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Sea level rise

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Abstract

1. Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*), contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years (*medium confidence*).

2. Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1 to 4 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*). Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century (*high confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of emissions pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*).

3. Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, RSL rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global mean sea level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss (*high confidence*).

4. As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called "nuisance floods") have increased 5- to 10-fold since the 1960s in several U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*).

5. Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf Coast states beyond what would be projected based solely on RSL rise. However, there is *low confidence* in the magnitude of the increase in intensity and the associated flood risk amplification, and these effects could be offset or amplified by other factors, such as changes in storm frequency or tracks.

12. Sea Level Rise

KEY FINDINGS

1. Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*), contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years (*medium confidence*).

2. Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1 to 4 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*). Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century (*high confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of emissions pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*).

3. Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, RSL rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global mean sea level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss (*high confidence*).

4. As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called "nuisance floods") have increased 5- to 10-fold since the 1960s in several U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*).

5. Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic

and Gulf Coast states beyond what would be projected based solely on RSL rise. However, there is *low confidence* in the magnitude of the increase in intensity and the associated flood risk amplification, and these effects could be offset or amplified by other factors, such as changes in storm frequency or tracks.

12.1 Introduction

Sea level rise is closely linked to increasing global temperatures. Thus, even as uncertainties remain about just how much sea level may rise this century, it is virtually certain that sea level rise this century and beyond will pose a growing challenge to coastal communities, infrastructure, and ecosystems from increased (permanent) inundation, more frequent and extreme coastal flooding, erosion of coastal landforms, and saltwater intrusion within coastal rivers and aquifers. Assessment of vulnerability to rising sea levels requires consideration of physical causes, historical evidence, and projections. A risk-based perspective on sea level rise points to the need for emphasis on how changing sea levels alter the coastal zone and interact with coastal flood risk at local scales.

This chapter reviews the physical factors driving global and regional sea level changes. It presents geological and instrumental observations of historical sea level changes and an assessment of the human contribution to sea level change. It then describes a range of scenarios for future levels and rates of sea level change, and the relationship of these scenarios to the Representative Concentration Pathways (RCPs). Finally, it assesses the impact of changes in sea level on extreme water levels.

While outside the scope of this chapter, it is important to note the myriad of other potential impacts associated with relative sea level (RSL) rise, wave action, and increases in coastal flooding. These impacts include loss of life, damage to infrastructure and the built environment, salinization of coastal aquifers, mobilization of pollutants, changing sediment budgets, coastal erosion, and ecosystem changes such as marsh loss and threats to endangered flora and fauna (Wong et al. 2014). While all of these impacts are inherently important, some also have the potential to influence local rates of RSL rise and the extent of wave-driven and coastal flooding impacts. For example, there is evidence that wave action and flooding of beaches and marshes can induce changes in coastal geomorphology, such as sediment build up, that may iteratively modify the future flood risk profile of communities and ecosystems (Lentz et al. 2016).

12.2 Physical Factors Contributing to Sea Level Rise

Sea level change is driven by a variety of mechanisms operating at different spatial and temporal scales (see Kopp et al. 2015a for a review). Global mean sea level (GMSL) rise is primarily driven by two factors: 1) increased volume of seawater due to thermal expansion of the ocean as it warms, and 2) increased mass of water in the ocean due to melting ice from mountain glaciers and the Antarctic and Greenland ice sheets (Church et al. 2013). The overall amount (mass) of ocean water, and thus sea level, is also affected to a lesser extent by changes in global land-water storage, which reflects changes in the impoundment of water in dams and reservoirs and river runoff from groundwater extraction, inland sea and wetland drainage, and global precipitation patterns, such as occurs during phases of the El Niño–Southern Oscillation (ENSO) (Church et al. 2013; Reager et al. 2016; Rietbroek et al. 2016; Wada et al. 2016, 2017).

Sea level and its changes are not uniform globally for several reasons. First, atmosphere–ocean dynamics—driven by ocean circulation, winds, and other factors—are associated with differences in the height of the sea surface, as are differences in density arising from the distribution of heat and salinity in the ocean. Changes in any of these factors will affect sea surface height. For example, a weakening of the Gulf Stream transport in the mid-to-late 2000s may have contributed to enhanced sea level rise in the ocean environment extending to the northeastern U.S. coast (Boon 2012; Sallenger et al. 2012; Ezer 2013), a trend that many models project will continue into the future (Yin and Goddard 2013).

Second, the locations of land ice melting and land water reservoir changes impart distinct regional "static-equilibrium fingerprints" on sea level, based on gravitational, rotational, and crustal deformation effects (Mitrovica et al. 2011) (Figure 12.1a–d). For example, sea level falls near a melting ice sheet because of the reduced gravitational attraction of the ocean toward the ice sheet; reciprocally, it rises by greater than the global average far from the melting ice sheet.

Third, the Earth's mantle is still moving in response to the loss of the great North American (Laurentide) and European ice sheets of the Last Glacial Maximum; the associated changes in the height of the land, the shape of the ocean basin, and the Earth's gravitational field give rise to glacial-isostatic adjustment (Figure 12.1e). For example, in areas once covered by the thickest parts of the great ice sheets of the Last Glacial Maximum, such as in Hudson Bay and in Scandinavia, post-glacial rebound of the land is causing relative sea level (RSL) to fall. Along the flanks of the ice sheets, such as along most of the east coast of the United States, subsidence of the bulge that flanked the ice sheet is causing RSL to rise.

Finally, a variety of other factors can cause local vertical land movement. These include natural sediment compaction, compaction caused by local extraction of groundwater and fossil fuels, and processes related to plate tectonics, such as earthquakes and more gradual seismic creep (Zervas et al. 2013; Wöppelmann and Marcos 2016) (Figure 12.1f).

Compared to many climate variables, the trend signal for sea level change tends to be large relative to natural variability. However, at interannual timescales, changes in ocean dynamics, density, and wind can cause substantial sea level variability in some regions. For example, there has been a multidecadal suppression of sea level rise off the Pacific coast (Bromirski et al. 2011) and large year-to-year variations in sea level along the Northeast U.S. coast (Goddard et al. 2015). Local rates of land height change have also varied dramatically on decadal timescales in some locations, such as along the western Gulf Coast, where rates of subsurface extraction of fossil fuels and groundwater have varied over time (Galloway et al. 1999).

[INSERT FIGURE 12.1 HERE]

12.3 Paleo Sea Level

Geological records of temperature and sea level indicate that during past warm periods over the last several millions of years, GMSL was higher than it is today (Miller et al. 2005; Dutton et al. 2015). During the Last Interglacial stage, about 125,000 years ago, global average sea surface temperature was about 0.5° ± 0.3°C (0.9° ± 0.5°F) above the preindustrial level [that is, comparable to the average over 1995–2014, when global mean temperature was about 0.8°C (1.4°F) above the preindustrial levels] (Hoffman et al. 2017). Polar temperatures were comparable to those projected for 1°C–2°C (1.8°F–3.6°F) of global mean warming above the preindustrial level. At this time, GMSL was about 6–9 meters (about 20–30 feet) higher than today (Dutton and Lambeck 2012; Kopp et al. 2009) (Figure 12.2a). This geological benchmark may indicate the probable long-term response of GMSL to the minimum magnitude of temperature change projected for the current century.

Similarly, during the mid-Pliocene warm period, about 3 million years ago, global mean temperature was about 1.8°–3.6°C (3.2°–6.5°F) above the preindustrial level (Haywood et al. 2013). Estimates of GMSL are less well constrained than during the Last Interglacial, due to the smaller number of local geological sea level reconstruction and the possibility of significant vertical land motion over millions of years (Dutton et al. 2015). Some reconstructions place mid-Pliocene GMSL at about 10–30 meters (about 30–100 feet) higher than today (Miller et al. 2012). Sea levels this high would require a significantly reduced Antarctic ice sheet, highlighting the risk of significant Antarctic ice sheet loss under such levels of warming (Figure 12.2a).

For the period since the Last Glacial Maximum, about 26,000 to 19,000 years ago (Clark et al. 2009), geologists can produce detailed reconstructions of sea levels as well as rates of sea level change. To do this, they use proxies such as the heights of fossil coral reefs and the populations of different salinity-sensitive microfossils within salt marsh sediments (Shennan et al. 2015). During the main portion of the deglaciation, from about 17,000 to 8,000 years ago, GMSL rose at an average rate of about 12 mm/year (0.5 inches/year) (Lambeck et al. 2014). However, there were periods of faster rise. For example, during Meltwater Pulse 1a, lasting from about 14,600 to 14,300 years ago, GMSL may have risen at an average rate about 50 mm/year (2 inches/year) (Deschamps et al. 2012).

Since the disappearance of the last remnants of the North American (Laurentide) Ice Sheet about 7,000 years ago (Carlson et al. 2008) to about the start of the 20th century, however, GMSL has been relatively stable. During this period, total GMSL rise is estimated to have been about 4 meters (about 13 feet), most of which occurred between 7,000 and 4,000 years ago (Lambeck et al. 2014). The Third National Climate Assessment (NCA3) noted, based on a geological data set from North Carolina (Kemp et al. 2011), that the 20th century GMSL rise was much faster than at any time over the past 2,000 years. Since NCA3, high-resolution sea level reconstructions have been developed for multiple locations, and a new global analysis of such reconstructions strengthens this finding (Kopp et al. 2016). Over the last 2,000 years, prior to the industrial era, GMSL exhibited small fluctuations of about ±8 cm (3 inches), with a significant decline of about 8 cm (3 inches) between the years 1000 and 1400 CE coinciding with about 0.2°C (0.4°F) of global mean cooling (Kopp et al. 2016). The rate of rise in the last century, about 14 cm/century (5.5 inches/century), was greater than during any preceding century in at least 2,800 years (Kopp et al. 2016; Figure 12.2b).

[INSERT FIGURE 12.2 HERE]

12.4 Recent Past Trends (20th and 21st Centuries)

12.4.1 Global Tide Gauge Network and Satellite Observations

A global tide gauge network provides the century-long observations of local RSL, whereas satellite altimetry provides broader coverage of sea surface heights outside the polar regions starting in 1993. GMSL can be estimated through statistical analyses of either data set. GMSL trends over the 1901–1990 period vary slightly (Hay et al. 2015: 1.2 ± 0.2 mm/year [0.05 inches/year]; Church and White 2011: 1.5 ± 0.2 mm/year [0.06 inches/year]) with differences amounting to about 1 inch over 90 years. Thus, these results indicate about 11–14 cm (4–5 inches) of GMSL rise from 1901 to 1990.

Tide gauge analyses indicate that GMSL rose at a considerably faster rate of about 3 mm/year (0.12 inches/year) since 1993 (Hay et al. 2015; Church and White 2011), a result supported by satellite data indicating a trend of 3.4 ± 0.4 mm/year (0.13 ± 0.02 inches/year) over 1993–2015 (update to Nerem et al. 2010). These results indicate an additional GMSL rise of about 7 cm (3 inches) since 1990 (Figure 12.2b, Figure 12.3a) and 18–21 cm (7–8 inches) since 1900. Satellite (altimetry and gravity) and in situ water column (Argo floats) measurements show that, since 2005, about one third of GMSL rise has been from steric changes (primarily thermal expansion) and about two thirds from the addition of mass to the ocean, which represents a growing land-ice contribution (compared to steric) and a departure from the relative contributions earlier in the 20th century (Church et al. 2013; Llovel et al. 2014; Leuliette 2015; Merrifield et al. 2015; Chambers et al. 2017; Leuliette and Nerem 2016) (Figure 12.3a).

In addition to land ice, the mass-addition contribution also includes net changes in global land-water storage. This term varied in sign over the course of the last century, with human-induced changes in land-water storage being negative (perhaps as much as about –0.6 mm/year [–0.02 inches/year]) during the period of heavy dam construction in the middle of the last century, and turning positive in the 1990s as groundwater withdrawal came to dominate (Wada et al. 2017). On decadal timescales, precipitation variability can dominate human-induced changes in land water storage; recent satellite-gravity estimates suggest that, over 2002–2014, a human-caused land-water contribution to GMSL of 0.4 mm/year (0.02 inches/year) was more than offset by –0.7 mm/year (–0.03 inches/year) due to natural variability (Reager et al. 2016).

Comparison of results from a variety of approaches supports the conclusion that a substantial fraction of GMSL rise since 1900 is attributable to human-caused climate change (Kopp et al. 2016; Slangen et al. 2016; Jevrejeva et al. 2009; Dangendorf et al. 2015; Becker et al. 2014; Marcos and Amores 2014; Slangen et al. 2014a; Marzeion et al. 2014; Marcos et al. 2017). For example, based on the long term historical relationship between temperature and rate of GMSL change, Kopp et al. (2016) found that GMSL rise would *extremely likely* have been less than 59% of observed in the absence of 20th century global warming, and that it is *very likely* that GMSL has been higher since 1960 than it would have been without 20th century global warming (Figure 12.3b). Similarly, using a variety of models for individual components, Slangen et al. (2016) found that about 80% of the GMSL rise they simulated for 1970–2005 and about half of that which they simulated for 1900–2005 was attributable to anthropogenic forcing.

Over timescales of a few decades, ocean–atmosphere dynamics drive significant variability in sea surface height, as can be observed by satellite (Figure 12.3c) and in tide gauge records that have been adjusted to account for background rates of rise due to long term factors like glacio-isostatic adjustments. For example, the U.S. Pacific Coast experienced a slower-than-global increase between about 1980 and 2011, while the western tropical Pacific experienced a faster-than-global increase in the 1990s and 2000s. This pattern was associated with changes in average winds linked to the Pacific Decadal Oscillation (PDO) (Bromirski et al. 2011; Zhang and Church 2012; Merrifield 2011) and appears to have reversed since about 2012 (Hamlington et al. 2016). Along the Atlantic coast, the U.S. Northeast has experienced a faster-than-global increase since the 1970s, while the U.S. Southeast has experienced a slower-than-global increase since the 1970s. This pattern appears to be tied to changes in the Gulf Stream (Yin and Goddard 2013; Ezer 2013; Kopp 2013; Kopp et al. 2015b), although whether these changes represent natural variability or a long term trend remains uncertain (Rahmstorf et al. 2015).

[INSERT FIGURE 12.3 HERE]

12.4.2 Ice Sheet Gravity and Altimetry and Visual Observations

Since NCA3, Antarctica and Greenland have continued to lose ice mass, with mounting evidence accumulating that mass loss is accelerating. Studies using repeat gravimetry (GRACE satellites), repeat altimetry, GPS monitoring, and mass balance calculations generally agree on accelerating mass loss in Antarctica (Shepherd et al. 2012; Scambos and Shuman 2016; Seo et al. 2015; Martín-Español et al. 2016). Together, these indicate a mass loss of roughly 100 Gt/year (gigatonnes/year) over the last decade (a contribution to GMSL of about 0.3 mm/year [0.01 inches/year]). Positive accumulation rate anomalies in East Antarctica, especially in Dronning Maud Land (Helm et al. 2014), have contributed to the trend of slight growth there (e.g., Seo et al. 2015; Martín-Español et al. 2016), but this is more than offset by mass loss elsewhere, especially in West Antarctica along the coast facing the Amundsen Sea (Sutterley et al. 2014; Mouginot et al. 2014), Totten Glacier in East Antarctica (Khazendar et al. 2013; Li et al. 2015), and along the Antarctic Peninsula (Seo et al. 2015; Wouters et al. 2015; Martín-Español et al.

2016). Floating ice shelves around Antarctica are losing mass at an accelerating rate (Paolo et al. 2015). Mass loss from floating ice shelves does not directly affect GMSL, but does allow faster flow of ice from the ice sheet into the ocean.

Estimates of mass loss in Greenland based on mass balance from input-output, repeat gravimetry, repeat altimetry, and aerial imagery as discussed in Chapter 11: Arctic Changes reveal a recent acceleration (Khan et al. 2014). Mass loss averaged approximately 75 Gt/year (about 0.2 mm/year [0.01 inches/year] GMSL rise) from 1900 to 1983, continuing at a similar rate of approximately 74 Gt/year through 2003 before accelerating to 186 Gt/year (0.5 mm/year [0.02 inches/year] GMSL rise) from 2003 to 2010 (Kjeldsen et al. 2015). Strong interannual variability does exist (see Ch. 11: Arctic Changes), such as during the exceptional melt year from April 2012 to April 2013, which resulted in mass loss of approximately 560 Gt (1.6 mm/year [0.06 inches/year]) (Tedesco et al. 2013). More recently (April 2014–April 2015), annual mass losses have resumed the accelerated rate of 186 Gt/year (Kjeldsen et al. 2015; Tedesco et al. 2016). Mass loss over the last century has reversed the long-term trend of slow thickening linked to the continuing evolution of the ice sheet from the end of the last ice age (MacGregor et al. 2016).

12.5 Projected Sea Level Rise

12.5.1 Scenarios of Global Mean Sea Level Rise

No single physical model is capable of accurately representing all of the major processes contributing to GMSL and regional/local RSL rise. Accordingly, the U.S. Interagency Sea Level Rise Task Force (Sweet et al. 2017; henceforth referred to as "Interagency") has revised the GMSL rise scenarios for the United States and now provides six scenarios that can be used for assessment and risk-framing purposes (Figure 12.4a; Table 12.1). The low scenario of 30 cm (about 1 foot) GMSL rise by 2100 is consistent with a continuation of the recent approximately 3 mm/year (0.12 inches/year) rate of rise through to 2100 (Table 12.2), while the five other scenarios span a range of GMSL rise between 50 and 250 cm (1.6 and 8.2 feet) in 2100, with corresponding rise rates between 5 mm/year (0.2 inches/year) to 44 mm/year (1.7 inches/year) towards the end of this century (Table 12.2). The highest scenario of 250 cm is consistent with several literature estimates of the maximum physically plausible level of 21st century sea level rise (e.g., Pfeffer et al. 2008, updated with Sriver et al. 2012 estimates of thermal expansion and Bamber and Aspinall 2013 estimates of Antarctic contribution, and incorporating land water storage, as discussed in Miller et al. 2013; Kopp et al. 2014). It is also consistent with the high end of recent projections of Antarctic ice sheet melt discussed below (DeConto and Pollard 2016). The Interagency GMSL scenario interpretations are shown in Table 12.3.

[INSERT FIGURE 12.4 HERE]

The Interagency scenario approach is similar to local RSL rise scenarios of Hall et al. (2016) used for all coastal U.S. Department of Defense installations worldwide. The Interagency approach starts with a probabilistic projection framework to generate time series and regional projections consistent with each GMSL rise scenario for 2100 (Kopp et al. 2014). That framework combines probabilistic estimates of contributions to GMSL and regional RSL rise from ocean processes, cryospheric processes, geological processes, and anthropogenic land-water storage. Pooling the Kopp et al. (2014) projections across RCP2.6, 4.5, and 8.5, the probabilistic projections are filtered to identify pathways consistent with each of these 2100 levels with median (and 17th and 83rd percentiles) picked from each of the filtered subsets.

Table 12.1. The Interagency GMSL rise scenarios in meters (feet) relative to 2000. All values are 19-year averages of GMSL centered at the identified year. To convert from a 1991–2009 tidal datum to the 1983–2001 tidal datum, add 2.4 cm (0.9 inches).

Scenario	**2020**	**2030**	**2050**	**2100**
Low	0.06 (0.2)	0.09 (0.3)	0.16 (0.5)	0.30 (1.0)
Intermediate-Low	0.08 (0.3)	0.13 (0.4)	0.24 (0.8)	0.50 (1.6)
Intermediate	0.10 (0.3)	0.16 (0.5)	0.34 (1.1)	1.0 (3.3)
Intermediate-High	0.10 (0.3)	0.19 (0.6)	0.44 (1.4)	1.5 (4.9)
High	0.11 (0.4)	0.21 (0.7)	0.54 (1.8)	2.0 (6.6)
Extreme	0.11 (0.4)	0.24 (0.8)	0.63 (2.1)	2.5 (8.2)

Table 12.2. Rates of GMSL rise in the Interagency scenarios in mm/year (inches/year). All values represent 19-year average rates of change, centered at the identified year.

Scenario	**2020**	**2030**	**2050**	**2090**
Low	3 (0.1)	3 (0.1)	3 (0.1)	3 (0.1)

Intermediate-Low	5 (0.2)	5 (0.2)	5 (0.2)	5 (0.2)
Intermediate	6 (0.2)	7 (0.3)	10 (0.4)	15 (0.6)
Intermediate-High	7 (0.3)	10 (0.4)	15 (0.6)	24 (0.9)
High	8 (0.3)	13 (0.5)	20 (0.8)	35 (1.4)
Extreme	10 (0.4)	15 (0.6)	25 (1.0)	44 (1.7)

Table 12.3. Interpretations of the Interagency GMSL rise scenarios

Scenario	**Interpretation**
Low	Continuing current rate of GMSL rise, as calculated since 1993 Low end of *very likely* range under RCP2.6
Intermediate-Low	Modest increase in rate Middle of *likely* range under RCP2.6 Low end of *likely* range under RCP4.5 Low end of *very likely* range under RCP8.5
Intermediate	High end of *very likely* range under RCP4.5 High end of *likely* range under RCP8.5 Middle of *likely* range under RCP4.5 when accounting for possible ice cliff instabilities
Intermediate-High	Slightly above high end of *very likely* range

	under RCP8.5 Middle of *likely* range under RCP8.5 when accounting for possible ice cliff instabilities
High	High end of *very likely* range under RCP8.5 when accounting for possible ice cliff instabilities
Extreme	Consistent with estimates of physically possible "worst case"

12.5.2 Probabilities of Different Sea Level Rise Scenarios

Several studies have estimated the probabilities of different amounts of GMSL rise under different emissions pathways (e.g., Church et al. 2013; Kopp et al. 2014; Slangen et al. 2014b; Jevrejeva et al. 2014; Grinsted et al. 2015; Kopp et al. 2016; Mengel et al. 2016; Jackson and Jevrejeva 2016) using a variety of methods, including both statistical and physical models. Most of these studies are in general agreement that GMSL rise by 2100 is *very likely* to be between about 25–80 cm (0.8–2.6 feet) under RCP2.6, 35–95 cm (1.1–3.1 feet) under RCP4.5, and 50–130 cm (1.6–4.3 feet) under RCP8.5, although some projections extend the *very likely* range for RCP8.5 as high as 160–180 cm (5–6 feet) (Kopp et al. 2014, sensitivity study; Jevrejeva et al. 2014; Jackson and Jevrejeva 2016). Based on Kopp et al. (2014), the probability of exceeding the amount of GMSL in 2100 under the Interagency scenarios is shown in Table 12.4.

The Antarctic projections of Kopp et al. (2014), the GMSL projections of which underlie Table 12.4, are consistent with a statistical-physical model of the onset of marine ice sheet instability calibrated to observations of ongoing retreat in the Amundsen Embayment sector of West Antarctica (Ritz et al. 2015). Ritz et al. (2015)'s 95th percentile Antarctic contribution to GMSL of 30 cm by 2100 is comparable to Kopp et al. (2014)'s 95th percentile projection of 33 cm under RCP8.5. However, emerging science suggests that these projections may understate the probability of faster-than-expected ice sheet melt, particularly for high-end warming scenarios. While these probability estimates are consistent with the assumption that the relationship between global temperature and GMSL in the coming century will be similar to that observed over the last two millennia (Rahmstorf 2007; Kopp et al. 2016), emerging positive feedbacks (self-amplifying cycles) in the Antarctic Ice Sheet especially (Rignot et al. 2014; Joughin et al. 2014) may invalidate that assumption. Physical feedbacks that until recently were not incorporated into ice sheet models (Pollard et al. 2015) could add about 0–10 cm (0–0.3 feet), 20–50 cm (0.7–1.6 feet) and 60–110 cm (2.0–3.6 feet) to central estimates of current century sea level rise under RCP2.6, RCP4.5 and RCP8.5, respectively (DeConto and Pollard 2016). In addition to marine ice sheet instability, examples of these interrelated processes include ice cliff instability and ice shelf hydrofracturing. Processes underway in Greenland may also be leading to accelerating high-end melt risk. Much of the research has focused on changes in surface albedo driven by the melt-associated unmasking and concentration of impurities in snow and ice (Tedesco et al. 2016). However, ice dynamics at the bottom of the ice sheet may be important as well, through interactions with surface runoff or a warming ocean. As an example of the latter, Jakobshavn Isbræ, Kangerdlugssuaq Glacier, and the Northeast Greenland ice stream may be vulnerable to marine ice sheet instability (Khan et al. 2014).

Table 12.4. Probability of exceeding the Interagency GMSL scenarios in 2100 per Kopp et al. (2014). New evidence regarding the Antarctic ice sheet, if sustained, may significantly increase the probability of the intermediate-high, high and extreme scenarios, particularly for RCP8.5, but these results have not yet been incorporated into a probabilistic analysis.

Scenario	**RCP2.6**	**RCP4.5**	**RCP8.5**
Low	94%	98%	100%
Intermediate-Low	49%	73%	96%
Intermediate	2%	3%	17%
Intermediate-High	0.4%	0.5%	1.3%
High	0.1%	0.1%	0.3%
Extreme	0.05%	0.05%	0.1%

12.5.3 Sea Level Rise after 2100

GMSL rise will not stop in 2100, and so it is useful to consider extensions of GMSL rise projections beyond this point. By 2200, the 0.3–2.5 meters (1.0–8.2 feet) range spanned by the six Interagency GMSL scenarios in year 2100 increases to about 0.4–9.7 meters (1.3–31.8 feet), as shown in Table 12.5. These six scenarios imply average rates of GMSL rise over the first half of the next century of 1.4 mm/year (0.06 inch/year), 4.6 mm/yr (0.2 inch/year), 16 mm/year (0.6 inch/year), 32 mm/year (1.3 inches/year), 46 mm/yr (1.8 inches/year) and 60 mm/year (2.4

inches/year), respectively. Excluding the possible effects of still emerging science regarding ice cliffs and ice shelves, it is very likely that by 2200 GMSL will have risen by 0.3–2.4 meters (1.0–7.9 feet) under RCP2.6, 0.4–2.7 meters (1.3–8.9 feet) under RCP4.5, and 1.0–3.7 meters (3.3–12 feet) under RCP8.5 (Kopp et al. 2014).

Under most projections, GMSL rise will also not stop in 2200. The concept of a “sea level rise commitment” refers to the long-term projected sea level rise were the planet’s temperature to be stabilized at a given level (e.g., Levermann et al. 2013; Golledge et al. 2015). The paleo sea level record suggests that even 2°C (3.6°F) of global average warming above the preindustrial temperature may represent a commitment to several meters of rise. One modeling study suggesting a 2,000-year commitment of 2.3 m/°C (4.2 feet/°F) (Levermann et al. 2013) indicates that emissions through to 2100 would lock in a likely 2,000-year GMSL rise commitment of about 0.7–4.2 meters (2.3–14 feet) under RCP2.6, about 1.7–5.6 meters (5.6–19 feet) under RCP4.5, and about 4.3–9.9 meters (14–33 feet) under RCP8.5 (Strauss et al. 2015). However, as with the 21st century projections, emerging science regarding the sensitivity of the Antarctic Ice Sheet may increase the estimated sea level rise over the next millennium, especially for high emissions pathways (DeConto and Pollard 2016). Large-scale climate geoengineering might reduce these commitments (Irvine et al. 2009; Applegate and Keller 2015), but may not be able to avoid lock-in of significant change (Lenton 2011; Barrett et al. 2014; Markusson et al. 2014; Sillmann et al. 2015). Once changes are realized, they will be effectively irreversible for many millennia, even if humans artificially accelerate the removal of CO_2 from the atmosphere (DeConto and Pollard 2016).

The 2,000-year commitment understates the full sea level rise commitment, due to the long response time of the polar ice sheets. Paleo sea level records (Figure 12.2a) suggest that 1°C of warming may already represent a long-term commitment to more than 6 meters (20 feet) of GMSL rise (Dutton and Lambeck 2012; Kopp et al. 2009; Dutton et al. 2015). A 10,000-year modeling study (Clark et al. 2016) suggests that 2°C warming represents a 10,000-year commitment to about 25 meters (80 feet) of GMSL rise, driven primarily by a loss of about one-third of the Antarctic ice sheet and three-fifths of the Greenland ice sheet, while the 21st century RCP8.5 emissions represent a 10,000-year commitment to about 38 meters (125 feet) of GMSL rise, including a complete loss of the Greenland ice sheet over about 6,000 years.

Table 12.5. Post-2100 extensions of the Interagency GMSL rise scenarios in meters (feet)

Scenario	**2100**	**2120**	**2150**	**2200**
Low	0.30 (1.0)	0.34 (1.1)	0.37 (1.2)	0.39 (1.3)
Intermediate-Low	0.50 (1.6)	0.60 (2.0)	0.73 (2.4)	0.95 (3.1)

Intermediate	1.0 (3.3)	1.3 (4.3)	1.8 (5.9)	2.8 (9.2)
Intermediate-High	1.5 (4.9)	2.0 (6.6)	3.1 (10)	5.1 (17)
High	2.0 (6.6)	2.8 (9.2)	4.3 (14)	7.5 (25)
Extreme	2.5 (8.2)	3.6 (12)	5.5 (18)	9.7 (32)

12.5.4 Regional Projections of Sea Level Change

Because the different factors contributing to sea level change give rise to different spatial patterns, projecting future RSL change at specific locations requires not just an estimate of GMSL change but estimates of the different processes contributing to GMSL change—each of which has a different associated spatial pattern—as well as of the processes contributing exclusively to regional or local change. Based on the process-level projections of the Interagency GMSL scenarios, several key regional patterns are apparent in future U.S. RSL rise as shown for the Intermediate (1 meter [3.3 feet] GMSL rise by 2100 scenario) in Figure 12.4b.

(1) RSL rise due to Antarctic Ice Sheet melt is greater than GMSL rise along all U.S. coastlines due to static-equilibrium effects.

(2) RSL rise due to Greenland Ice Sheet melt is less than GMSL rise in the continental U.S. due to static-equilibrium effects. This effect is especially strong in the Northeast.

(3) RSL rise is additionally augmented in the Northeast by the effects of glacial isostatic adjustment.

(4) The Northeast is also exposed to rise due to changes in the Gulf Stream and reductions in the Atlantic meridional overturning circulation (AMOC). Were the AMOC to collapse entirely—an outcome viewed as unlikely in the 21st century—it could result in as much as approximately 0.5 meters (1.6 feet) of additional regional sea level rise (Gregory and Lowe 2000; Levermann et al. 2005; see Ch. 15: Potential Surprises for further discussion).

(5) The western Gulf of Mexico and parts of the U.S. Atlantic Coast south of New York are currently experiencing significant RSL rise caused by the withdrawal of groundwater (along the Atlantic Coast) and of both fossil fuels and groundwater (along the Gulf Coast). Continuation of these practices will further amplify RSL rise.

(6) The presence of glaciers in Alaska and their proximity to the Pacific Northwest reduces RSL rise in these regions, due to both the ongoing glacial isostatic adjustment to past glacier shrinkage and to the static-equilibrium effects of projected future losses.

(7) Because they are far from all glaciers and ice sheets, RSL rise in Hawaiʻi and other Pacific islands due to any source of melting land ice is amplified by the static-equilibrium effects.

12.6 Extreme Water Levels

12.6.1 Observations

Coastal flooding during extreme high-water events has become deeper due to local RSL rise and more frequent from a fixed-elevation perspective (Menéndez and Woodworth 2010; Kemp and Horton 2013; Sweet et al. 2013; Hall et al. 2016). Trends in annual frequencies surpassing local emergency preparedness thresholds for minor tidal flooding (i.e., “nuisance” levels of about 30–60 cm [1–2 feet]) that begin to flood infrastructure and trigger coastal flood “advisories” by NOAA’s National Weather Service have increased 5- to 10-fold or more since the 1960s along the U.S. coastline (Sweet et al. 2014), as shown in Figure 12.5a. Locations experiencing such trend changes (based upon fits of flood days per year of Sweet and Park 2014) include Atlantic City and Sandy Hook, NJ; Philadelphia, PA; Baltimore and Annapolis, MD; Norfolk, VA; Wilmington, NC; Charleston, SC; Savannah, GA; Mayport and Key West, FL; Port Isabel, TX, La Jolla, CA; and Honolulu, HI. In fact, over the last several decades, minor tidal flood rates have been accelerating within several (more than 25) East and Gulf Coast cities with established elevation thresholds for minor (nuisance) flood impacts, fastest where elevation thresholds are lower, local RSL rise is higher, and extreme variability less (Ezer and Atkinson 2014; Sweet et al. 2014; Sweet and Park 2014).

Trends in extreme water levels (for example, monthly maxima) in excess of mean sea levels (for example, monthly means) exist, but are not commonplace (Menéndez and Woodworth 2010; Talke et al. 2014; Wahl and Chambers 2015; Reed et al. 2015; Marcos et al. 2017). More common are regional time dependencies in high-water probabilities, which can co-vary on an interannual basis with climatic and other patterns (Menéndez and Woodworth 2010; Grinsted et al. 2013; Marcos et al. 2015; Woodworth and Menéndez 2015; Wahl and Chambers 2016; Mawdsley and Haigh 2016; Sweet et al. 2016). These patterns are often associated with anomalous oceanic and atmospheric conditions (Feser et al. 2015; Colle et al. 2015). For instance, the probability of experiencing minor tidal flooding is compounded during El Niño periods along portions of the West and Mid-Atlantic Coasts (Sweet and Park 2014) from a combination of higher sea levels and enhanced synoptic forcing and storm surge frequency (Sweet and Zervas 2011; Thompson et al. 2013; Hamlington et al. 2015; Woodworth and Menéndez 2015).

12.6.2 Influence of Projected Sea Level Rise on Coastal Flood Frequencies

The extent and depth of minor-to-major coastal flooding during high-water events will continue to increase in the future as local RSL rises (Tebaldi et al. 2012; Horton et al. 2011; Woodruff et al. 2013; Kopp et al. 2014; Sweet and Park 2014; Buchanan et al. 2016; Hall et al. 2016; Dahl et al. 2017; Sweet et al. 2017). Relative to fixed elevations, the frequency of high-water events will increase the fastest where extreme variability is less and the rate of local RSL rise is higher (Hunter 2012; Tebaldi et al. 2012; Kopp et al. 2014; Sweet and Park 2014; Buchanan et al. 2016; Sweet et al. 2017). Under the RCP-based probabilistic RSL projections of Kopp et al. 2014, at tide gauge locations along the contiguous U.S. coastline, a median 8-fold increase (range of 1.1- to 430-fold increase) is expected by 2050 in the annual number of floods exceeding the elevation of the current 100-year flood event (measured with respect to a 1991–2009 baseline sea level) (Buchanan et al. 2016). Under the same forcing, the frequency of minor tidal flooding (with contemporary recurrence intervals generally <1 year [Sweet et al. 2014]) will increase even more so in the coming decades (Sweet and Park 2014; Moftakhari et al. 2015) and eventually occur on a daily basis (Figure 12.5b). With only about 0.35 m (<14 inches) of additional local RSL rise (with respect to the year 2000), annual frequencies of moderate level flooding—those locally with a 5-year recurrence interval (Figure 12.5c) and associated with a NOAA coastal flood warning of serious risk to life and property—will increase 25-fold at the majority of NOAA tide gauge locations along the U.S. coastline (outside of Alaska) by or about (±5 years) 2080, 2060, 2040, and 2030 under the Interagency Low, Intermediate-Low, Intermediate, and Intermediate-High GMSL scenarios, respectively (Sweet et al. 2017). Figure 12.5d, which shows the decade in which the frequency of such moderate level flooding will increase 25-fold under the Interagency Intermediate Scenario, highlights that the mid- and Southeast Atlantic, western Gulf of Mexico, California, and the Island States and Territories are most susceptible to rapid changes in potentially damaging flood frequencies.

[INSERT FIGURE 12.5 HERE]

12.6.3 Waves and Impacts

The combination of a storm surge at high tide with additional dynamic effects from waves (Stockdon et al. 2006; Sweet et al. 2015) creates the most damaging coastal hydraulic conditions (Moritz et al. 2015). Simply with higher-than-normal sea levels, wave action increases the likelihood for extensive coastal erosion (Barnard et al. 2011; Theuerkauf et al. 2014; Serafin and Ruggiero 2014) and low-island overwash (Hoeke et al. 2013). Wave runup is often the largest water level component during extreme events especially along island coastlines where storm surge is constrained by bathymetry (Tebaldi et al. 2012; Woodruff et al. 2013; Hall et al. 2016). On an interannual basis, wave impacts are correlated across the Pacific Ocean with phases of ENSO (Stopa and Cheung 2014; Barnard et al. 2015). Over the last half century, there has been an increasing trend in wave height and power within the North Pacific Ocean (Bromirski et al. 2013; Erikson et al. 2015) that is modulated by the PDO (Aucan et al. 2012; Bromirski et al.

2013). Resultant increases in wave run-up have been more of a factor than RSL rise in terms of impacts along the U.S. Northwest Pacific Coast over the last several decades (Ruggiero 2013). In the Northwest Atlantic Ocean, no long-term trends in wave power have been observed over the last half century (Bromirski and Cayan 2015), though hurricane activity drives interannual variability (Bromirski and Kossin 2008). In terms of future conditions this century, increases in mean and maximum seasonal wave heights are projected within parts of the northeast Pacific, northwest Atlantic, and Gulf of Mexico (Graham et al. 2013; Wang et al. 2014; Erikson et al. 2015; Shope et al. 2016).

12.6.4 Sea Level Rise, Changing Storm Characteristics, and Their Interdependencies

Future probabilities of extreme coastal floods will depend upon the amount of local RSL rise, changes in coastal storm characteristics, and their interdependencies. For instance, there have been more storms producing concurrent locally extreme storm surge and rainfall (not captured in tide gauge data) along the U.S. East and Gulf Coasts over the last 65 years, with flooding further compounded by local RSL rise (Wahl et al. 2015). Hemispheric-scale extratropical cyclones may experience a northward shift this century, with some studies projecting an overall decrease in storm number (Colle et al. 2015 and references therein). The research is mixed about strong extratropical storms; studies find potential increases in frequency and intensity in some regions, like within the Northeast (Colle et al. 2013), whereas others project decreases in strong extratropical storms in some regions (e.g., Zappa et al. 2013).

For tropical cyclones, model projections for the North Atlantic mostly agree that intensities and precipitation rates will increase this century (see Ch. 9: Extreme Storms), although some model evidence suggests that track changes could dampen the effect in the U.S. Mid-Atlantic and Northeast (Hall and Yonekura 2013). Assuming other storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters. A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf Coast States beyond what would be projected based solely on RSL rise (Grinsted et al. 2013; Lin et al. 2012; Little et al. 2015; Lin et al. 2016). In addition, RSL increases are projected to cause a nonlinear increase in storm surge heights in shallow bathymetry environments (Smith et al. 2010; Atkinson et al. 2013; Bilskie et al. 2014; Passeri et al. 2015; Bilskie et al. 2016) and extend wave propagation and impacts landward (Smith et al. 2010; Atkinson et al. 2013). However, there is low confidence in the magnitude of the increase in intensity and the associated flood risk amplification, and it could be offset or amplified by other factors, such as changes in storm frequency or tracks (e.g., Knutson et al. 2013, 2015)

TRACEABLE ACCOUNTS

Key Finding 1

Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*), contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years (*medium confidence*).

Description of evidence base

Multiple researchers, using different statistical approaches, have integrated tide gauge records to estimate GMSL rise since the late nineteenth century (e.g., Church and White 2006, 2011; Hay et al. 2015; Jevrejeva et al. 2009). The most recent published rate estimates are 1.2 ± 0.2 (Hay et al. 2015) or 1.5 ± 0.2 (Church and White 2011) mm/year over 1901–1990. Thus, these results indicate about 11–14 cm (4–5 inches) of GMSL rise from 1901 to 1990. Tide gauge analyses indicate that GMSL rose at a considerably faster rate of about 3 mm/year (0.12 inches/year) since 1993 (Hay et al. 2015; Church and White 2011), a result supported by satellite data indicating a trend of 3.4 ± 0.4 mm/year (0.13 inches/year) over 1993–2015 (update to Nerem et al. 2010) (Figure 12.3a). These results indicate an additional GMSL rise of about 7 cm (3 inches) rise since 1990. Thus, total GMSL rise since 1900 is about 18–21 cm (7–8 inches).

The finding regarding the historical context of the 20th century change is based upon Kopp et al. (2016), who conducted a meta-analysis of geological RSL reconstructions spanning the last 3,000 years from 24 locations around the world as well as tide gauge data from 66 sites and the tide gauge based GMSL reconstruction of Hay et al. (2015). By constructing a spatio-temporal statistical model of these data sets, they identified the common global sea level signal over the last three millennia and its uncertainties. They found a 95% probability that the average rate of GMSL change over 1900–2000 was greater than during any preceding century in at least 2,800 years.

The finding regarding the substantial human contribution is based upon several lines of evidence. Kopp et al. (2016), based on the long term historical relationship between temperature and the rate of sea level change, found that it is *extremely likely* that GMSL rise would have been <59% of observed in the absence of 20th century global warming, and that it is *very likely* that GMSL has been higher since 1960 than it would have been without 20th century global warming. Using a variety of models for individual components, Slangen et al. (2016) found that 69% ± 31% out of the 87% ± 20% of GMSL rise over 1970–2005 that their models simulated was attributable to anthropogenic forcing, and that 37% ± 38% out of 74% ± 22% simulated was attributable over 1900–2005. Jevrejeva et al. (2009), using the relationship between forcing and GMSL over 1850 and 2001 and CMIP3 models, found that ~75% of GMSL rise in the 20th century is attributable to anthropogenic forcing. Marcos and Amores (2014), using CMIP5 models, found that ~87% of ocean heat uptake since 1970 in the top 700 m of the ocean has been due to anthropogenic forcing. Slangen et al. (2014a), using CMIP5, found that anthropogenic forcing was required to explain observed thermosteric SLR over 1957–2005. Marzeion et al. (2014) found that 25% ± 35% of glacial loss over 1851–2010, and 69% ± 24% over 1991–2010, was attributable to anthropogenic forcing. Dangendorf et al (2015), based on time series analysis, found that >45% of observed GMSL trend since 1900 cannot (with 99% probability) be explained by multi-decadal natural variability. Becker et al. (2014), based on time series analysis, found a 99% probability that at least 1.0 or 1.3 mm/year of GMSL rise over 1880–2010 is anthropogenic.

Major uncertainties

Uncertainties in reconstructed GMSL change relate to the sparsity of tide gauge records, particularly before the middle of the twentieth century, and to different statistical approaches for estimating GMSL change from these sparse records. Uncertainties in reconstructed GMSL change before the twentieth century also relate to the sparsity of geological proxies for sea level change, the interpretation of these proxies, and the dating of these proxies. Uncertainty in attribution relates to the reconstruction of past changes and the magnitude of unforced variability.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence is *very high* in the rate of GMSL rise since 1900, based on multiple different approaches to estimating GMSL rise from tide gauges and satellite altimetry. Confidence is *high* in the substantial human contribution to GMSL rise since 1900, based on both statistical and physical modeling evidence. It is *medium* that the magnitude of the observed rise since 1900 is unprecedented in the context of the previous 2,700 years, based on meta-analysis of geological proxy records.

Summary sentence or paragraph that integrates the above information

This key finding is based upon multiple analyses of tide gauge and satellite altimetry records, on a meta-analysis of multiple geological proxies for pre-instrumental sea level change, and on both statistical and physical analyses of the human contribution to GMSL rise since 1900.

Key Finding 2

Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1 to 4 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*). Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century (*high* *confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of emissions pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*).

Description of evidence base

The lower bound of the *very likely* range is based on a continuation of the observed approximately 3 mm/year rate of GMSL rise. The upper end of the *very likely* range is based upon estimates for RCP8.5 from three studies producing fully probabilistic projections across multiple RCPs. Kopp et al. (2014) fused multiple sources of information accounting for the different individual process contributing to GMSL rise. Kopp et al. (2016) constructed a semi-empirical sea level model calibrated to the Common Era sea level reconstruction. Mengel et al. (2016) constructed a set of semi-empirical models of the different contributing processes. All three studies show negligible RCP dependence in the first half of this century, becoming more prominent in the second half of the century. A sensitivity study by Kopp et al. (2014), as well as studies by Jevrejeva et al. (2014) and by Jackson and Jevrejeva (2016), used frameworks similar to Kopp et al. (2016) but incorporated directly an expert elicitation study on ice sheet stability (Bamber and Aspinall 2013). (This study was incorporated in Kopp et al. [2014]'s main results with adjustments for consistency with Church et al. 2013). These studies extend the *very likely* range for RCP8.5 as high as 160–180 cm (5–6 feet) (Kopp et al. 2014, sensitivity study; Jevrejeva et al. 2014; Jackson and Jevrejeva 2016).

To estimate the effect of incorporating the DeConto and Pollard (2016) projections of Antarctic ice sheet melt, we note that Kopp et al. (2014)'s median projection of Antarctic melt in 2100 is 4 cm (1.6 inches) (RCP2.6), 5 cm (2 inches) (RCP4.5), or 6 cm (2.4 inches) (RCP8.5). By contrast, DeConto and Pollard (2016)'s ensemble mean projections are (varying the assumptions for the size of Pliocene mass loss and the bias correction in the Amundsen Sea) 2–14 cm (0.1–0.5 foot) for RCP2.6, 26–58 cm (0.9–1.9 feet) for RCP4.5, and 64–114 cm (2.1–3.7 ft) for RCP8.5. Thus, we conclude that DeConto and Pollard (2016)'s projection would lead to a –10 cm (–0.1–0.3 ft) increase in median RCP2.6 projections, a 21–53 cm (0.7–1.7 feet) increase in median RCP4.5 projections, and a 58–108 cm (1.9–3.5 feet) increase in median RCP8.5 projections.

Very likely ranges, 2030 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	11–18 (0.4–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)

RCP4.5	10–18 (0.3–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)
RCP2.6	10–18 (0.3–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)

Very likely ranges, 2050 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	21–38 (0.7–1.2)	16–34 (0.5–1.1)	15–28 (0.5–0.9)
RCP4.5	18–35 (0.6–1.1)	15–31 (0.5–1.0)	14–25 (0.5–0.8)
RCP2.6	18–33 (0.6–1.1)	14–29 (0.5–1.0)	13–23 (0.4–0.8)

Very likely ranges, 2100 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	55–121 (1.8–4.0)	52–131 (1.7–4.3)	57–131 (1.9–4.3)
RCP4.5	36–93 (1.2–3.1)	33–85 (1.1–2.8)	37–77 (1.2–2.5)
RCP2.6	29–82 (1.0–2.7)	24–61 (0.8–2.0)	28–56 (0.9–1.8)

Major uncertainties

Since NCA3, multiple different approaches have been used to generate probabilistic projections of GMSL rise, conditional upon the RCPs. These approaches are in general agreement. However, emerging results indicate that marine-based sectors of the Antarctic Ice Sheet are more unstable than previous modeling indicated. The rate of ice sheet mass changes remains challenging to project.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high* confidence that future GMSL rise over the next several decades will be at least as fast as a continuation of the historical trend over the last quarter century would indicate. There is *medium* confidence in the upper end of very likely ranges for 2030 and 2050. Due to possibly large ice sheet contributions, there is *low* confidence in the upper end of very likely ranges for 2100. Based on multiple projection methods, there is *high confidence* that differences between emission scenarios are small before 2050 but significant beyond 2050.

Summary sentence or paragraph that integrates the above information

This key finding is based upon multiple methods for estimating the probability of future sea level change and on new modeling results regarding the stability of marine based ice in Antarctica.

Key Finding 3

Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, RSL rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global-mean sea-level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss (*high confidence*).

Description of evidence base

The processes that cause geographic variability in RSL change are reviewed by Kopp et al. (2015a). Long tide gauge data sets show the RSL rise caused by vertical land motion due to glacio-isostatic adjustment and fluid withdrawal along many U.S. coastlines (PSMSL 2016; Holgate et al. 2013). These observations are corroborated by glacio-isostatic adjustment models, by GPS observations, and by geological data (e.g., Engelhart and Horton 2012). The physics of the gravitational, rotational and flexural "static-equilibrium fingerprint" response of sea level to redistribution of mass from land ice to the oceans is well established (Farrell and Clark 1976; Mitrovica et al. 2011). GCM studies indicate the potential for a Gulf Stream contribution to sea level rise in the U.S. Northeast (Yin et al. 2009; Yin and Goddard 2013). Kopp et al. (2014) and Slangen et al. (2014a) accounted for land motion (only glacial isostatic adjustment for Slangen et al.), fingerprint, and ocean dynamic responses. Comparing projections of local RSL change and

GMSL change in these studies indicate that local rise is likely to be greater than the global average along the U.S. Atlantic and Gulf Coasts and less than the global average in most of the Pacific Northwest. Sea level rise projections in this report are developed by an Interagency Sea Level Rise Task Force (Sweet et al. 2017).

Major uncertainties

Since NCA3, multiple authors have produced global or regional studies synthesizing the major process that causes global and local sea level change to diverge. The largest sources of uncertainty in the geographic variability of sea level change are ocean dynamic sea level change and, for those regions where sea level fingerprints for Greenland and Antarctica differ from the global mean in different directions, the relative contributions of these two sources to projected sea level change.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Because of the enumerated physical processes, there is *very high* confidence that RSL change will vary across U.S. coastlines. There is *high* confidence in the likely differences of RSL change from GMSL change under different levels of GMSL change, based on projections incorporating the different relevant processes.

Summary sentence or paragraph that integrates the above information

The part of the key finding regarding the existence of geographic variability is based upon a broader observational, modeling, and theoretical literature. The specific differences are based upon the scenarios described by the Interagency Sea Level Rise Task Force (Sweet et al. 2017)

Key Finding 4

As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called "nuisance floods") have increased 5- to 10-fold since the 1960s in several U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*).

Description of evidence base

Sweet et al. (2014) examined 45 NOAA tide gauge locations with hourly data since 1980 and Sweet and Park (2014) examined a subset of these (27 locations) with hourly data prior to 1950, all with a National Weather Service elevation threshold established for minor "nuisance" flood impacts. Using linear or quadratic fits of annual number of days exceeding the minor thresholds, Sweet and Park (2014) find increases in trend-derived values between 1960 and 2010 greater than 10-fold at 8 locations, greater than 5-fold at 6 locations, and greater than 3-fold at 7 locations. Sweet et al. (2014), Sweet and Park (2014), and Ezer and Atkinson (2014) find that annual minor tidal flood frequencies since 1980 are accelerating along locations on the East and Gulf Coasts (>25 locations, Sweet et al. 2014) due to continued exceedance of a typical high-water distribution above elevation thresholds for minor impacts.

Historical changes over the last 60 years in flood probabilities have occurred most rapidly where RSL rates were highest and where tide ranges and extreme variability is less (Sweet and Park 2014). In terms of future rates of changes in extreme event probabilities relative to fixed elevations, Hunter (2012), Tebaldi et al. (2012), Kopp et al. (2014), Sweet and Park (2014) and Sweet et al. (2017) all find that locations with less extreme variability and higher RSL rise rates are most prone.

Major uncertainties

Minor flooding probabilities have been only assessed where a tide gauge is present with >30 years of data and where a NOAA National Weather Service elevation threshold for impacts has been established. There are likely many other locations experiencing similar flooding patterns, but an expanded assessment is not possible at this time.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high* confidence that exceedance probabilities of high tide flooding at dozens of local-specific elevation thresholds have significantly increased over the last half century, often in an accelerated fashion, and that exceedance probabilities will continue to increase this century.

Summary sentence or paragraph that integrates the above information

This key finding is based upon several studies finding historic and projecting future changes in high-water probabilities for local-specific elevation thresholds for flooding.

Key Finding 5

Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf Coast states beyond what would be projected based solely on RSL rise. However, there is *low confidence* in the magnitude of the increase in intensity and the associated flood risk amplification, and these effects could be offset or amplified by other factors, such as changes in storm frequency or tracks.

Description of evidence base

The frequency, extent, and depth of extreme event-driven (for example, 5 to 100 year event probabilities) coastal flooding relative to existing infrastructure will continue to increase in the future as local RSL rises (Tebaldi et al. 2012; Horton et al. 2011; Woodruff et al. 2013; Sweet et al. 2013; Kopp et al. 2014; Buchanan et al. 2016; Hall et al. 2016; Sweet et al. 2017). Extreme flood probabilities will increase regardless of change in storm characteristics, which may exacerbate such changes. Model-based projections of tropical storms and related major storm surges within the North Atlantic mostly agree that intensities and frequencies of the most intense storms will increase this century (Grinsted et al. 2013; Lin et al. 2012; Little et al. 2015; Knutson et al. 2013; Lin et al. 2016). However, the projection of increased hurricane intensity is more robust across models than the projection of increased frequency of the most intense storms, since a number of models project a decrease in the overall number of tropical storms and hurricanes in the North Atlantic, although high-resolution models generally project increased mean hurricane intensity (e.g., Knutson et al. 2013). In addition, there is model evidence for a change in tropical cyclone tracks in warm years that minimizes the increase in landfalling hurricanes in the U.S. Mid-Atlantic or Northeast (Hall and Yonekura 2013).

Major uncertainties

Uncertainties remain large with respect to the precise change in future risk of a major coastal impact at a specific location from changes in the most intense tropical cyclone characteristics and tracks beyond changes imposed from local sea level rise.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *low confidence* that the flood risk at specific locations will be amplified from a major tropical storm this century.

Summary sentence or paragraph that integrates the above information

This key finding is based upon several modeling studies of future hurricane characteristics and associated increases in major storm surge risk amplification.

FIGURES

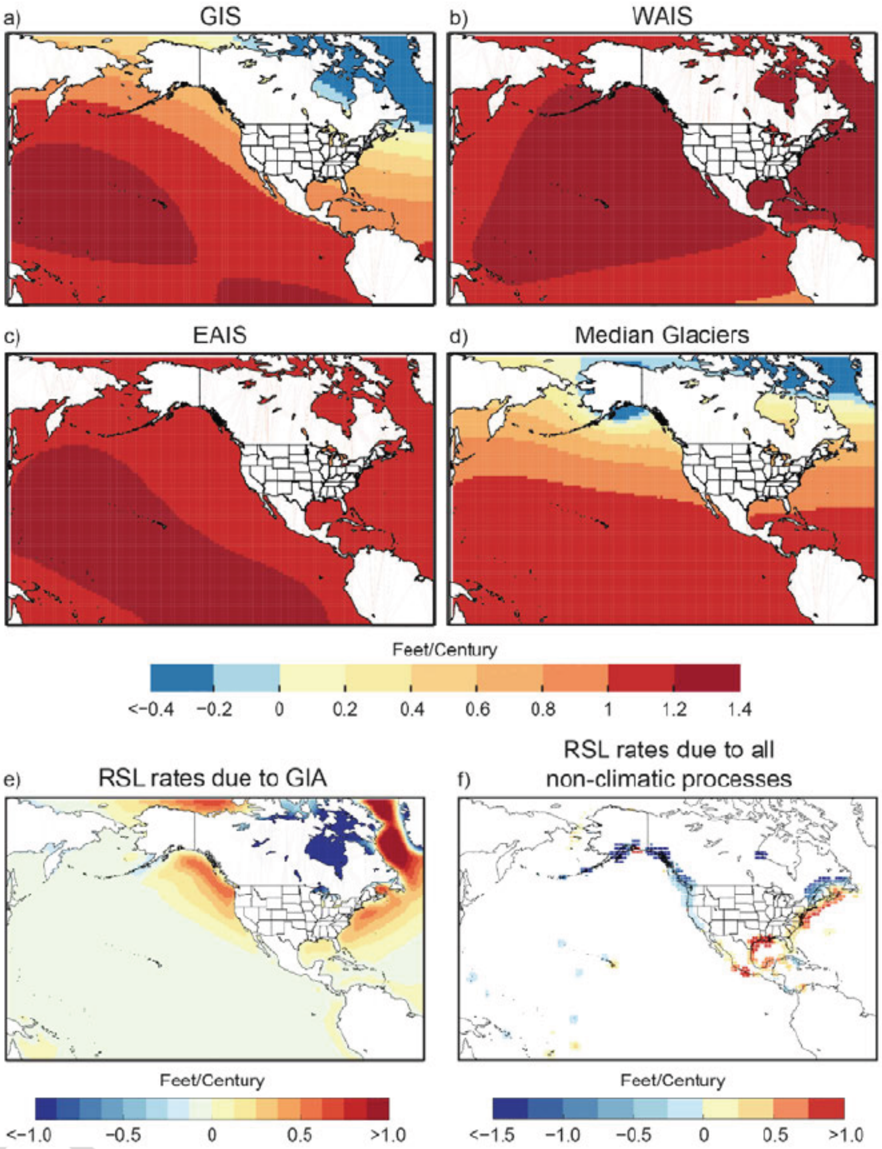


Figure 12.1: (a–d) Static-equilibrium fingerprints of the relative sea level (RSL) effect of land ice melt, in units of feet of RSL change per feet of global mean sea level (GMSL) change, for mass loss from (a) Greenland, (b) West Antarctica, (c) East Antarctica, and (d) the median projected combination of melting glaciers, after Kopp et al. (2014, 2015a). (e) Model projections of the rate of RSL rise due to glacial-isostatic adjustment (units of feet/century), after Kopp et al. (2015a). (f) Tide gauge-based estimates of the non-climatic, long term contribution to RSL rise, including the effects of glacial isostatic adjustment, tectonics, and sediment compaction (units of feet/century) (Kopp et al. 2014). [Figure source: (a)–(d) Kopp et al. 2015a, (e) adapted from Kopp et al. 2015a; (f) adapted from Sweet et al. 2017].

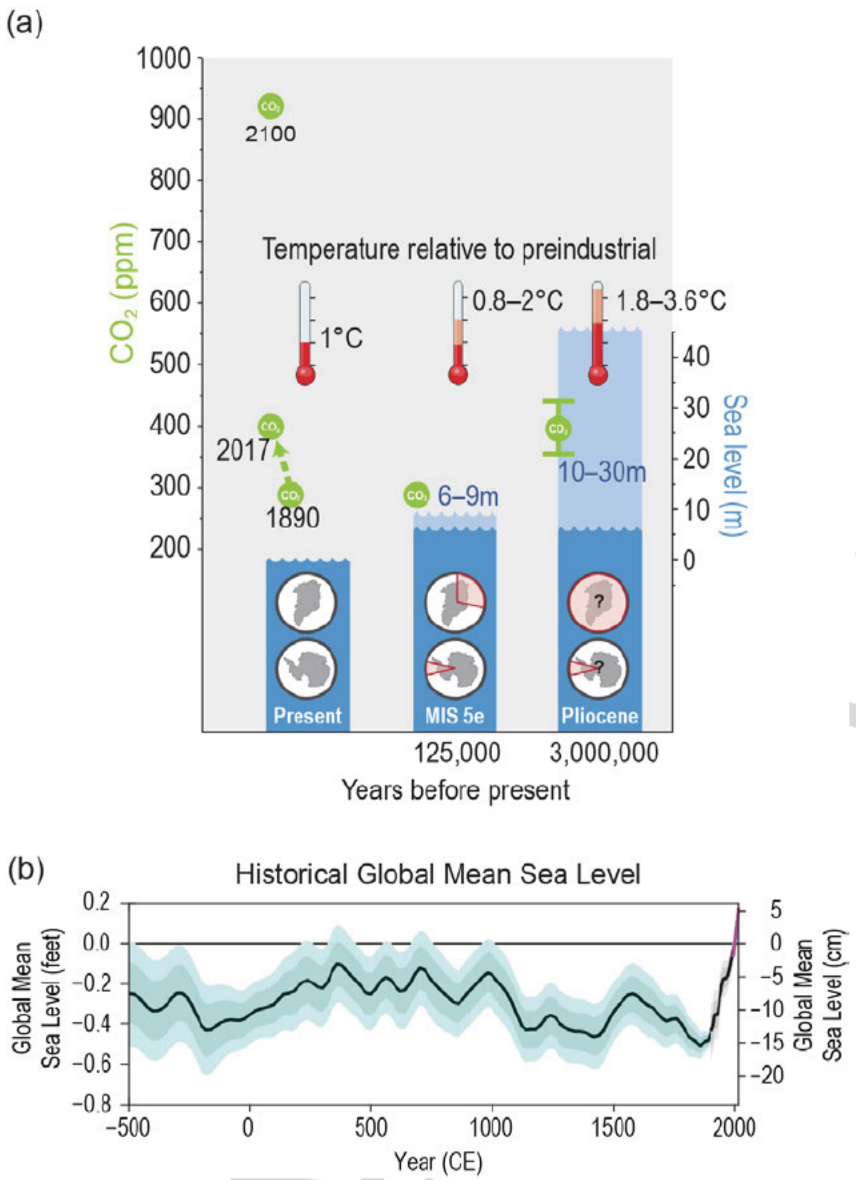


Figure 12.2: (a) The relationship between peak global mean temperature, maximum global mean sea level (GMSL), and source(s) of meltwater over three periods in the past with global mean temperature comparable to or warmer than present. Light blue shading indicates uncertainty of GMSL maximum. Red pie charts over Greenland and Antarctica denote fraction, not location, of ice retreat. (b) GMSL rise from –500 to 1900 CE, from Kopp et al. 2016's geological and tide gauge-based reconstruction (blue), from 1900 to 2010 from Hay et al. 2015's tide gauge-based reconstruction (black), and from 1992 to 2015 from the satellite-based reconstruction updated from Nerem et al. 2010 (magenta). [Figure source: (a) adapted from Dutton et al. 2015 and (b) Sweet et al. 2017].

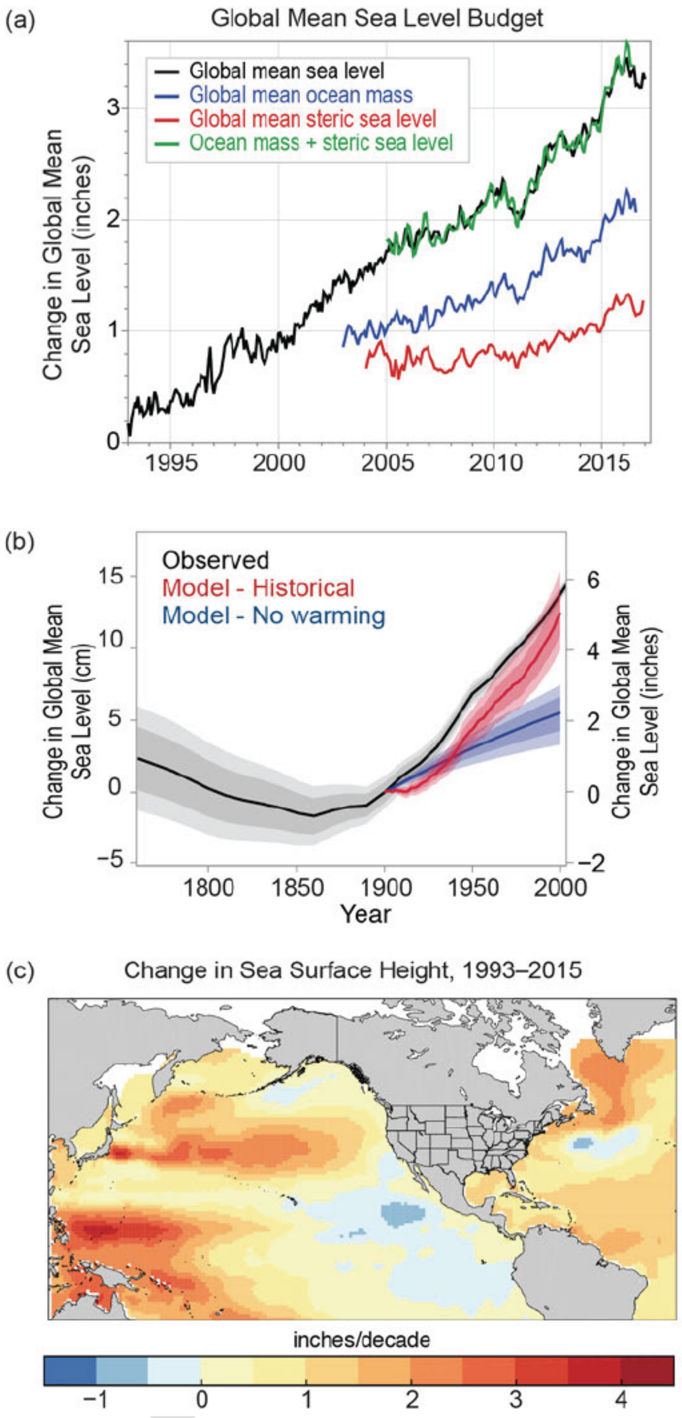
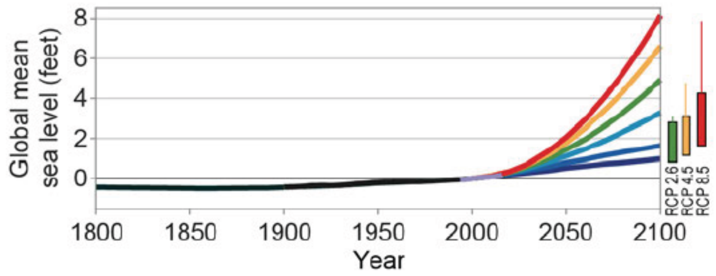


Figure 12.3: (a) Contributions of ocean mass changes from land ice and land water storage (measured by satellite gravimetry) and ocean volume changes (or steric, primarily from thermal expansion measured by in situ ocean profilers) and their comparison to global mean sea level (GMSL) change (measured by satellite altimetry) since 1993. (b) An estimate of modeled GMSL rise in the absence of 20th century warming (blue) and from the same model with observed warming (red), compared to observed GMSL change (black). Heavy/light shading indicates the

17th–83rd and 5th–95th percentiles. (c) Rates of change from 1993 to 2015 in sea surface height from satellite altimetry data; updated from Kopp et al. 2015a using data updated from Church and White 2011. [Figure source: (a) adapted and updated from Leuliette and Nerem 2016, (b) adapted from Kopp et al. (2016) and (c) adapted and updated from Kopp et al. 2015a].

(a)



(b) Projected Relative Sea Level Change for 2100 under the Intermediate Scenario

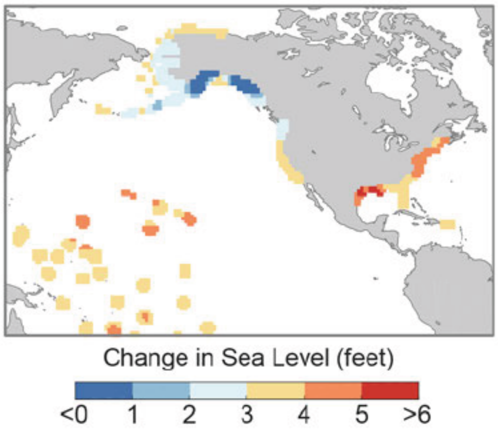


Figure 12.4: (a) Global mean sea level (GMSL) rise from 1800 to 2100, based on Figure 12.2b from 1800 to 2015, the six Interagency (Sweet et al. 2017) GMSL scenarios (navy blue, royal blue, cyan, green, orange and red curves), the *very likely* ranges in 2100 for different RCPs from this chapter (colored boxes), and lines augmenting the *very likely* ranges by the difference between the median Antarctic contribution of Kopp et al. 2014 and the various median Antarctic projections of DeConto and Pollard (2016). (b) Relative sea level (RSL) rise (feet) in 2100 projected for the Interagency Intermediate Scenario (1-meter [3.3 feet] GMSL rise by 2100) (Figure source: Sweet et al. 2017).

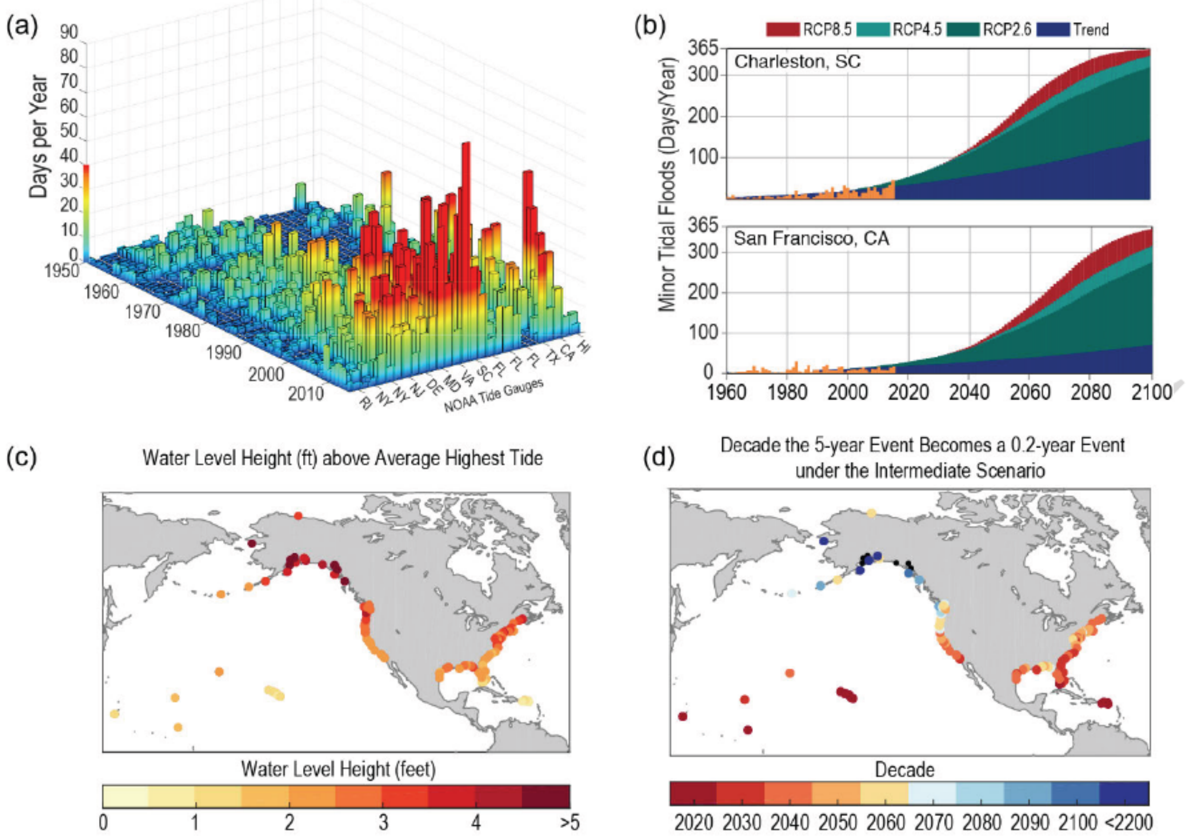


Figure 12.5: (a) Tidal floods (days per year) exceeding NOAA thresholds for minor impacts at 28 NOAA tide gauges through 2015 showing (b) historical exceedances (orange) for two of the locations—Charleston, SC and San Francisco, CA—and future projections through 2100 based upon the continuation of the historical trend (blue) and under median RCP2.6, 4.5 and 8.5 conditions. (c) Water level heights above average highest tide associated with a local 5-year recurrence probability and (d) the future decade when the 5-year event becomes a 0.2-year (5 or more times a year) event under the Interagency Intermediate scenario; black dots imply that a 5-year to 0.2-year frequency change does not unfold by 2200 under the Intermediate scenario. [Figure source: (a) adapted from Sweet and Marra 2016, (b) adapted from Sweet and Park 2014, (c) and (d) Sweet et al. 2017]

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