CHAPTER 19

Sea Level Rise

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Sea level rise is naturally a topic of concern to many Floridians. Our intention in this chapter is to give the reader enough information on this topic to inform decisions about future adaptation strategies. We begin by reviewing how we measure sea level and the reasons that sea level can change. At the global level, the problem is relatively simple in that globally averaged sea level can only increase if water is added to the ocean or the ocean warms. The situation is more complicated at the local level, where variations can occur (e.g., due to changes in wind and ocean current patterns, and differences in vertical land motion rates). We present summaries of global sea level change over several time scales, ranging from the modern day to the geological records. Although we have confidence in estimates of the rate of global mean sea level change, determining from observations whether the rate is increasing, or accelerating, is more challenging. Over the next century, sea level change in Florida is expected to follow the global trend reasonably closely, but on shorter time scales and in different localities some variations are inevitable. We end with a discussion of the future sea level rise projections for Florida that should form the basis for efforts to plan adaptation strategies.

Key Messages

- Unless greenhouse gas emissions are reduced, sea level will most likely increase by 1-2 meters over the next 50 to 100 years. The time scale is not certain, but the ultimate rise of sea level is. The only way to mitigate this risk is to reduce greenhouse gas emissions as soon as possible and to commit to lowered emissions in the future.
- The linkage between greenhouse emissions and sea level rise in incontrovertible. Sea level rise projections are often misinterpreted due a lack of understanding of this point. We cannot invoke any particular sea level rise projection without committing to the emission scenario associated with that sea level rise projection. The scatter seen in charts projecting sea level rise is due to the differing emission scenarios assumed, and is not due to uncertainty in the climate science that underlies the projections.
- On shorter time scales of a few years to a few decades, sea level rise fluctuations due to oceanic and atmospheric changes and vertical land motion can substantially increase the frequency of nuisance flooding events. Although these smaller sea level changes are likely ephemeral, these events can have large economic impacts.
- Sea level rise impacts in coming decades will be felt differently in different communities. Regional to local adaptations should be developed based on the best available science, and to support these efforts, scientists need to be involved at the local level. We do not discuss this point in our chapter, but would argue that an important outcome of this book is that local scientists, practitioners, and decision makers will have the information needed to inform at the local level.

Keywords

Sea level; Climate change; Vertical land motion; Last Glacial Maximum; Ice melt; Ocean warming; Tide gauges; Satellite altimetry

Introduction

Florida's vulnerability to sea level rise is obvious. Our population is predominantly in low-lying areas and our tourism-based economy depends heavily on the state's beaches. Most of you have heard of the impressive approach to planning for the sea level rise that has occurred in South Florida, but similar planning is now occurring in multiple regions around the state. As one example, the Tampa Bay region has formed the Climate Science Advisory Panel that is facilitated by Florida Sea Grant and the Tampa Bay Regional Planning Council, and other municipalities are taking similar independent actions.

It might seem that a state-wide approach would be better, but perhaps not. Different regions have unique problems and a one-size-fits-all approach is probably not best. Instead, different regions must plan to meet their own challenges and we should focus on providing local managers and political leaders with the best information and tools to help them. That is the aim of this chapter. We do not give a single sea level rise projection, but instead provide information that will give local decision makers the ability to best use the available tools and research.

This chapter is organized into four main sections. In the first, we review how sea level is measured on time scales ranging from millions to thousands of years to the instrumental record over the past 100 years, and we address why sea level changes at all. In the second section, we get to the actual data and see how sea level changes over the long time and space scales, where our information is the most reliable. In the third section, we examine regional changes in Florida and review our knowledge of what happens on shorter time scales, meaning season to season or year to year. This turns out to be very challenging. In the final section, we review projections of future sea level rise in Florida. Again, we show how the shorter our timeframe is for predictions and the more localized those predictions need to be, the more difficult the problem. On the other hand, long-term sea level changes can be projected with confidence.

How Do We Measure Sea Level and Why Does It Change?

Measuring Sea Level Changes

Tide gauge measurements of sea level extend back to the 18th century, and a fascinating history of the development of these measurements is given by David Cartwright (1999). The earliest tide measurements used a yard stick attached to a sea wall that was observed directly by a person to obtain measurements of the time and height of high and low tides. Later, a system was developed that consisted of a water surface following float inside a stilling well that served to dampen wave signals; when the motion of the float was coupled to a continuous pen recording on a strip chart, the modern tide gauge was born. This happened in Sheerness, England in 1827. These instruments are fully capable of observing climate change signals, but exist only along coastlines and on islands.

In the early 1990s, with the launch of the TOPEX/Poseidon satellite altimeter mission, global sea level measurements entered a new era. Satellite altimeters measure sea level globally on a roughly 10-day cycle by directly measuring the height of the sea level from space. While the precision at any point is not as good as a tide gauge, the key point is that the measurement is global. Sea level variations due to redistributing ocean volume from one point to another cancel out and the global average of the altimeter measurements is an excellent measurement of the changes in the volume of the ocean. We now have about 25 years of satellite altimetry measurements from multiple missions and we can determine the global mean sea level changes with unprecedented precision.

We can also infer past sea level changes via paleo methods. Kemp et al. (2015) have given an excellent review of these methods that explicitly separates sea level measurements according to time scale, which is a theme of this chapter. First, on the scale of millions of years, sea level is measured by inferring ice sheet volume from oxygen isotope data and assuming that ice lost or added means ocean volume has increased or decreased, or by dating the height of coastal geological features that are expected to stay near sea level. Second, since the last ice age, corals that grew near sea level are dated in tropical regions. Finally, over the past 2,000 years, sea level histories are obtained from salt marsh sediment cores, coral microatolls, and archaeological evidence.

Sea Level Changes Associated with Ocean Volume Change

The change in global mean sea level is a measure of the change in the ocean volume. Think for a moment about a bathtub containing still water. If you took a meter stick and measured the depth of the bathtub and multiplied times the area of the bathtub, you would get the volume of water in the tub. Now think about doing the same thing each day, month, or year. Why would the volume change with time? Suppose we turn on the water supply or open the drain. The water level would change because we have added or removed water from the tub. The only effective ways to do this in the ocean are to melt ice that is on the land and add the resulting water to the oceans, or to take water from the ocean via evaporation and turn it into ice on the land.

There is one other way to change the volume of the ocean, and that is to change to the average density of the ocean. In this case we have to think about the water in the bathtub being warmed. Why would that matter? When the water is warmed, it becomes less dense, expands, and takes up more space (more volume), so the water level increases. The reverse happens if the water is cooled.

How do we measure the amount of water added to the ocean and the average density of the ocean? Basically, the amount of water in the ocean is measured by satellite missions that measure the gravity field of the Earth, and the density of the water is determined by profiling floats that measure the density of the ocean. So how well can we monitor the change in the global mean sea level? Fig. 19.1 will be discussed fully in a later section; but for now, let us focus on the altimetry curve, which is the direct measurement of the global mean sea level from satellite altimetry and the sum of the global mean sea level change from the measurements of the ocean density and mass changes. The close agreement of these two independent estimates gives us confidence in the altimetry estimate of the global mean sea level change.

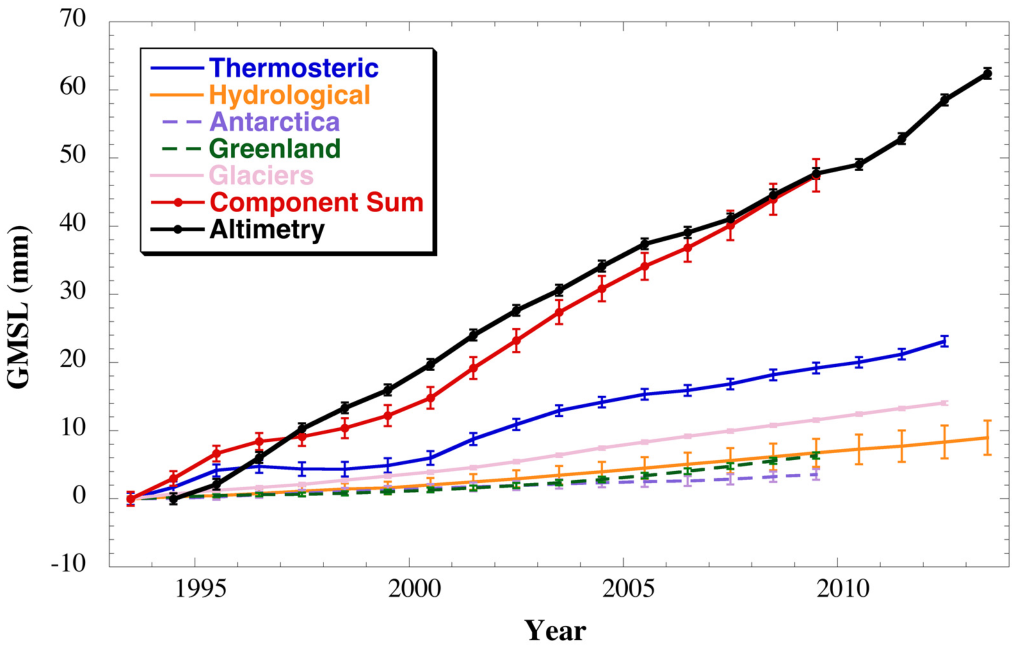

Figure 19.1 Three-year running means of global mean sea level rise (GMSL) from altimetry, its components, and the sum of the components from 1993.0-2014.0, as discussed in Chambers et al. (2016). Uncertainty bars are one standard error.

Regional Sea Level Changes Not Associated with Ocean Volume Change

The situation is much more complicated when we consider regional and local sea level changes due to contributions from oceanic, atmospheric, and geological processes. Spatial patterns of the regional changes are complex and time dependent. The global map of sea level change rates from satellite altimetry over the past 25 years provides an excellent example (Fig. 19.2), showing rates of change of both sign and magnitudes greater than 10 mm/yr, as compared to the globally averaged rate of about 3 mm/yr. The observed regional changes are mostly associated with changes in wind and ocean circulation patterns (e.g., Kohl and Stammer 2008; Levitus et al. 2005; Zhang and Church 2012; Timmerman et al. 2010; Qiu and Chen 2012). Closer to Florida, the most noticeable regional changes are observed in the northern Atlantic Ocean, where high rates of sea level rise have occurred along and north of the North Atlantic Current. High rates are also found along the southern edge of the North Atlantic gyre, in the subtropical Atlantic region.

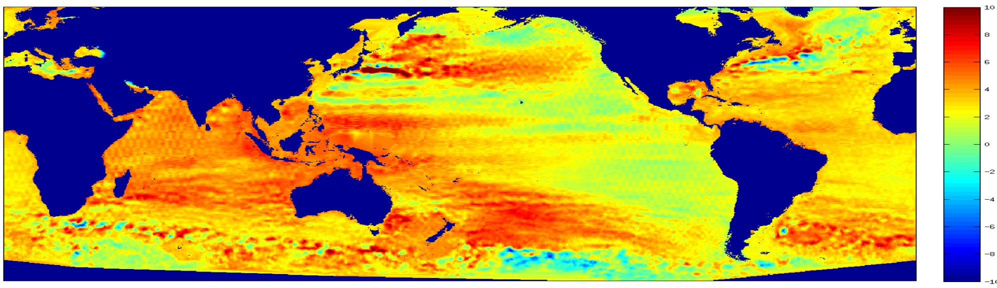

Figure 19.2. Global map showing rates of sea surface height (SSH) obtained from satellite altimetry for the period 1993-2017. The rates are in mm/yr.

Melting ice sheets in polar regions affect regional variability of sea level changes due to two processes: changes in ocean circulation and gravitational attraction. Increases in freshwater forcing can affect ocean circulation, and are suggested as an explanation of regional sea level changes in the northern Atlantic region (e.g., Yin et al. 2009). Melting ice sheets also reduce the mass of water stored in polar regions and, consequently, change the Earth's gravity field. As a result, near a melting ice sheet we counterintuitively expect decreases in sea level height. The geographic pattern of sea level change that results is sometimes referred to as a sea level fingerprint (Mitrovica et al. 2001; 2009). Basically, sea level height reduces near the source of a fresh water supply to the ocean and increases further away from the melting ice sheet.

Another important process that affects regional and local relative sea level changes is vertical land movement. If the land is moving vertically, then the sea level will appear to be moving in the opposite direction. This not only complicates the interpretation of the tide gauge data, but it is also important for determining the local impacts of sea level change; i.e., if sea level is rising and the land is falling, then the impacts will be more severe. Land subsidence or uplift can reach rates of more than 20 mm/yr, as observed in New Orleans (Dixon et al. 2006), for example. Causes of vertical land motion vary from the continuing response to melting ice sheets in the Pleistocene to local sediment compaction. The regional-scale subsidence due to delayed mantle flow, which is termed Glacial Isostatic Adjustment, affects the coastlines of the United States (Sella et al. 2007; Tamisea and Mitrovica, 2011; Karegar et al. 2016). Local-scale land subsidence occurs in many locations along the coast, especially in sediment-rich areas, such as river deltas, and reclaimed land and wetlands. For example, the land subsidence in New Orleans has occurred mainly in new neighborhoods built on reclaimed wetlands (Dixon et al. 2006).

The Global, Long-Term Context

Global Changes during the Instrumental Period

Nearly continuous records of sea level extend back to the early 18th century for several locations in Northern Europe (Fig. 19.3). Although there are differences over short time periods, the rates of sea level change from 1800 to 2000 are very similar. By the late 1800s and early 1900s, more and more tide gauges were placed around the world, including around Australia, Asia, and North and South America. A weighted average of all these tide gauges (Fig. 19.3) has a similar rate to the three long tide gauges in Northern Europe after 1880, and the record from the global sea surface height measurements from altimetry agrees well with the tide gauge average. All of this indicates that the average of the sparse tide gauges is a reasonable estimate of global mean sea level change. Estimating acceleration is, however, more difficult.

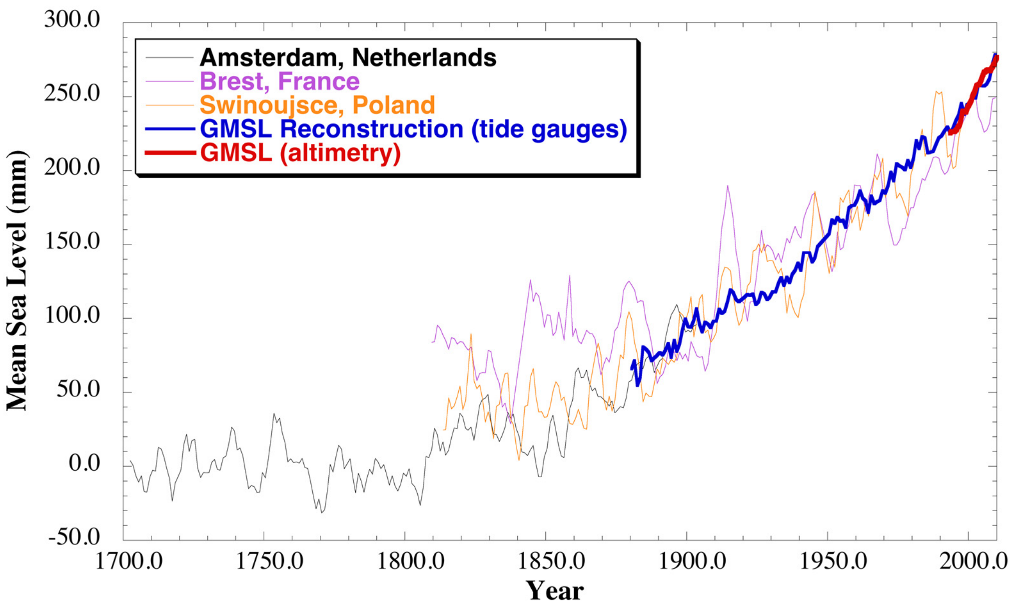

Figure 19.3. Five-year averages of sea level change recorded by tide gauges at three sites in Europe: The Netherlands, France, and Poland. The data have been corrected for vertical land movement predicted by a Post Glacial Rebound model (Peltier 2004). Data are from the Permanent Service for Mean Sea Level in Liverpool, UK. Also shown is yearly-averaged global mean sea level change from a weighted average of tide gauges (thick blue line) (Church and White 2011) and from satellite altimetry (thick red line) (Nerem et al. 2010).

The rate of global mean sea level rise since 1900 has been 1.7 ± 0.2 mm/year on average, while since 1993 the rate is higher at 3.2 ± 0.5 mm/year (Church et al. 2013; Rhein et al. 2013). Although this suggests an acceleration, it may reflect decade to decade fluctuations in sea level change rather than true long-term acceleration. Reconstructions of global mean sea level rise from tide gauges are unclear on this topic (e.g., Jevrejeva et al. 2008; Chambers et al. 2012; Rhein et al. 2013; Calafat et al. 2014; Natarov et al. 2016). To further complicate things, the change may not be a steady, continuous acceleration, (Woodworth et al. 2009). The net result is that in order to accurately detect accelerations with any confidence, one needs a very long record of fully global observations. This is only possible after 1993, with the advent of precision satellite altimetry.

Partitioning the observed global mean sea level into exact sources (i.e., density changes and addition of water to the ocean) is difficult for the time period before 1993, when observations of both ocean thermal expansion and the integrated mass loss of the Greenland and Antarctic ice sheets became available. After 1993, the partitioning is better known. Numerous studies have looked at the sea level budget over various time spans since 1993, and quantified how well one can partition the sources responsible for the observed trends (e.g., Church et al. 2013; Llovel et al. 2014; von Schuckmann et al. 2014; Dieng et al. 2015; Chambers et al. 2016; Reager et al. 2016). Here, we summarize the results of Chambers et al. (2016) for the period from 1993 through 2014 (Fig. 19.1).

The ocean density change due to warming is the largest single contributor to global mean sea level rise since 1993, accounting for about 40% of the trend. The upper ocean (0-700 m) explains about 28% of the trend, with approximately 8% coming from the middle layers (700-2000 m) and 4% from the deep ocean (> 2000 m depth). The contributors that combine to increase ocean mass (more water in the oceans) explain the remaining 60% of the trend. Glaciers and ice caps outside of Greenland and Antarctica caused 25% of sea level rise, hydrology (from pumping water from underground aquifers for irrigation) explained 15%, Greenland ice melt explained 12%, and Antarctic ice melt explained 7%. Note, however, the increasing separation of the contribution from Greenland relative to Antarctica (Fig. 9.1). This is due to an accelerated ice loss from Greenland that has been occurring since 2003 (Shepherd et al. 2012; Velicogna et al. 2014).

Sea Level Changes over the Past Few Millennia

Studies of sea level change over the last few millennia provide an important context for contemporary observations of sea level rise. Several high-resolution records of sea level change over the last few thousand years have been reconstructed using sediment cores from salt marshes (e.g., Gehrels et al. 2005; Kemp et al. 2011; Waller 2015). This technique relies on looking at the assemblages of foraminifera, which allows us to constrain the vertical position of sea level based on the presence and absence of the various foraminiferal taxa. This approach enables the position of sea level to be estimated with a high degree of certainty (< 0.10 m uncertainty). Similarly, a variety of dating techniques, including radiocarbon (carbon-14) dating, allow for precise age estimates. As a result, the salt marsh-derived sea level reconstructions for the past few millennia are considered to provide a very high-resolution and precise reconstruction of relative sea level through time.

Another approach to reconstructing sea level on this timescale relies on using coral microatolls as markers for the past position of sea level. Microatolls are corals that grow in very shallow water and therefore grow predominantly in a lateral direction, creating large, disc-shaped coral heads. Microatolls are renowned as very precise recorders of past sea level position and have been used to argue that there was very little change in global mean sea level during the last few millennia preceding the Industrial Era (e.g., Woodroffe et al. 2012).

Like the coral microatolls, data amassed from salt marshes also demonstrate very little change in local, or relative, sea levels over the last 2,800 years and prior to the Industrial Era (Kopp et al. 2016). These authors showed that global mean sea level varied by ±8 cm over the pre-Industrial Common Era, including a decline in sea level over a 400-year period that coincided with 0.2° C of global cooling. They also concluded that 20th century sea level rise was faster than during any of the 27 previous centuries (this includes the entire time window of their dataset). In this sense, the rapid warming that is associated with the Industrial Era and the associated increased emission of greenhouse gases (Rhein et al. 2013) appears to be coupled to a rapid rise in global mean sea level unlike any sea level rise that has occurred over the past 2,800 years.

Sea Level Changes on Geological Time Scales

On even longer timescales, fluctuations in temperature on geologic time scales have caused land-based ice sheets to grow and shrink in repeating cycles. Over the last million years, for example, large ice sheets have waxed and waned on 100,000-year cycles in the Northern Hemisphere, advancing over large tracts of North America, Europe, and Asia. Geologists have used the elevation of the Last Glacial Maximum (LGM) paleoshoreline, other markers of sea level position such as fossil corals that live near the sea surface, and models of glacial isostatic adjustment to estimate that sea level was 130-135 m lower then present (Yokoyama et al., 2001; Austermann et al. 2013; Lambeck et al. 2014; Dutton et al. 2015) (Fig. 19.4). As the Earth warms out of an ice age, rising temperatures cause land-based ice to melt and sea levels to rise. From the LGM to present, global mean sea level increased by about 130 m. This translates to an average of more than 80 cm of sea level increase per century. To put this in perspective, sea level rose by about 19 cm between 1901 and 2010, and is projected to increase by about 80 cm over the coming century (Church et al. 2013). The first lesson we can take from studying the geology is that increases in sea level similar to what are projected for the coming century are the norm in a warming climate, and it is the relatively slow rate of increase over the past few thousand years that is anomalous.

We are now in a warming period and it is natural to ask what the conditions were during the last warm period. Global mean temperatures were warmer than the pre-Industrial Era baseline by 1° C (similar to the temperature today), and atmospheric carbon dioxide concentrations were similar to the pre-Industrial Era value (280 ppm) during the Last Interglacial warm period that occurred about 125 thousand years ago. The best estimate for peak sea level during that time period is 6–9 m above present (Dutton et al. 2015). What are the implications of this? First, given physical limits on thermal expansion and melting of mountain glaciers, a significant amount of meltwater must have been derived from polar ice sheets in order to reach sea levels 6–9 m higher than present. Second, polar ice sheets have been very sensitive to past increases in global mean temperature of 1° C above the pre-Industrial Era level. And third, given that Greenland only partially melted during that time window, the high sea levels would have required approximately 5 m worth of sea level rise from melting of the Antarctic ice sheet (Dutton et al. 2015b). Relating these global numbers to the state of Florida, sea level rise during the last interglacial period inundated a significant fraction of the state, including most of South Florida (Fig. 19.4).

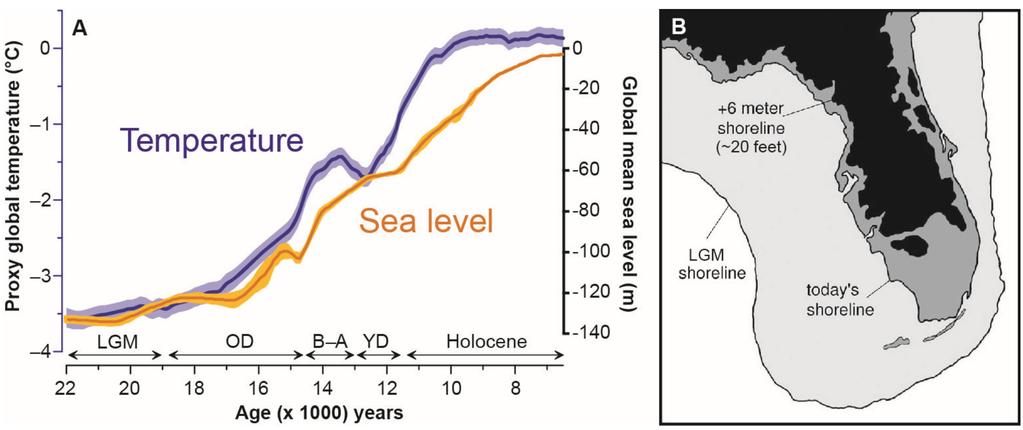

Figure 19.4. (A) Change in global mean temperature relative to the pre-Industrial Era (blue, Shakun et al. 2012), and in sea level (orange, Lambeck et al. 2014) from the LGM to 6,000 years ago. Abbreviations denoted on time axis represent climate intervals: Older Dryas (OD), Bolling-Allerod (B-A), Younger Dryas (YD). (B) Comparison of the shoreline during the LGM, today, and for a position representing ~ +6 meters (~ 20 feet) higher than present.

Sea Level Change in Florida

Difficulty of Determining Regional Rather Than Global Sea Level Changes

Long-term (> 60 years) sea level changes along the Florida coast, as determined from tide gauge measurements, are similar to the long-term global rates of 1.8-2.5 mm/yr (Church et al. 2013). Rates over shorter time spans, in particular after year 2000, are, however, higher and more variable, which illustrates the problem of estimating regional rather than global changes. The causes of these decadal scale changes are an active area of research, but there is a consensus that these changes are due to changes in wind and ocean current patterns (e.g., Yin et al. 2009; Sallenger et al. 2012; Ezer 2013; Ezer et al. 2013; Wdowinski et al. 2016; Rossby et al. 2014; Kopp 2013; Valle-Levinson et al. 2017). An unanswered question is whether the changes are ephemeral variations or sustained long-term changes. For example, decadal-scale changes in the rate of sea level rise occurring along the Florida coast is not unique to the post-2000 period, with long tide gauge records indicating that another accelerating period occurred during 1928–1948 (see the dashed black lines in Fig. 19.5). This does not mean that the recent changes are temporary, as accelerating change is forecast by climate models. Again, though, properly interpreting and projecting regional sea level change is still a challenging research problem.

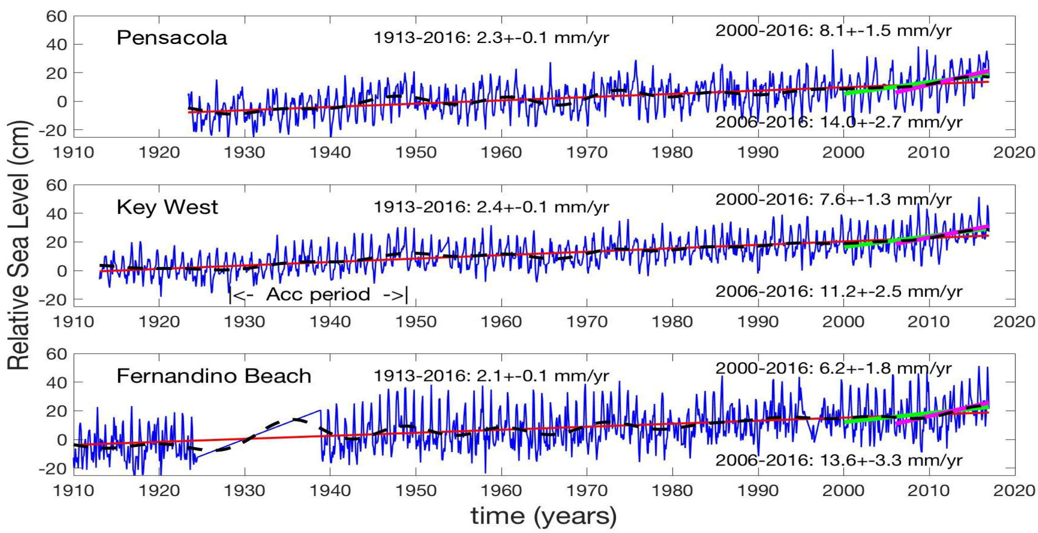

Figure 19.5. Sea level curves for three Florida sites with long tide gauge records (> 90 years) showing similar long-term rates of sea level rise (2.1–2.4 mm/yr). All three curves also show a decadal-scale acceleration in the rate of sea level rise between 1928–1948 and post-2000 (green line), which increased after 2006 (magenta). The data, yearly mean values, were obtained from the Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org/). The rates of sea level rise were calculated using a least-square linear fit algorithm and are indicated by solid lines. Dashed black lines present low pass filters fit with a 10-year cutoff, which are indicative of decadal-scale sea level variability.

Some of the observed variability in the rate of relative sea level change along the Florida coast is related to local vertical land movements, induced mainly by land subsidence in sediment-rich areas, such as river deltas, reclaimed land, and wetlands. Tide gauges, being attached to the land, measure the relative motion between sea level and land subsidence, or uplift. A recent report by the National Oceanic and Atmospheric Administration (NOAA) (Zervas et al. 2013) based solely on the tide gauge data lists 12 tide gauge locations in Florida and estimates the vertical ground movements to be in the range 0.1-0.5 mm/yr, which suggests that vertical land motions are not a major contributor over most of Florida’s coastline. A more robust method for estimating vertical land movements is based on global positioning system (GPS) measurements conducted at selected locations, which indicate that most Florida coastal land elevations are relatively stable, confirming the tide gauge-based results.

Interferometric Synthetic Aperture Radar (InSAR) is another geodetic technique widely used for detecting vertical land movements at the mm/yr level. This technique is particularly interesting because it can provide high spatial resolution maps (1-100 m pixel resolution) of land movements, unlike the point measurements obtained with GPS, and these give us information at the local scale. Although InSAR has been widely used to detect land subsidence (e.g., Dixon et al. 2006; Osmanaglu et al. 2011; Bock et al. 2012), it has rarely been used to measure land motions in Florida. Recently, though, Fiaschi and Wdowinski (2017) analyzed a synthetic aperture radar dataset acquired over southeastern Florida during the years 1994-2006 and detected 2-3 mm/yr of land subsidence in several localities in Miami Beach. The subsiding areas consist of houses that were built in 1920s and 1930s on reclaimed marshland, which was drained and filled with unconsolidated sediments. Although most of the land settlement occurs in the early years after reclaiming the land, these InSAR results indicate that the settlement process continues to affect these areas, which are located at low elevation and often subjected to coastal flooding. Extending InSAR analyses around Florida would be extremely valuable for advising decision makers at the city and county level.

Short-Term Variations in the Sea Level Change Rate

Although projections for future sea level rise typically depict a smooth rise over time, we know that there will be shorter-term variations (from seasonal- to decadal-scale) superimposed on this long-term pattern of sea level rise (Fig. 19.6). For example, along the coast of Florida there is a seasonal cycle of sea level variability that is primarily driven by meteorological and oceanographic processes. Wahl et al. (2014) have shown that tide gauge records along the Gulf of Mexico recorded a significant amplification of this seasonal sea level cycle from the 1990s onward. The net effect is that this change, coupled with a gradual rise in the base level of the sea surface, combined to double the risk of hurricane-induced flooding along the Florida Gulf Coast.

The seasonal cycle of sea level variability, with the highest sea levels occurring in the autumn months (Fig. 19.6), superimpose with twice-per-year maxima in the spring tide range. These peak tidal sea levels are a naturally occurring feature and are sometimes referred to as king tides. As sea level continues to rise, it will reach higher elevations during these times, and the duration and frequency of flooding will increase as the base level of the sea surface continues to rise. If certain areas already inundated with 1-2 ft of water during king tides, an anticipated sea level rise of 2 ft above present would translate to 3-4 ft of submergence during these events; the same is true for seasonal sea level extremes and storm surges caused by the winds. The point is that when a projection identifies a certain elevation for sea level at some time in the future, we can be certain that this elevation will be reached before then, and with increasing frequency, during the short-term extreme events.

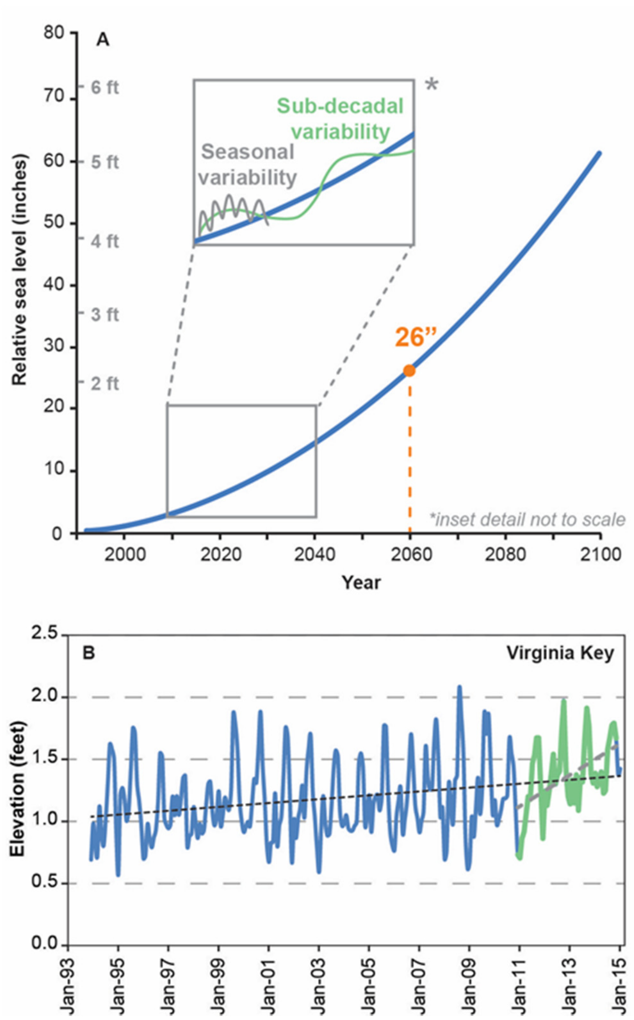

Figure 19.6. (A) Projection for sea level rise near Key West, with schematic variability in sea level on seasonal and sub-decadal time scales shown in inset. Projection for the year 2060 highlighted in orange. (B) Monthly mean sea level from Jan. 1993 to Feb. 2015 at the Virginia Key tide gauge (NOAA). The annual peaks are the seasonal king tides that occur in the autumn. The rate of sea level rise from Jan. 2011 to Dec. 2014 (gray dashed trendline) is higher than the longer-term average (black dashed line), demonstrating sub-decadal-scale variations in the rate of sea level rise.

Local precipitation can also magnify the effects of coastal flooding, particularly in coastal communities where the topographic gradient is low and there is no place for excess stormwater to go, especially if the ocean level is higher. It is not uncommon for multiple extreme high tide conditions to superimpose in time, which is another important observation that is not conveyed through simple sea level projection curves. For example, in October 2016, king tides, a storm swell associated with an offshore hurricane, and intense rainfall created a trifecta of conditions on one weekend that led to unusually high levels of coastal flooding in southeast Florida.

In addition to these short duration, intermittent, variations in sea level, there are also changes that persist for years to decades. As mentioned in the previous section, these changes are due to the sea level response to changes in the wind and ocean current patterns, which in turn respond to the large-scale changes in the Earth's temperature distribution. Basically, these changes provide a link from global warming to regional sea level change, and deciphering the relationships between the sea level changes and the changes in the winds and the ocean currents is an active research area. Understanding these changes is extremely important because the short-term events are on top of the background given by the larger-scale patterns, and can therefore amplify the impact of extreme events.

Sea Level Change in Florida Compared to Global Sea Level Changes

Clearly, understanding and projecting sea level change on time scales shorter than a few decades is challenging. Similar challenges exist when we attempt to project at specific locations or even regionally. Many people find it counterintuitive that we can more easily project global mean sea level for long lead times than we can determine what to expect in a particular harbor over the coming decade. And this is especially true when we try to project extreme sea level events. The reason for this is simply that there are many processes, as we have discussed, that affect regional or local sea level change on relatively short time scales; whereas for the global mean sea level, we only need to worry about the two processes that determine the ocean volume—adding water to the ocean and warming the ocean.

The result is that we have the most confidence in projections of global mean sea level on time scales longer than a few decades. However, we also know that regional and shorter time scale changes can complicate the application of these projections. So how useful are these global projections for Florida? We will give a possible answer to this question using the historical (20th century) tide gauge observations, but we need to be cautious about this. In essence, this approach uses past data to project future changes, and this implicitly assumes that the dynamics controlling future changes are the same as those observed during the past century. This assumption is worrisome. As many climate scientists say these days, the past is no longer a guide to the future.

The 20th century data from the tide gauges in and around Florida are shown in Fig. 19.7. For each tide gauge, we show the tide gauge record, the linear trend, and the global mean sea level reconstruction. Note that the gauges are plotted so that in the first column you move from Texas to the West Coast of Florida to the Keys; the second column goes from the Keys, along the East Coast of Florida and up to the Carolinas. We can see deviations between the gauges and the global reconstruction along the northern coast of the Gulf of Mexico and as we move north of Florida on the eastern coast. These differences can be attributed to vertical land motion. On the Florida coast, however, the sea level change during the 20th century is in good agreement with global sea level change. So, on the longer time scale, sea levels along Florida track the ocean volume changes (i.e., the global mean sea level) reasonably well. If we assume that this will remain true in the coming century, then we can conclude that the global sea level rise projections, which we will discuss in the next section, can be used as a zero order estimate of the sea level rise in Florida.

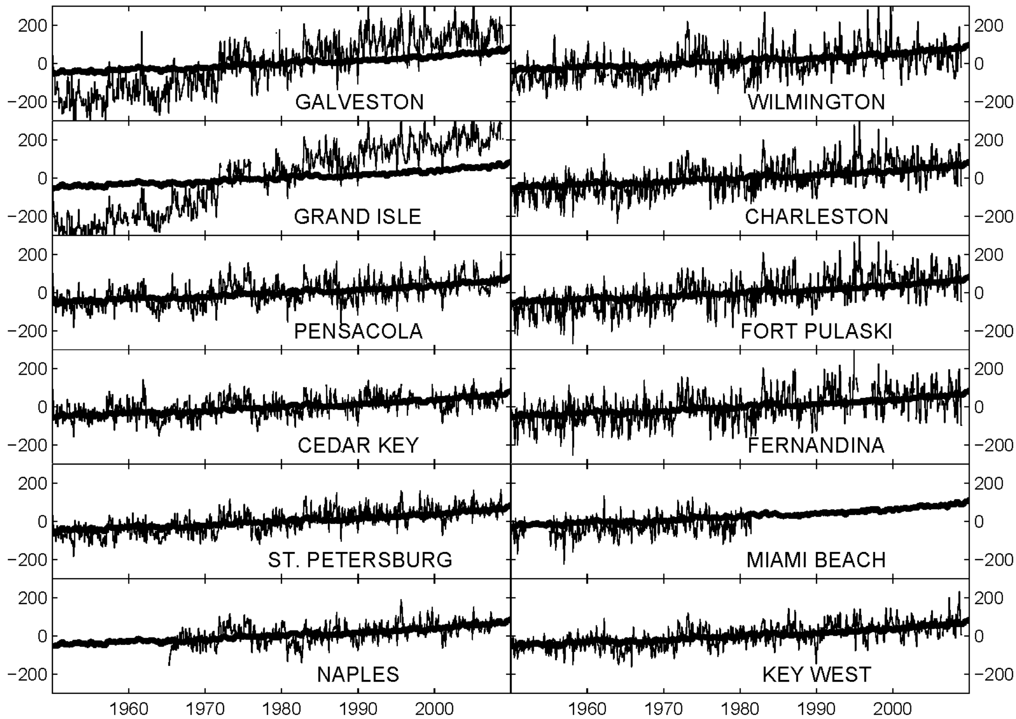

Figure 19.7. Sea level change around Florida as compared to the global reconstruction of Church and White (2011). On each panel, the solid curve is the long-term change observed at the tide gauge and the dashed curve is the global reconstruction. Units are millimeters. After Hine et al. (2016, Fig. 2.8).

Future Sea Level Rise

IPCC and National Climate Assessment Projections of Sea Level Change

This final section focuses on projections of future sea level rise in Florida. We will start with a brief summary of the global mean sea level projections based on the assessment by the Intergovernmental Panel on Climate Change (IPCC; Church et al. 2013) and the US National Climate Assessment (NCA; Parris et al. 2013). We have also included our own assessment of semi-empirical methods that were a contentious part of the IPCC assessment. The bulk of this section discusses projections for sea levels in Florida on several different time scales. We conclude with a short discussion of the uncertainties in the long-term, global projections and the prospects for reducing them.

The IPCC and NCA use somewhat different methods, but arrive at similar estimates for the sea level change by 2100. Note that when we refer to the NCA, we are referring the last assessment completed (Parris et al. 2013) and not the one that is presently under review. We decided to show the last official results, but we do acknowledge that if nothing changes substantially during the review, the sea level change by 2100 estimates will be somewhat higher than those given here. It is natural that our estimates will evolve as our observational series get longer and research continues, and this is not a cause for alarm. It only shows that our sea level projections and advice to the public needs to be regularly updated, as the NCA and IPCC assessments are updated about every five years. Concerning the methods, the NCA uses a panel of experts who review the literature and data and form a consensus projection. Interestingly, the older versions of the IPCC assessment used a similar method. The most recent, and presumably the next, IPCC assessment depends much more heavily on climate system models and requires only research that has been vetted in the peer-reviewed literature be used. There is, of course, a lag between research being conducted, papers being written, reviewed and read, and having the results implemented in the climate models, which slows the process somewhat.

An example projection using the NCA estimates is shown in Fig. 19.8. Again, note that using the IPCC assessment would give similar results. This particular assessment is from a report by the Tampa Bay Climate Science Advisory Panel mentioned at the beginning of this chapter. Bear in mind that it is tied to the Saint Petersburg tide gauge and thus tailored to the Tampa Bay region. The numbers will be discussed below, but we first want to stress the dependence of the sea level rise projection on the emission scenario chosen. To make this point we consider the IPCC's model-based method, but the point we will make also applies to the NCA approach. In order to do a sea level projection, we must first specify future greenhouse gas emissions into the atmosphere. This then allows models to compute the amount of surface warming, then the amount of ocean heating and ice melt, and finally the amount of global mean sea level increase. It is fallacious to look at a set of projections based on different emission scenarios and interpret the spread as uncertainty in the models. For a given scenario the spread between models is smaller than the difference between results for different scenarios.

Another point we have found confusing is that some people assume if we were to suddenly reduce emissions that the sea level would stop going up. We need to explain that if emissions are reduced to extremely small levels, it will still be a long time before the greenhouse gases already put into the atmosphere can be removed by natural processes. This idea and the concept of "committed" sea level rise has been nicely explained in an article by Strauss (2013).

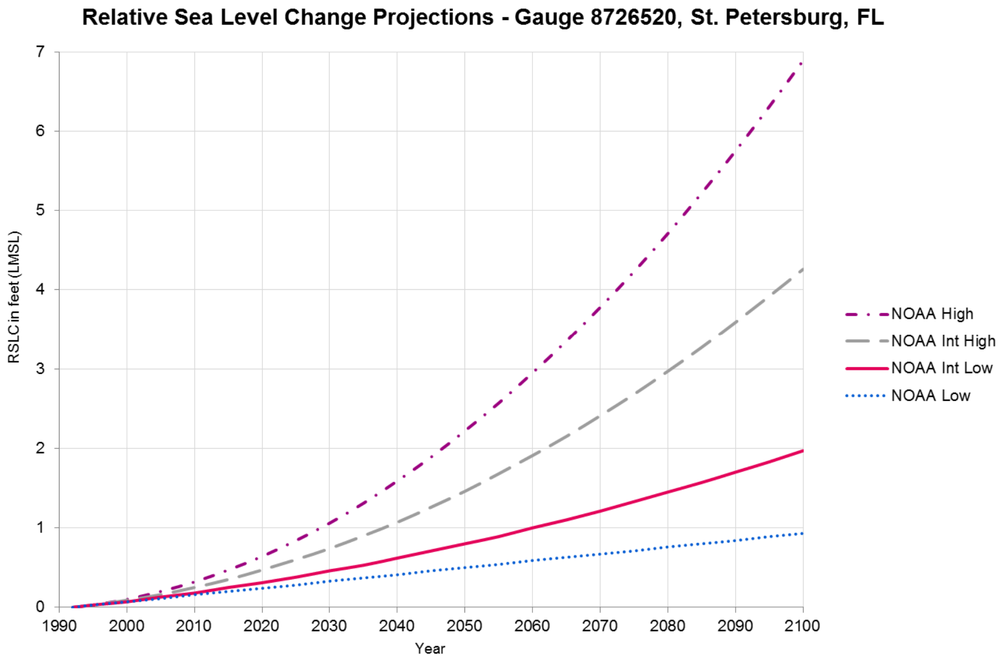

Figure 19.8 Sea level rise projections for Tampa Bay.

Empirical Projections of Sea Level Change

In addition to the IPCC and NCA methods, another method that has become popular for sea level projections is based on a semi-empirical scaling of globally averaged surface temperature to global sea level (Rahmstorf 2007; Grinsted et al. 2009). This approach is based on the observation that global averages of sea level and surface temperature tend to be highly correlated, and the physical understanding that as the Earth warms, sea level will increase from a combination of ocean warming and melting of land-based ice. After an empirical scaling is computed for historical surface temperature and global mean sea level measurements, the global average surface temperature taken from predictive climate models forced with different emissions scenarios can be scaled by the estimated parameter, and this will allow for prediction of a future sea level scenario.

The proponents of such models argue that surface temperature is better represented in ocean models than deep ocean warming, and that such a scaling can better represent the effects of ice dynamics than the process-based models used by the IPCC, which do not include ice dynamics (Church et al. 2013). However, these semi-empirical models also assume that the processes that drove sea level change in the past will be the same processes to drive it in the future. Considering the increasing contributions from the ice sheets, however, this assumption may not be entirely correct.

Some semi-empirical projections (Rahmstorf 2007; Grinsted et al. 2009) produce higher sea level predictions for 2100 than the process-based models for the same emission scenario, with upper ranges exceeding 1.5 m for the "business-as-usual" scenario (Church et al. 2013). However, the lowest probable range for the semi-empirical models does overlap with the highest probable range for the IPCC process-based models. These particular semi-empirical models may be biased, however, due to the time-period and sea level reconstructions used. For example, one group of semi-empirical models relied on temperature and sea level data mainly from the 20th century for calibration (Rahmstorf 2007). Another group used longer records of reconstructed global temperature but only a few regional sea level reconstructions (Grinsted et al. 2009). More recently, Kopp et al. (2016) used a sea level reconstruction for the past 3,000 years based on all globally available regional reconstructions and a statistical model that included global and regional patterns. When this global sea level reconstruction is combined with surface temperature to calibrate the scaling parameter, the resulting projections agree very well with the IPCC process-based model. Both means and ranges overlap. This suggests that the semi-empirical approach is quite sensitive to the data used, but after utilizing the most historical sea level data possible, the results are similar to the process-based model projections. This consistency increases our confidence in all of the approaches.

Sea Level Rise Projections for Florida on Various Timescales

As we have said, sea level rise projections are inextricably tied to projections of greenhouse emissions. Here, we present projections that assume emissions will continue to increase (i.e., the "business-as-usual" or "no action taken scenarios"). For planning purposes, we have to consider this to be the most likely scenario until we see evidence of aggressive mitigation actions within the United States and also globally. Under these scenarios, the last NCA and IPCC assessment suggest 2-3 ft of sea level rise on the 50 to 100-year time scale, but we expect that the next assessments will double these numbers. So on the 50 to 100-year time scale, we recommend planning for a 4-6 ft sea level increase. And, as stated previously, this global estimate is also what we expect to see in Florida over the next 50 to 100 years.

This projection for the next 50 to 100 years is where we have the most confidence. As explained, projecting over the next few years to 20 years or from 20 to 50 years is more difficult. That said, it is also very important for planning purposes. Cities and counties need to know what to plan for over the coming few years, developers need to plan for the coming decades, etc. Next, we will present our best estimates for the shorter time scales based on the processes discussed earlier in the chapter.

Future sea level increases will be mainly due to ice melting in Greenland and Antarctica. The spatial variations of sea level around the globe will depend on the location and rate of polar ice melt. But here in Florida, these contributions offset and we expect that the differences from the global rate will be less than 10%, meaning that if sea level increases globally by 100 cm, then Florida will experience increases within 90-110 cm.

On time scales of a few years to a few decades, the contribution of sea level changes due to changes in wind and ocean circulation patterns are potentially important but difficult to project, as discussed. This is because these wind and current pattern changes are expected to vary on multiple time scales, and because it is difficult to separate variability from trends. But for the next decade, we project that sea levels around Florida will be strongly affected by variability in rates due to atmosphere and ocean dynamics, translating to average sea level changes of about 10 cm, similar to the observed increase during 2006-2017. Given that these changes may be ephemeral rather than permanent, we could also see smaller changes; but in the most recent decade, sea level has been increasing sharply in parts of Florida and it is prudent to plan on the assumption that this type of short-term acceleration is possible in the future also.

On the 20 to 50-year time scale, we expect that sea level changes in Florida will be dominated by a combination of increasing global mean sea level, which will be seen in Florida as well, and high regional variability associated with wind and ocean current changes. Assuming that the present increased rates due to ocean and atmosphere changes continue, the projected sea level rise rates will be even higher than those observed since 2000 and sea level will rise by 30–45 cm, which is in the range of the NOAA-projected intermediate-low and intermediate-high curves. As stated earlier, however, we expect that the projected global rates will be higher than this, meaning that sea level increases of 50– 100 cm are definitely possible within the next 50 years.

Uncertainties in Projecting Global Mean Sea Level Change

We will conclude this chapter with a discussion of where the largest uncertainties in the long-term projections arise. Thermal expansion will likely be no more than 10– 30 cm over the next century, even at the highest "business-as-usual" emission scenario (Church et al. 2013). The contribution from glaciers not on the ice sheets will likely be of the same order, about 9–23 cm for the high emission scenario (Church et al. 2013). The ice sheets, on the other hand, hold huge amounts of ice—about 7 m of sea level equivalent for Greenland and 60 m for Antarctica. We are not suggesting that all of this ice will melt in the near future, but even a losing a small fraction (<2%) would raise sea level by a meter.

There are two major processes that act on the ice sheets and contribute to sea level rise. The first is the difference between summer surface melting and winter accumulation. This can be estimated from the atmospheric climate models, and is expected to be small over the next century (Church et al. 2013). The second process driving mass loss from the ice sheets is based on speeding up of the glaciers that move ice into the ocean, rapid thinning of the glaciers, or both. These dynamic processes can potentially lead to significant increases in sea level over decades. Our understanding of this process is still incomplete, but we have learned a great deal in the last decade from observations and models.

For instance, we now know that much of the bedrock under the Antarctic ice sheet actually sits below sea level, and that the bedrock slopes down from the coast. Most drainage glaciers in such regions, however, have a grounding line on a lip of bedrock above sea level (or just below) and a floating ice shelf. Both of these keep the glacier stable and limit the speed with which it can drain. However, in several regions the ice shelf has fractured, the glacier has sped up, and the leading edge of the glacier has retreated beyond the grounding line. Because of the slope of the bedrock, warmer ocean water can be forced under the ice sheet and melt the ice sheet from the bottom, making the glacier instable. This means the glacier will never be able to form another grounding line and will continue to discharge ice (and raise sea level) until it is gone. Evidence suggests this is already occurring in the Thwaites Glacier in the Amundsen Sea sector of Antarctica (Mouginot et al. 2014).

The problem related to predicting future sea level rise is modeling how long this will take. A recent model for all of Antarctica that includes ice dynamics found that under the "business-as-usual" emission scenario, the ice shelves begin to break apart and sea level starts to rise rapidly starting around 2050, going from no significant contribution before 2050 to an increase of 80 cm between 2050 to 2100 (DeConto and Pollard 2016). This is in contrast to the last IPCC report, which stated that these dynamic changes would contribute less than 23 cm of sea level rise by 2100. A better understanding of these dynamic ice processes is required in order to make more accurate projections.

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