2°C of global warming. Reaching 2°C instead of 1.5°C of global warming would lead to substantial warming of extreme hot days in all land regions. It would also lead to an increase in heavy rainfall events in some regions, particularly in the high latitudes of the Northern Hemisphere, potentially raising the risk of flooding. In addition, some regions, such as the Mediterranean, are projected to become drier at 2°C versus 1.5°C of global warming. The impacts of any additional warming would also include stronger melting of ice sheets and glaciers, as well as increased sea level rise, which would continue long after the stabilization of atmospheric CO_2 concentrations.

Change in climate means and extremes have knock-on effects for the societies and ecosystems living on the planet. Climate change is projected to be a poverty multiplier, which means that its impacts are expected to make the poor poorer and the total number of people living in poverty greater. The 0.5°C rise in global temperatures that we have experienced in the past 50 years has contributed to shifts in the distribution of plant and animal species, decreases in crop yields and more frequent wildfires. Similar changes can be expected with further rises in global temperature.

Essentially, the lower the rise in global temperature above pre-industrial levels, the lower the risks to human societies and natural ecosystems. Put another way, limiting warming to 1.5°C can be understood in terms of 'avoided impacts' compared to higher levels of warming. Many of the impacts of climate change assessed in this report have lower associated risks at 1.5°C compared to 2°C.

Thermal expansion of the ocean means sea level will continue to rise even if the increase in global temperature is limited to 1.5°C, but this rise would be lower than in a 2°C warmer world. Ocean acidification, the process by which excess CO_2 is dissolving into the ocean and increasing its acidity, is expected to be less damaging in a world where CO_2 emissions are reduced and warming is stabilized at 1.5°C compared to 2°C. The persistence of coral reefs is greater in a 1.5°C world than that of a 2°C world, too.

The impacts of climate change that we experience in future will be affected by factors other than the change in temperature. The consequences of 1.5°C of warming will additionally depend on the specific greenhouse gas emissions 'pathway' that is followed and the extent to which adaptation can reduce vulnerability. This IPCC Special Report uses a number of 'pathways' to explore different possibilities for limiting global warming to 1.5°C above pre-industrial levels. One type of pathway sees global temperature stabilize at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before declining later in the century (known as an 'overshoot' pathway).

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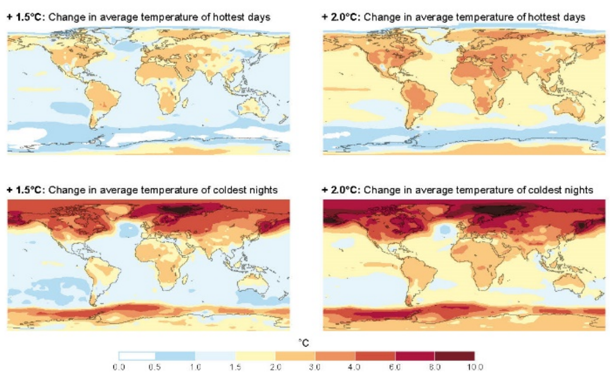
Such pathways would have different associated impacts, so it is important to distinguish between them for planning adaptation and mitigation strategies. For example, impacts from an overshoot pathway could be larger than impacts from a stabilization pathway. The size and duration of an overshoot would also have consequences for the impacts the world experiences. For instance, pathways that overshoot 1.5°C run a greater risk of passing through 'tipping points', thresholds beyond which certain impacts can no longer be avoided even if temperatures are brought back down later on. The collapse of the Greenland and Antarctic ice sheets on the time scale of centuries and millennia is one example of a tipping point.

FAQ3.1: Impact of 1.5°C and 2.0°C global warming

Temperature rise is not uniform across the world. Some regions will experience greater increases in the temperature of hot days and cold nights than others.



FAQ 3.1, Figure 1 | Temperature change is not uniform across the globe. Projected changes are shown for the average temperature of the annual hottest day (top) and the annual coldest night (bottom) with 1.5°C of global warming (left) and 2°C of global warming (right) compared to pre-industrial levels.

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Public Interest Energy Research (PIER) Program

White Paper

IMPACTS OF PREDICTED SEA-LEVEL RISE AND EXTREME STORM EVENTS ON THE TRANSPORTATION INFRASTRUCTURE IN THE SAN FRANCISCO BAY REGION

A White Paper from the California Energy Commission's California Climate Change Center

Prepared for: California Energy Commission

Prepared by: University of California, Berkeley

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PREFACE

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the California Climate Change Center to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions.

For more information on the PIER Program, please visit the Energy Commission's website http://www.energy.ca.gov/research/index.html or contract the Energy Commission at (916) 327-1551.

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ABSTRACT

Literature concerning the potential effect of climate change (sea-level rise inundation and 100-year storm events) on the San Francisco Bay region's transportation infrastructure is reviewed. Currently available geographical information system data is employed, and a review of how those datasets have been used in previous studies is reported. The second part of this paper presents methods. They include a higher-resolution digital elevation model for the Bay Area; a new approach using a digital surface model is introduced to improve the surface elevations of features and better calculate the risk of over-topping by sea level shifts and storm surges. A metric to assess change in the transportation infrastructure is introduced that calculates accessibility of first responders to the population at large. Sea level rise is incremented to the expected 1.4 meters in tandem with a 100-year flood to analyze the extent to which transportation assets are at risk of inundation.

The increased travel time from first responder locations to all neighborhoods in the region is measured for each iteration of the model. Local accessibility analysis for the entire San Francisco Bay region is performed to provide a synoptic view. Two localities are chosen to view in detail the impact on first-responder accessibility caused by sea level rise and a 100-year storm event. Next, the regional vulnerability of the transportation network to these events is assessed. This is accomplished by creating nodes that are the intersections of the major regional highways that surround the Bay. The loss of accessibility is measured by calculating the changes in travel time between these major nodes through iterations of our inundation model. Finally, the accessibility impacts to the hinterland from the major highway intersections for each peak water level iteration is determined, calculating the first and last 20 minutes of an origin-destination journey.

Keywords: climate change, sea level rise, flooding, inundation, extreme storms, peak water levels, transportation infrastructure vulnerability, ports, airports, roads, accessibility, first responder accessibility, travel time changes, digital elevation model, DEM, digital surface model, DSM, LiDAR, location-allocation.

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DISCLAIMER

All maps and tables and the associated analysis in this paper are intended to show the potential effect of sea-level rise in combination with extreme storm events on transportation infrastructure in the Bay Area. The maps and tables are based on model output which assumes various climate change scenarios. Our predictions are approximations to a complex hydrodynamic system, and our digital elevation and digital surface models are approximations to the real Earth surface. Inferences should be tempered by this fact. As such, our maps do not represent the exact location of flooding nor flooding depth, or the precise effect of these actions on accessibility or travel time. We do not account for government or private response to sea-level rise and extreme storm events which may include shoreline protection measures or other changes that will alter the shoreline and lands hydrologically connected to the San Francisco Bay. Please note that the electronic publishing process may have altered the height-to-width ratio of images in this paper from the original source. Other caveats are included in the text of this paper.

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Unless otherwise noted, all tables and figure are provided by the author.

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Section 1: Introduction

The nine county San Francisco Bay Area has an economy of almost $300 billion. The Bay Area economy ranks 24th in the world and on a per capita basis, it ranks ahead of all national economies. This region holds a leading position in global trade (Bay Area Council Economic Institute 2008). The Bay Area region has 620 miles of freeways and 800 miles of state highways. This region has 19,000 centerline miles of local roadways, which are owned and maintained by Bay Area cities and counties (MTC and Caltrans - D4 2008). The population of the Bay Area is almost 7.2 million, and residents take more than 21 million trips per day on average weekdays (MTC and Caltrans - D4 2008). In 2007, more than 82 percent of all trips were made by automobile. About 12 percent of all trips were by walking and biking and 5 percent by public transit. Around 488 million trips were taken and over 54 billion miles of travel were logged yearly on the road networks in the region. More than 26 billion miles of travel were conducted on the region's 620-mile freeway network. By 2035, the Bay Area's population is projected to reach 9 million, and MTC (Metropolitan Transportation Commission) predicts the number of trips will increase to 29.1 million each day (MTC 2009; MTC and Caltrans - D4 2008).

According to the Bay Conservation and Development Commission (BCDC), the Bay Area's rail network[1] has over 600 miles of track and moves both freight and passengers (BCDC 2009). Except for the Bay Area Rapid Transit (BART) and San Francisco Municipal Transportation Agency (MUNI), both passenger and freight service use the same tracks, so that the rail systems have a substantial amount of congestion. In addition, over the next 50 years, freight demand is expected to increase up to 350 percent (MTC 2007; BCDC,2009). Leading products handled by the rail system are steel, waste, scrap, petroleum products, crushed stone, and automobiles. The rail network connects multiple transportation sectors in the Bay Area. For example, the Ports of Richmond and Oakland heavily rely on rail to transport cargo containers. Passenger service connects the major work places in San Francisco, Oakland, and San Jose with other Bay Area cities and inland cities in the Central Valley (Sacramento and Stockton). BART is a critical component of the passenger rail network, providing commuter service in the region (BCDC 2009).

There are three international airports (San Francisco International Airport (SFO), Oakland International Airport (OAK), and San Jose International Airport (SJC)) in the Bay Area. The three airports processed around 60.6 million passengers and 1,451 thousand tons of cargo in 2007 (MTC and Caltrans - D4 2008). However, the long-term trend in air travel in the Bay Area has been reduced because of terrorist attacks in 2001, a national economic recession, and other factors (MTC, BCDC and ABAG 2011). Total Bay Area airport passengers are projected to number between 88–129 million in 2034. Air cargo volume has declined since 2000 reflecting the maturing of the air cargo business. Price competition from trucking and maritime shipping,

[1] The Santa Clara Valley Transportation Authority (VTA) also has a light rail system in the Bay Area. However, VTA is not included.

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among other factors, has reduced the overall level of air cargo shipment in the Bay Area by about 4 percent between 2000 and 2007 (MTC, BCDC and ABAG 2011).

The four major ports (Oakland, San Francisco, Redwood City, and Richmond) processed nearly 2,388 thousand twenty-foot equivalents (TEUs) of marine cargo and 29.4 million tons of bulk cargo in the region in 2007. The port of Oakland hosts the largest volume of cargo within the region (it is the nation's fourth busiest port) and carries more exports cargo than imports (MTC and Caltrans - D4 2008). Airports and sea ports are gateways to the rest of the country and the world and generate a significant amount of connected ground transit by cars, trucks, and rails.

Because infrastructure life-span is relatively long, transportation infrastructure is designed to perform under various natural conditions and within a specified range of extreme events. Due to the longevity of transportation infrastructure, current designs and decisions being made now will continuously affect our society during the life-span of these infrastructures. Accordingly, inappropriate decisions made today may lead to additional spending for retrofitting existing infrastructure or repair of serious system failures in the near and distant future (Kahrl and Roland-Holst 2008).

Although many uncertainties exist regarding the consequences of climate change, there is broad scientific agreement that global climate change is occurring and poses important challenges to our environment (Wilkinson et al. 2002). Increases in average mean temperatures, the number of warm days over mid- and high-latitude land areas, and precipitation and temperature extremes are projected to occur with a high degree of confidence. These changes will bring about melting of sea ice and glaciers at high northern latitudes, a warmer and expanded body of ocean water, sea-level rise, and greater flooding and higher storm surges along coastal areas (Intergovernmental Panel on Climate Change [IPCC] 2007; Transportation Research Board 2008).

Transportation professionals are considering climate-related factors in their planning and design of transportation systems (Transportation Research Board 2008). Therefore, it is natural to incorporate the impact of climate change into planning, design, and maintenance of transportation infrastructure, so that vital transportation systems will not fail under expected climate change scenarios. In addition, many decisions made today regarding transportation infrastructure affect the shape of development patterns and land use in the future. Therefore, it is critical that we project future climate change and understand the impact of climate change on transportation infrastructure.

In general, most studies related to climate change impacts on transportation infrastructure have focused on assessing and mapping the direct impact and failure of flooded sections of transportation networks, transshipment facilities (i.e., ports), or origin and destination depots (i.e., airports). However, fewer studies have explored the negative consequences for society and individuals due to the climate-related disruptions that are expected to occur more frequently. A major reason for the lack of these kinds of studies is the difficulty of converting physical damage to some other quantitative metric representing socio-economic damage. For this perspective, vulnerability analysis of transportation networks may be useful because

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vulnerability analysis can provide quantitative measures of the social and economic consequences of disruption.

In this study, we first summarize previously conducted studies relevant to the impact of climate change on transportation systems in general. Although we are mainly focused on the vulnerability assessments of transportation infrastructure from potential inundation (due to sea-level rise) in the Bay Area, we review a broader range of literature related to the impact of climate change on transportation infrastructure. Then, we conduct background research for vulnerability analysis on transportation infrastructure and climate change. In order to conduct the vulnerability assessment of the transportation infrastructure of the San Francisco Bay Area, we first transformed recently acquired Light Detection and Ranging (LiDAR) data for the Bay Area into models of ground elevation and models of surface elevation for roads, bridges, buildings, and other infrastructure. These higher resolution elevation and surface models are essential for accurately estimating potential inundation regions. We also created an up-to-date geographic information system (GIS) for the greater Bay Area. It includes important transportation-related GIS data, such as roads, airports, fire stations and hospitals, which are used in studying the effect of climate change on sea-level rise, as well as inundation due to severe storm events on the transportation network.

The research objectives of this study follow:

- Update an older digital elevation model (DEM)–based LiDAR study with a new, more densely sampled, and more accurate dataset.
- Introduce a digital surface model (DSM) to measure additional information about the surface elevations of objects on the ground and produce a more accurate and realistic surface base for flood inundation calculations.
- Examine, assess, and report flood inundation on transportation infrastructures, such as roads, railways, port facilities, airports, and other key facilities. We calculate peak water level (PWL) modeling estimates based on work by Heberger et al. (2009) where PWL = sea-level rise + a 100-year flood event. We assume climate change models are accurate and adopt a mean sea level (MSL) rise of 1.4 meters by the year 2100. We assume Knowles' (2009) output from his TRIM-2D hydrodynamic modeling is correct and adopt it as our 100-year flood event water levels. We do not examine the dozen or so ways in which levees can fail with or without storm surges as this falls outside the scope of this research. We do assume that overtopping, one of the most serious causes of levee failure, leads to inundation and infrastructure failure and renders roads inoperable.
- Introduce local metrics that map the horizontal impact on accessibility caused by disruptions of the transportation infrastructure system due to inundations. These metrics are applied to a series of origin and destination scenarios where we measure the impact of inundation on accessibility. Although we choose access of first responders to local households here (since local governments attempt to plan and design evenly distributed first responder access to citizens that results in a relatively uniform

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distribution of local origin-destinations), the process is universal and could be used to study altered access to all assets of interest.

- Measure node-to-node accessibility impacts on the major road traffic corridors and report travel time shifts between the major intersections, as these are the key nodes in the regional traffic infrastructure.
- Model accessibility impacts to the hinterland from the major highway intersections for each peak water level iteration, calculating the first and last 20 minutes of an origin-destination journey

1.1 Climate Models and Scenarios

In order to conduct viable assessments of the impact of climate change on transportation infrastructure, we need to include projections of relevant weather or climate parameters. These projections can be acquired based on our knowledge and understanding of our climate systems. The current understanding of the governing physical and chemical laws controlling the atmosphere-ocean-land systems that comprise earth's climate is quantified and coded in the form of a linked set of finite difference equations. The models, usually formulated in time-dependent fashion, are typically calculated over grid cells of 100–200 km horizontal distance, so by necessity they are approximate and represent many processes that operate on smaller, sub-grid scales using parameterizations. The models are calibrated and validated with historic data sets, and then driven with assumed external forcings, under which they can be used to estimate future climate changes.

Recent studies take advantage of climate projections developed by the Intergovernmental Panel on Climate Change (IPCC) process. Most global or regional scale climate projections are based upon one or more global climate models (GCMs) run under a set of greenhouse gas emission and aerosol scenarios, which in the last two IPCC climate change assessments were prescribed by the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000). Peterson et al. (2008) predicted the nation's climate changes relevant to transportation by using climate models and greenhouse gas emission scenarios. They collected and archived the resulting data from more than 25 models and used them for their assessment. In addition, three emission scenarios from SRES (B1: low emission; A1B: mid-range emission balanced on all energy sources; and A2: high emissions) are used. In a Gulf Coast study (Keim et al. 2008), up to 21 different GCM runs were used with three emission scenarios (B1, A1B, and A2) from SRES.

Global or regional climate models calculate a set of atmospheric, land, and oceanic variables such as temperature, precipitation, winds, ocean temperatures, and currents over coarse spatial scales. While climate change occurs on a global scale, the impacts of climate change on transportation infrastructure will differ depending on the geographic location and physiographic regions of that infrastructure. As a consequence, different parts of the nation have specific regional characteristics. Thus, in many cases, the outputs from the global climate models are applied as input variables for secondary-effect models that describe specific climate events (such as flooding, soil erosion, local sea-level rise, etc.). Because there is currently not a full understanding of the processes that control the melt and calving of grounded ice into the

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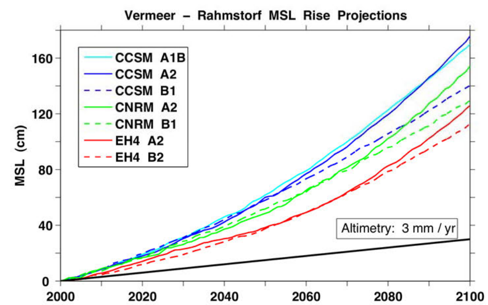
global ocean, the estimation of sea-level rise is only partially handled in GCMs. Consequently, in many cases, future sea-level rise is calculated using a secondary offline model or set of models. One family of these models, which is employed in this investigation, is the *semi-empirical* technique, as developed by Rahmstorf (2007). The Vermeer and Rahmstorf (2009) scheme for calculating global sea-level rise is used here.

Bromirski et al. (2012) used the Vermeer and Rahmstorf (2009) scheme to estimate MSL from the GCMs annual surface air temperature projections to quantify a set of MSL scenarios to the end of the century. By 2100 levels between 1.2 and 1.6 m were obtained by Bromirski et al. (2012) under the A1B and A2 scenarios for the CCSM GCM (see Figure 1). Somewhat different values of sea-level rise (SLR), though of the same order of magnitude were employed by Heberger et al. 2009. We use 1.4 m (55 inches) at the year 2100 as the central value of the suite of projections found in Bromirski et al. 2012.



Source: Bromirski et al. (2012)

Figure 1. Projections of Global Mean Sea-Level Rise Using the Surface Air Temperature Simulations from Various GCM Scenarios. The altimetry 3 mm/year trend estimate for global mean SLR is provided in black.

For the San Francisco Bay, a more detailed analysis was conducted (Heberger et al. 2009). Inundation maps were created from the climate change scenarios provided by the U.S. Geological Survey (USGS) (Knowles 2009, 2010). Knowles (2009, 2010) estimated a 100-year projection of MSL rise based on a global climate model (CCSM3) under A2 greenhouse gas emission scenarios for the San Francisco Bay region. Then, to calculate the land surface that is vulnerable to periodic inundation, high water elevation marks throughout the Bay were estimated by using the hydrodynamic model TRIM-2D. Previously calculated SLR estimations from the climate models were then used as a model input to estimate inundation areas. Knowles's work does not account for the effect of wind waves on water levels, land subsidence,

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the effect of levees, or fresh water inflows. All of these factors could increase winter flood peaks in estuaries.[2]

1.2 Potential Impact of Climate Change Relevant to Transportation

Transportation infrastructure is designed for typical weather and local climate conditions and is able to function under normal weather fluctuations or within a certain range of weather extremes. As the climate changes, resulting in more extreme and unusual weather patterns, it will cause serious problems for transportation infrastructure. However, no comprehensive inventory exists of the potential impacts of climate change on transportation. The potential impact of climate change on transportation systems can be assessed by the outcomes from the climate models and emission scenarios. Thus, it is convenient to categorize the potential impact by climate parameters (or factors) that are the outcomes of the model predictions.

The general outcomes from the climate models predict an increase in global temperature, changes in precipitation patterns, and SLR. The impact of climate change on transportation has been assessed for a wide variety of purposes and focuses, such as climate factors, geographic regions, and climate zones. For this study, we use key climate parameters to categorize the main impacts of climate change on transportation that are commonly used in the literature. We select four main key climate factors based on both the Transportation Research Board (2008) report and Gulf Coast studies (Keim et al. 2008), and we list the potential impact of climate change on transportation infrastructure. We exclude some key climate factors that are less relevant to the Bay Area's climate conditions (e.g., increases in Arctic temperatures). The selected climate factors are the main outcomes from the climate models and emission scenarios. The main climate factors are SLR, severe storms, temperature, and precipitation. Table 1 lists the effects on weather and climate conditions that are relevant for the transportation sector.

For this study we use Vermeer and Rahmstorf (2009) estimates to make the assumption that MSL rise to the end of the century will reach a level of 1.4 m. Following Cayan et al. (2008), we assume that sea-level rise in the San Francisco outer Bay will closely resemble global mean SLR. This is consistent with the Bromirski et al. (2012) predictions and is the average of the predictive models documented in Figure 1. We assume and use the sea-level rise and 100-year storm events predicted in the literature, but do not include less predictable factors such as Sierra Nevada snow melt.

[2] See Knowles' cited works for additional discussion on limitations of his study.

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Table 1. Impacts of Climate Change on Transportation

Climate Impact	Potential Impact	Potential Operational Impact
Sea-level rise and storm surge	Coastal road flooding	Disruption of traffic, delay of evacuation and emergency response, increased congestion. Permanent breaks in the topological structure of the overall transportation network
	Railway flooding	Disruption of traffic, delay, increased risk of hazardous material spill
	Underground tunnels and subway flooding	Disruption and slowdown of subway traffic resulting in increased car, bus, and train commuting
	Erosion of coastal roads and rails	Potential road slump or failure, potential railbed instability or failure
	Port flooding and damage	Negative impact on commerce and manufacturing from delays in cargo handling
	Bridge scour	Erosion of sediment from around bridge abutments or piers, adding to increased maintenance, potential failure, and periodic bridge closures
	Inundation of airport runways in coastal areas	Closure or slowdown in flight arrivals and departures, need for levee construction
	Higher tides at ports facilities	Erosion of shoreline adding to increased maintenance, need for levee construction, and periodic traffic disruption
Severe storms	Damage to facilities at ports	Increased maintenance costs, periodic closures, and transshipment disruptions
	Greater probability of infrastructure failure	Closure or major disruptions and slowdowns in traffic
	Decreased expected lifetime of infrastructure	More frequent and extensive emergency evacuation
Increased precipitation	Overloading of drainage systems, causing infrastructure damage due to flooding	Increases in traffic disruptions and slowdowns
	Damage to infrastructure due to landslides and mudslides	Increased traffic disruptions

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Table 1. (continued)

Climate Impact	Potential Impact	Potential Operational Impact
Increased temperature	Highway asphalt rutting	Vehicle overheating and tire deterioration; lane closures for highway repair
	Rail bucking	Increased travel time due to speed restrictions
	Lack of ventilation on underground transit system	Health/safety risks
	Thermal expansion of bridges	Frequent detours

Sea-Level Rise and Storm Surge

A National Research Council report (2008) states that the greatest impact of climate change for the U.S. transportation system will be flooding of roads, railways, the transportation system, and runways around coastal areas (especially along the Gulf and Atlantic Coasts) by the combined effect of sea-level rise and storm surges. Because California has an extensive coastline (approximately 1,100 miles of Pacific coast and 1,000 miles of shoreline along the San Francisco Bay), extreme weather events (such as severe storms or extreme precipitation), especially when exacerbated by sea-level rise will cause the high water levels and have substantial likelihood of being accompanied by sizable wind waves (Cayan et al. 2008). It is assumed that these events would produce the greatest impacts on California's transportation infrastructure (Kahrl and Roland-Holst 2008). Many California coastal areas are at risk from sea level extremes (Flick 1998), especially when sea level extremes are combined with winter storms. For example, very high seas and storm surge caused hundreds of millions of dollars in storm and flood damage in the San Francisco Bay Region in 1997–1998 (Ryan et al. 1999).

In general, streets are lower than the surrounding lands. Water draining from lands adjacent to streets is often drained by flowing into the streets. Thus, streets are the first places to be flooded. Roads in coastal areas will have more frequent flooding by sea-level rise because increased sea level renders the drainage system less effective (Titus 2002). For the entire California coast, Heberger et al. (2009) estimated 3,500 miles of roads will be at inundation risk of a 100-year flood event with a 1.4 m sea-level rise in combination with a 100-year flood as measured above the NAVD88 datum. Under current conditions, only 1,900 miles of coastal roads are at risk of 100-year flooding (detailed climate models and methods were addressed previously). Thus, the length of road at risk of a 100-year flood is almost doubled with a 1.4m sea-level rise compared to the road length at risk of a 100-year flood under current conditions. About half of the roads currently at risk are on the Pacific Coast and the other half (730 miles) are around the San Francisco Bay. A similar estimation was conducted for railways. One hundred and forty miles of railways in California are at risk of 100-year flooding. The length of railways at risk doubles to 280 miles with a 100-year flood event in combination with 1.4 m sea-level rise (above the

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NAVD88 datum). About 40 percent of the vulnerable railway lines are around the Pacific Coast and the other parts are in the San Francisco Bay area (68 miles).

The Bay Conservation and Development Commission (BCDC 2009) estimates approximately 99 miles of the major roads and highways are vulnerable to a 16 inch (0.4 m) sea-level rise and approximately 186 miles of the major roads and highways are at risk to a 55 inch (1.4 m) sea-level rise above the average highly monthly (MHW) tide in the Bay Area. Historic tidal data were referenced to find the highest average monthly tide to which sea-level rise estimates were added (Knowles 2008). Furthermore, the BCDC discusses the potential secondary impacts, such as the erosion of existing protective or highway structures from increased storm activities. Another secondary impact is increased congestion caused by more detouring from the impacted roads onto other roads. For the rail network, BCDC estimates approximately 70 miles are vulnerable to sea-level rise of 16-inches (0.4 m) while 105 miles are vulnerable to sea-level rise of 55-inches (1.4 m).

The California Department of Transportation (DOT 2009) also conducted a preliminary assessment of the vulnerability of the transportation system to sea-level rise in California. In their assessment, 350 miles of major streets and highways could be at risk with a 55 inch (1.4 m) sea-level rise by 2100. This study also calculated flooding areas by using topography and the street network in a GIS. However, only highways were included for estimating the impact of inundation. In the California DOT report, the preliminary vulnerability assessment of movement of goods (freight) was conducted and the assessment listed the priority goods movement routes in California affected by a 55 inch (1.4 m) sea-level rise. For the Bay Area, four priority trade route corridors were listed; I-80 in Alameda County, I-880 in Alameda County (from I-80 to US-101), I-80 in San Francisco County, and US-101 in San Francisco County (From I-80 to the San Francisco Airport).

For road and rail networks, as flooding risk increases, a large portion of transportation segments could be blocked by excessive flooding events. As a consequence, more disruption of traffic flow and congestion would be expected. Public transit disruptions by the blocked routes (more likely at underground tunnels or low-lying routes) would cause severe problems for commuters and travelers in the region and additional delays can occur due to increased automobile usage. Furthermore, blocked transportation segments may cause delays in evacuation and emergency response.

While flooding from extreme weather events is temporary, several network links classified as Lifeline Routes are critical to emergency-response and must be repaired and classified operational immediately following a major disaster. Eventually these inundated structures should be permanently repaired in order to make roads and rail networks function correctly, implying time plays a role in infrastructure response from the first flooding to a more permanent restoration. The restoration of infrastructure permanently submerged or even temporarily impacted by a 100-year storm surge may cause additional disruption for longer periods of time and require additional expenses. In addition, San Francisco and Oakland airports will be at risk to flooding, and we anticipate that inundation of runways will interrupt regular operations and cause the closure or delays in flight arrivals and departures.

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Naturally, ports are located at the waterfront, and are subsequently exposed to flooding and inundation events. Sea-level rise and storm surge caused by climate change will increase the frequency and magnitude of inundation if ports are not sufficiently protected from these events. Port flooding will have a negative impact on commerce because of delays in processing goods passing through the port. In addition, flooding on the nearby roads and rails could impair or prohibit access to the ports and, hence, the transport of goods and services would be disrupted.

Increased Precipitation

Increased precipitation is likely to cause more frequent overload of the current drainage system. Flooding events could happen not only near the coastlines, but also in inland areas which have insufficient drainage capacity. These events will likely increase the system-wide traffic disruptions and slow down traffic flow. More instances of extreme rainfall will likely contribute to more frequent erosion, tree fall, and landslides, resulting in increased maintenance costs (for both roads and rails). In addition, an increase in frequency of extreme precipitation would increase the rate of traffic accidents, so that the risk of injury and property damage would rise. As weather conditions have a critical influence on airport operations (taking off, landing, and increased traffic separation distances in terminal control areas (TCA) while in flight), extreme rainfall would cause delays due to decreased visibility and wind.

Increased Temperature

The impact of extreme heat on roads could be significant, as it can cause asphalt pavement rutting. Since some pavement materials degrade faster under higher temperature conditions, maintenance cost could increase and require earlier road replacement than anticipated. For rails, higher temperature is dangerous because extreme heat can cause rail bucking, in turn causing critical derailments. Consequently, the speed of transit via trains will likely be reduced under higher temperature conditions and this could cause additional delays on the rail system. Extreme heat may affect the comfort of passengers on public transportation systems. The lack of ventilation systems on underground transportation systems would impact passenger comfort and health. In addition, high temperatures can cause interruptions in electric power distribution due to excessive regional demands for cooling. Power interruptions could lead to delays in public transportation systems that are dependent on electricity (such as BART). As all infrastructure systems are interconnected and most are interdependent, small abnormal events on one system can cause failures of others. In airports, higher temperature reduces the density of air and airplanes at airports consume more fuel and need longer runways to take off. Under these conditions, the current runways may not provide enough length for safe takeoffs, so that closure or slowdown in flight arrivals and departures would be unavoidable.

1.3 Vulnerability of the Transportation Network

In the transportation literature, vulnerability does not yet have a commonly accepted definition, and its meaning may vary for different contexts. In climate change–related literature, the IPCC refers to vulnerability as "The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a

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system is exposed, its sensitivity, and its adaptive capacity." (IPCC 2001, p. 995) (IPCC Def. 1). Some of the definitions found in the literature are given in Table 2 below.

Table 2. Definition of Vulnerability in the Literature

Authors	Definition of vulnerability
Berdica (2002)	"a susceptibility to incidents that can result in considerable reductions in road network serviceability"
Husdal (2004)	"the non-operability of the network under certain circumstances"
Holmgren, Å . (2004)	"sensitivity to threats and hazards"
Laurentius (1994)	"vulnerability is a susceptibility for rare, though big, risks, while the victims can hardly change the course of events and contribute little or nothing to recovery"
Ford and Smit (2004)	"the susceptibility to harm in a system relative to a stimulus or stimuli"
Nicholls et al. (1999)	"the likelihood of occurrence and impacts of weather and climate related events"
BCDC(2011)	From the Intergovernmental Panel on Climate Change (IPCC 2007): Vulnerability "is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes."

Vulnerability analysis of transportation networks is important because the analysis can provide an insight into their tendency for disruption, the extent of the resulting consequences and the scope of mitigation measures required. Although vulnerability measures have been developed for various disruptions, these measures are also useful in assessing the consequences of climate-related disruption. Regardless of the type of disruption, a reduced level of service of transportation can happen any time.

Despite the significance of the subject, however, it is difficult to characterize network vulnerability because of the complexity and inter-connectivity of the problem. Consequently, the development of a quantitative assessment method is particularly important to manage risks associated with critical events and to compare the benefit and trade-off among various potential responses. Accordingly, several studies have focused on evaluating the vulnerability of the road system in part (or in whole) and determining the most vulnerable elements within the road system itself.

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Several studies have focused on assessing the vulnerability of transportation network to natural disasters and climate change. Suarez et al. (2005) analyze the impacts of flooding and climate change on the urban transport system of the Boston Metro Area, applying a four-stage (i.e., trip generation, destination choice, mode choice and route choice) transport modeling system. Sohn (2006) proposed an approach for assessing the significance of highway links in Maryland under flood damage by using an accessibility index. Chang et al. (2010) investigated the potential impact of climate change disruption caused by road closures in the Portland, Oregon. They incorporate climate change scenarios, a hydrologic model, a stream channel survey, a hydraulic model and a travel forecast model to assess the impact of climate change on transportation. BCDC (2011) used a Federal Highway Administration conceptual model for assessing vulnerability and risk of climate change effects on transportation infrastructure from Emeryville to Union City in the San Francisco Bay Area.

An important part of vulnerability analysis is to detect critical components in the network where a certain incident would cause particularly severe consequences. For this purpose, several studies estimate the effect of network degradation through eliminating specific links one at a time and assessing the impact on network operations of the deletion (D'Este 2003; Taylor and D'Este 2004). Taylor et al. (2006) analyze the road network at different levels by using various measures of decreased accessibility to assess the impacts of link failures in Australia. Jenelius et al. (2006) propose an approach for determining the most vulnerable road sections by measuring the link importance indices and site exposure indices of each link. These measures are derived based on the increment of generalized travel cost when links are blocked.

In this literature, accessibility-based consequence measures (increment of generalized cost) are commonly used to assess the vulnerability of road network. Although cutting a single link at a time and incrementing over all links can provide a comprehensive description of the vulnerability of the network, this analysis requires substantial computer power because of the high number of road intersections involved in the calculations. In addition, although it is a good metric of overall vulnerability of the network, it does not measure increased travel time for specific and often critical origin and destination thematic events, such as accessibility of first responders or accessibility to hospitals.

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Section 2: Data and Methods

2.1 Potential Inundation

Land surface (elevation) models and peak water levels are the key components needed to accurately estimate potential inundation areas in the San Francisco Bay region. We prepared the land surface models (DEM) by using highly accurate LiDAR data sets.

We follow the methodology of Heberger et al. (2009) for estimating PWLs. Peak water levels have two components: sea-level rise and a 100-year flood event. An important element of a flooding event is that storms coincide with high tides (Zetler et al 1985; Flick 1998).

The 100-year flood is a flood that has a 1/100, i.e., 1 percent chance of occurring per year. It can be shown that there is a 63 percent chance that a 100-year flood will occur over the next 100-year period and a 9.5 percent chance that it will occur over the next 10 years. In this paper we refer to the 100-year flood as a 100-year extreme storm event ((ESE_{100}). Our model has four sea-level rise (SLR_x) increments {x: 0 m, 0.5 m, 1.0 m or 1.4 m} to which we add the 100-year extreme storm event (ESE_{100}) without sea-level rise. Thus our model for peak water level can be written as: $PWL_x = SLR_x + ESE_{100}$. The flood levels (elevation (m)) for the 100-year extreme storm event with no sea-level rise ($PWL_{(0)}$) were provided by Noah Knowles of the USGS, as discussed further in the section Peak Water Levels below.

As pointed out by Heberger et al. (2009),this approach assumes that all tide datums (see the section below on Datums) will increase by the same amount as MSL is projected to increase. It is important to note that San Francisco has the longest continuous tidal record in North America (Bromirski et al. 2003), and when examining tidal datum statistics in the Bay proper, it is observed that mean higher high water (MHHW) rose at 155 mm/century, 92 percent faster than the MSL, and mean high water (MHW) rose at 145 mm/century, 80 percent faster than MSL (Flick et al. 2003). Because of these observations, it is prudent to modify the PWL predictions if the trends observed by Flick et al (2003) continue for extended periods in the future.

Ground Elevation Data (DEM)

We obtained and processed the most accurate, high spatial resolution ground elevation data currently available (see Table 3 and Figure 2). These (LiDAR) data are obtained using an optical remote sensing technology that can measure the distance to a target by illuminating the target with light pulses from a laser (Wehr and Lohr 1999) and are put through a rigorous quality control.[3]

We used two main LiDAR data sets that cover the San Francisco Bay, San Pablo Bay, and Suisun Bay. We obtained the North Bay LiDAR data (that covers areas north of the Bay Bridge) and the South Bay LiDAR data (that cover areas south of the Bay Bridge) from the USGS Center for

[3] See metadata description at:
http://www.csc.noaa.gov/crs/tcm/ldartdat/metatemplate/sfbay2010_template.html

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LIDAR Information Coordination and Knowledge (CLICK). The North Bay LiDAR data was collected by Fugro Earth Data, Inc. with a Piper Navajo twin engine aircraft utilizing a Leica ALS60 MPiA 200 kHz LiDAR sensor collecting returns as well as intensity. The South Bay LiDAR was collected by Dewberry with a Piper Navajo twin engine aircraft utilizing an Optech ALTM 3100EA 100 kHz LiDAR sensor collecting returns as well as intensity.

Both data sets were collected as a part of the California Costal LiDAR Project (CCLP). The spatial coverage of the data extends landward 500 m from the shoreline to approximately the 10 m topographic contour. The density of the data is nominally 1 point per 0.7 m^2. Both data sets were provided as a tiled structure (1.5 km by 1.5 km) and LAS 1.2 format (a common LiDAR data exchange format, which was introduced by the American Society of Photogrammetry and Remote Sensing; http://www.lasformat.org). The horizontal spatial reference system for these data sets is the Universal Transverse Mercator projection (NAD83, UTM Zone 10N), and the vertical spatial reference system is the North American Vertical Datum of 1988 (NAVD88).

The accuracy of the USGS LiDAR dataset was assessed by the prime contractor for the LiDAR acquisition campaign (Dewberry 2011a and 2011b). One of the metrics reported is for fundamental vertical accuracy (FVA) which is for the check points located on open terrain. For the USGS San Francisco Coastal LiDAR project, the vertical accuracy was specified to be 18 cm or less. The FVA at the 95 percent confidence level is 0.05 m for the National Oceanic and Atmospheric Administration (NOAA) LiDAR data and 0.12 m for the USGS LiDAR data. The horizontal accuracy is 2.0 m at the 95 percent confidence level for both datasets. So both regions meet and exceed project specifications for vertical accuracy.

We derived a DEM based on these data only after substantial processing of the LiDAR data. We converted the LiDAR point data cloud to raster datasets that provide terrain elevations for ground positions at regularly spaced horizontal intervals. This DEM is used in subsequent analyses. We also developed a DSM and discuss it in the section Digital Surface Model below.

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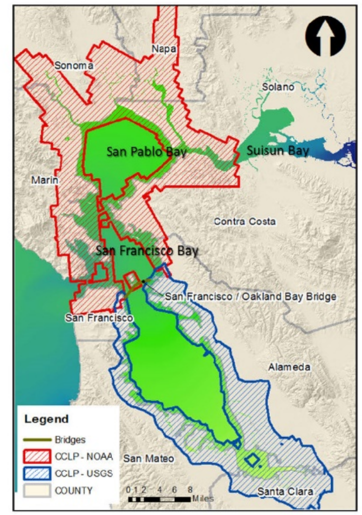

Figure 2. Sources of LiDAR Data Available for Studying the Impact of Climate Change on the Transportation Network of the SF Bay Area. California Coastal LiDAR Project - NOAA/USGS SF Bay LiDAR data. The LiDAR data were acquired in 2010–2011.

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Table 3. LiDAR Datasets Used for Potential Inundation Analysis (see Dewberry 2011a for USGS accuracy and 2011b for NOAA LiDAR accuracy)

Name	Projection		Accuracy	
	vertical	Horizontal	Fundamental vertical	Horizontal
NOAA California Coastal LiDAR Project	NAVD88	NAD83, UTM Zone 10N	0.05 meters at 95% confidence level	2.0 meters at 95% confidence level
USGS California Coastal LiDAR Project	NAVD88	NAD83, UTM Zone 10N	0.12 meters at 95% confidence level	2.0 meters at 95% confidence level

For the North Bay data (NOAA region), we obtained both the LiDAR point data and the DEM data so that we did not need to create a DEM for this region. Since the data were provided as a tiled structure, a total of 649 tiles from the DEM dataset were combined into one large file to determine the connectivity to the San Francisco Bay.

For the South Bay data (USGS region), we obtained the LiDAR point data only and therefore had to derive a DEM from them. Because the LiDAR point data contained classification information for each point, we selected certain classes of points, which represent ground surfaces (Class 2 = Ground Class; Class 9 = Water Class). That is, we used all points classified as a ground class. In addition, we included the points that are classified as water to derive the DEM as most of these points were from mudflats (wet ground). The LiDAR sensor uses near-infrared laser pulses. Water bodies absorb near-infrared light and hence do not have any return pulse. Therefore, including the LiDAR points of the water class that are mainly from mud flats or tidal flats is beneficial for generating more accurate and realistic ground elevation data for our study area.

Since the LiDAR point density is sufficiently high, we applied a linear interpolation method to convert the LiDAR point cloud into a DEM. In this procedure, if a single LiDAR point is found in a pixel (1m x 1m), it represents that pixel. If a pixel height is missing, it is interpolated from the surrounding pixels. If multiple LiDAR points exist in a pixel, then the pixel is assigned the highest height observed in that pixel. The interpolation was conducted on a tile-by-tile basis (the original data comprised 712 tiles, each 1.5 km by 1.5 km). If the interpolation is conducted one tile at a time, the edges of each DEM might have some discrepancies between neighboring tiles. In order to cope with this problem and create a seamless DEM data set, we prepared overlapped LiDAR point data sets between the tiles. Accordingly, we produced 1.7 km by 1.7 km tiles that have 100-meter overlap on each shared side between tiles. We conducted a linear interpolation and converted the LiDAR point clouds to a DEM for each tile and clipped out the

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DEM to the original tile size (1.5 km by 1.5 km). Finally, we combined all tiled DEMs into one large file to match the North Bay data.

DEMs created with high resolution LiDAR, as done in this study, produce surfaces that are more accurate and with less smoothing than is provided by the National Elevation Dataset (NED) from the USGS. Like our DEM, NED is a raster dataset, but NED has a horizontal resolution of either 30 or 10 m. In NED datasets, small but important objects, like seawalls, levees, bridges and reventments, would not be detected. In our DEM these important objects are both detected and well approximated. The USGS (http://ned.usgs.gov/Ned/accuracy.asp) points out that NED inherits the accuracy of the source DEMs. Likewise, our DEM inherits the accuracy of the source LiDAR used in its creation (see Table 3). This allows us to better predict where low-lying areas might be flooded, overtopped, and isolated from the rest of the land area.

Comparison of DEM Techniques

We selected three tiles, each of size 1500 x 1500 m, to compare the NOAA-supplied DEMs in our northern region (see Figure 3) with DEMs that utilized the same methods to produce DEMs in our southern region. Since the LiDAR point data is already classified into ground and non-ground, we selected only ground points and interpolated by using linear interpolation. We then calculated the difference between these two data sets with each tile comprising 2,250,000 raster values for height.

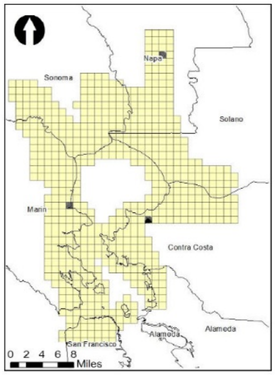

Figure 3. Tiles Used to Compare NOAA-Supplied DEMs and Study-Produced DEMs. The yellow grid represents the North Bay areas for which NOAA supplied LiDAR data and DEMs. Black squares represent the tiles used for the comparison.

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We conducted quality control by comparing the pixel height values of the sample tiles to those created using the methods reported in this paper. Figure 4 shows the result of this comparison. More than 63 percent of the raster elevations were within 1.5 inches of each other, and nearly 80 percent were within 2.5 inches. Ninety percent of the elevations were within 5.5 inches of each other. Since our methodology has a high correspondence to that used by NOAA, we applied our DEM methodology to the areas south of the Golden Gate Bridge for which no DEMs had been produced.

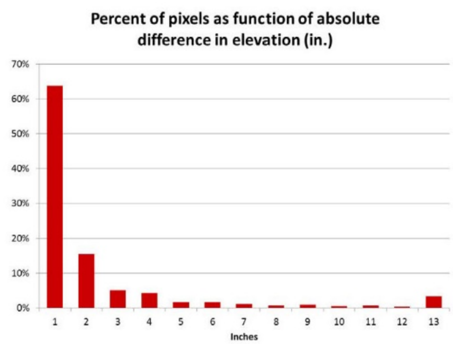

Figure 4. Percentage of Test Pixels (in 1m x 1m DEM cells) as a Function of Absolute Difference in Elevation (inches). Three test tiles (Figure 3) were used to compare two methods for producing DEMs: NOAA's and the methods reported in this paper.

Digital Surface Model

We prepared a digital surface model (DSM) to supplement the DEMs used in our analysis. DSMs contain information about not only the height of bare ground, but also the surface elevations of the objects on the ground (such as buildings, trees, houses, levees). In general, converting LiDAR points to a DEM requires filtering procedures that remove non-ground LiDAR points from the LiDAR point cloud. Although these filtering methods are well developed and in general perform adequately, some transportation objects (such as highways and bridges) may be removed during the LiDAR data filtering procedures used to create a DEM from LiDAR data. In these instances, using only a DEM may result in a false determination of the connectivity of the ground transportation network under a flooding event scenario.

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It is common to estimate the potential for inundation of the transportation network using only DEMs with geo-data layers within a GIS (e.g., Heberger et al. 2009; Knowles et al. 2009 and 2010). However, this approach is premised on the assumption that the elevation of transportation features and ground surfaces are the same. In some cases (e.g., local roads) this assumption is convenient and works well. However, in many cases (e.g., raised highways and bridges), the inundation of transportation features are overestimated due to the elevation error imposed by simply mapping ground surfaces. Figure 5(a)-5(d) illustrate an example showing the difference between a DEM and a DSM near the Point Richmond area. Here different surface products can produce differing inundation estimates.

Our method for creating DSMs is similar to that used in the creation of the DEMs. For the DEM we use only points representing ground surface (Class 2 = Ground Class; Class 9 = Water Class). In contrast, we included all classes of LiDAR points, except Class 7 (= Noise Class), to generate the DSM. We conducted the interpolation as we did for creating the DEM on a tile-by-tile basis. In this procedure, if a single LiDAR point is found in a pixel (1m x 1m) it represents that pixel. If a pixel height is missing, it is interpolated from the surrounding pixels. If multiple LiDAR points exist in a pixel, then the pixel is assigned the highest height observed in that pixel. To create seamless raster data, we prepared overlapped point data sets between the tiles. That is, we reproduced 1.7 km by 1.7 km tiles with 100-meter overlap on each side between tiles. We used a linear interpolation algorithm to convert the LiDAR point data into the DSM. Finally, we combined all tiled DSMs into one large file.

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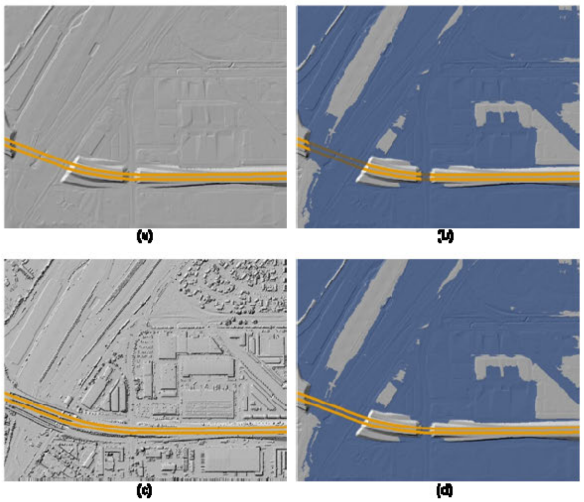

Figure 5. Example of the Difference between Using a DEM and a DSM Near Point Richmond. (a) Image is a DEM, (b) is the inundation area estimated with the DEM that shows the highway as inundated, (c) image is the DSM, and (d) shows the inundation area estimated using the DEM, but the highway elevation comes from the DSM that correctly represents the connectivity of the highway.

Water Flow Pathways

Previous studies, conducted by Heberger et al. (2009) and Knowles et al. (2009, 2010), also used high spatial resolution DEMs (2 m by 2 m horizontal resolution) to determine areas that are potentially flooded by sea-level rise and extreme storm events. However, those studies used water depth alone for estimating areas that would experience flooding. Consequently, some areas may be falsely classified as potential inundation areas because the studies do not consider water pathway, as discussed in the following paragraph, and some areas could be surrounded and thus protected by higher ground or objects such as levees. An example of solely using a DEM and water depth to determine a potential inundation area is illustrated in Figure 6.

In this study, we have sufficiently dense LiDAR coverage (nominally 1 point per 0.7 m²) to allow us to create 1m x 1m rasters containing elevation point data. This is roughly four times

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finer horizontal resolution than used in prior studies having 2m x 2m rasters for elevation point data. This increased horizontal resolution, combined with the high vertical accuracy of these datasets, leads to higher resolution DEMs and DSMs. In addition, we incorporate water flow pathways to improve our ability to estimate flood inundation areas. To do this, we used the connectivity of regions to waters of the San Francisco Bay or Pacific Ocean. The delineation of regions is calculated by using the DSM to obtain the elevations of artifacts, like roadways and levees, to determine whether they are barriers bounding a region or not. The regions that were not connected to water were excluded for the inundation estimation.

First, we compared the ground elevation surface (from the DEM) and the water surface raster. We then select the regions where the ground elevation was lower than the projected peak water level. We analyzed only the regions that are connected to the San Francisco Bay or Pacific Ocean and we removed all other regions that are not connected to these water sources. Hence, the regions that are not connected to the Bay or ocean are excluded from consideration as being in a potential inundation area. The "Region Group" function in ArcGIS was used to determine the connectivity. The function calculates "the identity of the connected region to which that cell belongs" (ESRI 2009). By comparing the elevation of the land and water surface, several regions where the lands are lower than the projected peak water levels were selected. Once selected, each region was assigned with different IDs and each cell in the same region given a same value (a region ID).

We used the DEM to validate region connectivity by eliminating the possibility of discontinuous polygons being hydraulically connected, resulting in valid flow pathways. This is analogous to the method employed by the NOAA Costal Service Center: they used the ArcGIS Spatial Analyst extension and applied similar procedures to account for local/regional tidal variability of mean high higher water for each area. Sea-level rise is added to MHHW. They also use hydrological connectivity to exclude hydrologically unconnected polygons and improve on the bathtub approach to modeling inundation. A description of their methodology can be found at: http://www.csc.noaa.gov/slr/viewer/assets/pdfs/Inundation_Methods.pdf

Figure 6 shows an example of the difference between using *water depth only* and the *water depth and flow path* inundation estimation methods. The *water depth only* method shown in Figure (6c) is based on the DEM only and does not account for the connectivity to the Bay or Pacific Ocean. The inundation estimation mapped in Figure 6d is based on both the DEM and the path that water flows inland over the terrain. Although the inland area is lower than the water level on the outside of the levee, the inland area is not inundated due to the protecting structures or levees. However, high water levels do cause levee stress that can eventually lead to failure, defined as a levee breach. Besides levee overtopping, high water loading functions can produce other failure mechanisms, such as sliding, slump spread, seepage and erosion (Moss and Eller 2007). The probability of levee failures due to high water levels during storm events is estimated to be 0.0579 per year according to the Delta Risk Management Strategy (DRMS) study (URS 2009). Although inundation or repeated inundation could lead to levee failure, failure rate modeling and prediction is outside the scope of this project.

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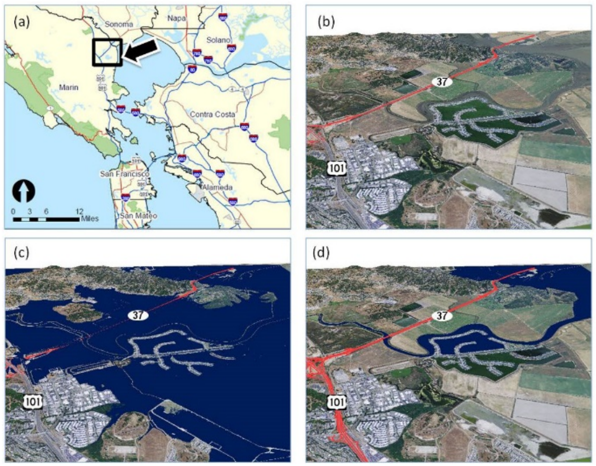

Figure 6. An Example of the Difference Between Inundation Estimation Methods. (a) Overview of an example area, (b) before inundation, (c) inundation estimation with water depth only, and (d) inundation estimation with water depth and flow path.

Transportation GIS Data

In order to conduct quantitative estimation of the impact of sea-level rise on transportation, we need accurate geo-data layers of transportation infrastructure. Various sources provide GIS data sets for different resources (road, rail, airports, ports, etc.).

Table 4 shows currently available GIS data sets relevant for our study on impact analysis. We list the most accurate and up-to-date data sets available. In general, most of these data are publicly available, so that we are able to download and use them directly. However, in some cases, additional processes are needed to improve the quality and usefulness of the data sets. For example, fire station data extracted from the FEMA Hazus (Hazard US) database has a limited number of stations and with outdated information. We employ an address matching algorithm (from the lists of station addresses) to create an accurate data set for fire stations.

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Table 4. GIS Data to Study the Impacts of Sea-Level Rise Relevant to Transportation Infrastructure

Categories	Data sources	Notes
Roads	Streetmap Pro (ESRI) (Sept. 2010)	The road network has routing information so that a network analysis is possible
Rails	Streetmap Pro (ESRI)	
BART	MTC	Bay Area Transit database
Airports (Runways)	Streetmap Pro (ESRI)	Transportation database
Healthcare facilities	California Statewide Health Planning and Development	Accessible via Cal-Atlas (http://www.atlas.ca.gov)
Fire stations	Address matching	The locations are geocoded by using Streetmap Pro street network.
Ortho images	National Agriculture Imagery Program (2009)	1 m spatial resolution, RGB, and near infra-red.

Datums

A diagram of the tidal datum elevations at the Alameda Station, Alameda, California, is illustrated in Figure 7. This is a display of the averages for the 1983–2001 epoch. Displayed tidal datums are Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Tide Level (MTL), Mean Sea Level (MSL), Mean Low Water (MLW), and Mean Lower Low Water (MLLW). In brief, MHW is the mean high water which is the average height of all high tides. MHHW is the mean higher high water, which is the average height of the higher of the two daily high tides. MLW is the mean low water, which is the average height of the two daily low tides. For more formal definitions of these and other tidal datums, see Heberger et al. (2009) or go to NOAA's website: http://tidesandcurrents.noaa.gov/datum_options.html.

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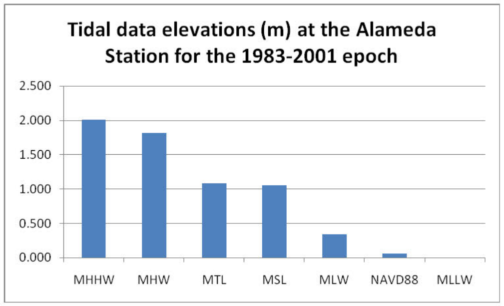

Source: Figure produced by Biging, Radke, and Lee using data from NOAA Tides and Currents (http://tidesandcurrents.noaa.gov/data_menu.shtml?unit=0&format=Apply+Change&stn=9414750+Alameda%2C+CA&type=Datums).

Figure 7. Different Tidal Datums at the NOAA Alameda Station.

Since the San Francisco International Airport (SFO) does not have a tidal station, the Alameda Station (NOAA Station ID: 9414750), being in the proximity of SFO, is used in this example to display tidal and reference datums. MSL is slightly more than 1.0 meter (1.051 m) above the MLLW reference datum, or 0.98 m above the NAVD88 reference datum at Alameda Station averaged over the 1983–2001 epoch. At this location, diurnal tidal heights can vary by over 2 m (see Figure 8).

DEM (and DSM) data are essential for undertaking the rising sea level and 100-year extreme storm inundation analysis on the transportation network of the greater Bay Area. Figure 9a shows a close-up of a DEM produced with our methodology (see the section Ground Elevation Data above) at SFO. In this figure (also refer to Section 3.1 Ports and Airports below and Figure 14), we can see the height of the runways exceeds approximately 3 m above the vertical datum (NAVD88) in this section of the airport. However, in Figures 14 and 15 it can be seen that large portions of the airport are below 2.6 m.

The diurnal tidal heights at Alameda Station can reach approximately 2.0 m above the MLLW datum, as evidenced from the 8/19/2010 daily tide predictions (Figure 8). The tide predictions from this NOAA Tides & Currents website can be projected into the future or back into the past for two calendar years only. The MHHW for the Alameda location is 2.01 m above MLLW, or 1.95 m above NAVD88, for the 1983–2001 epoch (see: http://www.ngs.noaa.gov/newsys-cgi-bin/ngs_opsd.prl?PID=HT0890&EPOCH=1983-2001). Thus, if sea level rise reaches 1 m over present mean sea level, SFO would be overtopped on occasions when astronomical tides reach 2 m. However, sea level actually exceeds high tides on occasions when storm effects elevate sea levels. As discussed more fully in section 3.1 Ports and airports below, this critical facility could

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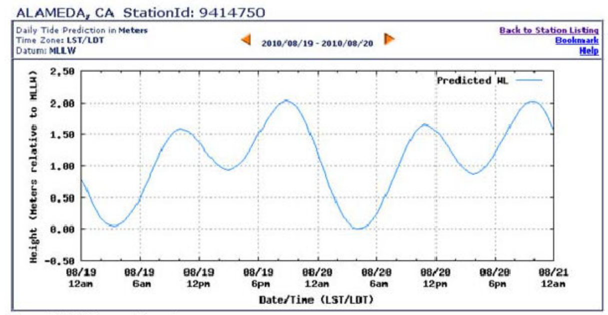
be overtopped if mean sea levels rises 0.5 m, when a 100-year storm event coincides with high astronomical tides.



Source: NOAA Tides and Currents
http://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=9414767

Figure 8. Daily Tide Height Prediction in Meters Relative to MLLW at Alameda Naval Air Station.

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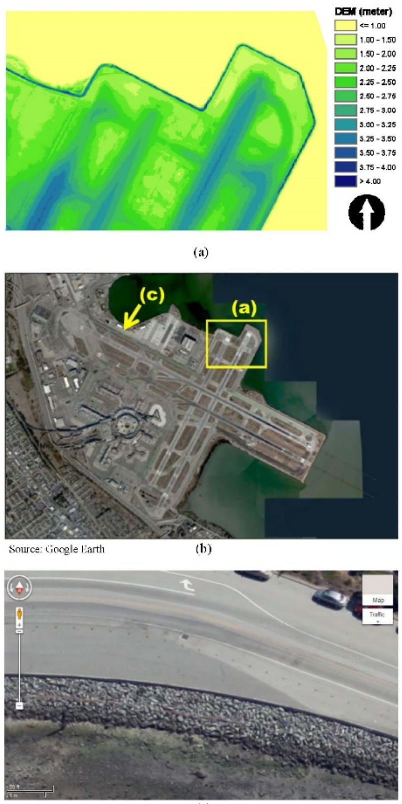

Figure 9. An Example of the DEM: San Francisco International Airport. (a) Detailed view of the DEM for SFO, (b) the overview of the area (Google Earth), and (c) an oblique view (Google Earth) of a retaining structure at SFO pointed to in (b). The elevation data set is referenced to NAVD88 vertical datum.

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Peak Water Levels

As pointed out in section 2.1 Potential inundation, land surface (elevation) models and peak water levels are the key components needed to estimate accurate potential inundation areas in the San Francisco Bay region. As stated earlier, our model has four sea-level rise (SLR_x) increments {x: 0 m, 0.5 m, 1.0 m or 1.4 m} to which we add the 100-year extreme storm event (ESE_{100}) without sea-level rise. Thus, peak water level is: $PWL_x = SLR_x + ESE_{100}$. The upper sea-level rise value of 1.4 m corresponds to the mean projection in year 2100 of sea-level rise under the climate models examined (Figure 1).[4]

Knowles (2009) used the TRIM-2D hydrodynamic model and historic variability based on long term gauge readings to model hourly water levels throughout the Bay over 100 years as measured from the NAVD88 datum.[5] Based on a 100-year projection of high water levels (with and without sea-level rise), he determined the high water levels which corresponded to the 100-year return interval. This data was provided by Dr. Knowles (USGS) to this project as a raster of 100 m horizontal resolution (Figure 10). This provides the water levels associated with a 100-year storm which, in our parlance, is the 100-year extreme storm event (ESE_{100}). This high water surface elevation is also used by Heberger et al. (2009). While the water levels are continuous, for interpretation purposes, they were placed into discrete classes to make it easier to read the water heights at the airports and other locations.

It is important to point out that we do not project localized rainfall, nor do we incorporate wave runup, wind-driven waves, or river stage forecasts into our model for peak water levels. These and other factors will cause variations in the PWLs that may lead to localized flooding. It should be clear that our predictions are approximations to a complex hydrodynamic system, and inferences should be tempered by this fact.

[4] Knowles (2009, 2010) uses an upper value of 1.5 m. So for his work, the maximum peak water level is $PWL_{(1.5)}$.

[5] We are able to compare the elevation of water and land surfaces (from geo-registered LiDAR data) without any conversion, since Knowles' 100-year flood elevations were measured from the same datum (NAVD88) as the LiDAR data.

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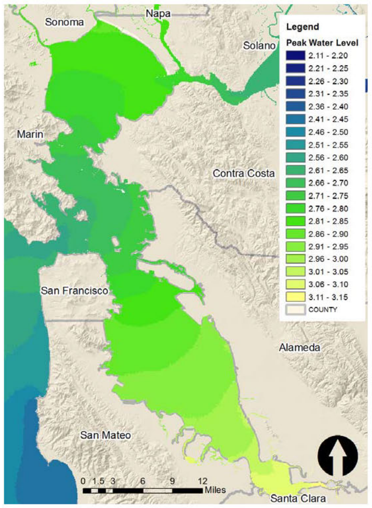

Source: Noah Knowles, USGS.

Figure 10. A 100-Year Storm Event Peak Water Surface in Raster Format. Water level elevations are in meters above the NAVD88 reference datum.

2.2 Assessing Vulnerability of the Road Network

First Responder Accessibility

Metrics can define and quantify the vulnerability of perturbed networks such as those that are inundated by flooding (Miller, 1999). Santos et al. (2010) outlines four types of reliability metrics: connectivity, travel-time, capacity, and vulnerability. Studies have successfully quantified the impact of flooding on interurban networks using county-scale data to identify critical transportation links (Sohn 2006), but the resolution and impact have remained relatively coarse. These regional-scale studies often contain modeling uncertainties that are not easily recognized, let alone quantifiable. We employ an accessibility metric at a local scale to quantify the disruption in movement in the road transportation system due to flooding. We choose accessibility to first responders to illustrate local disruption in the system, as fire stations are dispersed throughout the Bay Area in a planned attempt to evenly serve the entire population. Although we choose first responders, as their locations are planned and evenly distributed to

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best serve household access in the communities, the method is universal and could serve to model the localized disruption in movement between any service and the population at large.

This metric has its roots in a class of spatial analysis models known as location- allocation models that attempt to improve or optimize *demand* conditions by altering the allocation of *supply*. These mathematical models can solve a number of conditions where demand and supply are both points (point-to-point model), where supply is mapped as a point and demand lies within a region (point-to-polygon model), or where both demand and supply are mapped as regions (polygon-to-polygon model) (Radke and Lan 2000). We apply the point to polygon model here, where supply represents first responders (fire stations) and demand are the households mapped as regions of accessibility.

The simplest location-allocation solution to the point-to-polygon model is the Voronoi or Thiessen polygon model. Here movement in the system is unconstrained and all space (demand = regions containing households) is allocated to the closest supply point (the location of the first responders). Although a powerful concept with its roots embedded in graph theory, this solution is not very realistic in a ground transportation network where movement is constrained along roads.

We employed a constrained location-allocation model and measured the accessibility of first responders (supply) to households (demand) in a region demarcated by the first responder's apparatus traveling along the shortest path, the route of least impedance or resistance, to all households in the region. We assumed that all first responders optimize the cost (defined as time travel = speed limit X distance) of travel and choose the least-cost path. In this instance, the optimum path is the shortest path that is equal to the shortest time travel path. In other words, the first responder takes the fastest route to the household.

We measured this and map a service area for all first responders. We thresholded and classified the accessibility of each first responder in increments of 1 minute for the first 10 minutes of travel. We modeled present-day conditions and generated a baseline of accessibility. We then modeled four peak water levels, as discussed previously in the sections 2.1 Potential inundation and Datums above. After each run of the model, we subtracted our baseline and calculated a surface of loss in accessibility, the impact of flood inundation on the road transportation infrastructure and local access. This metric of impact is applicable to other forms of transportation infrastructure and other service (supply) infrastructure entities, such as hospitals, schools, work, food, social services, and many other basic needs that require movement from an origin to a destination along a transportation network.

Node-To-Node Accessibility Impacts on the Major Traffic Corridors

The impact of inundation due to rising sea levels and extreme storm events will be felt far beyond the local neighborhoods that are flooded. The Bay Area's transportation network includes and is critically dependent on several major highways that serve as not only the main building blocks of its topological skeleton, but also the main regional corridors of traffic flow. As a result, potential inundation of some of these major road sections has the potential of disrupting traffic flow across the entire region.

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Traversing a region involves an origin-destination event that would likely begin in a local neighborhood network, travel the shortest-time path to the nearest intersection (on ramp node) of the major highway system, travel the shortest-time path along that regional system to the nearest intersection (off ramp node) of the local destination network, and proceed along the shortest-time path route to the final destination. Impacts due to inundation on the major highway corridors would serve to disrupt regional travel flows. We modeled this potential impact on regional traffic flow by measuring the disruption of the major node-to-node travel times through various inundation scenarios. Figure 11 represents the major nodes and links of the major traffic corridors in the region that are at risk of potential inundation due to rising sea levels and serves as our map base in this regional analysis. Although we measured the travel time impact from node-to-node in this major highway network, we included the entire local and regional network in our shortest-time path calculations.

Applying the point-to-point location-allocation model, we mapped each supply node as a major intersection in our regional network sample (mapped in Figure 11) and demand as all the other major nodes in the regional network. We chose the nine counties surrounding the San Francisco Bay as the extent of our transportation network region. We calculated the point-to-point accessibility time for all node pairs using the current posted traffic speeds. Although all traffic condition scenarios throughout the day, week, month, and year could be modeled using our method, it would only serve to sensitize a variety of road condition scenarios unrelated to inundation and not relevant to the current study objectives. We modeled through a series of inundation scenarios and report the node-to-node impact on accessibility between the major corridor intersections.

We quantified regional vulnerability by calculating the loss of accessibility between nodes (highway intersections). We calculated the travel time (in minutes) in normal condition and the travel time under the potential inundation. In order to depict the loss of accessibility, we used the travel time increment under different conditions as shown below.

$$\textit{Increment of travel time} = \frac{\textit{Travel time under inundation}}{\textit{Travel time in normal condition}}$$

By using this metric, we assessed the vulnerability of road network connectivity around the Bay Area, which is exposed to the inundation due to sea-level rise and extreme storm events. Because we mainly focused on physical connectivity and the increment of travel cost (time or distance), we did not include any travel forecast (or behavior) model in our approach.

The failure of a specific road link causes more severe consequences when the alternative route requires more travel time. In addition, when a greater demand exists, the importance of the link increases. Hence, we calculated the weighted loss of accessibility by including traffic volume information (annual average daily traffic: AADT) in our approach, as shown below:

$$\textit{Weighted increment of travel distance} = \textit{increment of travel distance} \times \textit{AADT}$$

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We estimated the increment of travel distance for a specific link by subtracting the travel distance (in meters) under the normal condition from the travel distance under the disruption (inundation). Then we multiplied by the AADT value for the link to estimate the weighted loss of accessibility. We used traffic volume data (2010) from Caltrans (http://traffic-counts.dot.ca.gov/) to extract AADT for our analysis. Because our approach calculated node-to-node accessibility, multiple AADT values might exist for a specific link. As we assume complete loss of the connectivity between two nodes for our calculation, we used the maximum AADT value among the AADT values of the route segments.

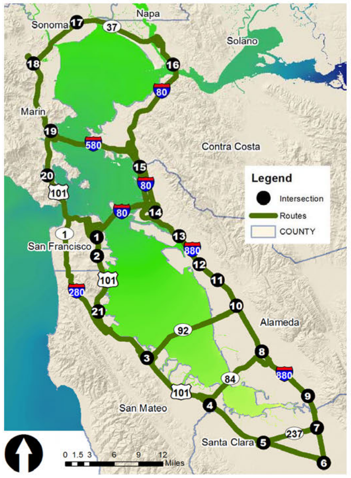

Figure 11. The Nodes and Links of the Major Traffic Corridors in the Region of Potential Inundation Due to Rising Sea Levels.

Hinterland Accessibility

Finally we employed a similar point-to-polygon location-allocation model to the one described in the section 2.2 First responder accessibility to measure the impact of accessibility in the hinterland of the major system. This models the local neighborhood network from origin to the nearest (in time) major highway node (on ramp), and it models the local neighborhood network from the major highway nodes (off ramps) to the final destination. Here the major highway intersections are the supply points and the regional hinterland the demand.

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Section 3: Results

3.1 Potential Inundation of Transportation Infrastructure

Roads and Rails

By using ground elevation models, digital surface models, and GIS data layers, we estimate the length of roads affected by inundation. The high water levels of a 100-year extreme event are projected with sea-level rise levels of 0 m, 0.5 m, 1.0 m, and 1.4 m. Under current conditions (see Table 5), we estimate 594.5 miles (49.3 miles of highways and 545.2 miles of local streets) of roads are at risk of a 100-year extreme storm event $PLW_{(0)}$. With $PWL_{(1.4)}$, that is a 1.4 m sea-level rise and 100-year extreme storm event, 1,688.2 miles of roads (169.5 miles of highways and 1,518.7 miles of local streets) are at risk. With $PWL_{(1.4)}$, the length of roads at inundation risk increases nearly three times compared to $PWL_{(0)}$, the 100-year flooding event without sea-level rise.

In this study, we estimate the length of roads by using not only elevation (depth) data, but also water path (connectivity to the water of the San Francisco Bay). Table 5 shows the results of the road inundation estimation which incorporates both the depth data and water path. In contrast, Table 6 shows the results of the road inundation estimation by using depth-only data (without water path). As expected, when we applied the depth-only method (see Table 6), all the results are overestimated regardless of water levels. However, the difference of the inundation length estimation between these two methods decreases as the water level increases. As the water level goes up, blocked water paths (by flood protection structures) can be connected, if the water level is higher than the structure. Hence, when the water level is low, more areas are determined as non-inundation because these areas are not connected to the San Francisco Bay or Pacific Ocean. When we use the depth-only method, the estimated length of risk is 744.2 miles and this approach overestimated by 25 percent (149.7 miles) compared to the extreme storm event (with no sea-level rise). Figure 12 shows the miles of highways and local roads in the Bay Area that are vulnerable to a100-year extreme event.

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Table 5. Miles of Road at Risk to a 100-Year Extreme Event by County and Type (Highway and Local) Using Water Depth and Water Paths Analysis

	Current risk		Risk with sea-level rise					
			0.5 m		1.0 m		1.4 m	
COUNTY	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)
ALAMEDA	1.0	46.4	12.4	195.3	21.6	358.5	31.7	471.3
CONTRA COSTA	0.1	3.5	0.1	11.3	2.7	29.1	4.2	49.4
MARIN	14.1	92.6	19.7	142.5	25.0	185.8	28.4	210.8
NAPA	0.9	5.2	1.0	7.6	1.0	9.6	1.2	14.4
SAN FRANCISCO	0.2	2.9	0.6	11.0	3.1	40.1	4.3	52.3
SAN MATEO	15.2	256.9	36.0	341.6	57.3	384.4	61.0	407.6
SANTA CLARA	5.9	75.5	8.7	113.6	9.9	142.6	11.0	177.6
SOLANO	4.2	7.0	6.7	19.3	14.6	48.7	15.9	59.2
SONOMA	7.6	55.2	8.5	65.3	10.1	72.1	11.9	76.2
Total	49.3	545.2	93.7	907.5	145.4	1270.8	169.5	1518.7

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Table 6. Miles of Road at Risk to a 100-Year Extreme Event by County and Type (Highway and Local) Using Water-Depth Only

	Current risk		Risk with sea-level rise					
			0.5 m		1.0 m		1.4 m	
COUNTY	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)
ALAMEDA	3.0	101.5	13.3	231.7	22.9	396.0	33.4	496.2
CONTRA COSTA	2.2	6.7	2.4	18.1	2.9	37.3	4.3	54.7
MARIN	14.5	108.8	19.9	153.7	25.0	191.7	28.4	213.5
NAPA	0.9	5.9	1.0	7.7	1.0	10.3	1.2	16.0
SAN FRANCISCO	0.3	6.8	1.1	20.6	3.1	51.1	4.3	64.1
SAN MATEO	16.4	287.6	37.2	349.5	57.5	389.8	61.2	412.2
SANTA CLARA	7.0	98.3	8.9	134.4	10.1	178.6	11.2	206.2
SOLANO	5.3	14.6	10.4	31.5	14.9	50.0	16.3	60.4
SONOMA	7.6	57.0	8.5	66.3	10.2	72.6	12.1	77.5
Total	57.1	687.1	102.7	1013.5	147.7	1377.3	172.5	1600.7

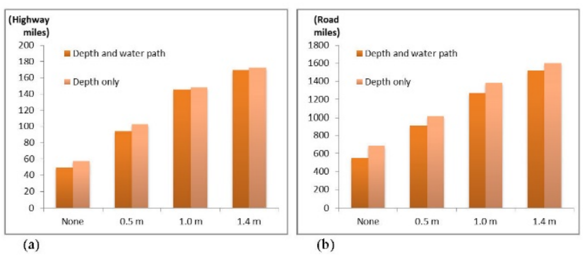

Figure 12. Miles Vulnerable to a 100-Year Extreme Event in the San Francisco Bay Area. (a) Highways, (b) local roads.

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The rail system in the Bay Area is important because the rail system transports a large amount of freight and people. Hence, disruption of operations brings significant impact and consequence to the region. We estimated the length of rails at risk to a 100-year flood event combined with different sea-level rise scenarios. With $PWL_{(1.4)}$, 155.7 miles of railways will be potentially at risk. With no SLR and a 100-year flood ($PWL_{(0)}$), 36.3 miles of railways will be at risk (see Table 7). Table 7 shows the amount of rails at risk when we use both water depth and water path analysis; whereas, Table 7 only uses water depth in determining inundation areas.

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Table 8 shows the results from using the depth-only method, which overestimates the amount of rails at risk.

Table 7. Miles of Rails at Risk to a 100-year Extreme Storm Event by County Using Water Depth and Water Paths Analysis

COUNTY	Current risk	Risk with sea-level rise		
		0.5 m	1.0 m	1.4 m
ALAMEDA	6.9	23.4	46.7	62.7
CONTRA COSTA	0.2	4.5	10.1	18.9
MARIN	9.0	14.5	18.7	19.7
NAPA	3.2	6.5	7.4	8.4
SAN FRANCISCO	0.0	1.2	1.9	2.2
SAN MATEO	4.9	8.7	10.7	12.7
SANTA CLARA	4.6	5.6	6.9	7.4
SOLANO	1.1	1.8	4.4	5.0
SONOMA	6.4	12.2	17.3	18.8
Total	36.3	78.4	124.0	155.7

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Table 8. Miles of Rails at Risk to a 100-Year Extreme Storm Event by County Using Water Depth-Only Data

COUNTY	Current risk	Risk with sea-level rise		
		0.5 m	1.0 m	1.4 m
ALAMEDA	11.0	26.8	48.6	63.1
CONTRA COSTA	1.0	5.3	10.9	19.3
MARIN	10.2	15.0	18.7	19.8
NAPA	4.4	6.6	7.7	8.4
SAN FRANCISCO	0.6	1.3	1.9	2.2
SAN MATEO	5.8	9.9	12.9	15.6
SANTA CLARA	5.9	7.4	8.9	9.6
SOLANO	2.1	3.3	5.3	6.1
SONOMA	6.4	12.2	17.4	18.8
Total	47.5	87.8	132.3	163.0

Ports and Airports

It is evident that sea-level rise and flooding pose risks to the Bay Area's ports and airports, primarily because they are in low lying coastal areas. Even if these facilities are adequately protected by levees, dykes, roads, or other human-made barriers (as seen in Figure 9), for current climate conditions, there is increased risk of failure and overtopping as a result of projected SLR in combination with 100-year flooding.

Figure 13 gives a synoptic view of the areas in the San Francisco Bay region we project to be impacted by a 100- year storm event in combination with either no sea-level rise ($PWL_{(0)}$) or 1.4m sea-level rise ($PWL_{(1.4)}$). It is clear that the ports and airports of the San Francisco Bay region are impacted under one or both of these scenarios. This is discussed in more detail below. There is generally good correspondence between Figure 13 here and Figure 5a in Knowles (2009, 2010). Our figure shows a larger extent of area affected by inundation under $PWL_{(1.4)}$ in the North Bay, particularly in Marin and Sonoma counties. Knowles (2009, 2010) excluded wetlands from his analysis, whereas we did not. Thus our work depicts the wetlands of the south Bay as inundated in a 100-year extreme storm. The differences between our work and Knowles' at the Oakland International Airport and San Francisco International Airport are discussed below.

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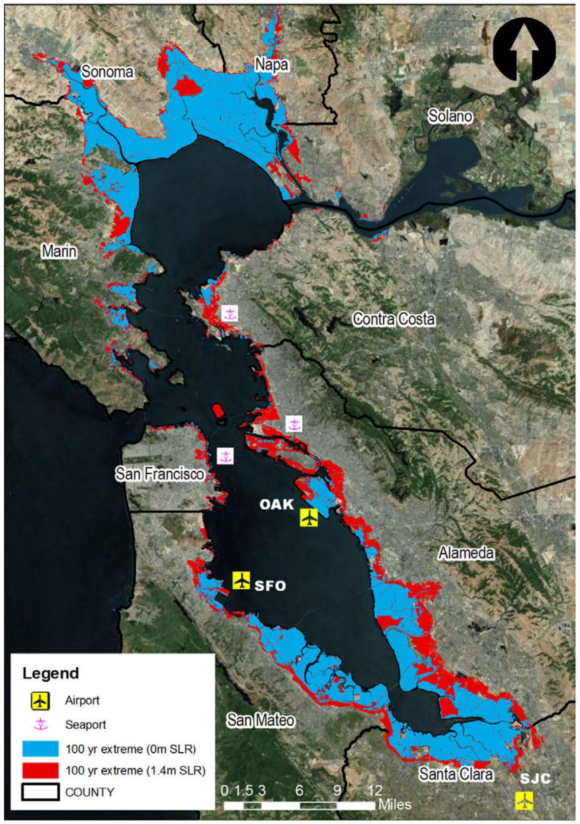

Figure 13. Locations in the San Francisco Bay Area Projected to be Impacted by a 100-Year Extreme Storm Event without and with 1.4 m Sea-Level Rise.

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Our DEM shows that large portions of the runways at the SFO (see Figure 14) and the OAK (not depicted) are less than 2.6m above the NAVD88 reference datum. Predicted water levels for the 100-year extreme storm event ($PLW_{(0)}$) are approximately 2.8–3.0 m above the NAVD88 datum throughout much of the Bay (see Figure 10). Thus extreme storm events alone may be sufficient to cause inundation at these airports.

Figure 14 shows no inundation at the (SF0) when the water level reaches 2.4 m above the reference datum (NAVD88). Although a large portion of the airport is lower than 2.4 m above the reference datum, there is no inundation inside of the airport property at this water height because there is a partial seawall (BCDC 2009). Figure 15 shows the potential for inundation when the water height reaches 2.5 m near SFO. The DEM for the airport shows the north part of SFO is particularly vulnerable because the boundaries of the north part of the airport are lower than other areas, as revealed by the DSM of the area (In Figure 15, the white arrows show the initial inundation water paths).

We calculated the ratio of runways at risk to a 100-year extreme storm event under various SLR values. Although there are several critical structures and facilities in airports, we calculated the inundation for the runways because this is a good representation of airport functions. Particular attention should be paid to the fact that the runways of both SFO and OAK are at risk for a 100-year flood event even without any sea-level rise (Figure 16).

All runways will be nearly 100 percent inundated with $PWL_{(1.0)}$ and entirely inundated with $PLW_{(1.4)}$. For the Oakland International Airport, the runways at the North Field are more vulnerable because these runways are located on the lower elevations (see BCDC 2011 for inundation depth at OAK with a 0.4 m SLR in conjunction with 100-year flood event). However, all runways at OAK will be inundated by a 100-year storm event without any sea-level rise ($PWL_{(0)}$). Of course it is likely that the airports will take actions to mitigate or reduce these potential effects.

In addition to sea-level rise that exceeds 1m, there are other pathways, not fully explored in this paper that could cause flooding. For example, high tides in the Bay routinely exceed 2 m above NAVD88, as evidenced by MHHW statistics compiled by NOAA (Figure 7). When large storms occur, they can add an additional component of anomalous sea level from barometric and wind-driven effects. This anomalous component, under extreme conditions, can add 0.5 m or more to astronomical tide levels. Thus, if mean sea level rises 0.5 m, and a large storm producing 0.5 m of anomalous sea level coincides with 2 m astronomical tides, the water level will reach 3 m, which is sufficient to cause inundation at SFO and OAK. This calculation ignores the effect of wind waves, which would add to the excess water levels and make such an event even more extreme.

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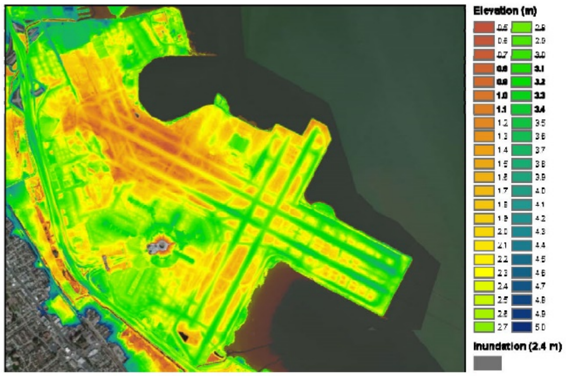

Figure 14. San Francisco International Airport. The potential inundation with the peak water level 2.4 m above the NAVD88 reference datum.

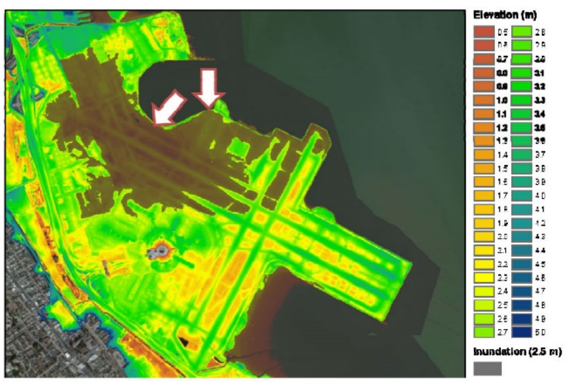

Figure 15. San Francisco International Airport. The potential inundation with the peak water level 2.5 m above the NAVD88 reference datum.

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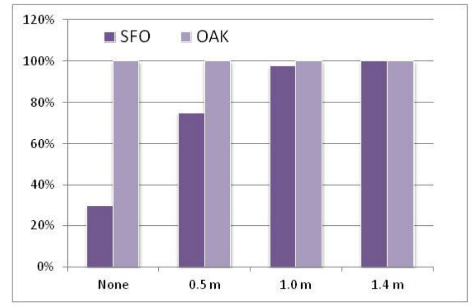

Figure 16. The Ratio of SFO and OAK Runway at Risk to a 100-Year Flood Event under Different Sea-Level Rise Values (none or 0 m, 0.5 m, 1.0 m, and 1.4 m).

The Port of Oakland

A difference between our findings (Figure 17) and prior estimates from Knowles (2009, 2010) (Figure 18) is worth mentioning. In the loop area near the Port of Oakland (7th Street and Maritime Streets; see Figure 19 for street names) slightly to the left of the center of the figure, Knowles predicts some areas of inundation (in red) with $PWL_{(1.5)}$ (Figure 18). In the current study (Figure 17), even at the highest peak water level examined ($PWL_{(1.4)}$) there is no inundation in this loop area. The approach to the Bay Bridge is at the north end of the Oakland Outer Harbor. Knowles predicts some inundation on both sides of the Bay Bridge approach with $PWL_{(0)}$ (see Figure 18). Our analysis indicates less flooding in this area at $PWL_{(0)}$ and more flooding for $PWL_{(0.5)}$ compared to Knowles. The area below the northern boundary of 7th Street experiences more extensive flooding at $PWL_{(1.0)}$ in Knowles' work than in ours with $PLW_{(1.0)}$. The same can be observed using $PWL_{(1.5)}$ and $PWL_{(1.4)}$, respectively. These same observations hold in the area directly north of 7th Street and bounded by the Nimitz freeway. Clearly the patterns are broadly similar, but the distributions of affected areas are different between these two studies. When results differ, it generally takes higher water levels to achieve inundation in our analysis than indicated in Knowles findings. We posit that this is due to the differences in the resolution of the DEMs used in these two studies and our use of the DEM, DSM, and water path (not solely water depth) in determining inundation areas.

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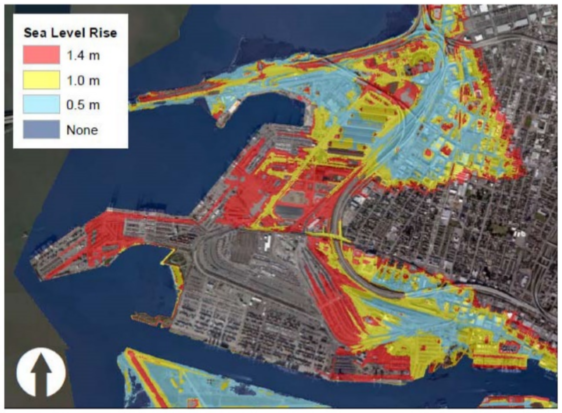
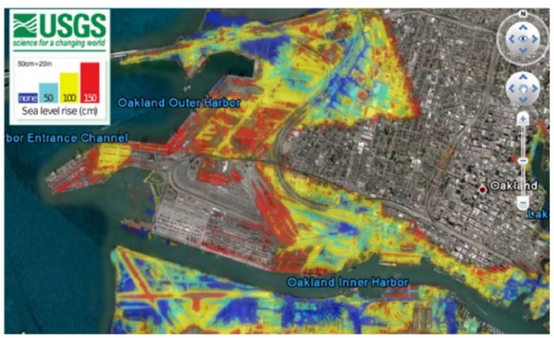


Figure 17. The Port of Oakland. This delineates the area at risk of a 100-year flood event under different sea-level rise elevations (none or 0 m, 0.5 m, 1.0 m, and 1.4 m) in the current study.



Source: USGS CASCaDE Project

Figure 18. Areas of Inundation at the Port of Oakland, Taken from the USGS CASCaDE Project (http://cascade.wr.usgs.gov/data/Task2b-SFBay/index.shtm) That Has Publicly Available Data Generated by Knowles (2009–2010). This delineates the area at risk of a 100-year flood event under different sea-level rise elevations (none or 0 m, 0.5 m, 1.0 m, and 1.5 m).

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Source: Google Earth

Figure 19. Roads of the Port of Oakland.

In Figure 20, we show the proportion of the Bay Area's three major ports that are inundated by our scenarios. With a 100-year flood with no sea-level rise ($PWL_{(0)}$), the Port of Oakland has virtually no portion flooded; about 10 percent of the Port of Richmond is flooded, and more than 25 percent of the Port of San Francisco is flooded. With $PWL_{(1.4)}$ the flooded area exceeds 50 percent at Oakland, is slightly less than 50 percent at Richmond and about 80 percent at San Francisco. Clearly these percent areas inundated with 100-year flooding are substantial by the time we reach 0.5 m of sea-level rise.

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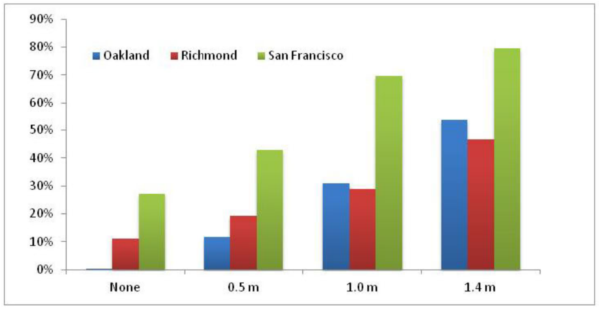

Figure 20. The Ratio of Areas of the Ports of Oakland, Richmond, and San Francisco at Risk to a 100-Year Flood Event under Different Sea-Level Rise (none or 0 m, 0.5 m, 1.0 m, and 1.4 m).

3.2 Loss of Accessibility by Inundation

As a quantitative measure of the vulnerability of the road network under potential inundation, we calculated the loss of accessibility by disruption. Below we report on the results of our accessibility analysis in two areas, Richmond in Contra Costa County and northern Santa Clara, by zooming in and mapping the detail of the analysis. We then zoom out and report and graph the overall results for the entire greater Bay Area.

Our approach for calculating the accessibility metric focuses on local accessibility when the density of the service providers (in this study, fire stations) is quite good and the locations of service providers are spatially well distributed over the service area, making the providers appear to be ubiquitous to the population around the Bay Area. There is great loss and devastation to homes and fire stations themselves due to different levels of flooding events. However, while some local networks experience accessibility impacts, there is no dramatic or unexpected major loss of accessibility under potential inundation in the Bay region as a whole. In our analysis for this area, there is no region that is expected to have excessive accessibility loss due to different levels of flooding events. It appears that as fire stations (supply) are inundated, so are properties (demand), and there is relatively little disruption in local access in the non-inundated areas. Of course, in the immediate aftermath of inundation there are local effects that are real and burdensome. When we talk about there being little disruption in local access, we are really speaking about equilibrium results after the hardship of the short-term effects diminishes.

With a 100-year storm event with no SLR ($PWL_{(0)}$), the greater Bay region will lose access to 16 first responder fire stations (Table 9). That figure jumps to 36 with $PWL_{(1.4)}$. In both of these

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scenarios, Marin and Napa county account for over 60 and 50 percent, respectively, of the first responder fires stations losses to these events. In the most extreme case, Alameda County loses 7 fire stations accounting for approximately 20 percent of the losses. The area (km^2) experiencing a 1–9 minute time delay grows by a factor of 2.5x from $PWL_{(0)}$ to $PWL_{(1.4)}$ (Table 10). The area that is non-accessible grows from approximately 10 km^2 with $PWL_{(0)}$ to nearly 300 km^2 with $PWL_{(1.4)}$.

Table 9. Loss of First Responder Fire Stations in the San Francisco Bay Study Region as a Function of Peak Water Levels

COUNTY	Peak Water Level			
	0.0 m	0.5 m	1.0 m	1.4 m
ALAMEDA	2	3	5	7
MARIN	4	6	8	9
NAPA	1	1	1	1
SAN FRANCISCO	1	1	3	4
SAN MATEO	6	9	9	10
SANTA CLARA	2	3	3	3
SOLANO	0	0	1	1
SONOMA	0	0	1	1
Total	16	23	31	36

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Table 10. Area (km^2) in Accessibility Classes in the San Francisco Bay Study Region. Time delay is for additional minutes above the current (normal) commute conditions due to delays caused by peak water levels.

Time delay	Peak Water Level			
to access	0.0m	0.5m	1.0m	1.4m
1 minute	46.07	58.08	78.41	82.33
2 minute	16.10	25.26	33.40	39.49
3 minute	7.98	13.75	21.98	27.00
4 minute	4.50	9.85	19.01	19.46
5 minute	2.92	6.90	12.05	17.30
6 minute	2.29	4.47	7.37	10.23
7 minute	1.85	3.36	4.68	6.25
8 minute	0.72	1.71	2.55	2.99
9 minute	0.16	0.56	0.69	0.82
Subtotal 1-9 min.	82.59	123.94	180.14	205.87
Non-Accessible	9.83	91.90	258.06	291.41

Loss of Accessibility in Richmond, California

Figures 21(a) to 21(e) represent the accessibility metric of fire stations under a 100-year extreme storm event and different sea-level rise scenarios: none or 0 m, 0.5 m, 1.0 m, and 1.4 m, respectively. In these figures, the gradual color change represents the different levels of accessibility. The green color represents good accessibility (travel time in minutes) and the red color represents poor accessibility. Figure 21(a) represents the accessibility measure under the normal condition (without any disruption). We use this accessibility metric as a baseline to calculate the change of the accessibility under different flooding and sea-level rise conditions.

With a 100-year extreme storm event plus 0.5 meter sea-level rise ($PWL_{(0.5)}$) we see the beginning of road flooding in the western most section of Richmond (Figure 21(c)). Richmond Lane and North Castro Street become impassable blocking road access to this area. With 1.0 meter or more sea-level rise and a 100-year extreme storm event ($PWL_{(1.0)}$), access from Point Richmond to Richmond proper becomes inaccessible. The majority of inland areas do not become inundated because they are naturally located away from the shoreline.

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Figure 21(f) shows the change in accessibility by a 100-year extreme storm event and sea-level rise with a 1.4 m water level ($PWL_{(1.4)}$) relative to normal conditions. The yellow color means no change and the gradual color change toward red represents the additional amount of access time compared to the access time under the normal condition (without any sea-level rise or flooding). As we expect, the inland area does not show any change (colored in yellow).

The major effect from a $PWL_{(1.4)}$ event is the large increment of non-accessible service area which is displayed in black. In addition, the areas to the southeast of Point Richmond show large increments in access time (4 minutes or more) from the sole fire station in Point Richmond. This occurs because this large flooding event blocks Cutting Boulevard. Because Cutting Boulevard is flooded, the southeastern route from the fire station (located in the north central part of Point Richmond) to the southern part of Point Richmond is not fully accessible. If these roads are blocked, the only access from the fire station to the southern part of Point Richmond is the road located on the western shoreline, so that fire fighters need to select a less efficient route under the flooding event.

(a)

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(b)

(c)

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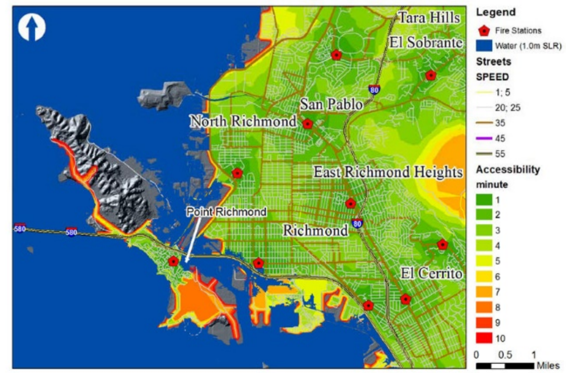

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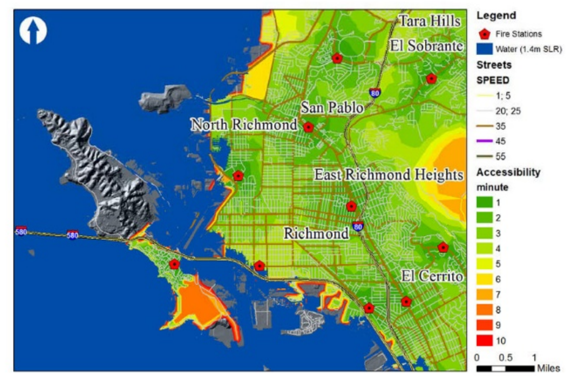

(e)

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(f)

Figure 21. Richmond First Responder Accessibility in Minutes. (a) Under normal conditions, (b) under a 100-year extreme storm event with no sea-level rise, (c) under a 100-year extreme storm event with 0.5 meter sea-level rise, (d) under a 100-year extreme storm event with 1.0 meter sea-level rise), (e) under a 100-year extreme storm event with 1.4 meter sea-level rise, and (f) the change in accessibility under a 100-year extreme storm event with 1.4 m sea-level rise relative to normal conditions.

Loss of Accessibility in Santa Clara, California

For the Santa Clara area, we calculate the same accessibility metric and acquire similar results. Figures 22(a)-22(e) show the accessibility of fire fighters in the northern part of Santa Clara County. In these figures, the gradual color change represents the different levels of accessibility. The green color represents good accessibility (time in minutes) and the red color represents poor accessibility. Figure 22(a) represents the accessibility measure under the normal condition (without any disruption). Figure 22(b), Figure 22(c), Figure 22(d) and Figure 22(e) represent different accessibility measures under a 100-year extreme storm event and different sea-level rise scenarios – none or 0 m, 0.5 m, 1.0 m, and 1.4 m, respectively.

The results of our analysis show that one fire station is lost with a 100-year extreme storm event with no sea-level rise ($PWL_{(0)}$). With 0.5 m sea-level rise and a 100-year extreme storm event ($PWL_{(0.5)}$), an additional fire station is inundated. However, the loss of service at these stations does not directly impact the calculation of the robustness of the road network accessibility, as the distribution of fire stations (supply) in this region is evenly dispersed with respect to the demand.

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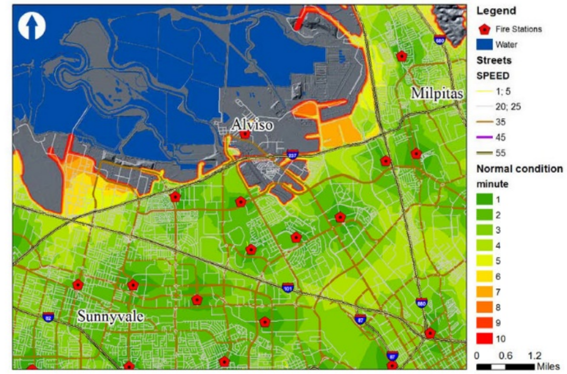

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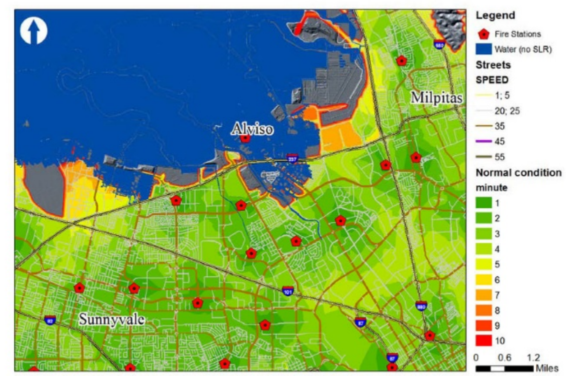

(b)

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(c)

(d)

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(e)

Figure 22. Santa Clara First Responder Accessibility. (a) Under a normal conditions, (b) under a 100-year extreme storm event with no sea-level rise, (c) under a 100-year extreme storm event with a 0.5 m sea-level rise, (d) under a 100-year extreme storm event with a 1.0 m sea-level rise, and (e) under a 100-year extreme storm event with a 1.4 m sea-level rise.

We conducted our local accessibility analysis for the entire San Francisco Bay Region and reported our results. Figure 23 below shows the reduction in accessibility in minutes under a 100-year storm event with 1.4 m sea-level rise ($PWL_{(1.4)}$) for the greater Bay region. Under this scenario, first responder fire stations become inaccessible in all counties except Contra Costa. The greatest concentration of losses occurs in Marin, San Mateo, and Alameda Counties. As discussed previously, the loss of service at many of these stations does not translate into reductions in accessibility at neighboring stations. That is, as the supply of fire stations is being reduced, so too is the demand from homeowners who are now isolated or removed due to inundation. In Marin County in particular, there are cases where neighboring fire stations are experiencing reductions in time accessibility as some road connections are cut off. In these cases, the delays can amount to 7 or 8 minutes. However, fewer similar cases can be found in other counties in the Bay Area.

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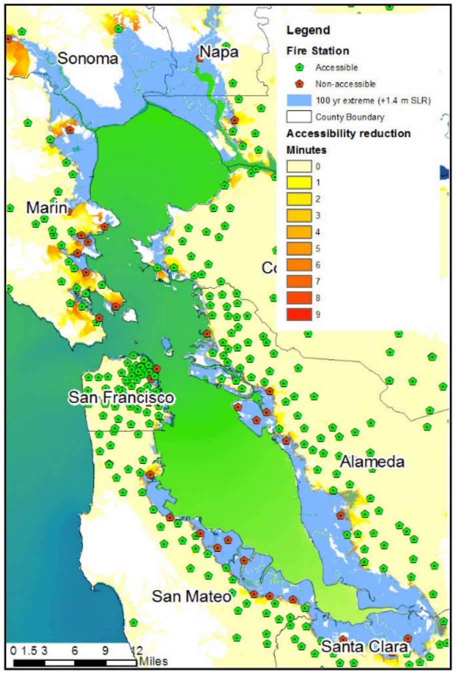

Figure 23. Time Reduction in Accessibility in First Responders under a 100-Year Storm Event in Combination with 1.4 m Sea-Level Rise.

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3.3 Zonal Vulnerability of the Traffic Network

As a quantitative measure of regional vulnerability of the road network under potential inundation, we calculated the loss of accessibility by measuring the impact of travel time between nodes (intersections) of the major regional transportation system surrounding the San Francisco Bay. Figure 24 maps the travel time increments (measured as multiples of normal travel time) between intersections after a 100-year extreme event with different sea-level rise scenarios ((a) none or 0 m, (b) 0.5 m, (c) 1.0 m, and (d) 1.4 m).

For $PWL_{(0)}$ in Figure 24(a) node 19 in Marin county becomes inaccessible via major San Francisco Bay highways and access time between nodes 17 and 18 increases by a factor of 4–5 times. Of course it is rare for any node to become absolutely inaccessible. For example, we could expand our search network outside the nine-county region, where it would be possible for one to traverse a distant network to achieve topological connectivity, but it would be misleading and not practical for our purposes here. In such a metric, node 19 above would still be accessible, but relatively, it would appear extreme and essentially isolated.

For practical computational purposes, we limited the calculations to the nine-county San Francisco Bay region transportation network. Most of the north-south access time in the bay region increases by a factor of 1–2 times. For $PWL_{(0.5)}$ in Figure 24(b) we see a dramatic increase in access time east-west (as much as a factor of 11 times) as access to cross bay bridges begins to fail. In addition, node 21 in north San Mateo County is rendered inaccessible via major highways. North-south access time increases between 1–3 times. Figure 24(c) illustrates the results from $PWL_{(1.0)}$, which are not dramatically different from a $PWL_{(0.5)}$ save for an increase by a factor of 6–11 times in access time between nodes 15 and 18. Finally, at a $PWL_{(1.4)}$ nodes 17 and 20 join nodes 19 and 21 and are no longer accessible via major highways. In addition, there are some increased east-west access times ranging from 3 times to 4–5 times normal access in the south bay. In this final model, both Napa and Sonoma counties become isolated via major highways and access to Marin County is severely constrained.

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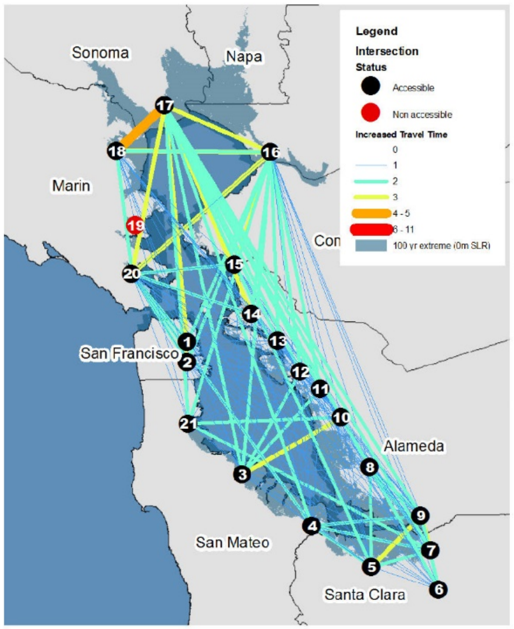

(a)

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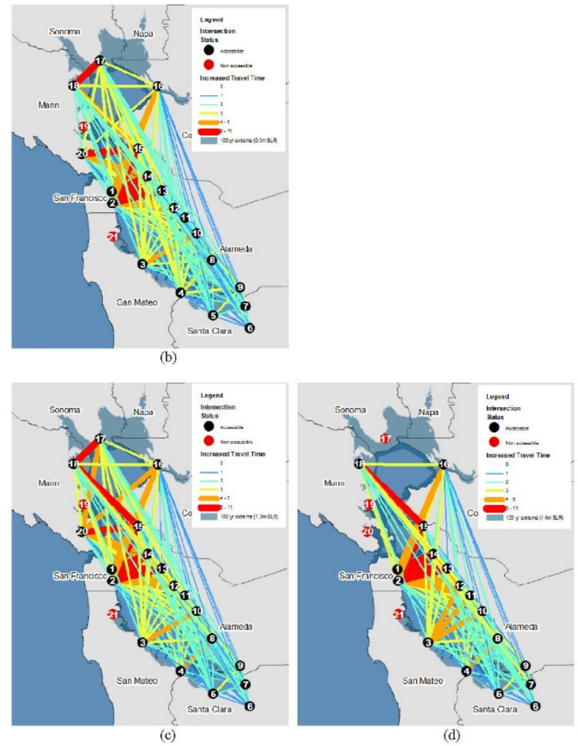

Figure 24. Increased Travel Time (as Multiples of Normal Travel Time) between Intersections after a 100-Year Extreme Event with Different Sea-Level Rise Scenarios. (An impressionistic graphic, due to the complexly of the connected graph). (a) None or 0 m, (b) 0.5 m, (c) 1.0 m, and (d) 1.4 m.

Figure 25(a-d) illustrates the greatest impact on individual links in the sample network by mapping the near neighbor accessibility. This figure essentially extracts and maps the increased access time (as multiples of normal travel times) to near neighbor nodes. We concluded that the

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east-west impedance dominates the north-south impact, and the major regional network itself breaks in several locations as key nodes become inaccessible. We assume much of the regional system remains accessible via secondary roadways further inland and not adjacent to areas of inundation.

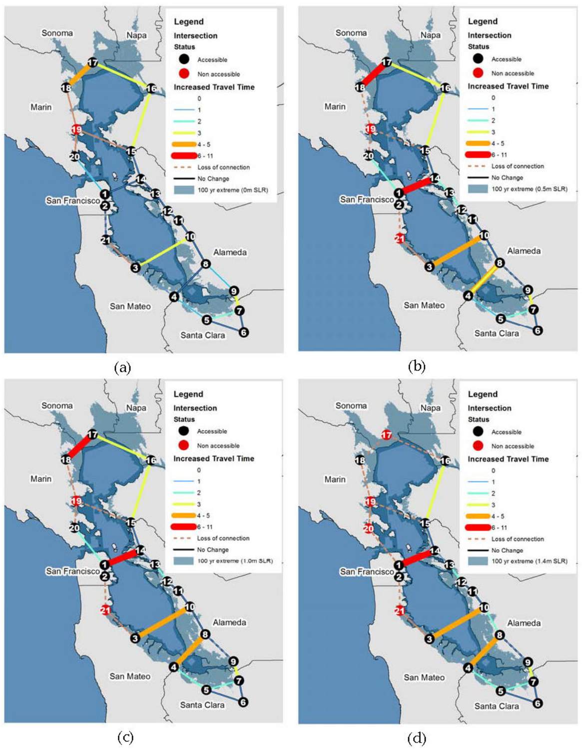

Figure 25. Increased Travel Time (as Multiples of Normal Travel Time) between Near-Neighbor Intersections after a 100-Year Extreme Event with Different Sea-Level Rise Scenarios. (a) None or 0 m, (b) 0.5 m, (c) 1.0 m, and (d) 1.4 m.

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Figure 26 shows the annual average daily traffic, which ranges from 44,000 to over 200,000 vehicles per day for the nearest neighbor links on the regional transportation network.

Figure 26. Annual Average Daily Traffic Between Near-Neighbor Intersections under Current Conditions.

Figure 27 shows the traffic volume–weighted increment of travel distance under the disruption of a 100-year extreme event with different sea-level rise scenarios ((a) none or 0 m, (b) 0.5 m, (c) 1.0 m, and (d) 1.4 m). For $PWL_{(0)}$ in Figure 27(a) we see major disruptions in Marin and San Mateo counties and increased traffic volume on the Carquinez (between nodes 15 and 16) and the San Mateo (between nodes 3 and 10) bridges to accommodate the diverted traffic. For $PWL_{(0.5)}$ in Figure 27(b), the Bay Bridge experiences extremely high volumes. The network volumes are not significantly affected by further inundation.

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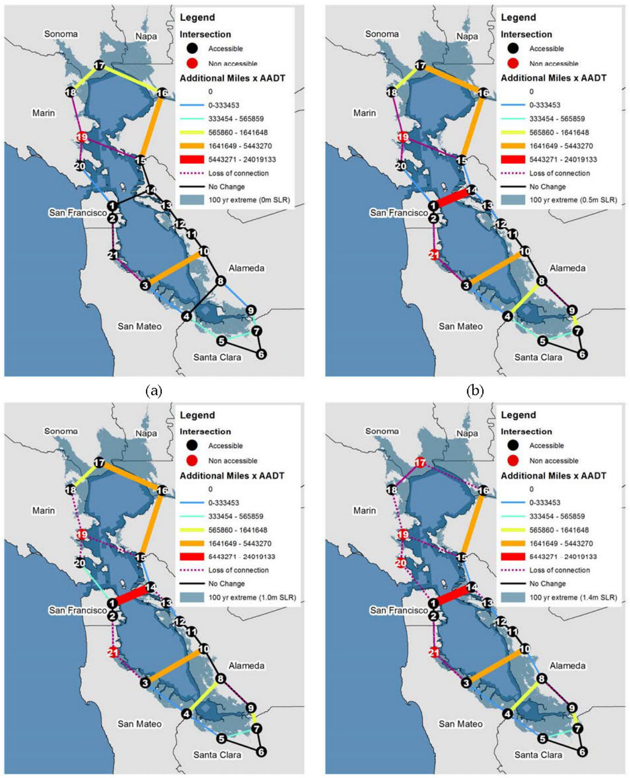

Figure 27. Traffic Volume–Weighted Increment of Travel Distance (Travel Distance Increments Multiplied by Traffic Volume) Between Nearest-Neighbor Intersections for the 100-Year Extreme Event with Different Sea-Level Rise Scenarios. (a) None or 0 m, (b) 0.5 m, (c) 1.0 m, and (d) 1.4 m.

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Finally, we quantitatively measured the impact on accessibility to the hinterland from the major highway intersections, characterizing the first and last 20 minutes of an origin-destination journey. Figure 28 maps the baseline with dark green polygons representing the 5-minute travel time penetration into the hinterland, while light green and orange represent 10- and 15-minute travel times into the hinterland from the major traffic corridor intersections respectively. Finally red polygons represent the 20-minute travel extent.

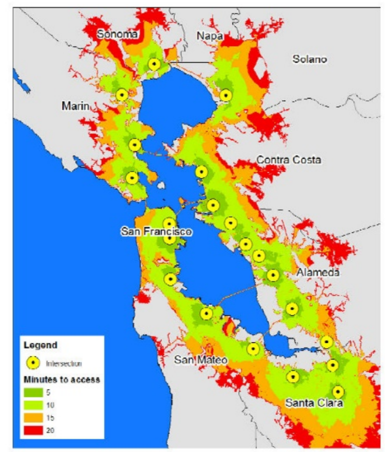

Figure 28. Hinterland Accessibility to Major Traffic Corridor Intersections.

Figures 29(a)–(d) show the impacts on hinterland accessibility to major traffic corridor intersections (major highway nodes). The results of our analysis show access into the hinterland in the North Bay is devastated by inundation. It begins for $PWL_{(0)}$ in Figure 29(a) and by the time of $PWL_{(1.4)}$ in Figure 29(d), the hinterland is unreachable from four major highway intersections. For the rest of the bay region, for the land that is not inundated, access to the major intersections is relatively stable.

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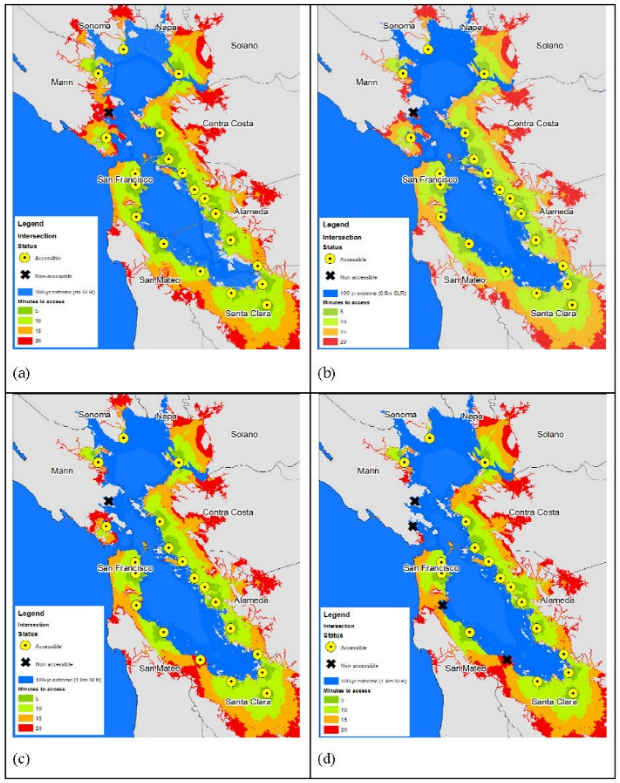

Figure 29. Impacts on Hinterland Accessibility to Major Traffic Corridor Intersections by a 100-Year Extreme Event with Different Sea-Level Rise Scenarios. (a) None or 0 m, (b) 0.5 m, (c) 1.0 m, and (d) 1.4 m.

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Section 4: Discussion and Conclusions

The potential effects that climate change will have on the San Francisco Bay Area's shoreline and infrastructure have been previously reported on in Knowles (2009, 2010), Heberger et al. (2009), and BCDC (2009). This report adds to that literature base by reanalyzing the greater Bay Area using newly created surface models (DEMs), derived from the latest LiDAR, which has a finer resolution in the x, y, and z dimensions than was available in these earlier studies. This yields a better three-dimensional representation of the bare ground elevation profile of the Bay Area. In our research, we found that utilizing a DEM to determine water depth overestimates the amount of inundation area. When we used a DEM in combination with a water path algorithm, we saw a reduction in the amount of area indicated to be flooded under sea-level rise and 100-year flooding from an extreme storm event.

We created a digital surface model of infrastructure and buildings. DSMs contain information about not only the height of bare ground but also about the surface elevations of the objects on the ground. For example, in the case of raised bridges or highways, using a DEM only would falsely indicate the particular infrastructure as inundated. The elevated positions of such infrastructure can be determined with a DSM, thus avoiding this type of false positive inundations. Our results show that the overestimation of inundation using solely a DEM is greatest at the lowest inundation levels and the difference decreases with increasing inundation levels.

We chose to consider the joint effect of increases in sea level with 100-year extreme storm events on first responders. Because first responders are well distributed throughout the cities and counties, they are a good choice for study. When roads or highways are deemed impassable, we can study the increase in time for first responders to reach locations in their area of responsibility. We employed a constrained location-allocation model and measured the accessibility of first responders (supply) to households (demand) in a region demarcated by the first responders traveling along the shortest path to all households in the region. Using this model, we can largely capture local affects and for the two examples we provided (Richmond and north Santa Clara), the road topology is broken at $PWL_{(0.5)}$ or greater. Although we chose first responders, the method is universal and could serve to model the localized disruption in movement between any service and the population at large.

We employ a collection of major highway intersections as nodes in a trans-regional commuter network. These intersections are used in an origin-destination analysis looking at the impact on accessibility, as measured by increases in commuter time, that sea-level rise and 100-year extreme storm events have on trans-regional commuting. Using this model, we captured regional commute impacts and showed the east-west regional movement is impacted from 3 to as much as 11 times normal, while north-south impacts range from no impact to less than 3 times normal at $PWL_{(0.5)}$ – $PWL_{(1.4)}$. We also showed several critical nodes become orphaned at $PWL_{(1.4)}$. We weighted these major regional links with weights based on traffic volume, and mapped the greatest traffic flow impacts. The cross-Bay links disrupt the greatest volumes of traffic and prove to be critical components of the regional network.

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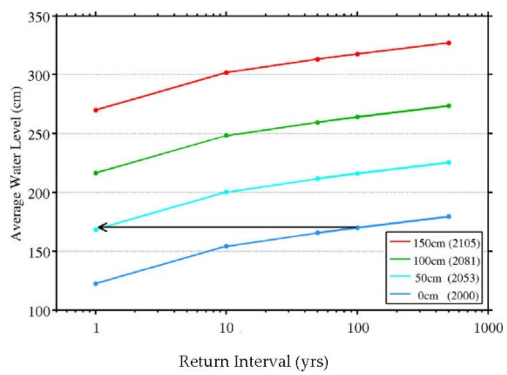
We modeled and measured the accessibility into the hinterland from the major nodes along the trans-regional commuter network. Our results show that access into the hinterland in the North Bay is devastated by inundation and there are areas such as north San Mateo County where access to the major transportation road system is impacted. However, for the rest of the bay region, for the land that is not inundated itself, access to the major intersections is relatively stable.

Finally, extreme PWL will occur with increasing frequency as a result of higher mean sea level (Cayan et. al 2008 and Knowles 2010). This could result in greater stresses on levees currently protecting infrastructure. Figure 30 (from Knowles 2010) implies that by mid-century, today's 100-year extreme storm event with $SLR_{(0)}$ may become a one-year peak event with a 50 -cm SLR. In other words, in mid-century, when sea level has risen 50 cm, it takes a lesser storm event to create an impact equivalent to a 100-year peak event occurring today. Likewise, Cayan (2008) shows that when SLR rises to 0.80 m by 2100, the occurrence of extreme events increases from approximately one hourly event in one year to over 17 events in the last 30 years of the century.



Source: Knowles (2010)

Figure 30. As Early as 2050, with Sea-Level Rise, the Water Level with a 1-Year Peak Event Could Equal Today's Water Level with 100-Year Peak Event.

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Glossary

A1B	mid-range emission scenario
AADT	Annual Average Daily Traffic
ABAG	Association of Bay Area Governments
B1	low-emission scenario
BART	Bay Area Rapid Transit
BCDC	Bay Conservation and Development Commission
CCLP	California Costal LiDAR Project
CCSM3	Community Climate System Model
CLICK	Center for LIDAR Information Coordination and Knowledge
DEM	digital elevation model
DOT	California Department of Transportation
DRMS	Delta Risk Management Strategy
DSM	digital surface model
ESE100	100-year extreme storm event
ESRI	Environmental Systems Research Institute
FVA	Fundamental Vertical Accuracy
GCM	Global Climate Model
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MSL	Mean Sea Level
MTC	Metropolitan Transportation Commission
MTL	Mean Tide Level
MUNI	Municipal Transportation Agency
NAD83	Universal Transverse Mercator projection
NAVD88	North American Vertical Datum of 1988
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration
OAK	Oakland International Airport
PIER	Public Interest Energy Research
PWL	Peak Water Level
$PWL_{(0)}$	no sea-level rise
RD&D	Research, Development, and Demonstration
SFO	San Francisco International Airport
SJC	San Jose International Airport

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SLR	sea-level rise
SRES	Special Report on Emissions Scenarios
TCA	Terminal Control Areas
TEUs	Twenty-foot Equivalents
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

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Article

A Rapid Assessment Method to Identify Potential Groundwater Flooding Hotspots as Sea Levels Rise in Coastal Cities

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Abstract: Sea level rise (SLR) will cause shallow unconfined coastal aquifers to rise. Rising groundwater can emerge as surface flooding and impact buried infrastructure, soil behavior, human health, and nearshore ecosystems. Higher groundwater can also reduce infiltration rates for stormwater, adding to surface flooding problems. Levees and seawalls may not prevent these impacts. Pumping may accelerate land subsidence rates, thereby exacerbating flooding problems associated with SLR. Public agencies at all jurisdiction levels will need information regarding where groundwater impacts are likely to occur for development and infrastructure planning, as extreme precipitation events combine with SLR to drive more frequent flooding. We used empirical depth-to-water data and a digital elevation model of the San Francisco Bay Area to construct an interpolated surface of estimated minimum depth-to-water for 489 square kilometers along the San Francisco Bay shoreline. This rapid assessment approach identified key locations where more rigorous data collection and dynamic modeling is needed to identify risks and prevent impacts to health, buildings, and infrastructure, and develop adaptation strategies for SLR.

Keywords: sea level rise; inundation; groundwater; coastal aquifer; flooding; urban planning; climate; infrastructure; California; San Francisco Bay; adaptation

1. Introduction

Sea levels are rising over most of the world's coastlines, and the rate of relative sea level rise (SLR) is projected to accelerate [1]. One of the impacts of SLR will be a rising water table in shallow, unconfined coastal aquifers [2]. Coastal regions that are currently above sea level do not typically manage this shallow coastal groundwater as a resource because it is often contaminated by agricultural chemicals, industry, or urban surface runoff. Maps of depth to this shallow groundwater are rare, although soil contamination is sometimes monitored locally using well samples. As a result, many coastal regions are unprepared to manage the potential impacts of a rising water table.

Shallow saline aquifers and unconfined freshwater aquifers with a direct saltwater interface (i.e., freshwater floating atop higher-density seawater) are affected by tidal fluctuation. These aquifers rise and fall with the tides, and the effects decrease exponentially farther inland [3–5]. In the zone where aquifers are affected by tidal flux, they are also affected by SLR. In "flux-controlled" systems, where the rate of groundwater discharge is constant as the sea level rises, SLR causes landward migration of the saltwater toe, otherwise known as saltwater intrusion [6,7]. This saltwater intrusion causes a lift in the level of the overlying freshwater [8]. Therefore, SLR causes an increase in the height as well as the salinity of the water table [4–6,8–10]. This eventually results in the emergence of groundwater as surface flooding, and also increases surface discharges of streams supplied by groundwater [2].

Before emergence occurs, rising groundwater infiltrates sewer pipes, causing a loss of sewage flow capacity. It also conveys pollutants to nearshore aquatic ecosystems, floods basements, causes heaving of foundations and underground structures, remobilizes soil contaminants, and increases the risk of liquefaction in seismic regions. In coastal areas constructed on former wetland soils, lowering the elevation of groundwater by pumping can accelerate subsidence [11].

Planning for rising and emergent groundwater at a regional scale requires mapping methods that are suitable for large geographic regions and heterogenous subsurface conditions produced by urbanization. Large empirical depth-to-groundwater datasets often exist for urban areas where leaky underground fuel or chemical storage tanks are regulated and monitored. Maps interpolated from these large empirical datasets can be used to support prioritization of limited flood adaptation resources by identifying "hot spots" in the distribution of risk. Similar methods were used to identify gaps in protection of species over large geographic datasets for conservation planning [12], to identify local extremes of the Urban Heat Island effect [13], and for risk assessment [14]. These types of rapid assessments represent conditions over large geographic areas, allowing public resources to be used strategically to gather new data and develop process-based models where future problems are most likely to occur [15]. In the case of groundwater data, the use of an empirical method that interpolates a surface from a dataset of present-day conditions can provide modelers with initial insights into the complex interactions between heterogeneous soil and infrastructure conditions and groundwater elevation and flow in an urban area [4,5]. While empirical methods that use interpolation do not model the dynamics of groundwater, they can be used over very large geographic areas and can reveal localized effects, such as cracked pipe joints, private water pumps, compacted road beds, or faulted sediment. These local anomalies might not appear in a process-based equilibrium model of the water table, yet could present a significant problem for local adaptation. An extensive well dataset allows managers in a coastal region to use interpolation to anticipate the flooding impacts of groundwater as the sea level rises.

Bay Area Sea Level Rise and Groundwater

Sea level has risen 1.1 mm/year on average at the Golden Gate since the historical record began in 1855 [16]. As the rate of rise increases over the next century, flooding is expected to affect a wide range of assets in the San Francisco Bay Area (Bay Area), including low-lying urban areas, two international airports, wetland ecosystems, and essential infrastructure [17,18]. If nothing is done to intervene, ecosystem shifts are likely to occur in San Francisco Bay (the Bay) that could cause all existing inter-tidal marshes to become mudflats with 1.24 m of sea level rise [19]. Extensive impacts on urban development are also anticipated; low-lying coastal homes, businesses, and infrastructure will be in danger of regular flooding as the sea level rises. Planners now have access to maps that predict direct seawater inundation at different sea levels [18,20]. While direct coastal inundation will have a considerable impact in the Bay Area, inundation due to rising groundwater levels is an SLR-induced threat that has received far less attention in coastal adaptation discussions and has been missing from maps of coastal flood risk. Yet, the importance of studying coastal groundwater dynamics in the context of urban and coastal zone management is recognized as an urgent need. In one study, twice as much urban land appeared to be at risk of flooding when rising groundwater was included in coastal flooding predictions [5].

New data on regional rates of land subsidence in the Bay Area indicated that additional flooding could be expected as a result of elevation changes [21]. Subsidence rates of more than 5 mm per year (and up to 10 mm per year in one location, between 2007 and 2010) were identified in areas where urban fill was placed over thick Bay mud deposits. A lower land surface will expose many new areas to flooding from seasonally high groundwater levels, as well as seawater.

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The rate of rise in the groundwater surface due to SLR is affected by a number of factors, including tidal forcing, aquifer geology, coastline change, shore slope, surface permeability, precipitation, and groundwater pumping [4–6]. Previous studies indicated that the relationship between SLR and the elevation of the water table is unlikely to be consistently linear, especially near streams [2,10,22]. However, several studies used a linear relationship to approximate the effect of SLR on groundwater levels in flux-controlled urban aquifers [4,5]. Since this method is only applicable in zones where the sea level and tidal fluctuations have an influence on the aquifer, one kilometer was used to represent the limit of that zone in these studies [5].

Like many other coastal regions, the Bay Area did not previously have a depth-to-water map for its shallow coastal aquifers, although some local studies were available. In this paper, we present a rapid assessment method to provide this critical planning tool using empirical data.

2. Materials and Methods

2.1. *Study Area*

The groundwater basins of the Northern San Francisco Bay Area are largely within valleys formed on alluvial fans. While the deep aquifers are disconnected, the shallow coastal aquifer is continuous in the alluvial deposits [23]. The shallow aquifer in the large Santa Clara Valley basin (which contains five sub-basins) is also unconfined. Due to groundwater withdrawals, saltwater intrusion has historically occurred in this basin. A reduction in pumping and concerted recharge efforts slowed the progression of saltwater inland [23,24]. For the purposes of our analysis, we assume that the shallow coastal aquifer is unconfined and has a direct connection to the Bay. This assumption is reasonable because most of the Bay-front within one kilometer of the Bay is composed of alluvial material and urban fill.

2.2. *Monitoring Well Data*

Our methods follow similar studies for Honolulu, HI [5] and three locations in coastal California (excluding the San Francisco Bay Area) [4] but cover a much larger geographic area than either of these studies. We used a dataset of groundwater monitoring well measurements that contained values for depth to the water table and covered portions of all nine Bay Area counties [25]. The data points were concentrated in heavily developed areas, with fewer wells in the northern Bay Area (Figure 1). We included wells within 1.6 km of the Bay edge to ensure continuity in our interpolated results, although the only results shown were within 1 km of the Bay. We used the San Francisco Estuary Institute's Bay Area Aquatic Resource Inventory delineation of open water and tidal wetland to define the Bay's edge [26].

We selected the minimum depth-to-water value for each well during the years 1996–2016. This represented the seasonal high water table during wetter years, allowing us to estimate the highest elevation of the water table. Where this maximum groundwater elevation occurred, remobilized pollutants and reduced sewer pipe capacity may have been present in an unusually wet year or during an exceptionally high tide event.

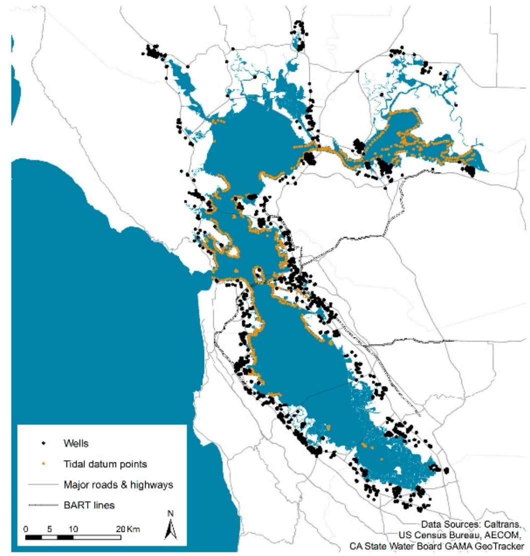

Figure 1. Well and tidal datum distribution. The highest density of data points was in the central and southern parts of the Bay Area, where more urban and industrial land uses are concentrated. Fewer wells and tidal datum measurements were available in the North Bay, where agricultural land use is more common.

2.3. *Quality Control for Monitoring Well Data*

Many urban wells in this dataset were in close proximity to wells used to measure the water quality in deeper aquifers. Therefore, we deleted wells with a minimum depth-to-water value greater than two standard deviations above the mean (i.e., deeper than 6.46 m). By deleting these wells, we had higher confidence that our interpolated surface represented the shallow coastal aquifer that was responsive to SLR and rainfall. A summary of the depth-to-water data is shown in Table 1.

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Table 1. Summary statistics for well minimum depth-to-water data included in the analysis.

Statistic	Value
Count	10,777
Minimum	0 m
Maximum	6.46 m
Mean	1.95 m
Median	1.75 m
Standard Deviation	1.21 m

2.4. Tidal Data

We also included tidal data points from a dataset produced for the Federal Emergency Management Agency and regional agencies [27]. To smooth the interpolated surface toward the Bay, we included 603 mean tide line points, and added 0.3 m to the elevation to reflect the expectation that freshwater usually lies above the mean tide line [28]. Since the tidal water levels varied substantially along the shoreline as a result of the hydrodynamics in San Francisco Bay, tide gauge locations alone were insufficient. The tidal dataset we used was calibrated to National Oceanographic and Atmospheric Administration tide gauges and provided extensive spatial coverage along the Bay shore.

2.5. Analysis

For each well point in the study area, we extracted a ground elevation from the United States Geological Survey (USGS) Coastal and Marine Geology Program 2 m digital elevation model (DEM). We then calculated the maximum water table elevation at each well point by subtracting the minimum depth-to-water value from this ground elevation, following the method used by Hoover et al. [4]. Next, we applied a set of interpolation algorithms to the groundwater elevations and tidal data points. A flowchart describing our analysis methods is shown in Figure 2.

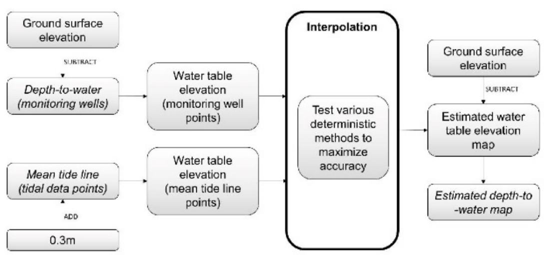

Figure 2. Flowchart of methods. Key inputs and outputs are shown in italics. Both deterministic and geostatistical methods have been used to predict a water table elevation surface from well data in other studies [29–32]. The dataset used here was not well-suited to kriging because it did not fulfill the assumption of stationarity necessary for this method. Data variance was not constant across the study area and could not be explained by directional trends. Given these limitations for geostatistical methods, we only compared deterministic interpolation methods.

To maximize the model accuracy, we compared a variety of methods to determine which was most successful at minimizing the prediction error. We compared the root-mean-square error (RMSE) of predicted values from each model using the cross validation function of the ArcGIS Geostatistical

Analyst toolbox (Table 2). Values of RMSE closer to zero indicated a more accurate model, and values of mean error (ME) closer to zero indicated a less biased model. For each interpolation technique, we chose the input parameters (e.g., power, number of neighbors included) that were most successful at minimizing RMSE, rather than those that produced the smoothest output.

Table 2. Comparison of various tested deterministic interpolation methods.

	Maximum Groundwater Elevation	
	RMSE	ME
Inverse Distance Weighting (IDW)	1.237	−0.021
Global Polynomial Interpolation (GPI)	3.114	−0.001
Radial Basis Functions (RBF): Multiquadric	**1.167**	**−0.010**
RBF: Completely Regularized Spline	1.579	−0.006
RBF: Spline with Tension	1.482	−0.006
RBF: Inverse Multiquadric	2.638	−0.003

The method that minimized the RMSE most successfully was the multiquadric radial basis function. A scatterplot of the actual water table elevations (elevation from DEM minus minimum measured depth-to-water) compared to the predicted water table elevations (output from the multiquadric radial basis function interpolation) is shown in Figure 3. Next, we subtracted the interpolated water table surface from the ground surface DEM to produce a depth-to-water map. We excluded areas greater than 1 km from the nearest well due to the increased uncertainty introduced by the lack of well or tidal data points in these areas.

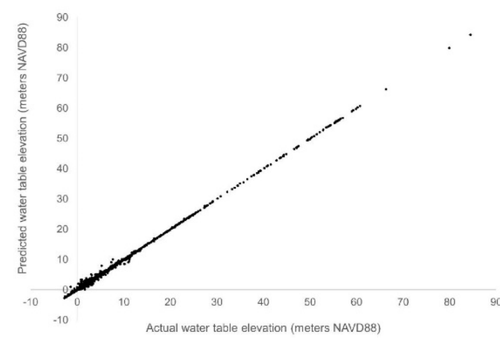

Figure 3. Actual water table elevation compared to predicted elevation from the interpolation. The "actual" water table elevation was ground elevation minus the minimum measured depth-to-water. The predicted water table elevation was the value extracted from the raster output of the radial basis function interpolation at the well point location. The plot includes points within the final study area only (i.e., within 1 km of the Bay edge).

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3. Results

Figure 4 shows the results of our depth-to-water modeling for the coastal Bay Area. A geospatial data file can be downloaded at https://datadryad.org/stash/dataset/doi:10.6078/D1W01Q We found that a shallow groundwater condition exists in many developed areas in the North Bay including Fairfield, Novato, San Rafael, and Petaluma, although fewer well data points were available for the North Bay in general. Many cities in the East Bay also had shallow groundwater along the Bay-front, placing major infrastructure (such as Interstate highways 580 and 880) at risk. Exposure to potential groundwater flooding was perhaps most severe in the Silicon Valley area, where the minimum depth-to-water was already less than one meter in large areas of Mountain View, Redwood City, and San Mateo. Figure 5 shows subset maps of groundwater conditions in selected highly urbanized areas.

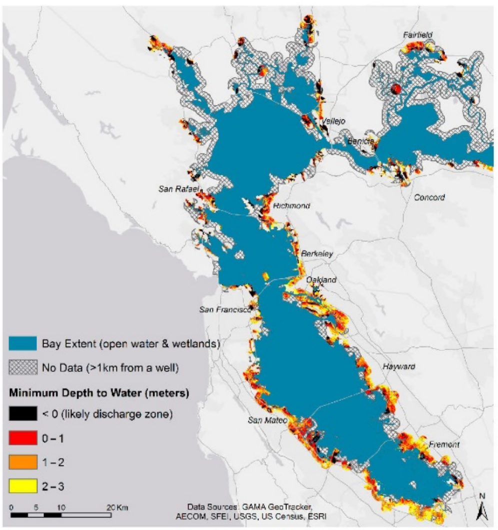

Figure 4. Minimum depth-to-water for the coastal San Francisco Bay Area. Shallow groundwater within one kilometer of the coast is shown in color, with the shallowest areas in red. Our method produced some negative values that suggested groundwater was already emergent, usually where there were no well points in the dataset at the base of a slope or in a valley. These areas (in black) most likely had very shallow groundwater with seasonal surface discharges, but a process-based model would be needed to quantify the volume.

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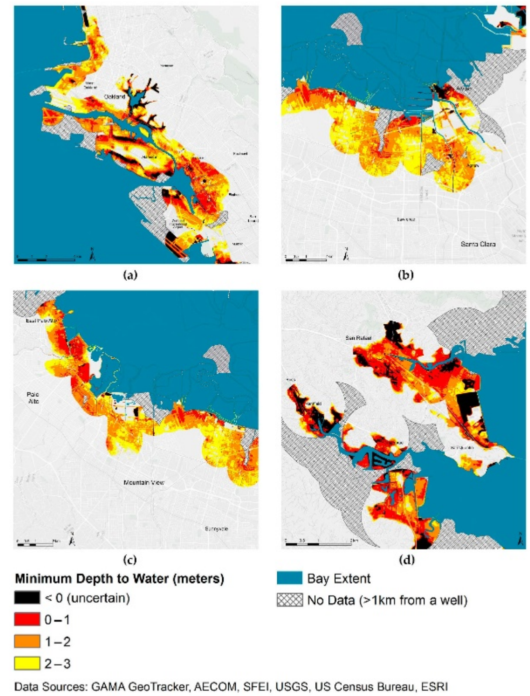

Figure 5. Maps of minimum depth-to-water in selected areas. **(a)** Shallow groundwater conditions were widespread in the Oakland area, including in some low-lying neighborhoods not directly connected to San Francisco Bay. **(b)** Alviso already experiences groundwater flooding during storms and this flooding will worsen as the sea level rises. The depth-to-water model was likely conservative in this area due to pumping, which results in artificially high depth-to-water values around a landfill. **(c)** Much of the Silicon Valley coastline had very shallow groundwater, threatening significant properties such as Google's headquarters. The areas along the shoreline with depth-to-water over 3 m are actively-pumped landfills. **(d)** Even in Marin County, where the coastline is dominated by steep bluffs, some low-lying coastal flatlands built on fill material were at risk of emergence due to a high groundwater table.

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Projecting Future Conditions

To determine the relationship between 1 m of SLR and a rising water table, we used a simple linear approximation within 1 km of the Bay edge. This replicated the distance used by Rotzoll and Fletcher [5] in Honolulu, HI based on measured tidal efficiencies, and by Hoover et al. [4] in three smaller areas along the California coast. Hoover et al. [4] described this linear approximation of the effect of rising sea levels on groundwater depth as conservative, because additional tidal effects would only increase the impacts on groundwater emergence and shoaling at high tides. Using this linear approximation of sea level rise impacts, areas of the map in Figure 4 where minimum depth-to-groundwater was less than one meter would likely experience groundwater emergence during the wet season of wet years with one meter of SLR. The State of California recommended that public agencies consider one meter of SLR likely at the Golden Gate by 2100 under the RCP 8.5 IPCC emissions scenario, and by 2150 under the RCP 4.5 and RCP 2.6 scenarios [33].

Figure 6 shows the minimum depth-to-groundwater in the highly urbanized Bay Area with 1 m of SLR. Our analysis revealed widespread areas where surface flooding from groundwater emergence is possible. Table 3 reports the extent of flooding from emergent groundwater with 1 m of SLR, compared to the extent of direct flooding from the Bay with the same SLR, based on projections from the *Our Coast, Our Future Flood Map* (USGS CoSMoS flood model) [20]. To match the groundwater study area, we excluded areas more than 1 km away from a groundwater monitoring well from the direct SLR flooded area calculation.

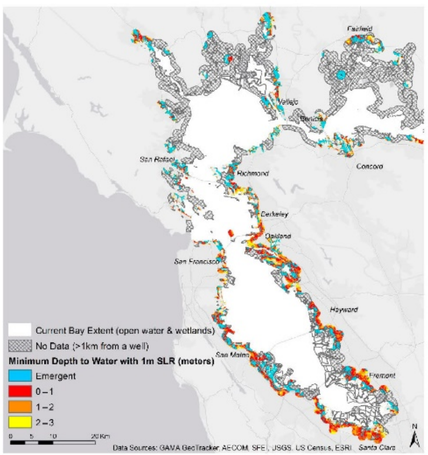

Figure 6. Future groundwater flooding. This map shows areas where groundwater is likely to emerge as surface flooding with 1 m of sea level rise (SLR). However, ponding may not necessarily occur in all of these areas, as the model does not account for surface discharge.

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Table 3. Comparison of flood extent from direct tidal flooding due to SLR and groundwater emergence due to SLR intrusion.

County	Extent of Potential Flooding with 1 m SLR, km² (% of Total)			
	Direct SLR only [1]	Emergent Groundwater only	Both Direct SLR [1] and Emergent Groundwater	Total
Alameda	3.3 (8%)	28.3 (72%)	7.7 (20%)	39.3
Contra Costa	0.7 (3%)	19.5 (87%)	2.2 (10%)	22.5
Marin	-	9.1 (65%)	4.8 (35%)	13.9
Napa	-	8.2 (98%)	0.2 (2%)	8.4
San Francisco	-	4.3 (88%)	0.6 (12%)	4.8
San Mateo	11.7 (30%)	8.3 (21%)	19.0 (49%)	39.1
Santa Clara	7.3 (56%)	2.3 (18%)	3.5 (27%)	13.1
Solano	1.3 (6%)	15.6 (68%)	6.1 (26%)	23.0
Sonoma	1.2 (9%)	9.3 (73%)	2.2 (17%)	12.7
Total	25.6 (14%)	104.9 (59%)	46.2 (26%)	176.8

[1] From the *Our Coast, Our Future Flood Map* [20], with 1 m of SLR and no storm event. The area calculation for direct SLR matches the extent of the groundwater study area; (1) areas greater than 1 km from well points were excluded, and (2) we assumed that the existing water line was the extent of open water and tidal wetland from the San Francisco Estuary Institute's Bay Area Aquatic Resource Inventory [26].

The results of our analysis, based on an interpolation of empirical groundwater well data and a linear relationship between SLR and groundwater levels, can be used to identify hotspots that require a second phase of analysis using higher-resolution elevation and hydrologic data, field measurements of tidal efficiency, and process-based models. Process-based models developed at smaller geographic scales may be able to account for recharge and discharge, the diminishing influence of SLR inland from the coast, wave run-up, and variations in geologic and infrastructure conditions.

4. Discussion

We created an interpolated surface that estimated the depth of shallow groundwater for 489 square kilometers of San Francisco Bay's coastline using measured depth-to-water and tidal data. This rapid assessment method indicated that many parts of the Bay Area coastline are vulnerable to rising groundwater. Based on these results, many San Francisco Bay Area communities should conduct further modeling studies to prepare for potential flooding from groundwater, in addition to direct flooding from SLR. Our study suggested that there is significant potential for groundwater flooding in important Silicon Valley economic hubs (e.g., Mountain View, East Palo Alto, Redwood City), East Bay cities with fast-growing populations (e.g., Oakland, Hayward, Fremont), and major transportation infrastructure, including freeways (e.g., Interstate 580) and airports (Oakland International Airport, San Francisco International Airport). Our results indicate that flooding from emergent groundwater could impact more land by area than direct SLR flooding, with a SLR scenario of one meter in seven of the nine Bay Area counties, and in the region as a whole (Table 3). However, the calculated area impacted by emergent groundwater does not account for surface discharge to streams and other water bodies.

In addition to groundwater emergence, risks posed to developed areas include increased infiltration and inflow of underground water and wastewater pipes [15], and increased liquefaction risks in active seismic zones. Rising groundwater can also mobilize contaminants from wastewater and legacy soil pollution, producing human and ecosystem health risks. Groundwater emergence is likely to occur even where levees and seawalls are built to serve as barriers to saltwater coastal inundation. These structures alone will be inadequate to prevent flooding and other hazards without additional adaptation measures.

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5. Conclusions

We used a rapid assessment interpolation method to create the first depth-to-groundwater map for the San Francisco Bay shore zone. The empirical data we used reflects existing human impacts from pumping, storm sewer infiltration, and leaky water pipes in a complex urban environment. We maximized the accuracy of the interpolated surface map by testing a variety of methods and selecting the one that minimized errors. The results of the analysis revealed widespread shallow groundwater conditions along most of the shore of San Francisco Bay. Using the conservative assumption of a linear relationship between SLR and shallow, unconfined groundwater depth within one kilometer of the shore, we showed that many densely developed areas are at risk from rising and even emergent groundwater as the sea level rises.

The method presented here is useful as a rapid assessment technique for comparing relative exposure to groundwater hazards and identifying hotspots where localized dynamic modeling is needed [15,34,35]. The minimum depth-to-water surface shown here did not represent a particular point in time, but rather an estimate based on the shallowest measurement taken at each monitoring well in the dataset during the study timeframe. Sampling was not consistent over time in this best-available dataset. Therefore, seasonal changes in precipitation and infiltration were not captured by this minimum depth-to-water method, although they are an important consideration [30]. Since it was empirical rather than modeled, the dataset we used for this interpolation reflected human impacts on coastal groundwater, including current pumping and leaky pipes. In many areas, the results shown here were influenced by local leachate pumping at landfills or other groundwater pumping that was already in place to prevent flooding.

Any interpolation-based method contains errors. More consistent sample point coverage would have reduced the level of error introduced by interpolation. Additionally, the simple linear approximation we used to estimate rising groundwater levels due to SLR did not account for a number of factors that would have been important to consider in a more nuanced modeling effort. Additional factors to consider in future refinements of this technique include the diminishing influence of SLR inland from the coast, the potential effects of tides, waves, and extreme rainfall events, and the need for more accurate local measurements to establish the effects of different geologic conditions and underground pipe and pump systems on the level of groundwater rise. Modeling efforts incorporating measurements of tidal influence and groundwater flow, such as those that Habel et al. conducted in regard to Honolulu, HI [36], are needed in the areas that were identified as potential hotspots by our method.

While previous studies established the existence of rising groundwater due to SLR [2,4–6,9,10,22,31], as well as the potential impact at case study sites [2,4,5,28,31,37], this paper provides a method for building a regional-scale view of the potentially widespread impacts on surface flooding, underground infrastructure, and the health of people and ecosystems. Understanding the full range of SLR impacts is essential for prioritizing adaptation investments, and selecting appropriate strategies in coastal cities [15,35,36]. Other low-lying urban areas around the world with shallow and unconfined coastal aquifers have an urgent need to identify the potential for future groundwater flooding as a result of sea level rise. In eastern and southeastern US, major metropolitan regions around rivers and bays such as Boston, New York, Philadelphia, Baltimore, Washington DC, Norfolk, Charleston, Ft. Lauderdale, Miami, Tampa, and Galveston could benefit from similar assessment methods for groundwater flooding that make use of existing groundwater quality datasets. On the west coast, Seattle, Tacoma, and many smaller cities and towns on bays along the Oregon, Washington, and California coasts are likely to face groundwater flooding. Many low-lying cities along bays and deltas in northwestern Europe, coastal areas of the United Kingdom, coastal Africa, South America, and Southeast Asia face similar threats. The rapid assessment method presented here provides a valuable approach for the identification of hotspots where rising groundwater poses a threat to urban development and human health. Once hotspots are identified, process-based groundwater data collection and modeling efforts will be needed at a local scale to more

fully represent the dynamics of rising groundwater in coastal zones and to account for variables such as projected future changes in subsidence, recharge, and discharge rates.

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