Special Report:

Sea Level and Climate Change

Judith Curry
Climate Forecast Applications Network

25 November 2018

Contact information:
Judith Curry, President
Climate Forecast Applications Network
Reno, NV 89519
404 803 2012
curry.judith@cfanclimate.com
http://www.cfanclimate.net

Sea Level and Climate Change

Judith Curry
Climate Forecast Applications Network

Executive Summary

This Report assesses the scientific basis for projections of future sea level rise. The Report evaluates the projections from the Intergovernmental Panel on Climate Change (IPCC) and recent national assessments regarding sea level rise. The uncertainties and challenges at the knowledge frontier are assessed in the context of recent research, particularly with regards to natural variability. The following four issues frame this Report:

1. Whether recent global sea level rise is unusual.

At least in some regions, sea level was higher than present around 5000 to 7000 years ago. After several centuries of sea level decline following the Medieval Warm Period, sea levels began to rise in the mid 19th century. Rates of global mean sea level rise between 1920 and 1950 were comparable to recent rates. It is concluded that recent change is within the range of natural sea level variability over the past several thousand years.

2. The extent to which recent global sea level rise is caused by human-caused global warming, relative to natural causes of global sea level rise.

The slow emergence of fossil fuel emissions prior to 1950 did not contribute significantly to 19th and early 20th century sea level rise. Identifying a potential human fingerprint on recent sea level rise is confounded by the large magnitude of natural internal variability associated with ocean circulation patterns. There is not yet any convincing evidence of such a fingerprint on sea level rise associated with human-caused global warming.

3. The extent to which local sea level rise is influenced by the global sea level rise, relative to local vertical land motion and local land use practices.

In many of the most vulnerable coastal locations, the dominant causes of local sea level rise problems are natural oceanic and geologic processes and land use practices. Land use and coastal engineering in the major coastal cities have brought on many of the worst local problems, notably landfilling in coastal wetland areas and groundwater extraction.

4. The amount of sea level rise (global and local) projected for the 21st century.

Local sea level in many regions will continue to rise in the 21st century – independent of global climate change. There are numerous reasons to think that projections of 21st century sea level rise from human-caused global warming are too high, and some of the worst-case scenarios strain credulity.

Understanding climate change and sea level rise involves incomplete information from a fast-moving and irreducibly uncertain science. The challenges of understanding the causes of sea level rise and projecting future climate change and sea level rise are well-recognized by the international community of climate and sea level researchers, as summarized in the World Climate Research Programme (WCRP) Grand Challenges.

1. The alarm over sea level rise

The public discourse on the threat of sea level rise is typified by these dire statements from climate scientists:

> "That's the big thing – sea-level rise – the planet could become ungovernable."[1]
> – Dr. James Hansen, former Director, NASA GISS
>
> "We're talking about literally giving up on our coastal cities of the world and moving inland."[2] – Dr. Michael Mann, Penn State University

The alarm over sea level rise is not so much about the 7-8 inches or so that global sea level has risen since 1900. Rather, it is about projections of 21st century sea level rise from human-caused global warming.

This Report refers extensively to the Assessment Reports prepared by the Intergovernmental Panel on Climate Change (IPCC AR4, 2007; IPCC AR5, 2013), since these Reports are used to guide policies developed by the UN Framework Convention on Climate Change, including the 2015 Paris Agreement.

According to the IPCC, the projected 21st century sea level rise depends on the amount of greenhouse gas emissions. The *likely* range of projected sea level rise by the end of the 21st century is from 0.26 to 0.82 m [10 to 32 inches], depending on the emissions scenario.

The primary concern over future sea level rise is related to the potential collapse of the West Antarctic Ice Sheet, which could cause global mean sea level to rise substantially above the IPCC's likely range in the 21st century. The IPCC AR5 has medium confidence that this additional contribution from the West Antarctic ice sheet would not exceed several tenths of a meter [less than a foot] during the 21st century.

Subsequent to the IPCC AR5, there has been a focus on the possible worst-case scenario for global sea level rise. Estimates of the maximum possible global sea level rise by the end of the 21st century range from 1.6 to 3 meters [5-10 feet], and even higher. These extreme values of possible sea level rise are regarded as extremely unlikely or so unlikely that we cannot even assign a probability. Nevertheless, these extreme, barely possible values of sea level rise are becoming anchored as outcomes that are driving local adaptation plans.[3]

---

[1] http://nymag.com/intelligencer/2017/07/scientist-jim-hansen-the-planet-could-become-ungovernable.html?gtm=top&gtm=bottom
[2] https://www.sciencefriday.com/segments/hurricane-harvey-and-the-new-normal/
[3] https://www.scientificamerican.com/article/prepare-for-10-feet-of-sea-level-rise-california-commission-tells-coastal-cities/

Is the alarm over sea level rise a false alarm, or not? The following four issues frame this report:

1. Whether recent global sea level rise is unusual in context of the historical and geological record.
2. The extent to which recent global sea level rise is caused by human-caused global warming, relative to natural causes of global sea level rise.
3. The extent to which local sea level rise is influenced by the global sea level rise, relative to local vertical land motion and land use practices.
4. Projections of sea level rise (global and local) for the 21st century, from all causes.

This Report critically evaluates the assessment and conclusions from the IPCC and other recent assessment reports regarding sea level rise, and includes an assessment of recent research and the knowledge frontiers. The IPCC and other assessment reports have been framed around assessing support for the hypothesis of human-caused climate change. As a result, natural processes of climate variability have been relatively neglected in these assessments. Arguments are presented here supporting the important and even dominant role that natural processes play in global and regional sea level variations and change.

Understanding and predicting sea level rise is a vibrant and active area of research. The challenges and uncertainties are well recognized by international scientific community, as formulated by the World Climate Research Programme (WCRP) Grand Challenge on Regional Sea Level Change and Coastal Impacts (WCRP, 2017a).

2. Mechanisms of sea level variations

Changes in sea level occur over a broad range of temporal and spatial scales. As context for the concerns about future sea level rise from human-caused global warming, it is important to understand the broad range of factors that influence sea level. Rovere et al (2016) provides a helpful overview of the definitions of sea level, why it varies and how it is measured.

An understanding of sea-level change requires maintaining a clear distinction between *global* (or eustatic) sea-level and *local relative* sea-level. Sea level changes can be driven by either variations in the masses or volume of the oceans ('eustatic'), or by changes of the sea surface relative to the land ('relative').

2.1 Global

Eustatic change (as opposed to local change) results in an alteration to the global sea levels due to changes in either the volume of water in the world's oceans or net changes in the volume of the ocean basins. Determination and interpretation of sea level rise is complicated by the fact that both mean sea level and the solid earth surface move vertically with respect to each other. This movement in effect changes the shape of the 'bathtub'.

The primary contributors to global, eustatic sea level change are the expansion of the ocean as it warms and the transfer to the ocean of water from melting ice locked in mountain glaciers and continental ice sheets. Additional contributions are from changes in land-water storage and the shape of the ocean basins. Figure 2.1 provides a schematic of these processes.

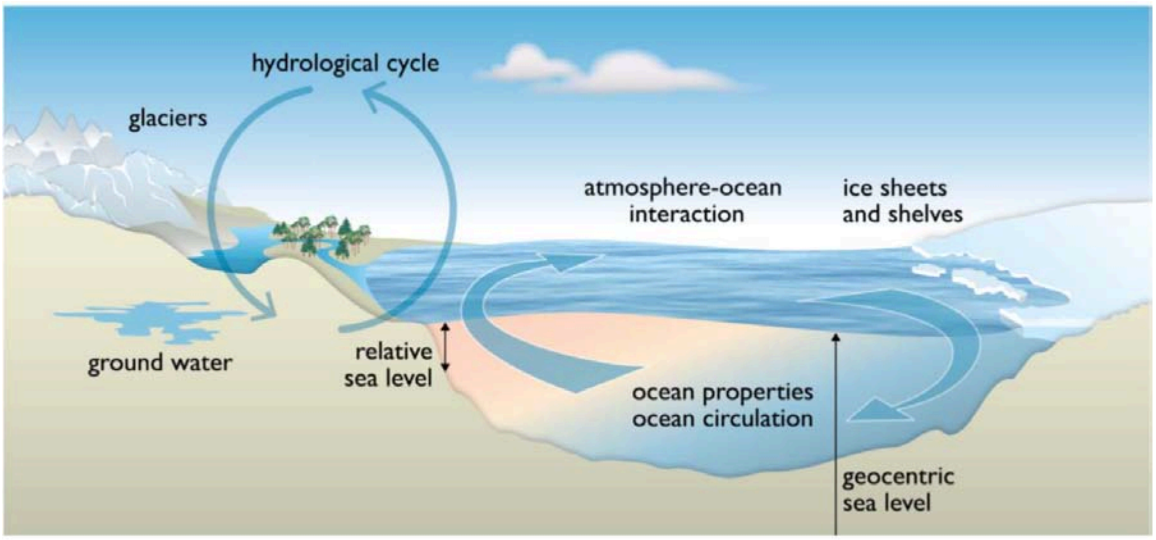

Figure 2.1: Climate sensitive processes and components that influence global sea level. The term 'ocean properties' refers to ocean temperature, salinity and density, which influence and are dependent on ocean circulation. [IPCC AR5 WGI, Chapter 13]

Sea level also changes in response to changing volume of the ocean basins. Some land movements occur because of *isostatic* adjustment of the Earth's mantle since the end of the last ice age. The weight of the ice sheet depresses the underlying land, and when the ice melts away the land slowly rebounds. This is referred to as *glacial isostatic adjustment* (GIA). The Earth's ocean basins have been expanding slightly since the end of the last ice age via geological processes including converging and diverging plate tectonics, uplift of the collision margin, basin subsidence of the extensional crust, volcanic activities in the oceanic region, delta buildup, ocean floor height change and sub-marine mass avalanche. Hence, the amount of water added to the oceans is changing sea level less than it would if the size of the ocean basins was fixed.

Melting of glaciers and ice sheets since the end of the last ice age has transferred water mass from the land to the oceans. This mass transfer contributes to present-day sea level change due to the ongoing deformation of the Earth and the corresponding changes of the ocean floor height and gravity (glacial isostatic adjustment). Ice sheets have long response times and continue to respond to past climate change, while responding to current climate conditions as well.

Melting of sea ice has no impact on sea level – water or ice that is already floating does not change the sea level by melting/freezing. Ice on a continent that melts and runs into the ocean increases sea level due to increasing the amount of ocean water. Antarctic ice shelves are in the ocean but are supported by the continent of Antarctica – melting these ice sheets will increase sea level.

The global hydrological cycle influences the amount of rainfall over land versus ocean. Interannual variations in global sea level are caused by different rainfall patterns in El Niño versus La Niña years.

Land-based water management practices such as water impoundment in dams and reservoirs, irrigation and ground water extraction influence the amount of water stored in the ground or on its surface. This storage influences the amount of surface water runoff into the ocean, and so influences sea level.

2.2 Regional

Figure 2.2 shows a map of sea level trends over the period 1993-2014. Complex spatial patterns result from ocean and atmospheric circulation systems, vertical movements of the sea floor, and changes in gravity due to water mass redistribution. As a result, the locally observed sea level behavior can differ significantly from the global average. Note the very large sea level rise anomalies in the tropical west Pacific, the South Pacific and Indian Ocean, although this pattern appears to have reversed since 2011 (Hamlington et al., 2016).

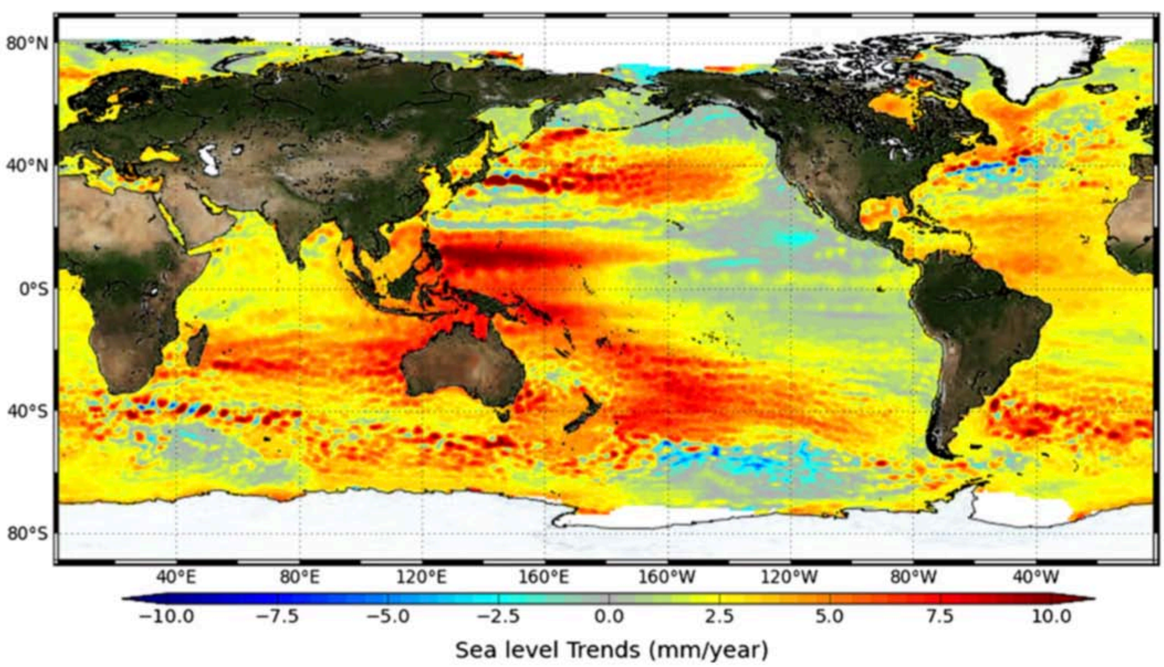

Figure 2.2: Regional mean sea level trends over the 1993-2014 period (Ablain et al. 2016)

2.3 Local

Observed rates of mean global sea level rise can have little relevance for a specific location. Multiple causes of local sea level rise were recognized by the IPCC AR5:

- "[L]ocal sea level trends are also influenced by factors such as regional variability in ocean and atmospheric circulation, subsidence, isostatic adjustment, coastal erosion, and coastal modification." [IPCC AR5 WG II Section 18.3.3]
- "Anthropogenic causes of regional sea level rise include sediment consolidation from building loads, reduced sediment delivery to the coast, and extraction of subsurface resources such as gas, petroleum, and groundwater. Regional sea level rise can exceed global mean sea level rise by an order of magnitude reaching more than 10 cm/yr." [IPCC AR5 WG II Section 5.3.2.2]

Human causes of local sea level rise include sediment compaction from building loads, reduced sediment delivery to the coast, and extraction of subsurface resources such as groundwater, gas and petroleum. Engineering practices that influence the natural flow of sediment have a substantial influence on deltas and coastal morphology.

Marshes naturally keep pace with sea level rise by trapping sediment and growing plants. Diminished sediment supply or human-induced sinking can reduce the effectiveness of marshes in replenishing the coast. Coastal landfills that displace wetlands not only stop this replenishment process, but these landfill regions can sink through compaction under the weight of heavy building loads.

Individual locations are also subject to substantial variations in sea level from tides and storm surges. Storm surges from hurricanes or mid-latitude cyclones can be as high as 40 feet. Local tides of magnitude up to 40 feet vary on timescales ranging from hours to years. Extreme local sea levels can arise from combinations of astronomical tides, storm surges, wind waves and swell, the annual cycle and interannual variability.

3. Is the recent sea level rise unusual?

To assess whether the recent sea level rise is unusual, it is important to understand the variability of sea level and its rates of change over the historical and geologic records. Further, it is important to understand the reliability of these data sets and the uncertainties introduced from the analysis methods.

The IPCC AR5 WGI (2013) provided the follow summary statements:

> "It is very likely that the mean rate of global averaged sea level rise was 1.7 [1.5 to 1.9] mm/year between 1901 and 2010 . . . and 3.2 [2.8 to 3.6] mm/year between 1993 and 2010. It is likely that similarly high rates occurred between 1920 and 1950."

> "The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (high confidence)."

> "There is very high confidence that maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 5 meters higher than present, and high confidence that it did not exceed 10 meters above present."

The recent rate of sea level rise is about 3 mm/year. For reference, 3 mm is the height of two stacked pennies (U.S. coins). This chapter critically evaluates our knowledge base for documenting current and past sea level rise.

3.1 The geologic record

The geologic record provides some constraints and insights into understanding how much, and how fast, sea level might rise in the coming centuries. It also provides critical context for understanding whether current sea levels and rates of sea level rise are unusual.

How is past sea level revealed in the geologic records? Proxy records of sea level are preserved in a variety of marine and terrestrial settings, such as sediments and organisms in deep ocean cores or once-submerged shorelines, and uplifted fossil reefs. Analysis of oxygen isotopes in tiny ocean organisms, and radiometric techniques are used to interpret and date the records (for a summary, see Horton et al., 2018).

During the past 20,000 years (the Holocene), since the end of the last glaciation, sea level has risen by a total of about 120 meters [400 feet]. Figure 3.1 shows sea level for the last 24,000 years. Sea level was lowest between 22,000 and 18,000 years ago, rising sharply between 15,000 and 8,000 years ago.

During the deglaciation occurring between 19,000 and 8,000 years ago, sea level rose at extremely high rates (Cronin, 2012). At the onset of the deglaciation, a ~ 500-year long event may have contributed as much as 10 m to sea level, with an average rate of about 20 mm/year. During the rest of the early Holocene, the rate of sea level rise varied from a low of about 6-10 mm/year to as high as 30–60 mm/year during brief periods of accelerated sea level rise. For reference, these values are compared to modern values of sea level rise ranging from 1 to 3 mm/year.

On average, sea level has been relatively stable over the past 6,000 years. Of particular interest is the so-called 'mid-Holocene high-stand' between about 6000 and 3000 years ago, when sea level in some regions was up to several meters higher than present (e.g. Prieto et al. 2016; Chiba et al. 2016; Bradley et al. 2016; Accordi and Carbone, 2016). The sea level high-stand was associated with the so-called Climatic Optimum or the Holocene Optimum, during 8000 to 4000 BC, when average global temperatures reached their maximum level during the Holocene and were warmer than preindustrial temperatures by an estimated 0.6 to 0.8 ^{o}C (Horton et al, 2017).

Rohling et al. (2013) provide an overview on what we know about rates of sea level rise in the Holocene, past ice ages and interglacials, concluding that modern change is within the range of ‘normal’ processes.

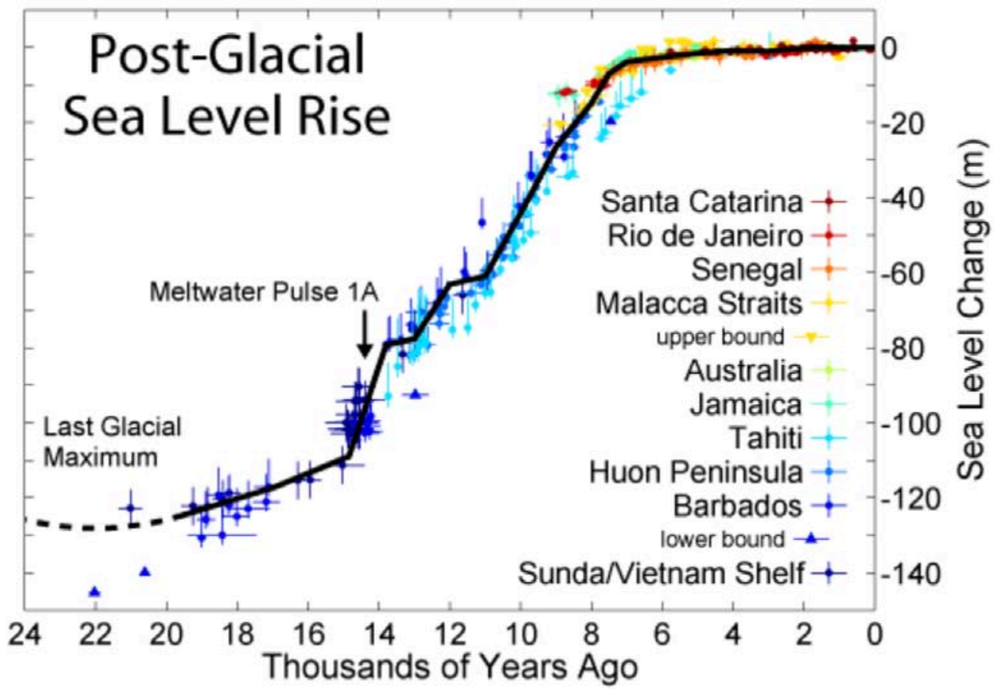

Figure 3.1 Estimated global sea level changes since the Last Glacial Maximum (~21,000 years ago). This figure was prepared by Robert A. Rohde from published data, and is incorporated into the Global Warming Art project. https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png

In the past decade, three analyses have been published on global sea levels over the past two millennia – Grinsted et al (2009), Kopp et al. (2016) and Kemp et al. (2018) (Figure 3.2). These three analyses differ substantially, reflecting the large uncertainties in such reconstructions.

Kopp et al. found that global sea level varied by ~ ± 7 – 11 centimeters [2.8 – 4.3 inches] over the past 2500 years, with a notable decline over 1000–1400 A.D. coinciding with ~0.2 °C of global cooling. The sea level peaks in 300-1000 A.D. and the current peak are not comparable owing to different data analysis methods. Kemp et al. is essentially an update on Kopp et al. (with many of the same coauthors). Changes in Kemp et al. include markedly higher sea levels circa -900 to -700 years, a sharp decline in sea level between -700 and -400 years, and substantially lower sea levels between 1100 and 1300 years.

The Kopp/Kemp estimates differ markedly from Grinsted et al. (2009) that identifies global sea level variations having larger amplitude and much higher sea levels during the Medieval Warm Period. These two approaches and datasets differ considerably, and there has been no consistent assessment of the differences between the reconstructions.

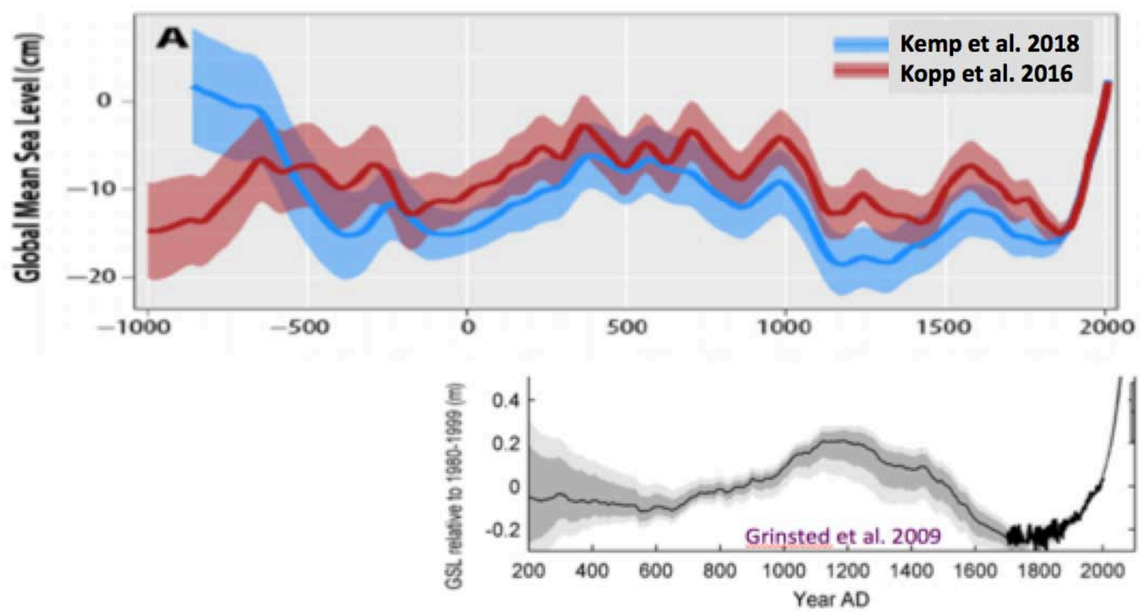

Figure 3.2 Reconstructions of global sea level rise over the past ~2000 years, including glacial isostatic adjustment. Kopp et al. (2016) and Kemp et al. (2018) – global sea level anomalies in centimeters (cm), Grinsted et al. (2009) – global sea level anomalies in meters (m). (curve after 2006 is projection). Note the large differences during the Medieval Warm Period (950-1250 AD).

The Kemp/Kopp and Grinsted analyses did not settle the issue of whether sea levels during the Medieval and Roman Warm Periods were higher than current levels, or whether there were any decadal-scale periods with large rates of sea level rise.

It is useful also to consider historical and archaeological information. Hubert Lamb's (1995) book *Climate History and Modern World* offers his analysis on this issue:

> "The water level may have dropped by 2 meters [6.5 feet] or more between 2000 and 500 BC. What does seem certain is that there was a tendency for world sea level to rise progressively during the time of the Roman Empire, finally reaching a high stand around 400 AD comparable with, or slightly above, present".
>
> "Our survey of the European scene during the warmer centuries of the Middle Ages would not be complete without mention of the things that suggest a higher stand of the sea level, which may have been rising globally during that warm time as glaciers melted".

3.2 Tide gauge record of sea level change

Tide gauges measure the variations of sea level relative to a fixed point of known elevation above mean sea level. Several tide gauge records extend back to the 18th century. Reconstructions of global sea levels prior to 1992 (the beginning of the satellite era) rely solely on the tide gauge record.

There are numerous challenges to reconstructing a record of global sea level changes over time from tide gauges. The primary challenge is the sparseness of the measurements (Figure 3.3). Additional challenges include: uneven distribution around the world; missing data; spatial and temporal variations in ocean circulations; and vertical land movements. Because of these challenges, calculating global mean sea level rise from the limited tide gauge network has proven to be difficult.

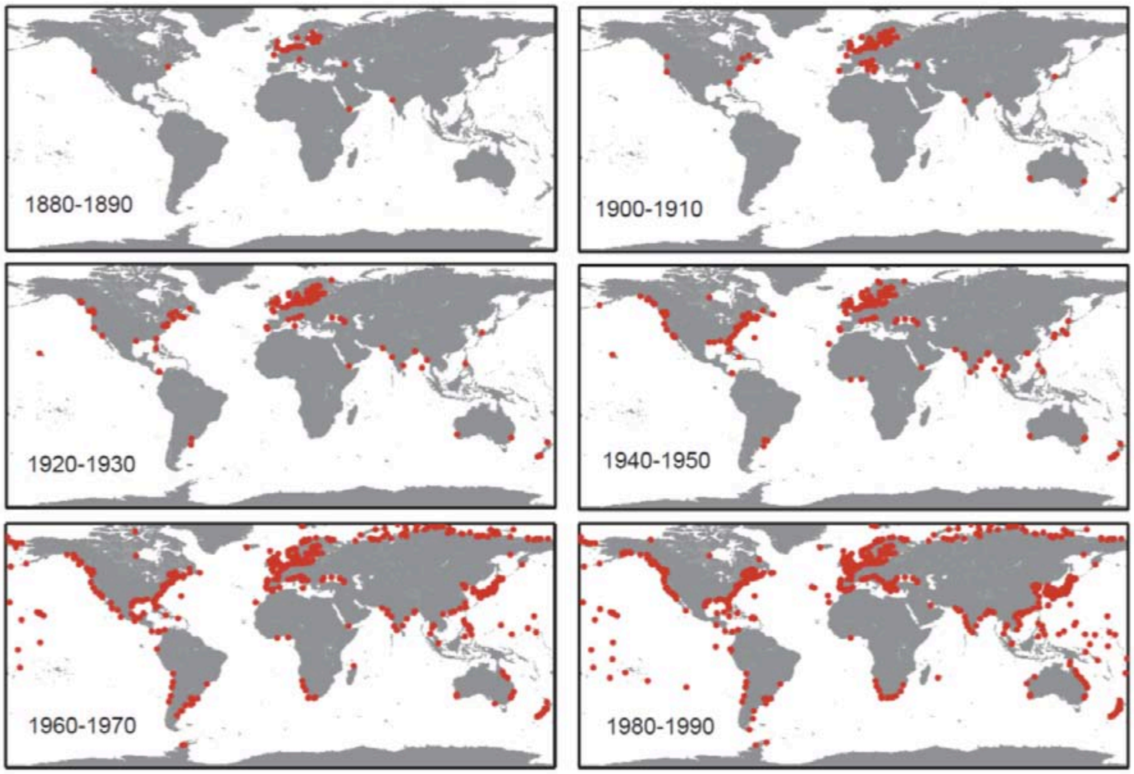

Figure 3.3: Location of tide gauges (red dots) that had at least one year of observations within the decade indicated. (IPCC AR5 WG I, Figure 3.A.4)

3.2.1 Has global sea level rise accelerated since the 19th century?

Central to attempts to attribute the recent sea level rise to human-caused global warming is to assess whether the rate of sea level rise has increased. From the IPCC AR5:

> "AR4 concluded that there was "high confidence that the rate of global sea level rise increased from the 19th to the 20th century" but could not be certain as to whether the higher rate since 1993 was reflective of decadal variability or a further increase in the longer-term trend. It has been clear for some time that there was a significant increase in the rate of sea level rise in the four oldest records from Northern Europe starting in the early to mid-19th century. The results are consistent and indicate a significant acceleration that started in the early to mid-19th century, although some have argued it may have started in the late 1700s." [IPCC AR5 WG1 Section 3.7.4]

A recent paper by Watson (2017a) has assessed sea level rise and its acceleration from European tide gauge data. Watson (2017) used Single Spectrum Analysis (SSA) as a time series analysis method to analyze the sea level records. Watson presents evidence that the SSA is a superior method relative to the simple quadratic models that have been used previously to detect sea level rise acceleration. Watson examined the four longest European records (Amsterdam, Netherlands, 246 years; Stockholm, Sweden, 214 years; Brest, France, 208 years; and Swinoujscie, Poland, 202 years). The analysis showed rates of sea level rise that vary over time and that that sea level rise has steadily increased over time, peaking at or near the recent end of the time series record. Watson concluded that there is no consistent or compelling evidence that recent rates of rise are abnormal in the context of the historical records available across Europe.

3.2.2 20th century global sea level variations

Below is a summary of the status of 20th century sea level estimates from the tide gauge observations at the time of the 2013 IPCC AR5:

> "Tide gauges with the longest nearly continuous records of sea level show increasing sea level over the 20th century. There are, however, significant interannual and decadal-scale fluctuations about the average rate of sea level rise in all records. Different approaches show very similar long-term trends, but noticeably different interannual and decadal-scale variability. The rate from 1901 to 2010 is 1.7 [1.5 to 1.9] mm/year, which is unchanged from the value in AR4." [IPCC AR5 WG I Section 3.7.2]

Since publication of the IPCC AR5 in 2013 with its highly confident assessment of a *very likely* mean sea level rise rate between 1900 and 2010 of 1.7 ± 0.2 mm/year, or 1.5 ± 0.2 mm /year from 1900 to 1990, the following global mean sea level rise estimates have been published:

Table 3.1: Recent estimates of 20th century mean global sea level rise

Source	Rate of SLR	Period
Jevrejeva et al (2014)	1.9 ± 0.3 mm/year	20th century
Kopp et al. (2016)	1.4 ± 0.2 mm/year	20th century
Mitrovica et al. (2015)	1.2 ± 0.2 mm/year	1900–1990
Hay et al. (2015)	1.2 ± 0.2 mm/year	1900–1990
Thompson et al. (2016)	1.7 ± 0.3 mm/year	20th century
Dangendorf et al. (2017)	1.1 ± 0.3 mm/year	1900–1990

A translation of these rates into inches per century: 1.9 mm/year equals 7.5 inches; 1.5 mm/year equals 6 inches; 1.1 mm/year equals 4.3 inches.

The highest and lowest of these estimates do not have overlapping ranges, and the range of these recent values exceeds the range from the IPCC AR5. Hence there is substantial uncertainty in the overall sea level rise over the 20th century, ranging from 4.3 inches to 7.5 inches.

A graph comparing the time series of different global sea level rise analyses since 1900 is provided in Figure 3.4. The major discrepancies among these different analyses relate to tide gauge selection, vertical land motion corrections, area weighting and statistical analysis methods.

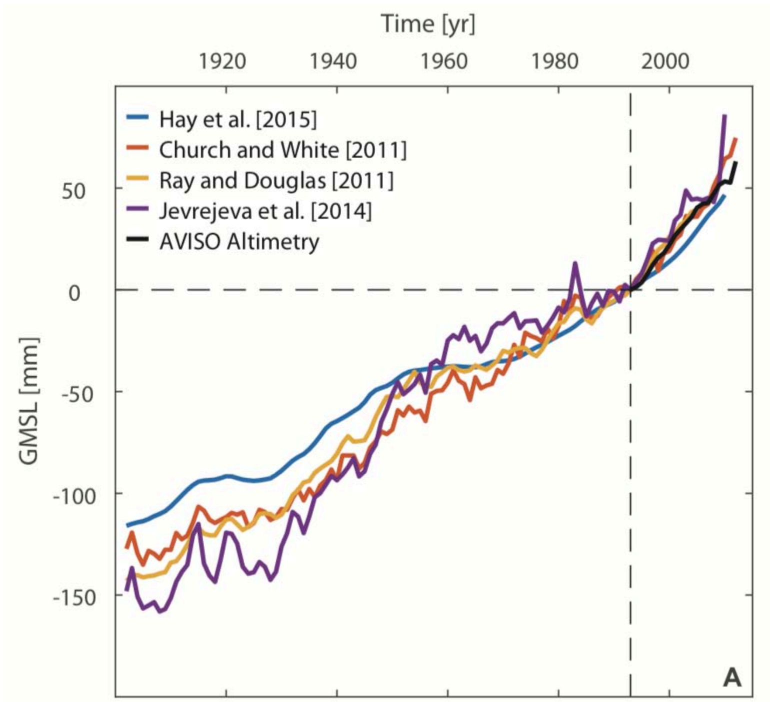

Figure 3.4 Different global mean sea level reconstructions over the common period from 1902 to 2012. All series have been adjusted to be zero in 1993 (dashed lines). Dangendorf and Marcos (2018)

With regards to rates of sea level rise (Figure 3.5), the IPCC AR5 concluded that it is likely that a sea level rise rate comparable to that since 1993 occurred between 1920 and 1950:

> "It is *very likely* that the mean rate of global averaged sea level rise was 1.7 [1.5 to 1.9] mm/year between 1901 and 2010 . . . and 3.2 [2.8 to 3.6] mm/year between 1993 and 2010. It is likely that similarly high rates occurred between 1920 and 1950."

There are several recent analyses of rates of sea level rise over the 20th century, that also identify a mid-century peak in rates of global sea level rise: Hay et al. (2015), Hamlington and Thompson (2015), Dangendorf et al. (2017). These analyses show a mid-century peak in the rate of sea level rise, with the current peak slightly higher but within the range of uncertainty.

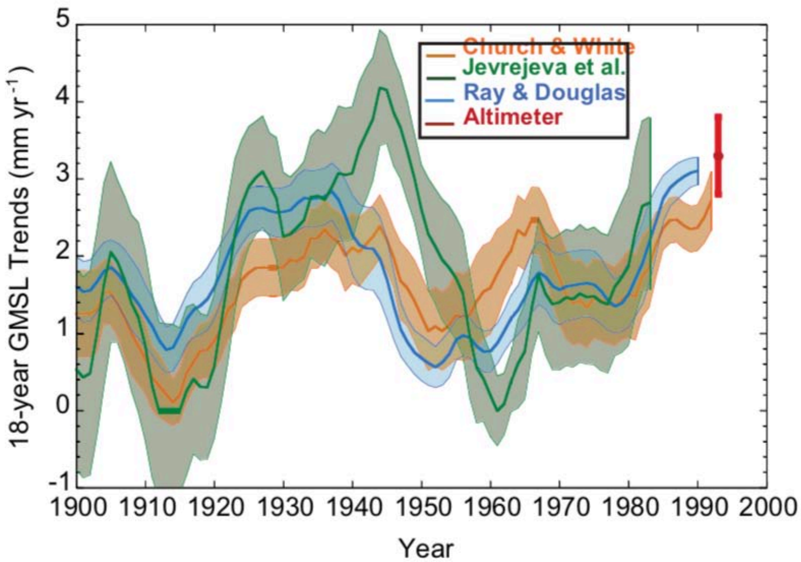

Figure 3.5 18 year trends of global mean sea level rise estimated at 1-year intervals. The time is the start date of the 18-year period and the shading represents the 90% confidence. The estimate from satellite altimetry is also given, with the 90% confidence given as an error bar. [IPCC AR5 WG 1 Chapter 3 Figure 3.14]

The significance of the early 20th century acceleration in global sea level rise is this: This acceleration in the early 20th century was not caused by human-caused warming; hence the recent acceleration in global sea level rise (since 1995) cannot be attributed to human-caused warming without explaining why the mid-century acceleration occurred and why these same factors do not explain the recent acceleration.

3.4 Satellite observations of global sea level rise

Satellite measurements of global sea level have been available since 1992, which has expanded our understanding of the variability of global sea level rise. Complex analysis methods are required to transform raw satellite measurements into sea level variations, including the correction and piecing together of records collected over many years by aging and changing satellites.

Figure 3.6 shows the time series of satellite-derived global mean sea level. The average rate of sea level rise over this period is estimated from the satellite data sets to be 2.6 to 3.2 mm/year (Horton et al, 2018). Substantial interannual variations are seen, which are associated primarily with the El Niño Southern Oscillation (ENSO). The large trend between 2011 and 2016 is associated with a very strong LaNiña (2011) and a very strong El Niño (2016). These variations are associated with changes in the global hydrological cycle and the distribution of rainfall over land versus over ocean. There is a tendency for land water deficit including groundwater (and temporary increase of the global mean sea level) during El Niño events and the opposite during La Niña (e.g. Fasullo et al. 2013).

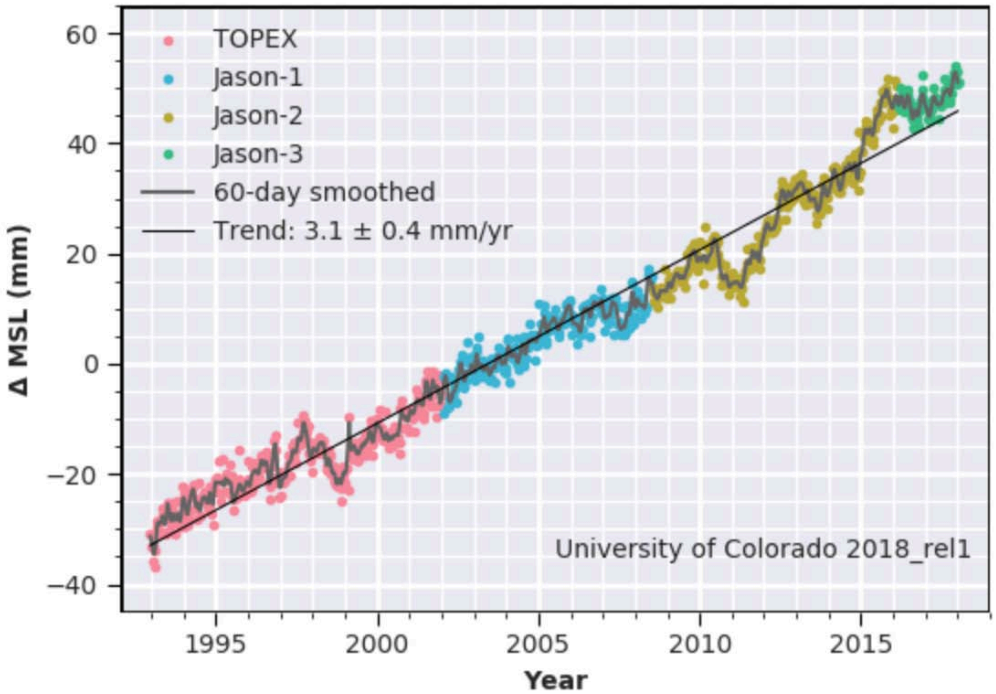

Figure 3.6 Global mean sea level anomalies derived from satellite altimeter data, with seasonal cycle removed University of Colorado, downloaded 2/12/18 http://sealevel.colorado.edu

Calibrating the satellite observations to obtain global sea level is a complex undertaking (e.g. Nerem et al. 2007). Many adjustments must be made to the raw measurements to account for atmospheric delays, ocean tides, variations in wave height, etc. In addition, the sea level measurements can be affected by the method used to process the altimeter waveforms, and by the techniques and data used to compute the orbit of the satellite. The calibration of satellite instruments drifts with time, causing substantial biases that undergo continual calibration and changes to the processing algorithms.

The JASON (2017) Products Handbook provides a detailed technical reference on processing and interpretation of the raw satellite data used to determine sea level. The errors in many of the processing steps are measured in centimeters. Many of the uncertainties in the data processing are even larger than the inherent measurement uncertainty. Assessment of errors in the satellite-derived sea level data set seems to be derived from the differences between the results of independent analyses of the data set (e.g. Nerem, 2007), rather than careful consideration of all of the uncertainties involved. The end result is that the calibrations are far larger than the resulting changes in global mean sea level. New errors and sources of uncertainty in the altimeter data set continue to be identified (e.g. Nerem et al., 2018).

Another complexity in the processing of the satellite data to determine sea level rise is the application of glacial isostatic adjustment (GIA) (e.g. CU 2007). The correction for GIA accounts for the fact that the ocean basins are getting slightly larger because of the Earth's rebound following the deglaciation at the end of the last ice age. As a result, some land regions are rising and some ocean bottoms are falling. The mean rate of sea level change due to GIA is estimated at -0.3 mm/year, with an uncertainty of at least 50%. Since the ocean basins are getting larger due to GIA, this reduces the relative sea level rise that is seen along the coasts. This means that if we measure a change in global mean sea level of 3 mm/year, the volume change is actually closer to 3.3 mm/year because of GIA. The rationale for applying the GIA correction is so that the sea level time series reflects only changes in ocean water volume.

Budgets of the component processes contributing to sea level rise can in principle be used as a check on the altimeter-derived sea level rise. The budget from Chen et al. (2017) shows both GIA adjusted and unadjusted rates of sea level rise. The unadjusted values show a *deceleration* in the rate of sea level rise, whereas the adjusted values show acceleration. The implication of this is that if we did not adjust for the increasing size of the ocean basis, there would be no acceleration in sea level rise.

As concluded by Munk (2007) with respect to the satellite measurements:

> "At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology. Both systematic and random errors are of concern, the former particularly, because of the changes in technology and sampling methods over the many decades, the latter from the very great spatial and temporal variability. It remains possible that the database is insufficient to compute mean sea-level trends with the accuracy necessary to discuss the impact of global warming – as disappointing as this conclusion may be."

3.4 The 'acceleration' debate

The important question is not '*is the long-term rate of sea-level rising?*' since the geological, tide-gauge and satellite record all agree that it is. Rather, the key questions are: '*is the **rate** of sea-level rise increasing?*' and '*is any acceleration in the rate of sea-level rise unusual?*'

The IPCC AR5 acknowledges that a long time series is needed to detect acceleration in sea level rise from human-caused climate change:

> "While technically correct that these multidecadal changes represent acceleration/ deceleration of sea level, they should not be interpreted as change in the longer-term rate of sea level rise, as a time series longer than the variability is required to detect those trends." [IPCC AR5 WGI Section 3.7.4]

The rate of global mean sea level rise during the satellite period (since 1993) of 2.9 ± 0.3 mm/year is about twice as large as the rate during the period 1900-1993 (1.5 ± 0.2 mm/year). Is the recent increase in the rate of sea level rise real, or does it reflect an apples-to-oranges comparison using fundamentally different measuring technologies and assumptions?

There have been several studies that compare the tide gauge with satellite values during the period since 1993, finding good agreement between the tide gauge analyses and the satellite-derived values (e.g. Jevrejeva et al. 2014; Hay et al. 2015; Dangendorf et al. 2016). However, these analyses are far from simple comparisons with tide gauges. The tide gauges are used as part of a global reconstruction that accounts for ocean volume redistribution, local observations of vertical land motion, ongoing glacial isostatic adjustment, present-day ice melt and land water storage.

Apart from this complexity in attempting to compare tide gauges with satellite determinations of sea level rise, there is evidence from tide gauges of some acceleration in the 1990's (Figure 3.7). For several decades prior to the late-1980s or so, the global trend is relatively steady. After 1989, there is a sharp increase in the rate of sea level that continues through the 1990's.

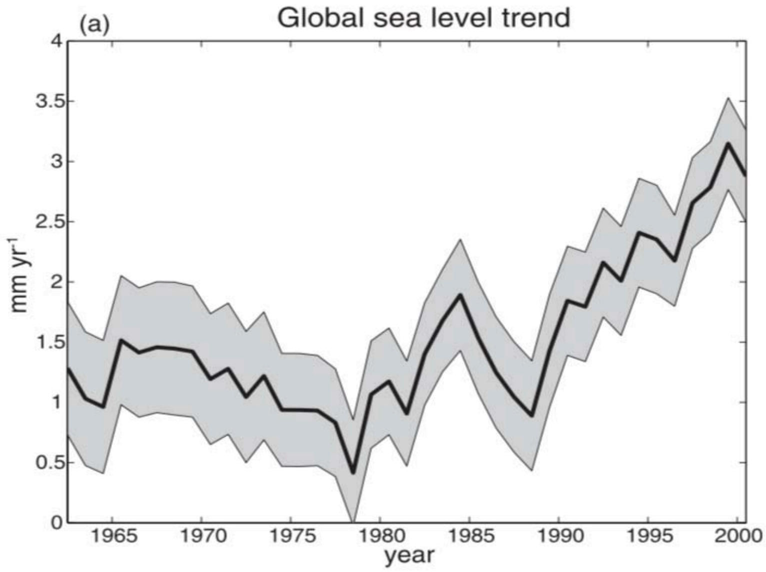

Figure 3.7. Tide guage derived global sea level trends for 1962-2000 estimated over 15-yr segments and plotted vs the midyear of the segment. The vertical land motion correction and the GIA correction of 0.3 mm/year are included. The shaded region indicates one standard error. (Merrifield et al., 2009)

Merrifield et al. (2009) noted that the Northern Hemisphere oceans play a surprisingly small role in this acceleration of sea level rise. Dangendorf et al. (2016) found that this sharp increase was geographically dominated by the Indian Ocean–Southern Pacific region, marking a transition from lower-than-average rates before 1990 toward higher rates in recent decades. Merrifield et al. (2009) identified a covariation of regional sea level in the tropics and southern oceans that represents a shift from a state where the two regions once varied out of phase to now apparently varying more in phase. These 'hot spot' regions are clearly visible in the spatial map of rates of sea level rise (Figure 2.2).

3.5 Summary

Is the recent sea level rise (since 1993) of magnitude 3 mm/year unusual? Based on the data available and its uncertainties, the recent sea level rise is not judged to be unusual.

Based on paleoclimate evidence from a variety of locations, sea level was apparently higher than present at the time of the Holocene Climate Optimum (~ 5000 years ago), at least in some regions. Whether or not sea level was higher than current levels during the Medieval Warm Period (MWP) remains uncertain, and there is substantial disagreement among different reconstructions of sea level during the MWP.

Tide gauges show that sea levels began to rise during the 19th century, after several centuries associated with cooling and sea level decline. Recent research has concluded that there is no consistent or compelling evidence that recent rates of rise are abnormal in the context of the historical records back to the 19th century that are available in Europe. Tide gauges also show that rates of global mean sea level rise between 1920 and 1950 were comparable to recent rates.

The recent acceleration in mean global sea level rise observed from satellites since 1993 disappears if no glacial isostatic adjustment is applied. This implies that any acceleration in the increase in volume of water is countered by expanding ocean basins.

The World Climate Research Programme (WCRP) Grand Challenge on Regional Sea Level Changes and Coastal Impacts (WCRP 2017a) states:

> "Large uncertainties remain in reconstructing past sea level changes and in monitoring contemporary sea level within an integrated framework."

The 2017 WCRP Conference Report on Regional Sea Level Changes and Coastal Impacts (WCRP 2017b) states:

> "Additional paleodata, particularly local evidence in the polar regions, in conjunction with improved earth, ice sheet and sea-level models, are needed both to better characterize the natural variability and non-anthropogenic contributors to ongoing sea-level rise, and to develop a better understanding of sea-level high stands, rates of change, and ice-sheet behavior in past states of the world warmer than at present."

4. What are the causes of recent global sea level rise?

To make credible predictions of future sea level rise, we must first understand the mechanisms that have produced past and current sea level change. The issues of detecting recent acceleration in sea level rise and arguments attributing sea level rise to human-caused global warming deserve critical evaluation, in context of a possible high sea level projection pathway in the 21st century.

The outstanding issue in the scientific debate surrounding the causes of sea level rise is whether the elevated rates during recent decades represent acceleration in the long-term rate of change that can be attributed to human-caused warming, or a temporary increase due to natural climate variability.

Detection and attribution of anthropogenic signals in sea level change is a new and rapidly developing field. In the terminology of the IPCC (e.g. Hegerl et al. 2010), a change in an observed variable such as sea level rise is 'detected' if it is demonstrated that the likelihood of such a change occurring due to internal variability is small. 'Attribution' quantifies the evidence for a causal link between the observed change and specific external forcing—such as solar variability or changes to the atmospheric composition.

There are three main challenges to identifying a sea level rise signal from human-caused global warming:

- The timescales in the ocean are very long, and there can be substantial lag time between external forcing and the realization in sea level change.
- High-amplitude natural internal variability in the ocean basins on time scales from the interannual to the millennial.
- Strong regional variations in the signal.

In the IPCC AR5 WG I Chapter 10 on Detection and Attribution, there was no formal attribution analysis of total sea level change. However, the AR5 made the following statements regarding sea level rise, glaciers and ice sheets. Here are the key summary statements:

> "It is *very likely* that there is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s. This is based on the high confidence in an anthropogenic influence on the two largest contributions to sea level rise, that is thermal expansion and glacier mass loss." [IPCC AR5 WG I SPM]
>
> "Anthropogenic influences *likely* contributed to the retreat of glaciers since the 1960s and to the increased surface mass loss of the Greenland ice sheet since 1993. Due to a low level of scientific understanding there is low confidence in attributing the causes of the observed loss of mass from the Antarctic ice sheet over the past two decades." [IPCC AR5 WG I SPM]

This chapter critically evaluates these conclusions from the IPCC in context of recent research and observations in the earlier part of the 20th century.

4.1 Causes of 20th century sea level rise

The overall increase of sea level since the mid 19th century and the rising concentrations of atmospheric CO_2 have suggested a causal relation. Figure 4.1 illustrates the problem with attributing long-term sea level rise to human-caused global warming associated with CO_2 emissions. This figure shows that global sea levels were rising steadily long before fossil fuel emissions became substantial. Since CO_2 emissions from fossil fuels did not become substantially large until after 1950, understanding the causes of recent sea level rise is clearly more complex than a naïve attribution to increasing levels of atmospheric CO_2.

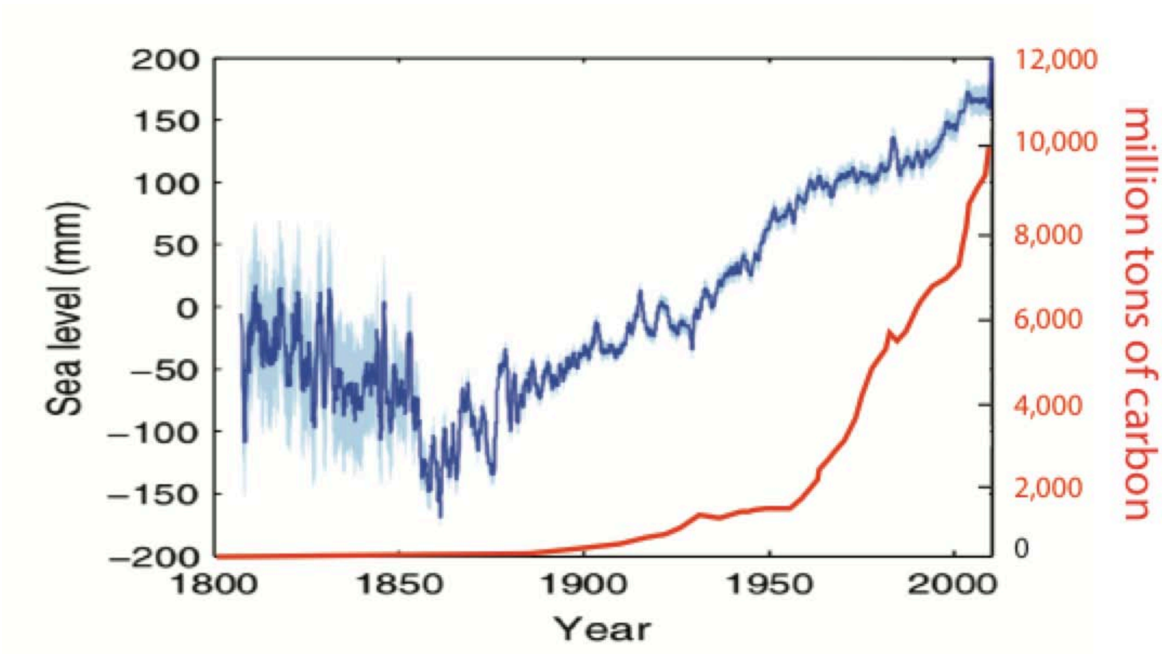

Figure 4.1: Time series of sea level anomalies (blue) Jevrejeva et al. (2014). Million tons of carbon emitted from burning fossil fuels from the Carbon Dioxide Information Analysis Center (CDIAC 2014)

The challenge of attributing recent sea level rise to human-caused global warming is aptly summarized by oceanographer Walter Munk (2007):

> "In looking for causes, I have applied the 'Sherlock Holmes procedure' of eliminating one suspect after another. The procedure has left us without any good suspect. Thermal expansion was the candidate of choice at the time of the first IPCC review. *The computed steric rise [from warming] is too little, too late, and too linear."*

4.2 Budgets of sea level rise

Insights into the causes of recent sea level rise are provided by efforts to understand the budget of sea level rise using global satellite data. Table 4.1 summarizes contributions to recent sea level rise from different sources (mm per year), from both the IPCC AR4 (2007) and AR5 (2013):

Table 4.1 Comparison of components of recent sea level rise budget for the IPCC AR4 and AR5 (mm/year).

	AR4 (1993-2003)	AR5 (1993-2010)
Thermal expansion	1.6	1.1
Glaciers	0.77	0.76
Greenland ice sheet	0.21	0.33
Antarctic ice sheet	0.21	0.27
Land water storage	---	0.38
Sum	2.9	2.84
Observed	3.1	3.2

The IPCC's assessment of the sea level rise budget has evolved from the AR4 (2007) to the AR5 (2013). The contribution from thermal expansion [ocean warming] is one third smaller in AR5 and land water storage is completely new in AR5. Land water storage, the third largest term in the AR5 budget, is a factor that was not included in the AR4. The growing realization of the importance of land water storage to sea level rise has diminished the percentage of sea level rise that is attributed to ocean warming. Subsequent to the AR5, new research (Wada et al., 2017) indicates a smaller contribution from land water storage.

Chen et al. (2017) provides an updated analysis of the budget of sea level rise during the satellite era (Figure 4.2). The key finding is that global mean sea level rise increased from 2.2 ± 0.3 mm/year in 1993 to 3.3 ± 0.3 mm/year in 2014. The mass contributions (from glacier and ices melting) increased from about 50% in 1993 to 70% in 2014. The largest increase has come from the contribution from the Greenland ice sheet, which is less than 5% of the global mean sea level rate during 1993 but more than 25% during 2014. The increase in the rate of sea level rise is largely attributed to increased melting of the Greenland ice sheet.

Estimates of individual elements of the sea level rise budget are associated with substantial uncertainty. Even the steric component (associated with thermal expansion from warming), seemingly the most straightforward component, is associated with substantial uncertainty (MacIntosh et al., 2017). Uncertainties include biases in the temperature measurement systems and changes with time in the measurement systems, selection of density state function, unsampled variability and changes with time to the observing density, and methods for infilling for locations/periods when no direct observations are available.

Wunsch (2018) identified lower bounds on uncertainties in ocean temperature trends for the period 1994-2013. The trend in integrated ocean temperature was estimated by Wunsch to be 0.011 ± 0.001 ^{o}C/decade (note: this rate of warming is much less than the surface warming, owing to the large volume of ocean water). This corresponds to a 20-year average ocean heating rate of 0.48 ±0.1 W/m^2 of which 0.1 W/m^2 arises from the geothermal forcing. I have rarely seen geothermal forcing (e.g. underwater volcanoes) mentioned as a source of ocean warming – the numbers cited by Wunsch reflect nearly a 20% contribution by geothermal forcing to overall global ocean warming over the past two decades.

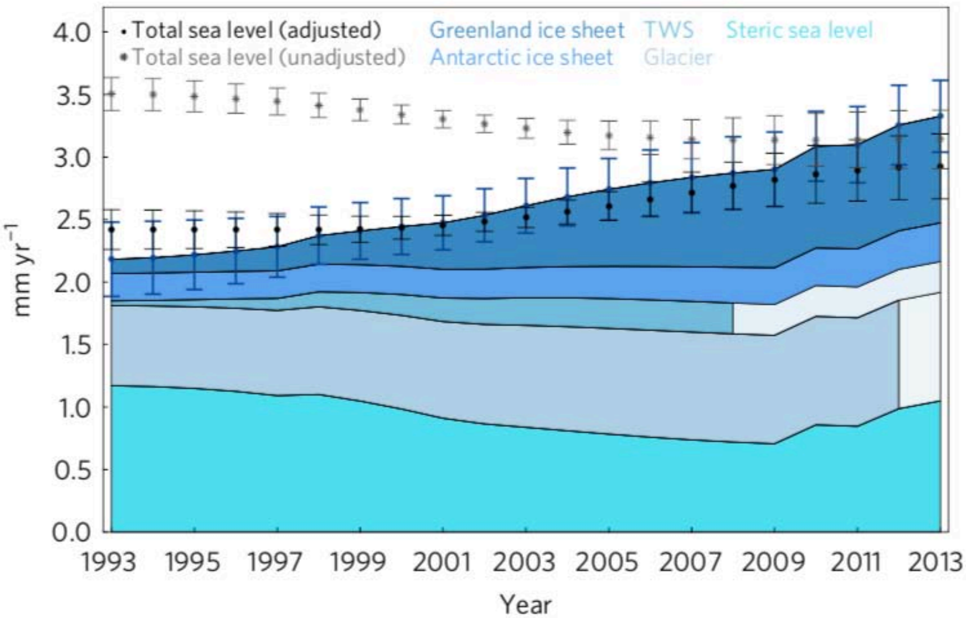

Figure 4.2 Annual closure of the global mean sea-level budget. Ocean thermal expansion (steric sea level), total water storage on land (TWS), glaciers, Greenland ice sheet, Antarctic ice sheet. The time series of the loss of mass from the glaciers and the anthropogenic TWS stops in 2012, and 2009, respectively. Their rates in the years up to 2014 are assumed unchanged and shown in a lighter color. (Chen et al. 2017)

The World Climate Research Program Global Sea Level Budget Group (WCRP 2018) found that the current global mean sea level budget can be closed to within 0.3 mm yr^{-1} (about 10%). They found that ocean thermal expansion, glaciers, Greenland and Antarctica contribute, respectively, 42%, 21%, 15% and 8% to the global mean sea level over the period 1993–2017. They concluded:

> "However, important uncertainties still remain, which affect several terms of the budget; for example the GIA correction applied to GRACE data over Antarctica or the net land water storage contribution to sea level. The latter results from a variety of factors but is dominated by groundwater pumping and natural climate variability. Both terms are still uncertain and accurately quantifying them remains a challenge."

4.2.1 Glaciers and Greenland ice sheet

Chen et al. (2017) identified melting from the Greenland ice sheet to be the primary cause of acceleration in sea level rise since 1993. Here we assess our understanding as to what is causing this recent acceleration.

The IPCC AR5 reached the following conclusions regarding the recent contributions of mass loss from glaciers and the Greenland ice sheet to global mean sea level rise:

> "Overall, there is very high confidence that globally, the mass loss from glaciers has increased since the 1960s" [IPCC AR5 WG I Chapter 4, p343-344]

> "There is very high confidence that the Greenland ice sheet has lost ice and contributed to sea level rise over the last two decades." [IPCC AR5 WG I Chapter 4, p 349]

Considering only the period since the 1960's is misleading in terms of interpreting the cause of this mass loss. During the 1930's, Greenland was very warm, with substantial ice melt. From the IPCC AR5:

> "Over Greenland, temperature has risen significantly since the early 1990s, reaching values similar to those in the 1930s." [IPCC AR5 WG I Chapter 4, p 353]

> "Along Greenland's west coast temperatures in 2010 and 2011 were the warmest since record keeping began in 1873, resulting in the highest observed melt rates in this region **since 1958**." [IPCC AR5 WG I Section 10.5.2]

> " . . . indicates continuous mass loss from glaciers after about 1850 (Figure 4.12a, top). Most notable is the rapid loss from Greenland glaciers in the Marzeion et al. simulations during the **1930s**. Other studies support rapid Greenland mass loss around this time." [IPCC AR5 WG I Chapter 4, p. 343-344]

Figure 4.3 from the IPCC AR5 indicates that the recent onset of glacier melting occurred around 1850, with maximum rates of melting in 1900-1959. The IPCC's main conclusions that refer to 'since the 1960s' and 'since the 1970s', neglect what was going on in the early half of the 20th century, which provides important context for understanding recent glacial melting.

LeClerq et al. (2014) developed a new data set of worldwide glacier fluctuations. The data set shows relatively small fluctuations until the mid-19th century, followed by a global retreat that was strongest in the first half of the 20th century.

The recent acceleration in the mass loss from Greenland motivates a focused look at the mass balance of the Greenland ice sheet.

Fettweis et al. (2008) estimated the Greenland mass balance for the 20th century (Figure 4.4, top). A key conclusion was that the high surface mass loss rates of recent years are not unprecedented in Greenland's history of the last hundred years. It is seen that the largest negative values of the surface mass balance occur during the period ~1925 – 1940, and then since 1995. Greenland was anomalously warm in the 1930's and 1940's, with temperatures comparable to 21st century temperatures.

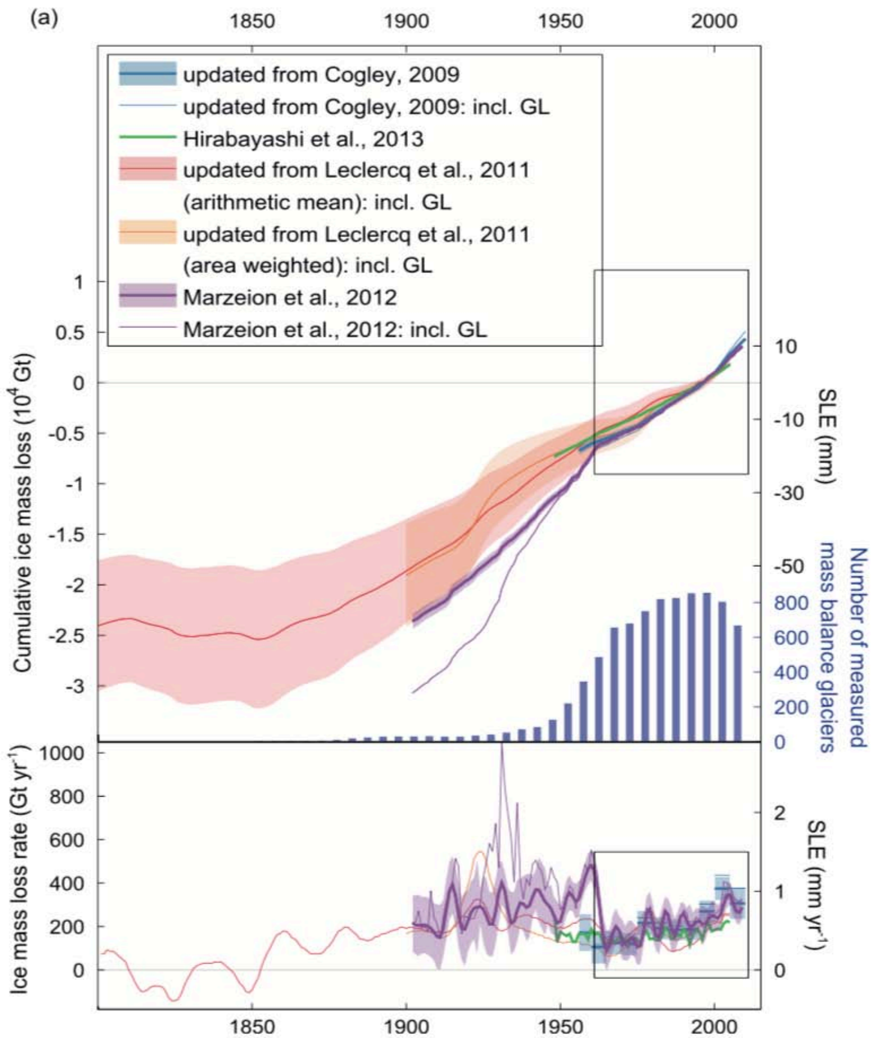

Figure 4.3: Global cumulative (top graphs) and annual (lower graphs) glacier mass change for (a) 1801–2010. The cumulative estimates are all set to zero mean over 1986–2005. [IPCC AR5 WG I Figure 4.12]

The recent acceleration in Greenland melt has been largely attributed to natural variability associated with large-scale ocean and atmospheric circulation patterns – the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO) (Hahn et al. 2018). The bottom panel in Figure 4.4 lines up the Atlantic Multidecadal Oscillation (AMO) index with the Fettweis et al. diagram of Greenland ice sheet mass balance. In general, years with positive AMO index are associated with relatively high Greenland runoff volume and vice versa[4] (Hanna, 2013; Mernild et al., 2017). Fettweis et al. (2013) found that an increase in the negative phase of the North Atlantic Oscillation (NAO) explains about 70% of summer warming since 2003.

[4] The positive (warm) phase of the AMO is also associated with high activity in Atlantic hurricanes.

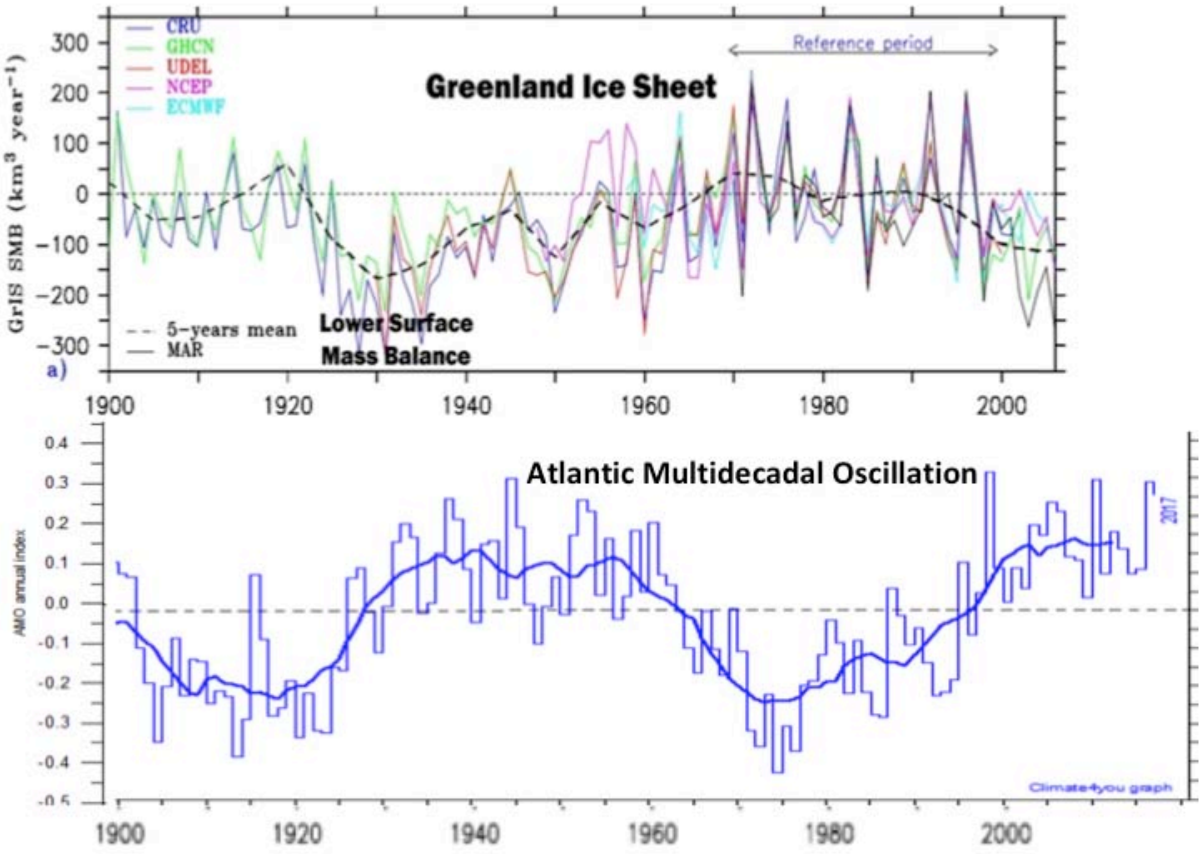

Figure 4.4 (top) Time series of the Greenland ice sheet surface mass budget anomaly. The reference period is 1970–1999. The 5-yr running mean of the ensemble mean is shown in dashed black. Fettweis et al. (2008). (bottom) Time series of the Atlantic Multidecadal Oscillation (AMO).

Hofer et al. (2017) found that the reduction in Greenland's mass balance since 1995 is caused by decreasing summer cloud cover, which has a warming effect from increased solar radiation. The observed reduction in cloud cover is strongly correlated with a state shift in the North Atlantic Oscillation (NAO), promoting high-pressure conditions in summer that inhibits cloud formation and also reduces precipitation. Wang et al. (2018) identified a stabilizing cloud feedback over Greenland, involving clouds, snowmelt, snow metamorphism and surface albedo.

The implications of the relationship between Greenland melting and the multi-decadal ocean oscillations are profound – the negative early 20th century mass balance for Greenland is coincident with the 'bump' in rate of sea level rise in Figure 3.5.

Van den Broeke et al. (2017) concluded that this pronounced variability of the large-scale circulation and therefore surface mass balance imposes severe limits on the unambiguous detection of long-term Greenland ice sheet mass loss acceleration that can reliably be attributed to anthropogenic climate change.

Recent research has also raised the possibility of geothermal melting of the Greenland ice sheet. Rysgaard et al. (2018) showed that the existence of geothermal heat sources beneath the Greenland ice sheet could explain high glacial ice speed areas such as the Northeast Greenland ice stream. Rogozhina et al. (2016) used ice-penetrating radar and ice core drilling and found that large parts of the north-central Greenland ice sheet are melting from below. The implications of Greenland geothermal activity for historical or future sea level rise are unknown.

4.2.2 Antarctica

Antarctica provides numerous challenges for interpreting its contributions to past and future sea level rise. Attributing any loss of Antarctic ice mass to CO_2 emissions is confounded by the fact that Antarctica has overall been cooling and is the location of very active geologic processes.

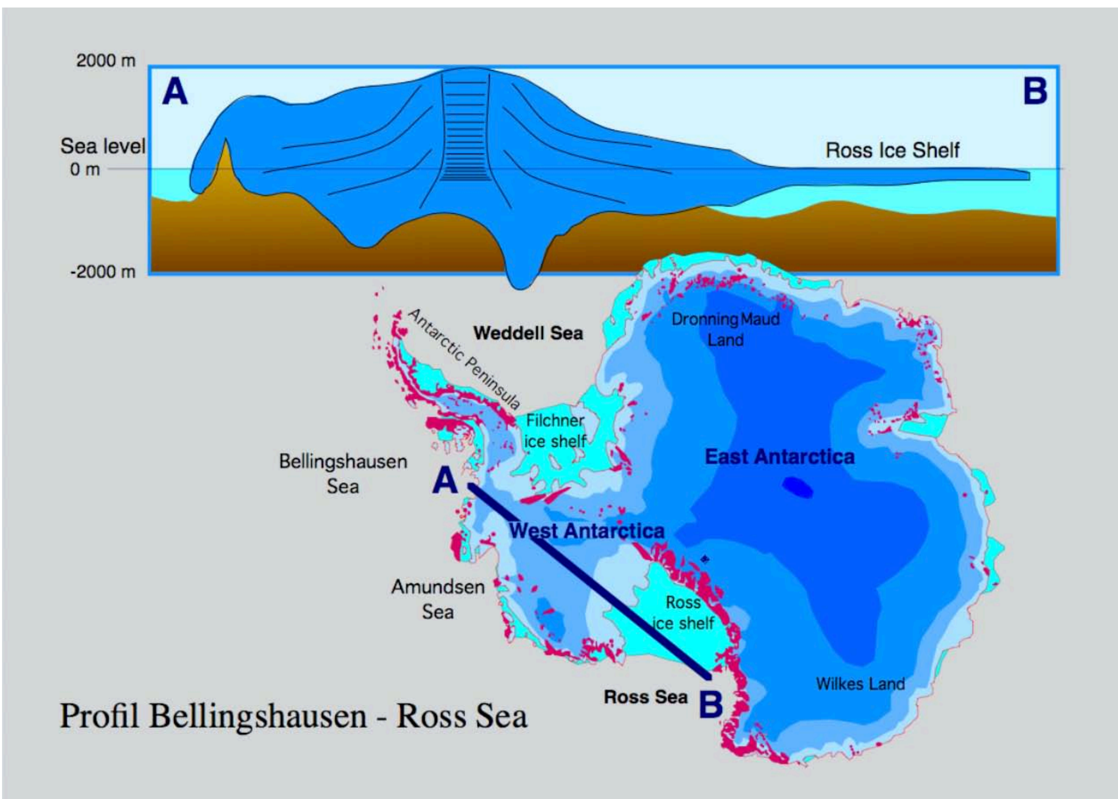

Figure 4.5 Profile through the Antarctic ice sheet (A) Bellingshausen Sea – West Antarctic ice sheet – Ross ise shelf Ross Sea (B). The profile shows that most of the West Antartic ice sheet is grounded below sea level. If the contact line of the ice to the bottom rocks is lost seaward of the grounding line, the ice sheet becomes significantly thinner, forming a shelf ice. From Hans Grobe, www.creativecommons.org/licenses/by-a/2.5)

The geography of the Antarctic ice sheets is shown in Figure 4.5. Temperature reconstructions for Antarctic show little change in East Antarctic surface air temperatures, but warming since 1958 over West Antarctic and the Antarctic Peninsula (Nicolas and Bromwich, 2014). Since the late 1990s, the Antarctic Peninsula has cooled, decadal temperature changes for West Antarctic and the Antarctic Peninsula are within the large natural climate variability (Turner et al., 2016; Smith and Polvani, 2017). Ice core records show similar conditions to the 1990's occurring 1% of the time in the past 2000 years (Steig et al., 2013). The 2002 collapse of the Larsen B ice shelf in the eastern Antarctic Peninsula was unprecedented for the past 11,000 years (Domack et al., 2005) and followed strong warming between the 1950's and 1990's.

The IPCC AR5 concluded that anthropogenic forcing has likely made a substantial contribution to surface temperature increases since the mid 20th century over every continental region *except* Antarctica [IPCC AR5 SYR SPM 1.2]. The IPCC AR5 further concluded that East Antarctica *gained* mass during the period 1992-2011 [WG I Chapter 4, p352]. The West Antarctic Ice Sheet is losing mass at an increasing rate [WG I Chapter 4, p 352]. However, this mass loss is associated with ice dynamics and glacier discharge, rather than melting. The IPCC AR5 states that since the 1950's, warming in West Antarctica has *not* manifested itself in enhanced surface melting nor in increased snowfall [WG I Chapter 4, p 354]. The AR5 concluded that there is *low confidence* in attributing the causes of the observed loss of mass from the West Antarctic Ice Sheet since 1993 due to a low level of scientific understanding [WG I Section 10.5.2].

More recently, Bamber et al. (2018) finds that sea level mass budget approach suggests a near balance overall for the Antarctic ice sheet. Estimates for the last decade indicate that mass loss from the West Antarctic Ice Sheet (WAIS) has been partly compensated for by gains from the East Antarctic Ice Sheet (EAIS). Early satellite imagery suggests that mass loss for part of the Amundsen Sea Embayment of West Antarctica began as early as the 1970s. It is possible, therefore, that recent regional trends (i.e. gains over the EAIS and losses in the WAIS) may have existed for decades prior to our ability to detect them.

The West Antarctic Ice Sheet (WAIS) contains slightly less than 10% of the total mass of the Antarctic ice sheets. The Western Antarctic Ice Sheet is classified as a marine ice sheet, meaning that its bed lies well below sea level – the weight of the ice has caused the underlying rock to sink by between 0.5 and 1 kilometer. Under the force of its own weight, the ice sheet deforms and flows over the bedrock. Rapid ice-stream flow is a poorly understood non-linear process, with streams starting and stopping for unclear reasons. When ice reaches the coast, it either breaks away or continues to flow outward onto the water, resulting in a floating ice shelf extending from the continent.

West Antarctic ice shelf break-up and disintegration events over the past 5 decades have led to speed-up, thinning, and retreat of upstream tributary glaciers and increases to rates of global sea-level rise. Since publication of the IPCC AR5, there has been a very rapid development in our understanding of the WAIS and its potential for collapse.

Kingslake et al. (2018) discovered that the West Antarctic Ice Sheet underwent a major retreat between 10,000 and 12,000 years ago, at the close of the last Ice Age. The retreat left the ice sheet 135,000 square miles smaller than its current size – but it did not collapse. Over the subsequent millennia, the ice loss spurred uplift in the sea floor (isostatic rebound), allowing the ice sheet to regrow toward today's configuration.

The Amundsen Sea Embankment is regarded as the most vulnerable regions of the WAIS. Jenkins et al. (2018) studied seawater temperatures in the Amundsen Sea and found a cycle of warming and cooling, with melt changing by a factor of 4 between cool and warm extremes over decadal time scales. This study demonstrates that discontinuous ice retreat linked with ocean variability is at present more influential than changes in the longer term mean state. The authors also show evidence for linking this cycle to El Niño in the tropical Pacific Ocean.

A recent paper by Barletta et al. (2018) found that the ground under the rapidly melting Amundsen Sea Embayment of West Antarctica is rising at the astonishingly rapid rate of 41 millimeters, or more than 4 cm, per year. This rise is acting to stabilize the WAIS.

Melting at the base of the ice sheet is a factor that was not described in the IPCC AR5. Subglacial lakes are present beneath the ice sheets. In the West Antarctic, there is evidence suggesting that sub-glacial meltwater production is influenced by an active volcanic geothermal heat source. The West Antarctic Ice Sheet lies atop a major volcanic rift system (Marcos et al., 2017). De Vries et al. (2017) identified 138 volcanoes that are widely distributed throughout West Antarctic. Loose et al. (2018) identified an active volcanic heat source beneath the Pine Island Glacier, which is the fastest moving and fastest melting glacier in Antarctica. While volcanic heat can be traced to dormant volcanoes, what the scientists found at Pine Island was new. The discovery of volcanoes beneath the Antarctic ice sheet means that there is an additional source of heat to melt the ice and lubricate its passage toward the sea. This newly discovered source of heat is having an as yet undetermined effect on the glacier mass balance.

The occurrence of surface melt in Antarctica has hitherto been associated with the austral summer season, when the dominant source of melt energy is provided by solar radiation. Munneke et al. (2018) used *in situ* and satellite observations to show that events of intense surface melt on Larsen C Ice Shelf occur frequently throughout the dark Antarctic winter, with peak intensities sometimes exceeding summertime values. These multiday melt events are driven by outbreaks of warm and dry föhn wind descending down the leeside of the Antarctic Peninsula mountain range. From 2015 to 2017, ~23% of the annual melt flux was produced during winter.

In summary, it is very difficult to make a credible argument that emissions of CO_2 have had any significant impact on the West Antarctic Ice Sheet to date. The recent mass balance of the West Antarctic Ice Sheet is dominated by the dynamics of glacier flow, glacial rebound processes, and ocean circulation variations.

4.2.3 Synthesis of land ice contribution to sea level during the satellite era

A recent review paper by Bamber et al. (2018) provides a synthesis of what is known about the land ice contribution to sea level during the satellite era. This study analyzed separately the contributions from the Greenland Ice Sheet, the West Antarctic Ice Sheet, the East Antarctic Ice sheet, and land glaciers. The key summary figure (Figure 4.5) shows substantial interannual variability, along with an overall trend of increasing mass loss.

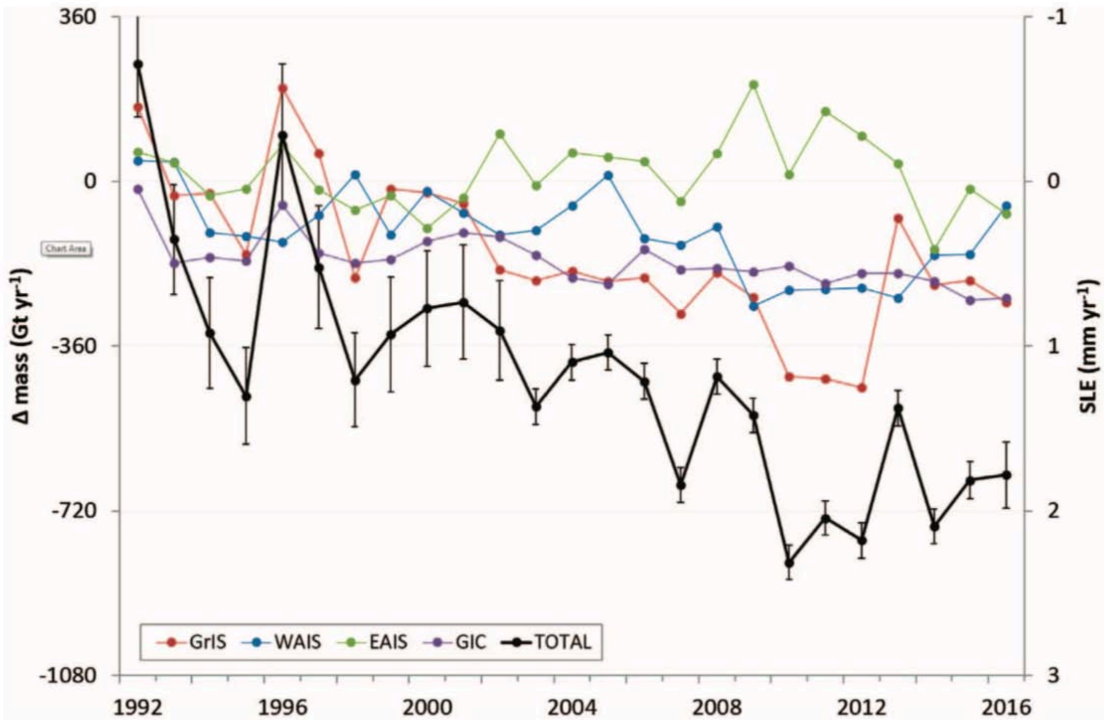

Figure 4.5: Annual time series of mass trends (sea level equivalent, SLE) for the Greenland Ice Sheet (GrIS), West Antarctic Ice Sheet (WAIS), East Antarctic Ice Sheet (EAIS), glaciers and ice caps (GIC). Bamber et al. (2018)

Bamber et al. found the contribution to sea level rise from land ice to increase from 0.31 ± 0.35 mm for 1992–1996 to 1.85 ± 0.13 mm for 2012–2016. Their updated analysis results in a reduction of 6 ± 1.1 mm compared to a recent sea level budget estimate of the land ice contribution for 2003– 2015 (Dieng et al., 2017), equivalent to a difference of 0.46 mm/year. To close the sea level rise budget, this smaller land ice contribution implies a positive contribution from land hydrology and/or the global isostatic adjustment, neither of which have anything to do with global warming.

While making a significant contribution to our understanding of land ice mass balance contributions to global sea level rise, the Bamber et al. paper highlights significant uncertainties in our ability to understand quantitatively the causes of sea level rise even during the satellite era.

4.3 Detection of recent sea level rise acceleration

In the context of climate change detection and attribution arguments, 'detection' is the process of demonstrating that some aspect of climate or its impacts has changed in some defined statistical sense, whereby its likelihood of occurrence by chance due to internal variability alone is determined to be small.

Natural, internal climate variability associated with ocean circulations introduces strong changes in regional sea level on timescales from years to decades (and even longer), making it very difficult to detect any signal from an increase in atmospheric CO_2 above the unforced internal variability. For example, sea level variability in the Pacific Ocean related to El Niño Southern Oscillation (ENSO) and to the Pacific Decadal Oscillation (PDO) is of the order of ±10–20 cm, which masks any sea level changes due to increasing CO_2 (e.g. Figure 2.2).

Even if the projections of future sea level rise are realized, detection research indicates that it will take decades before any anthropogenic signal is potentially detectable (e.g. Lyu et al., 2014; Jorda et al., 2014; Bilbao et al., 2015). In regions of high internal variability, the trend due to externally forced signal is masked during longer time spans than in regions of low internal variability. These 'Time of Emergence' analyses argue that we have not yet detected unusual sea level rise in any of the individual ocean basins.

Further complicating the detection of any human-caused signal on global sea level rise is the existence of a quasi-periodic 60-year signal in the sea level rise data that appears in every ocean basin (Chambers et al. 2012) – this is consistent with high rates of sea level rise observed during the 1940's and 1950's (Figure 3.5).

This complication was recognized by the IPCC AR5:

> "A long time-scale is needed because significant multidecadal variability appears in numerous tide gauge records during the 20th century. The multidecadal variability is marked by an increasing trend starting in 1910–1920, a downward trend (i.e., leveling of sea level if a long-term trend is not removed) starting around 1950, and an increasing trend starting around 1980." [IPCC AR5 WGI Chapter 3]

4.4 Attribution of recent sea level rise

The IPCC AR5 did not conduct a formal attribution analysis of global or regional sea level rise. Two papers (circa the AR5) came to opposite conclusions regarding the causes of recent sea level rise. Jevrejeva et al. (2009) used a statistical model that showed that human-caused warming was responsible for up to 70% of sea level rise since 1900. Gregory et al. (2013), on the other hand, stated:

> "The largest contribution to global mean sea level rise during the twentieth century was from glaciers, and its rate was no greater in the second half than in the first half of the century, despite the climatic warming during the century. Only

> thermal expansion shows a tendency for increasing rate as the magnitude of anthropogenic global climate change increases, and this tendency has been weakened by natural volcanic forcing. Greenland ice sheet contribution relates more to regional climate variability than to global climate change; and the residual, attributed to the Antarctic ice sheet, has no significant time dependence. The implication of our closure of the budget is that a relationship between global climate change and the rate of global mean sea level rise is weak or absent in the twentieth century. The lack of a strong relationship is consistent with the evidence from the tide gauge datasets, whose authors find acceleration of global mean sea level rise during the twentieth century to be either insignificant or small."

Recent attribution analyses of global mean sea level rise are summarized in a review paper authored by Marcos et al. (2016):

- Becker et al. (2014) concluded that the anthropogenic contribution to sea level rise during the twentieth century is more than **50%** of the observed global sea level rise rate, with a 99% confidence level.
- Dangendorf et al. (2015) concluded that it is virtually certain that at least 45% of the observed global sea level rise during the twentieth century is of anthropogenic origin, and extremely likely that it is at least 61% and very likely at least **68**%.
- Kopp et al. (2016) estimated the anthropogenic fraction as about **50%**.
- Slangen et al. (2016) found the anthropogenic forcing explains only 15 ± 55% of the observations before 1950, but increases to become the dominant contribution after 1970 (**69 ± 31%**), reaching 72 ± 39% in 2000 (**37 ± 38**% over the period 1900-2005).

Slangen et al. (2016) has reached a reasonable conclusion regarding the attribution of sea level rise to anthropogenic forcing: 37 ± 38% over the period 1900-2005. However the increasingly greater percentages cited since 1970 and 2000 by Slangen et al. reflect a disputed attribution of the recent Greenland melting to anthropogenic forcing, rather than to the 1995 shift to the warm phase of the Atlantic Multi-decadal Oscillation (Section 4.2.1).

4.5 Conclusions

Global mean sea level has been increasing since the mid-19th century. This increase is loosely associated with 'coming out of the Little Ice Age', caused by a combination of changes in external forcing from volcanoes and the sun and long-term ocean oscillations. The relatively slow emergence of fossil fuel emissions prior to 1950 did not contribute significantly to 19th and early 20th century sea level rise.

The recent acceleration in mean global sea level rise (since 1995) is driven by mass loss from Greenland, which appears to have been larger during the 1930's. The onset of the recent increase in mass loss from Greenland coincides with the shift of the Atlantic

Multidecadal Oscillation to its warm phase. This shift changed atmospheric circulation and cloudiness patterns, resulting in more solar warming of Greenland that causes increased summer melting.

There is substantial multi-decadal variability in the sea level change record, including an apparent 60-year oscillation. This variability confounds detection of sea level rise acceleration and its attribution to human-caused climate change. In view of the multiple modes and periods of internal variability in the ocean, it is likely that we have not yet detected the full scale of internal variability effects on regional and global sea level change.

In summary, no scientific consensus has been reached yet as to how a possible acceleration in sea level rise could be separated from internal climate variability. These challenges are well understood by the international community of sea level researchers. The World Climate Research Programme (WCRP) CLIVAR Grand Challenge on Regional Sea Level Change and Coastal Impacts (WCRP, 2017a) states:

> "Despite considerable progress during the last decade, major gaps remain in our understanding of past and contemporary sea level change and their causes. These uncertainties arise from limitations in our current conceptual understanding of relevant physical processes, deficiencies in our observing and monitoring systems, and inaccuracies in statistical and numerical modeling approaches to simulate or forecast sea level."

5. Projections of 21st century sea level rise

The concern about sea level rise is driven primarily by projections of future sea level rise. Projections of future sea level rise can be made in the following ways:

- Extrapolation of recent trends
- Semi-empirical approaches based on past relationships of sea level rise with temperature
- Process-based methods using models

The challenge in making 21st century projections is aptly summarized by oceanographer Walter Munk (2007):

> "We are in the uncomfortable position of extrapolating into the next century without understanding the last."

5.1 IPCC's 21st century projections

The IPCC's sea level rise projections are directly tied to projections of surface temperature, which are based upon simulations from global climate models; however global climate models do not directly predict sea level rise.

The climate model simulations of 21st century climate referenced in the IPCC AR5 are based on more than 30 different global climate models from international climate modeling groups. The climate models simulate changes based on a set of scenarios of human-caused forcings from changing atmospheric composition, primarily from fossil fuel emissions. 'Radiative forcing' is the difference between insolation (sunlight) absorbed by the Earth and the energy radiated by the Earth and its atmosphere back to space. Radiative forcings are influences that cause changes to Earth's climate system by altering the Earth's radiative equilibrium, forcing temperatures to rise or fall.

A new set of emissions scenarios, the Representative Concentration Pathways (RCPs), was used for the climate model simulations in the IPCC AR5. In all RCPs, atmospheric CO_2 concentrations are higher in 2100 relative to present day as a result of a further increase of cumulative emissions of CO_2 to the atmosphere during the 21st century. The four RCPs are named according to radiative forcing target level for 2100 (Table 5.1). The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents. The four selected RCPs include one mitigation scenario that leads to a very low forcing level (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6) and one very high baseline emission scenarios (RCP8.5).

Table 5.1: Overview of Representative Concentration Pathways (RCP). From van Vuuren et al. (2011).

	Description[a]
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100.
RCP6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).

RCP8.5 is sometimes referred to as a 'business as usual' scenario. It is not. Rather, it is an extreme scenario that may be impossible, given constraints on recoverable fossil fuel supply (e.g. Wang et al., 2016). Ritchie and Dowlatabadi (2017) explain that RCP8.5 contains a return to coal hypothesis, requiring increased per-capita coal use that is based on systematic errors in coal production outlooks. Ritchie and Dowlatabadi recommend that RCP8.5 should not be used as a benchmark for future scientific research or policy studies.

The IPCC AR5 projections of sea level rise are only partially based on the global climate model simulations [IPCC AR5 WG I, Section 13.5.1]:

- Thermal expansion associated with warming of the ocean is derived directly from the global climate model simulations.
- Changes in glacier and surface mass balance are calculated from regional models or empirical relationship between increase precipitation and increased temperature.
- Contributions from ice sheet dynamics are assessed from either ice sheet models and/or statistical projections.
- Projections of changes in land-water storage due to human intervention is assessed from the published literature and is treated as independent of emissions scenario.

Table 5.2 summarizes the IPCC AR5 global temperature and sea level rise projections for 2046-2065 and 2081-2100. The upper limit of the likely range of projected sea level rise for 2081-2100 for the extreme RCP8.5 emission scenario is 0.82 m [2.7 feet].

Table 5.2 Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century relative to the reference period of 1986-2005. [IPCC AR5 WG I Summary for Policy Makers Table SPM.2]

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range[c]**	**Mean**	***Likely* range[c]**
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range[d]**	**Mean**	***Likely* range[d]**
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

For each of the IPCC scenarios, thermal expansion is the largest contributor, accounting for about 30–55% of the projected sea level rise. Glaciers make the next largest contribution – by 2100, 15-55% of the present glacier volume is projected to disappear under RCP2.6, and 35-85% under RCP8.5. The Greenland ice sheet makes a positive contribution to sea level rise, whereas Antarctica gives a negative contribution. There is a relatively small positive contribution from human intervention in land-water storage, predominantly due to increasing extraction of groundwater. [IPCC AR5 WG I 13.5.1]

5.2 Climate model limitations

Sea level rise projections for the 21st century are only as valid as the climate model simulations upon which they are based. Chapters 11 and 12 of the IPCC AR5 describes uncertainties in the climate model-based projections:

> "Projections of future states of the global climate are subject to several sources of uncertainty. The first source of uncertainty arises from natural internal variability, which is intrinsic to the climate system, and includes phenomena such as variability in the mid-latitude storm tracks and the ENSO. The existence of internal variability places fundamental limits on the precision with which future climate variables can be projected. The second is uncertainty concerning the past, present and future forcing of the climate system by natural and anthropogenic forcing agents such as greenhouse gases, aerosols, solar forcing and land use change. The third is uncertainty related to the response of the climate system to the specified forcing agents, which is referred to as the 'climate sensitivity.'" [AR5 WG I Section 11.3.1.1]

> "Simplifications and the interactions between parameterized and resolved processes induce 'errors' in models, which can have a leading-order impact on projections. Also, current models may exclude some processes that could turn out to be important for projections) or produce a common error in the representation of a particular process." [AR5 WG I Section 12.2.3]

A key issue is to what extent model errors produce erroneous decision-relevant model outcomes. As an example of fundamental climate model error, consider the biases in global mean absolute surface temperatures as simulated by climate models (Figure 5.1). Temperatures of the coldest models are almost as close to temperatures of the Last Glacial Maximum as they are to observed 20th century temperatures. Further, average 21st century temperature changes under the RCP4.5 and RCP2.6 scenarios are within the modeled temperature range for the 20th century.

Temperatures simulated by global climate models are nearly always represented as anomalies from some historical baseline temperature (e.g. Figure 5.2) – it is argued that the modeled trend matters, not the absolute temperatures. However, biases in modeled temperatures (up to 2^{o}C) raise serious concerns about the ability of the model to simulate processes and feedbacks that are temperature dependent (e.g. cloud formation, surface evaporation, sea ice freezing/melting, glacier melting). These issues raise serious questions about the climate models' ability to reliably predict the sensitivity of the Earth's climate to increasing concentrations of CO_2.

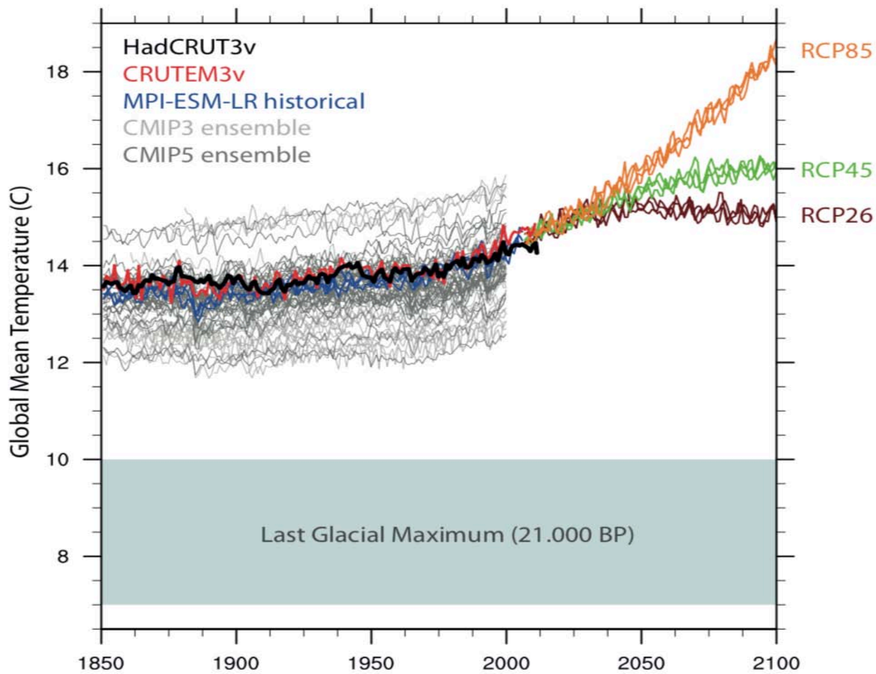

Figure 5.1. Absolute temperatures from climate model historical realizations and future scenarios. Black line is the HadCRUT3v blended land and ocean temperature dataset and red line is CRUTEM3v land-only temperatures. Blue lines are three historical realizations, while orange, green and brown are future RCP-scenario realizations with the MPI-ESM-LR model, and light gray lines are the first historical realization from each model found in the CMIP3 (for IPCC AR3) dataset and dark gray lines the corresponding CMIP5 (for IPCC AR5) historical realizations. (Mauritsen et al., 2013)

5.2.1 Are climate models trending too 'hot'?

The IPCC AR4 (2007) made the following projection for near term warming:

> "For the next two decades, a warming of about 0.2°C per decade is projected." [IPCC AR4 WG1 SPM, p 12] [Note: for the period 2011-2030]

At the time of the IPCC AR5 (2013), this rate of warming had not been realized, and there had been slowdown in warming during the period 1998-2012:

> "[T]he rate of warming over the past 15 years (1998–2012) of 0.05 [–0.05 to +0.15] °C per decade is smaller than the rate calculated since 1951 (1951–2012) of 0.12 [0.08 to 0.14] °C per decade." [IPCC AR5 SPM, p 5]

Figure 5.2 [IPCC AR5 WG I Figure 11.25] compares the near-term climate model temperature projections with observations.

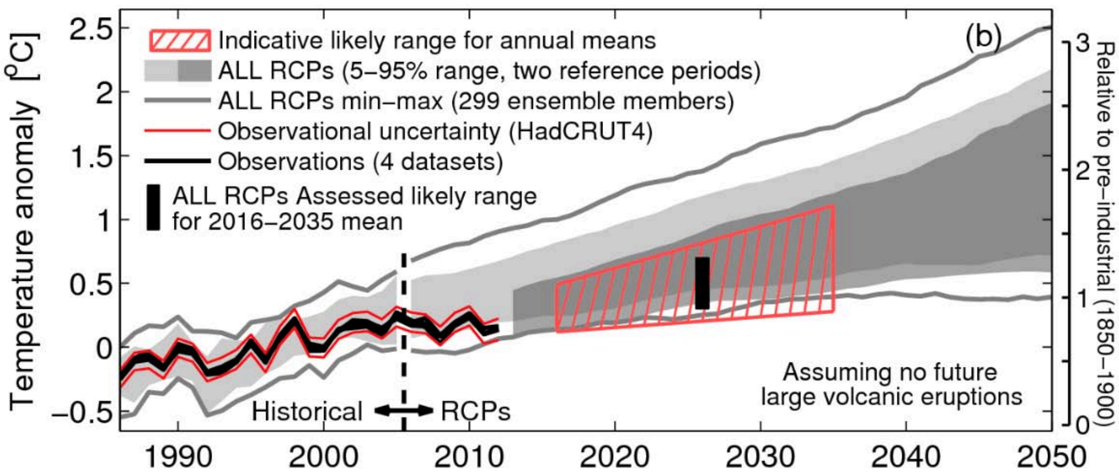

Figure 5.2 Synthesis of near-term projections of global mean surface air temperature (GMST). Simulations and projections of annual mean GMST 1986–2050 (anomalies relative to 1986–2005). Projections from climate models showing the 5 to 95% range using a reference period of 1986–2005 (light grey shade) and all RCPs using a reference period of 2006–2012, together with the observed anomaly for (2006–2012) to (1986–2005) of 0.16°C (dark grey shade). The maximum and minimum values from climate models using all ensemble members and the 1986–2005 reference period are shown by the grey lines (also smoothed). Black lines show annual mean observational estimates. The red-hatched region shows the indicative likely range for annual mean GMST during the period 2016–2035 based on the likely range for the 20-year mean GMST anomaly for 2016–2035. [IPCC AR5 WG I Figure 11.25]

The observed temperatures between 2000-2012 are at the bottom of the envelope of climate model simulations. The AR5 then made the following projection:

> "[I]t is likely (>66% probability) that the global mean surface temperature anomaly for the period 2016–2035 will be in the range 0.3°C to 0.7°C. [This range] is also consistent with the [climate model] 5 to 95% range for all four RCP scenarios of 0.36°C to 0.79°C, using the 2006–2012 reference period, after the upper and lower bounds are reduced by 10% to take into account the evidence that some models may be too sensitive to anthropogenic forcing." [IPCC AR5 WG1 Section 11.3.6.3]

The red hatching in Fig. 11.25 (Figure 5.2) reflects the judgment by the AR5 authors that lowers the projected warming out to 2035 relative to the climate model simulations. The AR5 concludes:

> "However, the implied rates of warming over the period from 1986–2005 to 2016–2035 are lower as a result of the hiatus: 0.10°C to 0.23°C per decade, suggesting the AR4 assessment was near the upper end of current expectations for this specific time interval." [IPCC AR5 WG1 Section 11.3.6.3]

The author of Figure 11.25 – Ed Hawkins of Reading University – provides an annual update. Figure 5.3 includes the global surface temperature data through 2017.

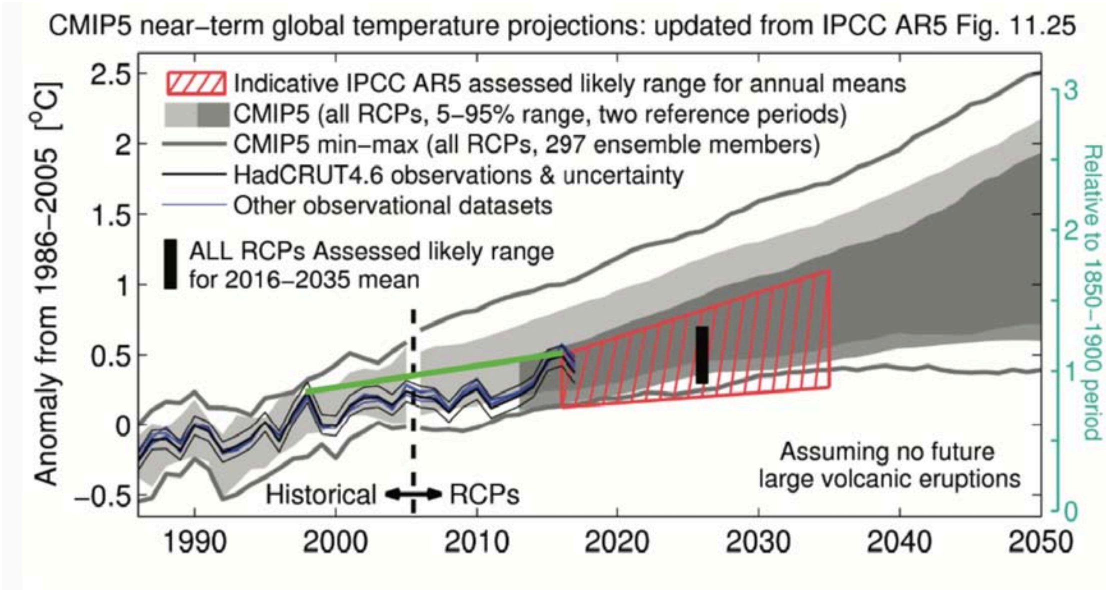

Figure 5.3. Following Figure 5.1, with surface temperature observations through 2017. Figure from Hawkins (2018) Added green line between 1998 and 2016 reflects the trend between two strong El Niño years.

The large El Niño of 2016 has returned the observed temperature curve to near the middle of the envelope of climate model simulations; however the previous large El Niño of 1998 was at the top of the envelope of climate model simulations. The recent data since 2012 continues to indicate that the sensitivity of at least some of the climate models to CO_2 forcing is too high.

A key issue is the uncertainty of sensitivity of climate models to CO_2. The equilibrium climate sensitivity (ECS) is a measure of the climate system response to sustained radiative forcing, defined as the amount of warming in response to a doubling of atmospheric CO_2.

For over thirty years, climate scientists have presented a *likely* range for ECS that has hardly changed. The ECS range of 1.5−4.5 ^{o}C in 1979 (Charney et al. 1979) is unchanged in the 2013 IPCC AR5. While previous assessments have provided a 'best estimate' of 3.0 ^{o}C, the AR5 did not provide a best estimate value for ECS, stating:

> "No best estimate for equilibrium climate sensitivity can now be given because *of a lack of agreement on values across assessed lines of evidence"*. [IPCC AR5 WG I Summary for Policymakers D.2]

At the heart of the uncertainty surrounding the values of ECS is the substantial difference between values derived from global climate models versus values derived from changes over the historical instrumental data record using global energy budget analyses. The median ECS given in IPCC AR5 for current generation atmosphere-ocean global climate models was 3.2 ^{o}C, versus 2.0 ^{o}C for the median values from historical-period energy budget based studies.

Subsequent to the IPCC AR5, Lewis and Curry (2015) used an observationally-based energy budget methodology using the AR5's global forcing and heat content estimate time series to derive a median ECS estimate of 1.6 ^{o}C, which makes the discrepancy with global climate models even larger. A recent update by Lewis and Curry (2018) with more recent data concluded that high estimates of ECS derived from a majority of global climate models are statistically inconsistent with observed warming during the historical period. Lewis and Curry further concluded that the observationally-constrained values of ECS imply 21st century warming under increased CO_2 forcing of only 55-70% of the mean warming simulated by global climate models.

The approach used by Lewis and Curry implicitly assumes that all warming since the mid 19th century has been caused by radiative forcing, with some account for the contribution of the Atlantic Multidecadal Oscillation. This approach neglects the possibility of warming from additional longer-term modes of ocean circulations. Hence, if such longer term modes of ocean circulations have contributed to warming since the mid-19th century, then the values of climate sensitivity estimated by Lewis and Curry would be too high. This implies the possibility of even lower levels of warming relative to what has been predicted by global climate models.

5.2.2 Constraints and assumptions for 21st century predictions

Apart from the uncertainties in the climate models described above, there are two overarching problems with these projections (Curry, 2018):

- The scenarios of future climate are incomplete, focusing only on emissions scenarios.
- The ensemble of climate models do not sample the full range of possible values of ECS, only covering the range 2.1 to 4.7 ^{o}C and neglecting values between 1 and 2.1 ^{o}C, with values between 1.5 and 2.1 ^{o}C being within the IPCC AR5 *likely* range.
- The opportunistic ensemble of climate model simulations used in the IPCC assessment reports does not provide the basis for the determination of statistically meaningful probabilities.

The IPCC AR5 acknowledges the constraints, assumptions, contingencies and uncertainties of their projections of future climate change:

> "With regard to solar forcing, the 1985–2005 solar cycle is repeated. Neither projections of future deviations from this solar cycle, nor future volcanic radiative forcing and their uncertainties are considered." [IPCC AR5 WG I Section 12.2.3]

> "Any climate projection is subject to sampling uncertainties that arise because of internal variability. [P]rediction of the amplitude or phase of some mode of variability that may be important on long time scales is not addressed." [IPCC AR5 WG I Section 12.2.3]

The climate model projections of 21st century surface temperature and sea level rise are therefore contingent on the following assumptions [IPCC AR5 WG1 Section12.2.3]:

1. Emissions follow the specified concentration pathways (RCP).
2. Climate models accurately predict the amount of warming in 21st century. [See section 5.2.1 for evidence that climate models are too sensitive to CO_2 and produce too much warming.]
3. Solar variability follows that of the late 20th century, which coincided with a Grand Solar Maximum.
4. Natural internal variability of ocean circulations does not impact temperature or sea level rise on these timescales.
5. Major volcanic eruptions are not considered.

Each of these contingent assumptions, with the possible exception of natural internal variability, most likely contributes to a warm bias in the 21st century climate model projections.

5.3 Worst-case sea level rise scenarios

The worst-case scenario clarifies the upper bound of possible scenarios. The worst-case scenario is judged to be the most extreme scenario that cannot be falsified as impossible based upon our background knowledge (e.g. Betz et al., 2010).

It is estimated that fully melting Antarctica would contribute about 60 meters [197 feet] of sea level rise, and Greenland would contribute more than 7 meters [23 feet], with an additional 0.5 meters [1.6 feet] of sea level rise from glaciers. How much of this melt is potentially realizable in the 21st century?

The primary concern over future sea level rise in the 21st century is related to the potential collapse of the West Antarctic Ice Sheet, which could cause global mean sea level to rise substantially above the IPCC's 'likely' range. The IPCC AR5 has medium confidence that this additional contribution from the West Antarctic ice sheet would not exceed several tenths of a meter of sea level rise during the 21st century [IPCC AR5 WG1 Chapter 13].

Subsequent to the IPCC AR5 (2013), there has been considerable focus on the worst-case scenario for global sea level rise, and our 'background knowledge' is rapidly changing. Worst-case scenarios for 2100 are driven by the RCP8.5 emissions scenario, and are associated with collapse of the West Antarctic Ice Sheet.

The West Antarctic Ice Sheet rests on bedrock below sea level, making the ice sheet vulnerable to melting from the ocean. If these marine ice shelves – the floating extensions of glacial ice flowing into the ocean – lose mass, their buttressing capacity is reduced, accelerating seaward ice flow. This self-sustaining process is known as Marine Ice Sheet Instability (MISI). There is increasing evidence that accelerated retreat may be underway in several major Amundsen Sea outlets in West Antarctica, (e.g., Rignot et al., 2014) supporting the MISI hypothesis. The disappearance of ice shelves allows formation of ice cliffs, which may be inherently unstable if they are tall enough to generate stresses that exceed the strength of the ice. This ice cliff failure can lead to ice sheet retreat via a process called marine ice cliff instability (MICI), that has been hypothesized to cause partial collapse of the West Antarctic Ice Sheet within a few centuries (DeConto and Pollard, 2016).

Recent estimates of the worst-case scenario for global sea level rise in the 21st century range from 1.6 to 5 meters [5 – 16.4 feet] (see LeCozannet et al, 2017 for an overview), with the recent NOAA Report (NOAA, 2017) using a value of 2.5 meters [8.2 feet]. The highest of these values of sea level rise imply rates of sea level rise of almost 100 mm/year [4 inches/year] by the end of the 21st century. For reference, the current global rate of sea level rise is about 3 mm/year.

Are these scenarios of sea level rise by 2100 plausible? Or even possible?

From the IPCC AR5:

> "These high rates are sustainable only when the Earth is emerging from periods of extreme glaciation. During the transition of the last glacial maximum about 21,000 years ago to the present interglacial . . . coral reef deposits indicate that global sea level rose abruptly by 14 to 18 meters in less than 500 years, in which the rate of sea level rise reached more than 40 mm/year." [AR5 WG1 FAQ 5.2]

Rohling et al. (2013) provide a geologic/paleoclimatic perspective on the worst-case scenario for 21st century sea level rise. These high projected rates of sea level rise are larger than the rates at the onset of the last deglaciation, even though today's global ice volume is only about a third of that at the onset of the last deglaciation. Starting from present-day conditions, such high rates of sea level rise would require unprecedented ice-loss mechanisms, such as collapse the West Antarctic Ice Sheet or activation of major East Antarctic Ice Sheet retreat.

Bamber and Aspinall (2013) conducted an expert elicitation from 26 experts regarding the assessment of 21st century sea level rise from the ice sheets. The study found a median estimate of 29 cm, with the 95th percentile value of 84 cm. On the critical question of whether recent ice-sheet behaviour is due to variability in the ice sheet–climate system or reflects a long-term trend, expert opinion is shown to be both very uncertain and undecided. The paper concluded with this statement:

> "We find an overwhelming lack of certainty about the crucial issue of the origin of recent accelerated mass loss from the ice sheets. Without a clearer understanding of the role and importance of internal variability in ice sheet–climate behaviour, predictions based on numerical modelling or extrapolation of observed trends are compromised."

Ritz et al. (2015) provide an analysis of the worst-case scenarios from West Antarctic ice sheet instability, using a numerical ice sheet model supplemented by statistical modelling of the probability of marine ice sheet instability onset. Of particular concern is instability that may be underway throughout the Amundsen Sea Embayment (ASE), which contains ice equivalent to more than a meter of global sea level rise. Ritz et al. project that the West Antarctic ice sheet will contribute up to 30 cm sea level equivalent by 2100, where the ASE dominates. Their assessment suggests upper bound estimates from low-resolution models and physical arguments (0.5-1.0 m sea level equivalent by 2100) are implausible under current understanding of physical mechanisms and potential triggers.

Improvements to ice sheet models are providing new insights. DeConte and Pollard (2016) used a model coupling ice sheet and climate dynamics that linked atmospheric warming with hydrofracturing of buttressing ice shelves and structural collapse of marine-terminating ice cliffs. Their calculations showed that Antarctica has the potential to contribute more than a meter of sea-level rise by 2100. In addition to ocean-driven buttressing of the ice shelves from below, melting on ice-shelf surfaces can cause thinning by percolation of the meltwater, which upon refreezing reduces the ice sheet viscosity and speeds its flow, also influencing crevassing and calving rates (hydrofracturing). Given enough atmospheric warming from above or ocean warming from below, cliff faces can collapse.

The Larsen C and George VI ice shelves are regarded as the most vulnerable for future break up events. Using numerical ice sheet models, Schannwell et al. (2018) found the centennial sea-level commitment of Larsen C embayment glaciers following immediate shelf collapse is low (< 2.5 mm to 2100). The response of inland glaciers to a collapse of the George VI Ice Shelf may add up to 8 mm [0.3 inch] to global sea levels by 2100 due in part to the mechanism of marine ice sheet instability.

While on the subject of worst-case scenarios of sea level rise, we should not ignore potential geologic 'wild cards.' In the more likely category of geologic impacts on the time scale of the 21st century is geothermal heat flux in the vicinity of the Greenland and Antarctic ice sheets. A partial collapse of the West Antarctic Ice Sheet during the 21st century is not impossible, but if this extremely unlikely event were to occur, it may be more likely to be caused by a geologic event than by greenhouse gas emissions. However, it is impossible to assign probabilities to such unprecedented wild card events, and they are regarded as extremely unlikely.

In summary, Kopp et al (2017) state that the response of polar ice sheets to forcing remains an area of 'ambiguity' and 'deep uncertainty'.

5.4 Best case sea level rise scenarios

There has been much less focus on the possible best-case scenario, which is defined as the lowest sea level rise for the 21st century that cannot be falsified as impossible based upon our background knowledge. Why bother with the best-case scenario, when it is clearly not relevant for decision making that is driven by worst-case, 'black swan' events? Consideration of the best case is needed to provide bounds on future sea level rise. Further, verification/falsification analysis of the best case can provide important insights into uncertainty and the possible impacts of neglected processes.

Parris (2012) recommended a lower bound of 0.2 m [8 inches] for 21st century global mean sea level rise, which is basically the observed rate of sea level rise during the 20th century. NOAA (2017) recommends that this value be revised upward to 0.3 m [12 inches]. The primary reason for this revision is that the global mean sea level rise rate as measured by satellite altimeters has averaged 3 mm/year for almost a quarter-century.

NOAA's assessment of the lower bound of possible sea level rise for the 21st century explicitly assumes that all future sea level rise is caused by CO_2 emissions. Figure 4.1 shows that global sea levels were rising steadily long before fossil fuel emissions became substantial. Since CO_2 emissions from fossil fuels did not become substantially large until after 1950, understanding the causes of recent sea level rise is clearly more complex than a simple attribution to increasing levels of atmospheric CO_2, revealing the existence of additional processes.

It is difficult to defend an argument that it is impossible for the 21st century sea level rise to occur at the same average rate as observed in the 20th century, especially since many if not most individual tide gauge records show no recent acceleration in sea level rise.

Is it possible for global sea level to *decrease* over the 21st century? Looking at the paleoclimate record, Kemp et al. (2018) have provided an estimate mean global sea level for the past 3000 years. There are several periods with substantial rates of sea level decline, notably 1000 to 1150 AD and 700 to 400 BC. While it is difficult to resolve century-scale variations in mean global sea level change from the paleo data set, sea level decreases of the magnitude determined by Kemp et al. (about half the magnitude of the 20th century rate)[5] are not sufficient to completely counter the projected sea level rise from human caused global warming. Given the thermal inertia present in the oceans and ice sheets, it is arguably impossible for sea level rise to decrease on the time scale of the 21st century.

However, it is arguably possible for 21st century sea level rise to be less than in the 20th century. Possible scenarios of solar variations, volcanic eruptions and internal variability associated with large-scale ocean circulations could combine to reduce the rate of 21st century sea level rise. The relative importance to sea level change of human-caused warming versus natural climate variability depends on whether equilibrium climate sensitivity is on low end of the range (1 to 2 ^{o}C) or the high end (>4 ^{o}C) of current estimates.

A future transition to the cool phase of the Atlantic Multidecaadal Oscillation (AMO) and/or positive phase of the North Atlantic Oscillation (NAO) would slow down (or possibly even reverse) the mass loss from Greenland, and hence slow down the rate of global sea level rise. We have seen such a scenario recently during the 1970's and 1980's (Fettweis et al, 2013). The implications of such a scenario in the 21st century would significantly reduce sea level rise potentially for many decades, with the relative

importance of this scenario for Greenland depending on whether equilibrium climate sensitivity to CO_2 is on low end of the range or the high end of current estimates.
An additional best-case scenario relates to the recent finding by Barletta et al. (2018) that the ground under the rapidly melting Amundsen Sea Embayment of West Antarctica is rising at a rate of more than 4 cm per year. This rise is acting to stabilize the West Antarctic Ice Sheet. Ice loss spurs uplift in the sea floor (isostatic rebound), which is occurring rapidly owing to low viscosity under the Amundsen Sea Embayment. Such processes have a strong direct impact on WAIS evolution at the centennial time scale. Gomez et al. (2015) articulate a negative feedback process whereby the combination of bedrock uplift and sea surface drop associated with ice sheet retreat significantly reduces ice sheet mass loss.

5.5 Recent projections of global sea level rise

Since the IPCC AR5 was published in 2013, new scenario and probabilistic approaches have been used for 21st century sea level rise projections. However, these new projections are based on the same climate model simulations that were used in the IPCC AR5.

Horton et al. (2014) report on an expert elicitation of 90 experts actively publishing on sea level, regarding their expectations for sea level change by 2100. For a scenario that limits warming to <2^{o}C above pre-industrial temperatures, the median 'likely' range provided by the experts is 0.4 to 0.6 m. For the high warming scenario of 4.5 ^{o}C by 2100, the median likely ranges are 0.7 to 1.2 m by 2100. However, 5 of the 90 respondents cited a value exceeding 3 m, with the highest value exceeding 6 m.

The U.S. Climate Science Special Report (CCSR, 2017) provides the following projections regarding global mean sea level rise by 2100: relative to the year 2000, GMSL is *very likely* to rise by 1.0–4.3 feet (30–130 cm) by 2100 (very high confidence in lower bound; low confidence in upper bound).

In 2017, the U.S. National Oceanic and Atmospheric Administration (NOAA) published a Technical Report entitled *Global and Regional Sea Level Rise Scenarios for the United States* (NOAA, 2017) that bounds the set of global mean sea level rise scenarios for the year 2100. They use an 'extreme' upper-bound scenario for global sea level rise of 2.5 meters [8 feet] by the year 2100. They also revised estimates of the lower bound upward from 0.2 meters to 0.3 meters [8 inches to 12 inches] by the year 2100.

Table 5.3 from the NOAA (2017) Report provides probabilities of the global mean sea level exceeding each sea level rise scenario for each of three emissions scenarios (RCPs). Scenarios exceeding 1.5 meters [4.9 feet] of sea level rise in the 21st century have a probability of less than 1% for RCP4.5.

Table 5.3: Probability of exceeding global mean sea level (median value) scenarios in 2100 (NOAA 2017).

GMSL rise Scenario	RCP2.6	RCP4.5	RCP8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%

In assessing the credibility of these scenarios, it is instructive to consider the rates of sea level rise associated with these scenarios (Table 5.4). The scenarios are anchored in year 2000 (i.e., a 1991–2009 epoch). Consideration of the rates in 2010 for all but the Low and Intermediate-Low scenarios shows rates that are higher than what has been observed during the decades surrounding 2010, seemingly falsifying the higher scenarios. However, DeConte and Pollard (2016) point out that ice sheet mass loss may not change linearly and could transition to the higher scenarios later in the century, so current sea-level observations cannot exclude future extreme outcomes.

Table 5.4: Rise rates (in millimeters per year for 19-year averages centered on decade) associated with the median GMSL scenario heights this century (NOAA 2017).

GMSL Scenario Rates (mm/year)	2010	2020	2030	2040	2050	2060	2070	2080	2090
Low	3	3	3	3	3	3	3	3	3
Intermediate-Low	4	5	5	5	5	5	5	5	5
Intermediate	5	6	7	9	10	12	13	14	15
Intermediate-High	5	7	10	13	15	18	20	22	24
High	6	8	13	16	20	24	28	31	35
Extreme	6	10	15	20	25	30	35	40	44

The rates of sea level rise for 2050, which is only three decades into the future, imply a near doubling to 8-fold increase of the rates of sea level rise relative to the early 21st century. The Extreme scenario cites a rate of sea level rise for 2090 of 44 mm/year, higher than any sustained values reached during the peak of the deglaciation. Given the relatively low value of sea level rise thus far in the 21st century, achieving the Extreme value of sea level rise would require even greater rates of sea level rise in the 2nd half of the 21st century than shown in Table 5.4.

Such estimates of extreme sea level rise by 2100 require something truly extraordinary and unprecedented to happen, in response to a projected increase in atmospheric CO_2. These extreme rates of sea level rise seem implausible, and may be regarded as impossible based upon our background knowledge. The upper bound, worst-case scenario remains a topic of deep uncertainty and active research.

5.6 Confidence, uncertainty, and decision-support relevance of climate model predictions

The projections of 21^{st} century sea level rise are ultimately derived from global temperature projections by the global climate models. IPCC Fourth Assessment Report provided the following conclusion about climate models:

> "There is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above." [IPCC AR4 Chapter 8, p. 600]

Is this level of confidence in climate model projections justified? Given the complexity of the Earth climate system, the foundational basis for the knowledge claims made based on global climate models warrants greater scrutiny (e.g. Loehle, 2018; Curry 2018).

Attempts to assess climate model adequacy through comparing their outputs with observed data is fraught with challenges: inadequacy of data, selection of variables to confirm and on which time and space scales, a vast and multi-dimensional parameter space to be explored, model initialization and internal variability, and concerns about circularity with regards to data used in both model tuning and confirmation.

Parker (2009) argues that known climate model error is too pervasive to allow climate model confirmation to be of use (e.g. Figure 5.1). Parker (2011) contends that robustness (how well models agree with each other) does not objectively increase confidence in simulations of future climate change. Assessing climate model coherence with background knowledge is limited because of empirical parameterizations (and model 'tuning') and because model complexity and analytic impenetrability precludes the precise evaluation of the location of parameter(s) that are producing the prediction error.

Assessing the adequacy of climate models for the purpose of predicting future climate is particularly difficult and arguably impossible. It is often assumed that if climate models reproduce current and past climates reasonably well, then we can have confidence in future predictions. However, any agreement with observations may to a substantial degree be due to tuning (calibration) rather than to the model structural form. Further, the models may lack representations of processes and feedbacks that would significantly influence future climate change. Hence, reliably reproducing past and present climate is not a sufficient condition for a model to be adequate for long-term projections, particularly for high-forcing scenarios that are well outside those previously observed in the instrumental record.

Curry (2018) argues that 21^{st} century climate projections are characterized by 'deep uncertainty.' Deep uncertainty implies that the scientific basis for developing outcomes (scenarios) is weak; future outcomes lie outside of the realm of regular or quantifiable expectations. Apart from the issue of unknown future greenhouse gas emissions and uncertainties associated with equilibrium climate sensitivity to CO_2 (described in Section 5.2.1), we have very little basis for developing future scenarios of solar variation, volcanic eruptions and long-term internal climate variability associated with ocean circulations. The likelihood of unanticipated climate outcomes (surprises) needs to be acknowledged.

Given the inadequacies of current climate models and the deep uncertainty surrounding 21st century projections, how should we interpret the multi-model ensemble simulations of the 21st century climate used in the IPCC assessment reports? Curry and Webster (2011) summarize concerns about using probabilities from the ensemble of climate models. Current climate model ensembles are not designed to sample uncertainty in a thorough or strategic way. Stainforth et al. (2007) argue that model inadequacy and an inadequate number of simulations in the ensemble preclude producing meaningful probabilities from the frequency of model outcomes of future climate.

While climate models continue to be used by climate scientists to increase understanding about how the climate system works, they are also playing a central role in developing international, national and local policies. There is a gap between what climate scientists can provide versus the information desired by policy makers. Both climate scientists and policy makers need to accept the limits of probabilistic methods in conditions of ambiguity and deep uncertainty that characterize climate change. Encouraging overconfidence in the realism of current climate model simulations and sea level rise projections can lead to undesirable policy outcomes.

5.7 Conclusions

The issue with sea level rise projections is whether they are credible, based upon our background understanding of the myriad and complex processes that determine sea level change and the limitations of climate models. The idea of CO_2 emissions as a 'control knob' for sea level rise (e.g. Hansen et al. 2016) is not supported by the evidence, as explained in Chapter 4.

Emissions scenario choice exerts a great deal of influence on predicted sea level rise after 2050. Horton et al. (2018) provide the following summary assessment of sea level rise forecasts. Given that RCP8.5 has been judged to be extremely unlikely, if not impossible, values are shown here only for the RCP2.6 and RCP4.0 scenarios:

- median projections range from 0.4 to 0.9 m [15.7 to 35.4 inches]
- very likely range (5-95%) is 0.2–1.6 m [7.9 inches to 5 feet]

Based on the arguments presented here, the following ranges of 21st century sea level rise predictions are classified in terms of strength of the knowledge base, contingent on the climate model temperature projections being correct:

- >0.18 to 0.51 cm [7 inches to 1.67 feet]: Well justified. This is the AR4 'likely' range for all scenarios except for the most extreme scenario. These estimates are based on well-understood and quantified physical processes.
- >0.51 cm to 1 m [1.67 to 3.3 feet] Possible, based on growing understanding of ice sheet dynamics, but associated with substantial quantitative uncertainty.

- >1 to 1.6 m: [3.3 to 5.2 feet] Possible but weakly justified, including poorly understood processes such as marine ice cliff instability
- >1.6 m to 2.5 m: [5.2 to 8.2 feet] Borderline impossible, requiring a cascade of extremely unlikely events.
- >2.5 m [8.2 feet]: Impossible. Relies on RCP8.5 and a cascade of poorly understood extreme events.

The predictions of 21st century sea level rise reported by Horton et al. (2018) will be too high if climate models are predicting too much warming. Reasons for thinking that climate models are predicting too much warming were summarized to include:

- Observed warming for the past two decades is less than the average rate of warming predicted by climate models.
- The ensemble of climate models do not sample the full range of possible values of equilibrium climate sensitivity, only covering the range 2.1 to 4.7 ^{o}C and neglecting the lowest 20% of the likely range from the IPCC AR5.
- The scenarios of future climate neglect future scenarios of solar variability, volcanic eruptions and multi-decadal and longer-term internal variability, arguably result in producing too much warming in the 21st century.

As an example of a scenario not included in these projections: A future transition to the cool phase of the AMO and/or positive phase of the NAO would slow down (or possibly even reverse) the mass loss from Greenland, and hence slow down the rate of global sea level rise. The relative importance of this scenario for Greenland depends on whether equilibrium climate sensitivity to CO_2 is on low end of the range or the high end of current estimates.

The challenges of projecting future climate change and sea level rise are well-recognized by the international community of climate and sea level researchers, as summarized in the World Climate Research Programme (WCRP) Grand Challenges. The WCRP Grand Challenge on Clouds, Circulation and Climate Sensitivity (WCRP, 2017c) states:

> "The spread of climate sensitivity estimates is unacceptably large, mostly as a result of uncertain changes in clouds. The cloud problem contributes to an inability to usefully constrain the upper bound, and the relative reliability, of differing estimates of climate sensitivity."

> "Long-standing model biases limit the reliability of climate model predictions/ projections on all time and space scales. But model development is hindered by a lack of understanding of how a poor representation of cloud-scale processes and cloud scale dynamics contribute to model biases in the large-scale circulation features and influence future projections."

The WCRP Grand Challenge on Regional Sea Level Rise (WCRP, 2017a) states:

> "A significant part of this large uncertainty arises from inappropriate (or sometimes missing) model representations of some physical processes that affect sea level and needs to be reduced for more accurate sea level projections."
>
> "Projections on multi-decadal timescales by ocean and ice sheet models currently exhibit substantial uncertainty."
>
> "Improved sea level predictions/projections, particularly over the next decades, are critically dependent on understanding observed natural variability, accurately reproducing it in models, and mapping its future behavior under climate change."

The WCRP Grand Challenges on Glaciers/Ice Sheets (WCRP, 2017d) states:

> "Complex and in many cases poorly understood processes, specific to the cryosphere, contribute significantly to the challenge that high latitudes pose from the viewpoint of physically-based climate modelling and prediction."

The bottom line is that sea level will continue to rise in the 21st century, probably at a rate that equals or exceeds the 7-8 inches observed in the 20th century. The sea level rise scenarios presented by IPCC/NOAA are arguably possible (whether extreme scenarios above 2 m are possible is debatable), but probabilities cannot be meaningfully provided for these scenarios (e.g. Curry, 2018).

And what about the wildcard events, such as collapse of the West Antarctic Ice Sheet or some major geological event? They are wildcards and extremely unlikely; the West Antarctic Ice Sheet is arguably more likely to destabilize or collapse in the 21st century from geologic events than it is from any change to the climate.

Kopp et al. (2017) state:

> "The breadth of published projections, as well as of remaining structural uncertainties, highlight the fact that future sea-level rise remains an arena of deep uncertainty."

6. U.S. coastal sea level rise

Observed and predicted rates of mean global sea level rise may have little relevance for specific locations. Pietrafesa et al. (2016) describes the rich spectrum of signals that determine local sea level rise. Pietrafesa et al. articulates the problems for local communities trying to apply global scale sea level predictions to locations experiencing much more complex trends.

To make credible predictions of local sea level rise, all of the local causes of sea level change and variations need to be understood. At the 2017 *Conference on Regional Sea-level Changes and Coastal Impacts*, Kathleen White of the U.S. Army Corps of Engineers made the following statement:

> "If we only look at the problem starting with just the climate signal, then it leads down a different path than if we look at components of sea level rise that are important to decision-makers."[6]

6.1 Overview of local sea level change

An overview of sea level rise along U.S. coasts is provided by Figure 6.1 from NOAA. In Canada and Alaska (and also northern Washington), sea level is actually decreasing, owing to uplift from glacial rebound. Most of the Pacific coast has rates of sea level rise of 0 to 3 mm/year (green arrows). The largest rates of sea level rise are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

Note that the majority of the locations have sea level trend values that are less than the 3 mm/year (light green arrows) cited as the current rate of global mean sea level rise derived from satellite observations. Recall from Chapter 2 the differences between relative local sea level change versus eustatic mean global sea level change (associated with the value 3 mm/year). Eustatic values of sea level change include corrections for vertical land motion and glacial isostatic adjustment associated with changing size of the ocean basins.

Houston and Dean (2011) analyzed 57 U.S. tide gauges that had record lengths of at least 60 years (through 2010). Their analysis did not indicate acceleration in sea level in U.S. tide gauge records during the 20th century. The data show small decelerations on average, with 30 gauge records showing deceleration and 27 showing acceleration.

Watson (2016) analyzed U.S. sea level records (through 2014), using the Singular Spectrum Analysis (SSA) time series analysis method. Watson concluded that at the 95% confidence level, no consistent or substantial evidence (yet) exists that recent rates of sea level rise are higher or abnormal in the context of the available historical records.

Specific cities considered in the sections below include 5 of the global cities ranked by Hallegate et al. (2013) as being at greatest risk from sea level rise – Miami, New York, New Orleans, Tampa-St. Petersburg and Baltimore.

[6] http://sciencedocbox.com/Geology/74213642-Conference-report-regional-sea-level-changes-and-coastal-impacts-july-2017-new-york-usa.html

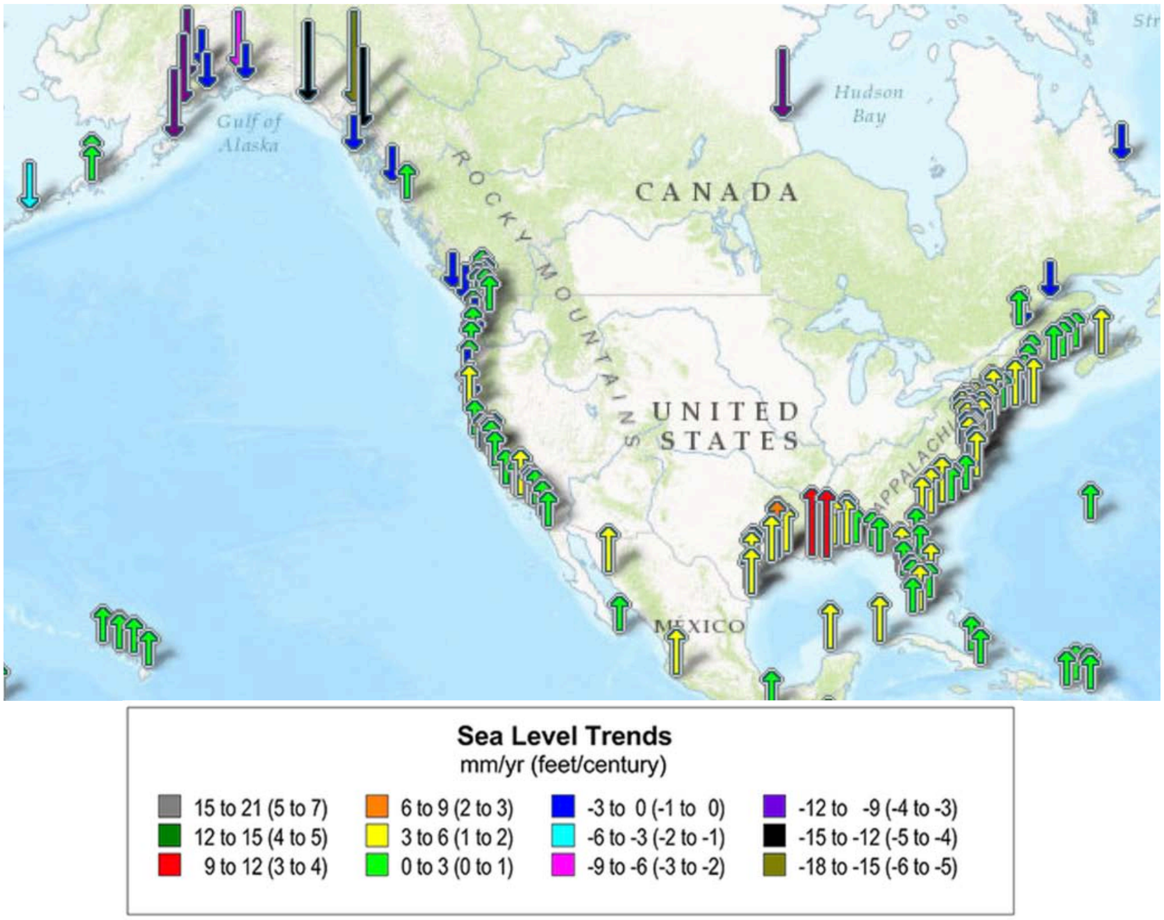

Figure 6.1. Map of rates of sea level rise along the U.S. coast (NOAA, https://tidesandcurrents.noaa.gov/sltrends/)

6.2 Vertical land motion

Measurements of relative sea level rise conflate the rise in the volume of seawater with local vertical land motion. Hence in examining local sea level changes, it is important to also consider the local vertical land motion. Absolute local sea level rise is the sum of relative sea level rise and the local vertical land motion.

As summarized by Woppelman and Marcos (2016), a wide range of processes can cause vertical land motion along the coasts, having amplitudes comparable to the sea level signals expected from land-ice melting or ocean thermal expansion. Vertical land motion on the coasts can locally exacerbate (subsidence) or mitigate (uplift) the risk of sea level rise. Local changes in sea level vary considerably from place to place and can deviate substantially from the rate of global mean sea level change.

Sea level change that is observed with respect to a land-based reference frame is defined as relative sea level (RSL) change. Most of the processes that can cause RSL changes are not related to climatic causes (Figure 6.2) and can act over a large span of spatial and temporal scales. The focus here is on processes that change RSL on timescales of a century or less.

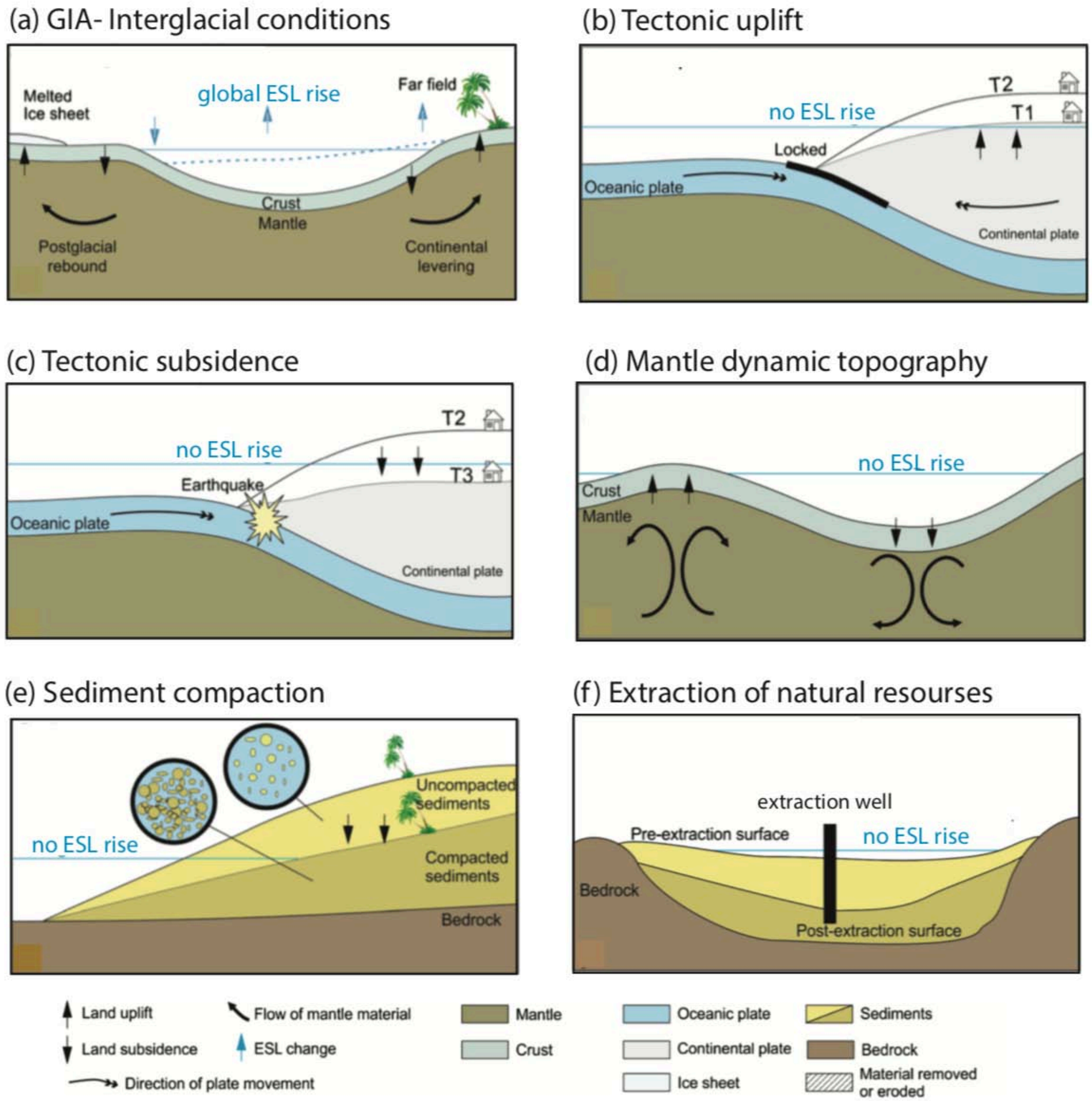

Figure 6.2. Processes contributing to relative sea level changes. a) glacial isostatic adjustment (GIA) and redistribution of water masses following ice sheet melting; b) seismic-related uplift; c) seismic-related subsidence along a subduction thrust fault; d) mantle dynamic topography causing RSL rise (crustal subsidence) in case of divergent mantle flow movements, and RSL fall (crustal uplift) in case of converging mantle flow movements; e) sediment compaction causing RSL rise; f) RSL change caused by extraction of natural resources (e.g. groundwater). ESL: eustatic sea level. After Rovere et al. (2016).

Tectonic uplift or subsidence is one of the primary causes of RSL changes (Figure 6.2 a,b,c). A shoreline moving upwards or downwards due to the presence of systems of geologic faults can experience a RSL fall or rise. Mantle dynamic topography is caused by mantle flow that drives significant vertical motions of the crust (Fig. 2d). Sediments deposited in a coastal area can be subject, through time, to loss of volume that causes subsidence and therefore a RSL rise. Mechanical (e.g. consolidation of sediments), biological (e.g. biochemical degradation) and human-driven (e.g. land drainage) processes can cause or accelerate sediment compaction. Figure 2e shows how RSL fall is caused by sediment progressively losing its porosity and expelling interstitial water due to the effects of loading of younger sediments. Subsidence due to sediment compaction is a major driver of current RSL rise in many regions.

Human activities triggering subsidence are soil drainage (e.g. for urban development purposes) or subsurface mining of resources such as groundwater, oil or gas (Figure 2f). As summarized by Rovere et al., the magnitude of relative sea level rise caused by human activities is often considerable. In coastal cities of Indonesia, for example, natural gas and groundwater extractions contribute to subsidence rates up to 22 cm/year.

The development of Earth models to predict postglacial rebound enabled the prediction of vertical land motion at coarse spatial scales. However, these models do not include the other processes shown in Figure 6.2, which have relatively short spatial scales. Local vertical land motion of relevance to local sea level change is best measured using a Global Positioning System (GPS) station. GPS began to be used to adjust tide gage data for vertical land motion around 1997. Data sets of continuous GPS observations are still relatively short compared to tide gauge records, and there are many tide gauges that do not have collocated GPS. This introduces an additional source of uncertainty as to how representative the GPS estimates of recent vertical land motion are of long-term land motion at tide gauges. The working hypothesis is that vertical land motion occurred at a steady rate over the decades to century timescales in which the tide gauge was operational and that it is continuing at the same steady rate over the GPS period. This issue becomes a concern especially for areas affected by geologic processes or local ground deformation such as settling of landfill or underground fluid extraction.

6.2.1 U.S. west coast

Several published GPS solutions are available for estimating west coast vertical land motions, each of which uses a different number of stations, timespan, and/or processing software. A comprehensive analysis of west coast sea level rise, including vertical land motion, is provided by NAS (2012). The analysis determined rates of historical sea-level change along the California, Oregon, and Washington coasts using 12 tide gages.

Montillet et al. (2017) constructed coastal Pacific Northwest profiles of vertical land motion (VLM) at 47 coastal stations. The analysis shows that VLM varies regionally but smoothly along the Pacific coast and inland Puget Sound with rates ranging from +4.9 to −1.2 mm/year. Uplift rates of 4.5 mm/year persist along the western Olympic Peninsula of northwestern Washington State and decrease southwards.

Shirzaei and Burgmann (2018) conducted a comprehensive analysis of vertical land motion in the San Francisco Bay area. Most of the Pacific shorelines and areas adjacent to the San Francisco Bay are subject to subsidence at less than ~2 mm/year. Portions of Treasure Island, San Francisco, San Francisco International Airport, and Foster City are subsiding as fast as 10 mm/year. Santa Clara Valley to the south of the Bay is characterized by uplift at 1 to 2 mm/year, likely due to rising ground-water levels during this period. Most of the subsiding areas are located on mud deposits or man-made landfills subject to long-term compaction.

Howell et al. (2016) found that much of the Los Angeles Basin, Orange County, San Diego County and the Bakersfield area are sinking 2 to 3 millimeters a year. By contrast, Santa Barbara and San Luis Obispo counties, and a large portion of San Bernardino County, are rising at about the same rate. Hammond et al. (2016) provide an image of GPS-derived vertical land motion for California (Figure 6.3). For reference, the latitude of San Francisco is 37.7N and San Diego is 32.7N. The dominant sources of vertical deformation in California are a combination of groundwater variations and regional earthquake cycle strain of the many active faults in the region.

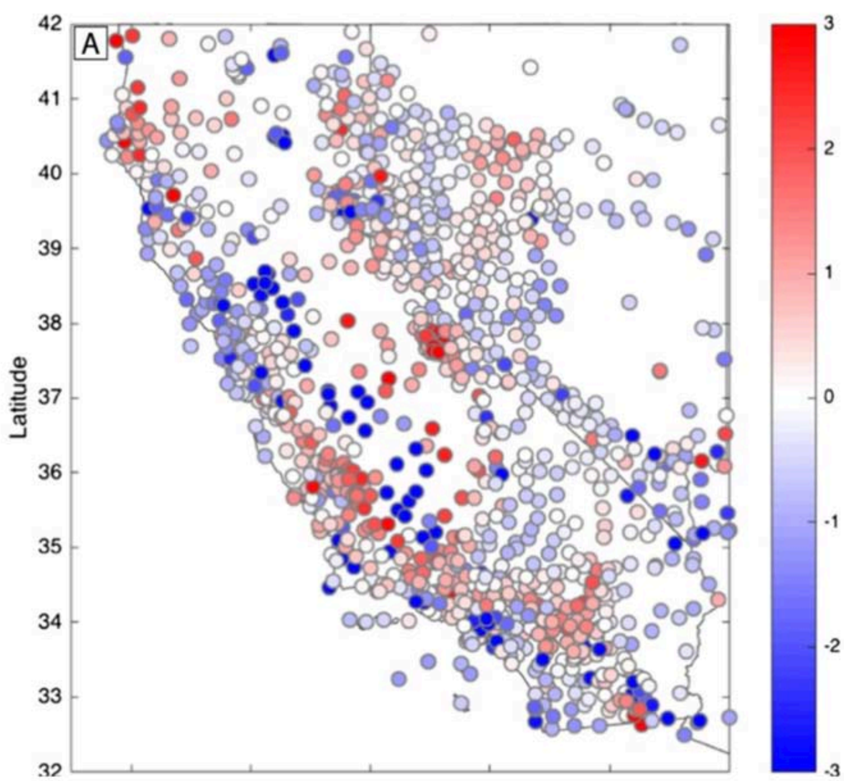

Figure 6.3. GPS observations of vertical land motion (mm/year) Hammond et al. (2016)

6.2.2 U.S. Gulf coast

Letetrel et al. (2018) provides an overview of vertical land motion along the Gulf of Mexico coast. The estimated vertical rates range from slow subsidence in the South of Florida to high subsidence rates in Texas and Louisiana of up to 7 mm/yr. Comparison with the post-glacial rebound model indicates that the drivers of the subsidence on the Gulf of Mexico shelf are local. The large variability in vertical land motion is mostly due to the subsidence induced by groundwater withdrawal, extraction of hydrocarbons, land reclamation and sedimentation.

The Texas coast from Port Isabel to Galveston presents the greatest range in the rate of vertical land movement. The rate of subsidence increases from Port Isabel to Galveston by changing from -1.9 to -4.2 mm/yr, with pronounced subsidence in Freeport (-7 mm/yr). The East Texas area, including Freeport and Galveston, is directly influenced by the fluid withdrawals due to a combination of groundwater and oil and gas extraction. An additional subsidence factor is compaction from sediment discharge from area rivers.

The Mississippi Delta's highest vertical land motion is at Grand Isle, which is located over a barrier island directly exposed to the Mississippi river discharge. The processes driving subsidence in Coastal Louisiana include: tectonic, Holocene sediment compaction, sediment loading, glacial isotactic adjustment, anthropogenic fluid withdrawal and surface water drainage and management. The complexity of estimating the subsidence rates in this area is due to the multiple physical processes contributing to subsidence, each of which occurs at a distinct spatial and temporal scale.

6.2.3 U.S. Atlantic coast

As summarized by Karegar et al. (2016), Eastern North America is experiencing spatially variable, long-term vertical motion due to glacial isostatic adjustment (GIA). Many places in the Eastern U.S. have been sinking for thousands of years and will continue to sink for thousands more. Even though the ice retreated long ago, the U.S. East Coast and Great Lakes regions are still slowly sinking.

Although GIA is the dominant contributor to vertical land motion in this region, other processes also contribute to crustal movement. Groundwater withdrawal and recharge induce spatially and temporally variable vertical motion in the Atlantic coastal plain. Sediment loading, sediment compaction, topographic relaxation of the slowly eroding Appalachians, ridge push generated by cooling of the oceanic portion of the North American plate, and mantle flow-induced dynamic topography are additional active processes that contribute to vertical motion in this region.

All stations from New Hampshire to mid-Florida show subsidence rates of <3 mm/year. The highest subsidence rates concentrate in a coastal region from northern Delaware and Maryland to the northern part of North Carolina. Locations that sit atop a coastal plain, such as the Jersey Shore, are seeing the fastest rates of subsidence, since the geology of the coastal plain features more settling of the land from groundwater depletion and long-term sediment compaction. By contrast, Mid-Atlantic coastal locations that are built on top of bedrock, such as New York City, have relatively low subsidence rates.

6.2.3 Summary of local vertical land motion

Table 6.1 shows authoritative estimates of local vertical land motion (VLM) derived from GPS for Seattle, San Francisco, San Diego, Galveston, Grand Isle LA, St. Petersburg FL, Providence RI, New York City, and Baltimore MD. Each of these locations is sinking.

Table 6.1. Estimates of Vertical Land Motion from continuous GPS (mm/year).

	Pacific coast[a]	Gulf Coast[b]	Atlantic coast[c]
Seattle	-1.10 ± 0.90a		
San Francisco	-1.44 ± 0.50a		
San Diego, CA	-3.00 ± 0.20a		
Galveston, TX		-4.70 ± 0.4	
Grand Isle, LA		-7.10 ± 0.4	
St Petersburg, FL		-0.50 ± 0.4	
Providence, RI			-0.63 ± 0.09
New York, NY			-1.32 ± 0.30
Baltimore, MD			-1.39 ± 0.19

[a] NAS (2012)
[b] Letetrel et al. (2015)
[c] Karegar et al. (2016)

6.3 Absolute local sea level rise

This section examines the relative and absolute sea level rise for the nine locations shown in Table 6.1. The relative sea level rise estimated from the tide gauge measurements is obtained from NOAA.

Table 6.2 shows absolute sea-level rise (ASLR), determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR) and the vertical land motion (VLM; Table 6.1) measurements. The GPS data extend back in time only one to two decades, while some tide gage records are more than 100 years long. Following NAS (2012), it is assumed that the GPS adjustment remains constant over the entire length of the sea-level record. This assumption is more likely valid where the vertical land motion is dominated by GIA, but it is open to question where subsidence or uplift is the primary geophysical cause.

The absolute sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local sinking of the land. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, San Diego, Seattle, Galveston, Grand Isle.

No attempt has been made in Table 6.2 to quantify uncertainties in ASLR. As per Section 6.2, there is uncertainty in determination of vertical land motion. As per Figure 6.1, there is uncertainty in the trend of sea level rise. Further, the calculation of ASLR assumes that values of RSLR and VLM refer to a common period.

Table 6.2. Absolute sea level rise (mm/year) (RSLR plus VLM), using relative sea level rise (RSLR) values from NOAA (https://tidesandcurrents.noaa.gov/sltrends/) and VLM values from Table 6.1.

Location	RSLR	VLM	ASLR
Seattle, WA	+2.05	-1.10	+0.95
San Francisco, CA	+1.96	-1.44	+0.52
San Diego, CA	+2.17	-3.00	- 0.29
Galveston, TX	+6.49	-4.70	+1.79
Grand Isle, LA	+9.08	-7.10	+1.98
St Petersburg, FL	+2.75	-0.50	+2.25
Providence, RI	+2.27	-0.63	+1.64
New York City, NY	+2.84	-1.32	+1.52
Baltimore, MD	+3.15	-1.39	+1.76

6.4 Pacific coast

Along the west coast of the U.S., the El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) affect winds and ocean circulation, raising local sea level during warm phases (e.g., El Niña) and lowering sea level during cool phases (e.g., La Niña). Pietrafesa et al. (2016) found that sea level along the West Coast can be enhanced or suppressed by the order of 10–20 cm from year to year, in association with wind fields changing in keeping with ENSO and the PDO. Transition of the PDO and ENSO to colder phases may result a relative overall drop in Eastern Pacific coast sea level and a rise in Western Pacific coast sea level (e.g. Bromirski et al. 2011).

6.4.1 Seattle, Washington

Over the past 100 years, relative sea level in Seattle has risen by 8 inches (Figure 6.3), at a rate of 2.05 mm/year. Vertical land motion in the region is variable, with an estimated average rate of -1.10 mm/year. Samsonov et al. (2016) identified abrupt sinking of 2.5 cm in portions of Seattle during the period 2012-2014, which was linked to tunnel boring for the Alaskan Way Viaduct replacement project.

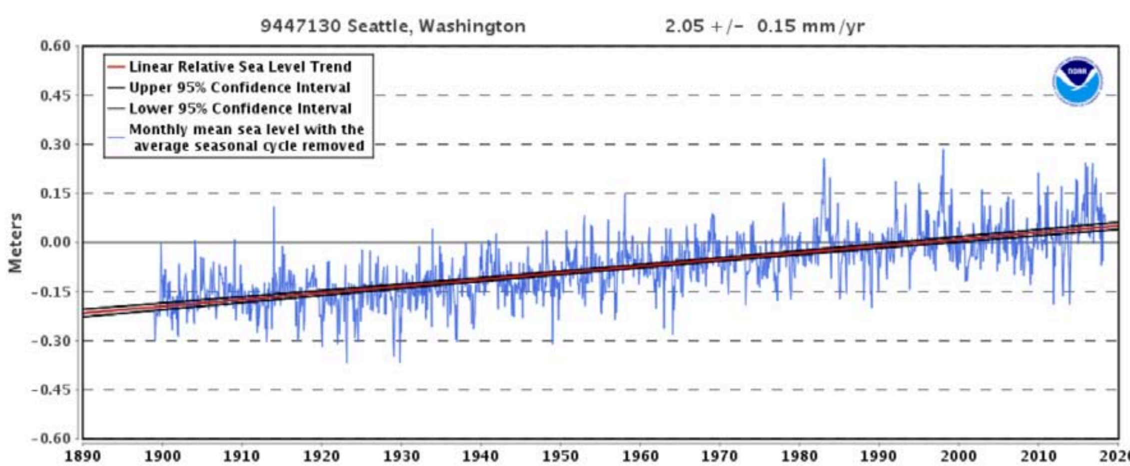

Figure 6.3. Tide gauge measurements at Seattle, WA, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

6.4.2 San Francisco Bay area

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.7 inches, at an average rate of 1.96 mm/year (Figure 6.4). As shown in Table 6.2, San Francisco's vertical land motion is -1.44 mm/year (sinking), producing a recent rate of absolute sea level rise of +0.52 mm/year. Shirzaei and Burgmann (2018) found that Portions of Treasure Island, San Francisco International Airport, and Foster City are subsiding as fast as 10 mm/year. Landfill zones are sinking due to soil compaction, at a rate as much as one-half inch per year, threatening coastal infrastructure including the San Francisco International Airport. The problems in the San Francisco Bay area have been caused primarily by sinking in landfill regions that were formerly wetlands, not by the slow creep of global sea level rise.

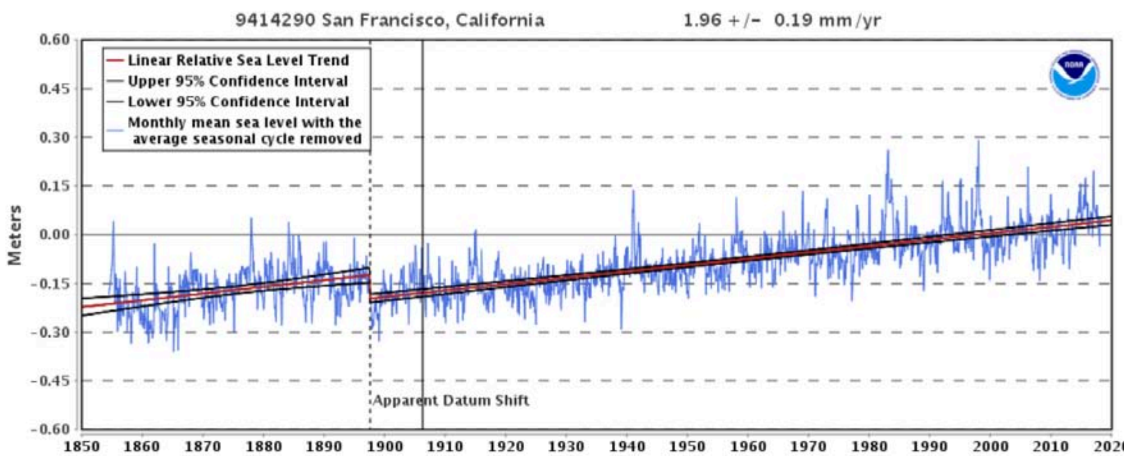

Figure 6.4. Tide gauge measurements at San Francisco, California, obtained from NOAA (downloaded 8/2/18). https://tidesandcurrents.noaa.gov/sltrends/.

6.4.3 San Diego, California

Over the past 100 years, relative sea level in San Diego has risen by 8.5 inches, at an average rate of 2.17 mm/year (Figure 6.3a). The vertical land motion is highly variable in the San Diego region. NAS (2012) reports that San Diego is sinking (-3.00 mm/year), whereas La Jolla is rising (+2.10 mm/year).

Sea level rise is a particular concern at Imperial Beach (Revell Coastal, 2016). The coastal geology offshore of Imperial Beach is a shallow sloping continental shelf that has been dissected by the Tijuana, Otay, San Diego, and Chollas Rivers. Three dams in the region have reduced the sand supply by an estimated 49% (Willis and Griggs 2003) and erosion rates at Imperial Beach have escalated. From 1940 to 2005, beach nourishment projects added almost 40 million cubic yards of sand to this cell in an effort to mitigate coastal erosion, with overall mixed results in stabilizing the shore. Recent El Niños led to extensive flooding and beach loss along the coast. The problem of diminishing sand supplies has been exacerbated by bluff-top development that decreases the supply of sand from eroding cliffs (Limber et al. 2018).

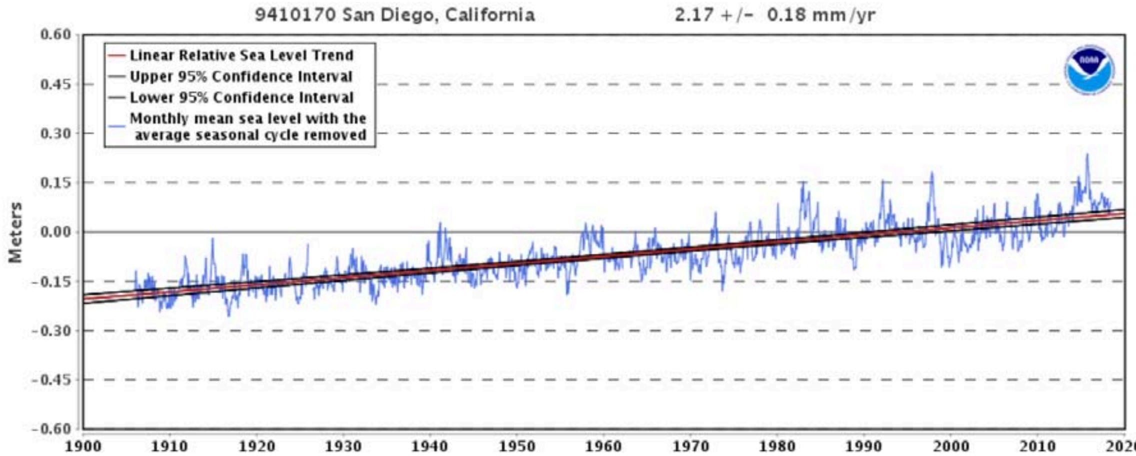

Figure 6.5. Tide gauge measurements at San Diego, CA, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

6.5 Gulf coast

Pietrafesa et al. (2016) found seasonal to multi-decadal sea level variability to be temporally coherent across the Gulf of Mexico coastline. Sea level has risen at a faster rate in the western than in the eastern Gulf. Kennedy et al. (2007) found that in the eastern Gulf of Mexico, low sea level events in the winter months are more frequent during El Niño (warm phase) conditions when compared to a neutral ENSO phase.

6.5.1 Galveston - Houston

There are long-term tide gauge measurements at Galveston Pier 21 and Galveston Pleasure Pier, both showing approximately the same amount of sea level rise. Galveston Pier 21 has seen sea level rise of 2.13 feet in the past century, or a rate of 6.49 mm/year. Vertical land motion (subsidence) at Galveston is estimated at -4.70 mm/year (Table 6.1), yielding a value of absolute sea level rise of +1.79 mm/year (Table 6.2).

A recent report by the U.S. Geologic Survey (Kasmarek and Ramage, 2017) found that most of the land-surface subsidence in the Houston-Galveston region has occurred as a direct result of groundwater withdrawals. This caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 ft of subsidence had occurred in Houston. Most compaction that occurs as a result of groundwater withdrawals is irreversible; even if groundwater levels rise, compacted sediments and the associated land-surface lowering would remain.

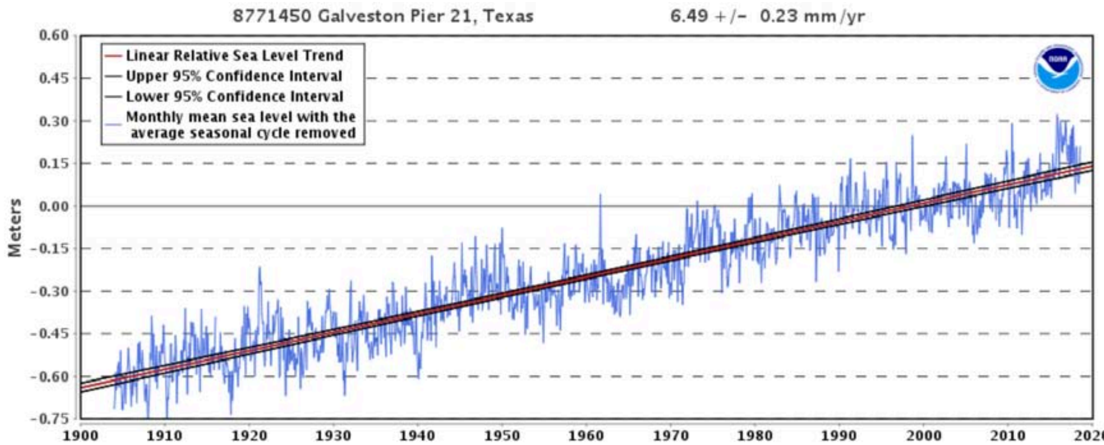

Figure 6.6. Tide gauge measurements Galveston Pier, TX, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

6.5.1 New Orleans and the Mississippi delta

Tide gauge measurements at Grand Isle, Louisiana, show that sea level has risen almost 3 feet over the last 100 years and at an average rate of 9.08 mm/year. Letetrel et al. (2015) found that vertical land motion (subsidence) is -7.10 mm/year at Grande Isle. From Table 6.2, the absolute sea level rise at Grand Isle is +1.98 mm/year.

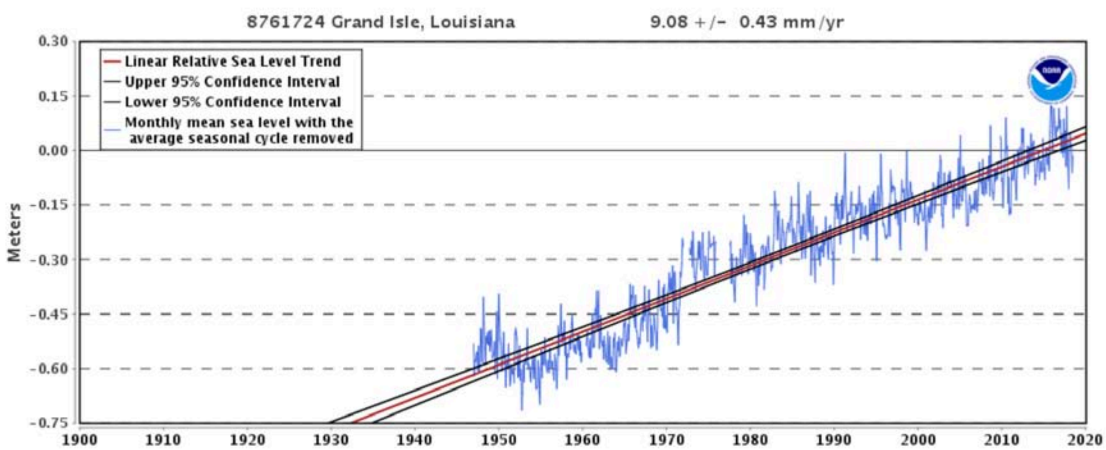

Figure 6.7. Tide gauge measurements at Grand Isle, LA, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

The issues of sea level rise and land loss in the Mississippi delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi river being the dominant drivers. Since the 1950s, the suspended sediment load of the Mississippi River has decreased by ~50% due primarily to the construction of dams in the Mississippi basin. A new subsidence map of coastal Louisiana (Nienhuis, 2017) finds the coastal region to be sinking at about one third of an inch per year (or 9 mm/year). For a city whose elevation averages one to two feet below sea level, sea level rise from human caused warming is not the dominant driver for the problems that New Orleans is facing.

Much ado has been made about the 'climate refugees' from Isle de Jean Charles off the coast of Louisiana, which is disappearing. In 1955, there were 22,000 acres while there are 320 acres today[7]. The principal problem traces back to the Great Mississippi Flood of 1927 when the U.S. Army Corps of Engineers responded by building giant levees to constrain the river, which stopped the flow of sediment into its delta (Kolker et al, 2018). These refugees are more accurately referred to as 'Mississippi flood mitigation refugees.'

6.6.3 St. Petersburg and Tampa Bay

Tide gauge measurements at St. Petersburg, FL, show that sea level has risen at a rate of 11 inches per century, or 2.75 mm/year. Letetrel et al. (2015) determined that vertical land motion (subsidence) is -0.50 mm/year at St Petersburg. From Table 6.2, the absolute sea level rise is 2.25 mm/year. Located on the west coast of Florida, the Tampa Bay region has nearly 700 miles of shoreline. Along the western side of the Tampa Bay region lies a barrier island system that have predominantly sand beaches and are highly developed.

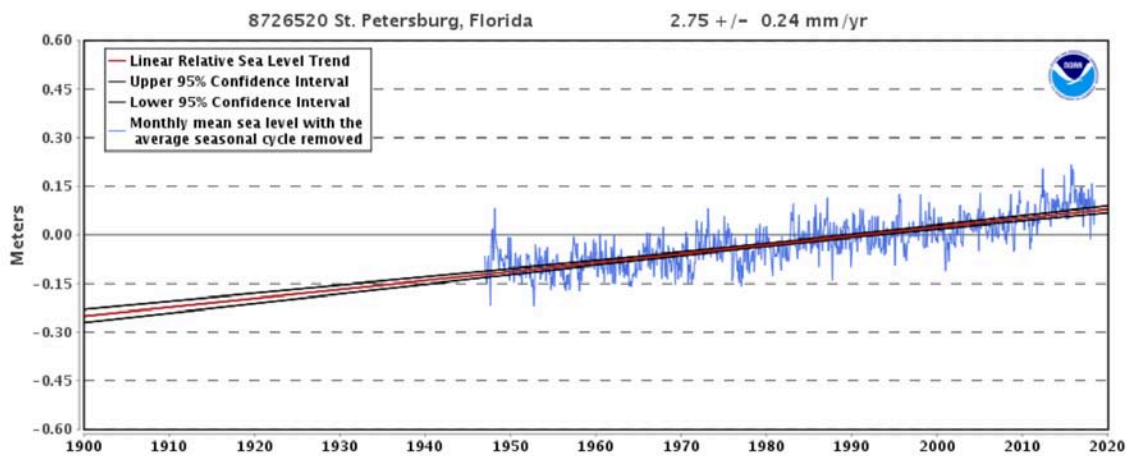

Figure 6.8. Tide gauge measurements at St. Petersburg, FL, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

6.6 Atlantic coast

The mid-Atlantic region along the East Coast of the United States has been identified as a 'hot spot' of accelerated sea level rise (SLR) since sea level acceleration (i.e., an increase with time of SLR rate) there is much larger than global acceleration (e.g. Ezer et al. 2013). In addition to large land subsidence around the Chesapeake Bay area, sea level acceleration in the mid-Atlantic has been found to be highly correlated with recent

[7] https://www.independent.co.uk/news/world/americas/time-almost-up-island-louisiana-sinking-into-the-sea-american-indians-coastal-erosion-isle-de-jean-a8280401.html

offshore shift and weakening in the Gulf Stream just north of Cape Hatteras as seen in satellite altimeter data.

Temporal and spatial variations of sea level change on the Atlantic coast are correlated with the Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and Gulf Stream North Wall (GSNW) indices, all of which are currently within the range of past variability (Kopp et al. 2013).

6.6.1 Rhode Island

There are long-term tide gauge measurements at Newport and Providence, respectively showing that sea level has risen 11 and 9 inches over the last 100 years and at rates averaging 2.75 and 2.27 mm/year. Karegar et al. (2016) found that vertical land motion (subsidence) is -0.63 mm/year at Providence. From Table 6.2, the absolute sea level rise is 1.64 mm/year at Providence.

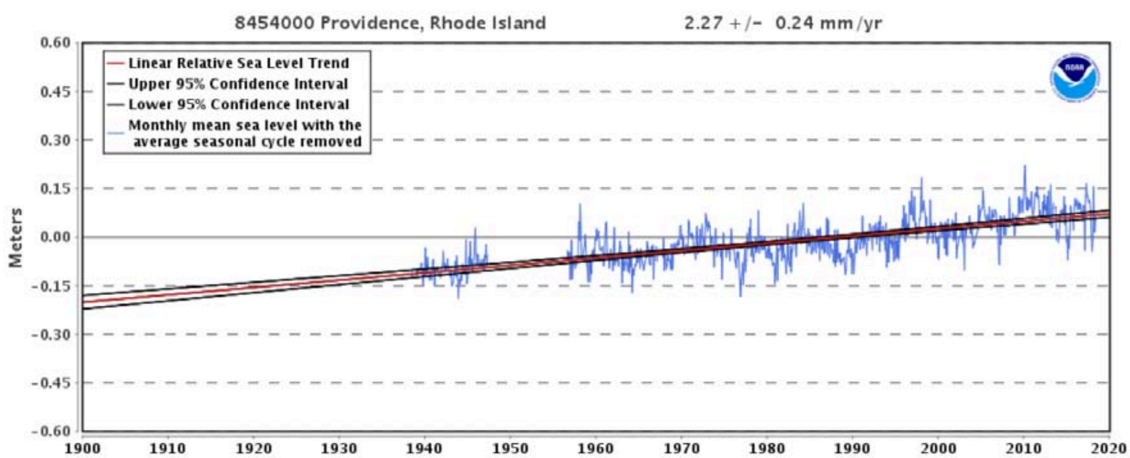

Figure 6.9. Tide gauge measurements at Providence, RI, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

In Rhode Island, there are approximately 7,000 people living within the 7-foot sea level rise inundation zone, according to a R.I. Statewide Planning report.[8] The report states:

> "Nonetheless, it is clear that the current circumstances in Rhode Island can be viewed with optimistic caution. Though sea level rise and storm surge are likely to present clear difficulties in many areas, it should be recognized that the threats being faced are not entirely new: previous generations also faced inundation from major storm events, and as a result many key assets in Rhode Island are either well protected, or have not survived the state's 380 year history. Most major transportation systems are located well away from flood zones, and some population centers have built up systems of flood defense. As a result the vulnerabilities described in these projects are not of an existential nature."

[8] http://www.planning.ri.gov/planning-areas/climate- change/sea-level-rise.php

6.6.2 New York City

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. In New York City, relative sea level has risen 11 inches over the past century, at an average rate of 2.84 mm/year. Karegar et al. (2016) found that vertical land motion in the New York City area is occurring at a rate of -1.32 mm/year (subsidence), corresponding to roughly 5 inches per century. From Table 6.2, the absolute rate of sea level rise at The Battery location is 1.52 mm/year, or about 54% of the measured relative sea level rise.

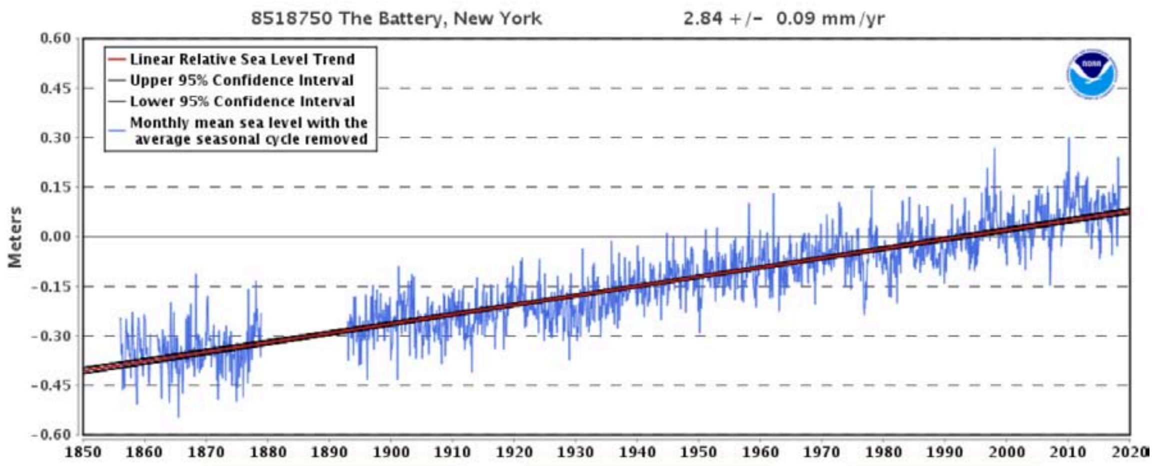

Figure 6.10. Tide gauge measurements at The Battery, New York, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

Kemp et al. (2017) found that relative sea level in New York City rose by ~1.70 meters [5.5 feet] since ~575 A.D., including ~0.38 meters [1.2 feet] since 1850 A.D. The rate of relative sea level rise increased markedly at 1812–1913 from ~1.0 to ~2.5 mm/year. A recent acceleration in sea level rise between 2000 and 2014 has been attributed to an increase in the Atlantic Multidecadal Oscillation and southward migration of the Gulf Stream North Wall index (Miller et al., 2013).

6.6.3 Baltimore and the Chesapeake Bay area

In Baltimore, relative sea level has risen 12 inches over the past century, at an average rate of 3.15 mm/year. Karegar et al. (2016) found that vertical land motion in Baltimore is occurring at a rate of -1.39 mm/year (subsidence), corresponding to roughly 5 inches per century. From Table 6.2, the absolute rate of sea level rise at Baltimore is 1.76 mm/year, or about 56% of the measured relative sea level rise.

Baltimore is located on the fall line between the Piedmont Plateau and the Atlantic Coastal Plain, which divides Baltimore into 'lower city' and 'upper city'. Baltimore's waterfront is particularly vulnerable to the impacts of sea level rise because of its dense development and low-lying areas.

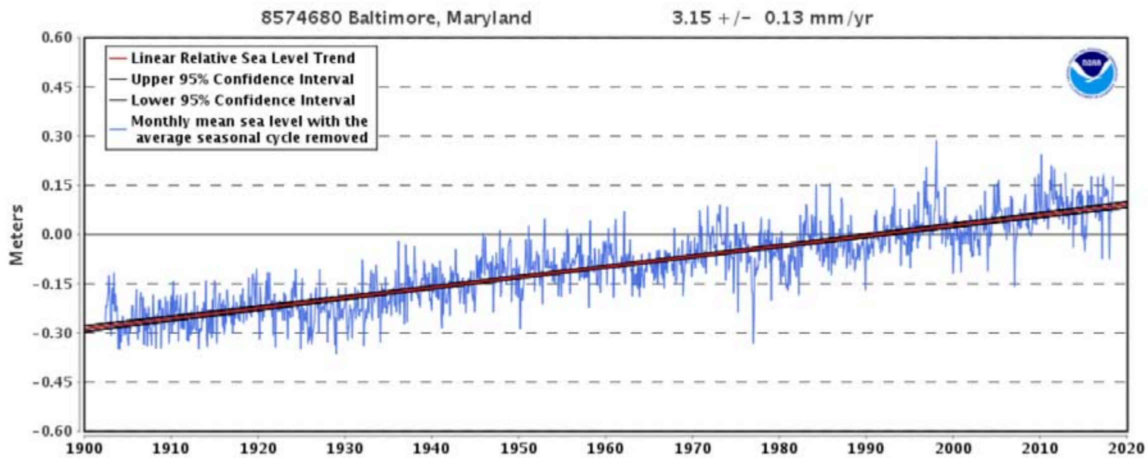

Figure 6.11. Tide gauge measurements at Baltimore, MD, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

In the Chesapeake Bay region south of Baltimore, land subsidence is significantly larger owing to ground water withdrawal. Eggleston and Pope (2013) report that land subsidence has been observed since the 1940s in the southern Chesapeake Bay region at rates of 1.1 to 4.8 mm/year. The aquifer system in the region has been compacted by extensive groundwater pumping in the region at rates of 1.5- to 3.7 mm/year, which accounts for more than half of observed land subsidence in the region.

6.6.4 Miami and South Florida

The closest tide gauge to Miami on the Florida peninsula having a continuous record extending back several decades is Naples, FL. From the data record since 1965, Naples shows a rate of sea level rise equivalent to 11 inches per century, or 2.80 mm/year. Baki Iz et al. (2017) cites an average value of vertical land motion for Florida of -1.40 mm/year. There is sufficient regional variability so that it is not justified to use these values to calculate a value of absolute sea level rise for Miami.

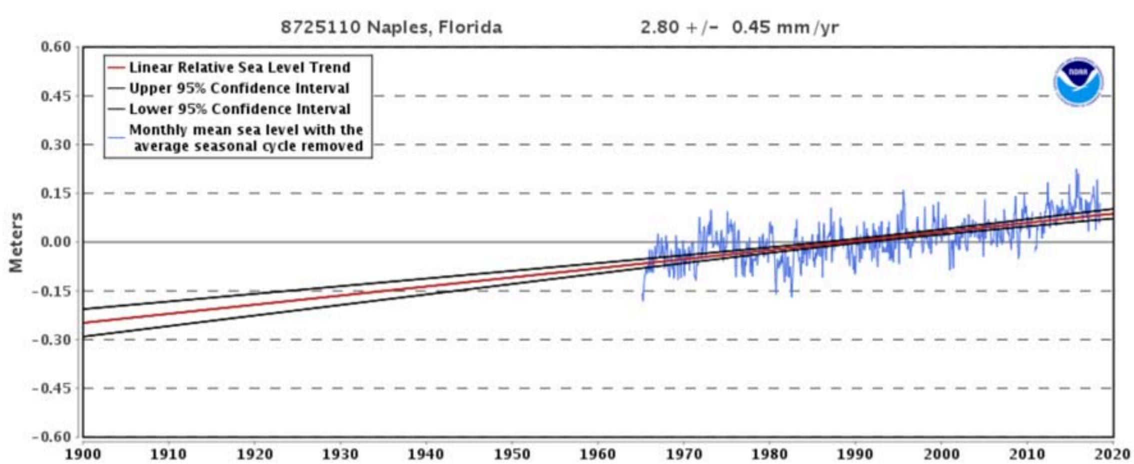

Figure 6.12. Tide gauge measurements at Naples, FL, obtained from NOAA (downloaded 8/2/18).https://tidesandcurrents.noaa.gov/sltrends/.

Miami has a population of more than 5.5 million living at an elevation of 6 feet or less above sea level. The solid ground under South Florida is mostly limestone made of compressed ancient reefs that are full of tiny holes. That means salty water is rising up through the ground itself and is more prone to saturation by seawater. From 2011 to 2015, the rate of sea level rise across the southeastern U.S. increased by a factor of six, from 3 mm/year to 20 mm/year, which was caused by a change in the North Atlantic Oscillation ocean circulation pattern (Valle-Levinson et al. 2017). Apart from its low elevation and porous geology, Miami's recent problems with sea level rise are caused primarily by a change in the circulation patterns in the Atlantic rather than the slow creep of global sea level rise.

6.7 Local projections for the 21st century

Local sea level projections differ from global projections owing to local temperature variations, wind-driven differences in ocean heights, gravitational and deformational effects of melting glaciers and ice sheets, and vertical land motions along the coast. Apart from uncertainties and concerns about projections of global sea level rise raised in Sections 5.2 and 5.6, there are additional uncertainties associated with each of these factors. As the projection period lengthens, uncertainty in the projections grows. At short timescales (2030 and perhaps 2050), when the models more closely represent the future system, confidence in the global and regional projections is higher. By 2100, however, projections have very large uncertainties.

NOAA (2017) has made local sea level change projections for the entire U.S. coast that includes both climatic and non-climatic sea level change. Scenario projections of local relative sea level (RSL) rise include the following notable patterns:

- Future RSL rise is amplified along the Northeast U.S. coast due to the effects of GIA, the far-field static equilibrium effects of Antarctic melt, and reduced transport of the Gulf Stream System. Future RSL rise is partially reduced by intermediate-field static-equilibrium effects associated with relative proximity to Greenland and many northern glaciers.

- RSL rise is amplified along the western region of the Gulf of Mexico and much of the Atlantic coast by withdrawal of groundwater. Far-field static equilibrium effects of Antarctic melt are also amplified in these two regions.

- Future RSL is amplified along the Pacific Coast of the continental U.S. due to far-field static-equilibrium effects of Antarctic ice sheet melt.

- Future RSL is reduced along the U.S. Pacific Northwest coast due to proximity to the Alaskan glaciers from both ongoing GIA to past glacier shrinkage and to the static-equilibrium effects of projected future losses.

Figure 6.13 from NOAA (2017) illustrates projections out to 2060 for New York City, Miami, Galveston and San Francisco, for 5 different scenarios (see Table 5.3).

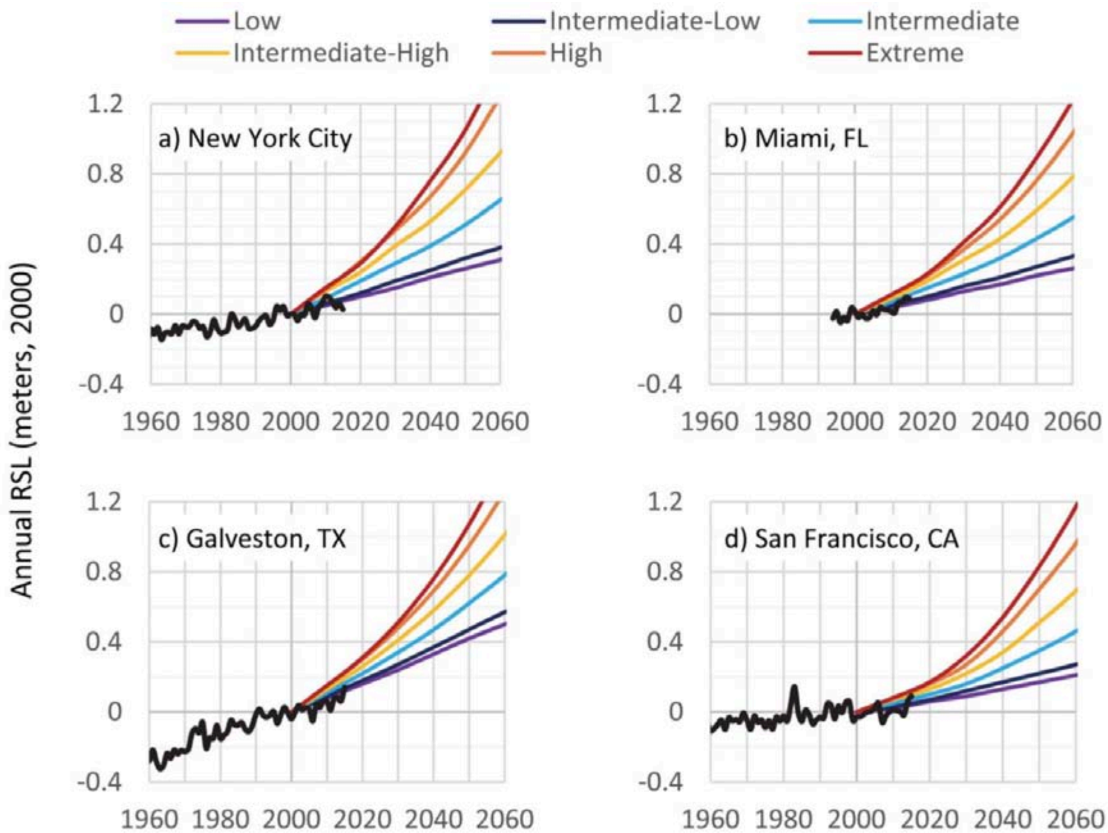

Figure 6.13. Average annual RSL for New York City, San Francisco, Galveston, and Miami with their respective (median-value) RSL under the six scenarios. The NOAA RSL observations (tidesandcurrents.noaa.gov/sltrends) are shown relative to the midpoint (year 2000) of the 1991–2009 epoch, which is the reference level for the scenarios. [NOAA 2017]

NOAA's predictions do not include the influence of oceanic circulation patterns. Hu and Deser (2013) used a 40-member ensemble of climate model simulations to evaluate the dynamic and thermosteric (warming) components of sea level change (but not including contributions from glaciers and ice sheets). Each of the 40 realizations represents a plausible outcome of climate change in the presence of internal variability of ocean circulations over the next 50 years, and their spread represents the irreducible uncertainty of the predicted future climate. Hu and Deser (2013) found that simulated regional sea level rise at mid-century can vary by a factor of 2 depending on location (Figure 6.14), with the North Atlantic and Pacific showing the greatest range. This variation in regional sea level rise results primarily from internal variations in ocean circulations. For the next 50 years, ocean circulation patterns are expected to reduce U.S. west coast sea level rise relative to the global average, and increase U.S. Atlantic coast sea level rise relative to the global average.

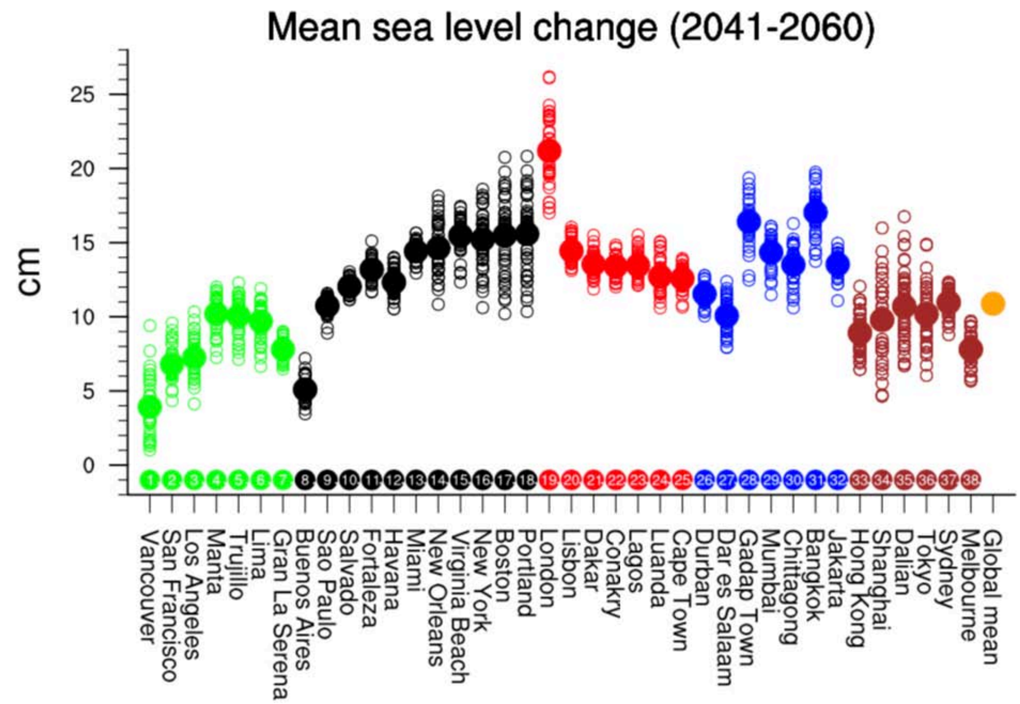

Figure 6.14. Simulated change in sea level (cm) between the periods 2041–2060 and 1980–1999 at selected coastal cities from the 40-member climate model ensemble. The top panel shows the city locations, color-coded by region. The bottom panel shows the sea level changes using the same regional color-coding, with open circles for each of the 40 ensemble members and filled circles for the ensemble mean. (Hu and Deser, 2013)

Little et al. (2014) addresses the uncertainties in global and local sea level rise projections derived from global climate model simulations at different lead times, in terms of the relative importance emissions scenario, climate model error, and natural internal variability. Because of the long response times of the deep ocean, much of the 21st century sea level response is driven by 20th and early 21st century forcing. The emergence of emissions scenario dependence will vary depending on location and on the model used – later in a model with a higher degree of internal variability and/or weaker scenario dependence. Along the U.S. coast, internal variability is as large as that due to RCPs until about 2060. Local sea level assessments should thus consider the role of regional internal variability and should not expect a differentiation of sea level rise trajectories for different emissions scenarios through at least midcentury. In the northeastern United States, this differentiation could be obscured through most of the twenty-first century. These results emphasize that the time of emergence will vary greatly, depending on a model's climate forcing, response to climate forcing (climate sensitivity), and representation of internal variability.

6.8 Conclusions

In each of the locations on the U.S. coast considered in this analysis, approximately half of the local sea level rise has been caused by local vertical land motion. No statistically significant acceleration in sea level rise has been identified in any of these locations.

Projections of local sea level rise are even more uncertain than those for global sea level rise, owing to added uncertainties associated with vertical land motion, ocean circulation patterns, and local gravitational and deformation associated with melting ice sheets in Greenland and Antarctica.

Local accelerations in absolute sea level rise required to effect 21st century projections of 30 inches or more require very large acceleration in the rates of sea level rise, to rates of sea level rise that have not been observed since the deglaciation over 10,000 years ago.

And finally, to what extent can be any meaningful reduction in local and global sea level rise in the 21st century from policies that reduce the emissions of greenhouse gases?

Marzeion et al. (2018) found that contemporary glacier mass is in disequilibrium with the current climate and that mass loss is already committed in response to past greenhouse gas emissions. Consequently, mitigating future emissions will have only very limited influence on glacier mass change in the 21st century.

The difference in projected mean sea level rise between the RCP2.6 and RCP6.0 emissions scenarios (Table 5.1) is 0.4 m [15.7 inches] versus 0.48 m [18.9 inches] – a difference of 3.2 inches by the end of the 21st century.

Kopp et al. (2017) argue that if the DeConte and Pollard (2016) scenario of West Antarctic Ice Sheet collapse is correct, then the mitigation potential for 2011 is 90 cm between the RCP8.5 and RCP2.6 emissions scenarios. This points to significantly larger mitigation benefit, if this scenario is correct. However, the worst-case scenarios are tied to RCP8.5, which is extremely unlikely and may be impossible (e.g Ritchie and Dowlabati, 2017).

7. Conclusions

Mean global sea level has risen at a slow creep for more than 150 years; since 1900, global mean sea level has risen about 7-8 inches. The implications of the highest values of projected sea-level rise under future climate change scenarios are profound, with far reaching socioeconomic and environmental implications. However, these projections are regarded as deeply uncertain and the highest of these projections strain credulity.

The IPCC and other assessment reports are framed around providing support for the hypothesis of human-caused climate change. As a result, natural processes of climate variability have been relatively neglected in these assessments. Arguments have been presented here supporting the important and even dominant role that natural processes play in global and regional sea level variations and change.

1. Is the recent sea level rise (since 1993) of magnitude 3 mm/year unusual?

No, although this conclusion is conditional on the quality of the global sea level data. The available evidence shows the following:

- Sea level was apparently higher than present at the time of the Holocene Climate Optimum (~ 5000 years ago), at least in some regions.
- Tide gauges show that sea levels began to rise during the 19th century, after several centuries associated with cooling and sea level decline. Tide gauges also show that rates of global mean sea level rise between 1920 and 1950 were comparable to recent rates.
- Recent research has concluded that there is no consistent or compelling evidence that recent rates of sea level rise are higher or abnormal in the context of the historical records back to the 19th century that are available across Europe.

2. Has recent global sea level rise been caused by human-caused global warming?

Identifying a potential human fingerprint on recent sea level rise is confounded by the large magnitude of natural internal variability associated with ocean circulation patterns. There is not yet convincing evidence of a fingerprint on sea level rise associated with human-caused global warming:

- The slow emergence of fossil fuel emissions prior to 1950 did not contribute significantly to sea level rise observed in the 19th and early 20th centuries.
- The recent acceleration in mean global sea level rise (since 1995) is caused by mass loss from Greenland that appears to have been larger during the 1930's, with both periods associated with the warm phase of the Atlantic Multidecadal Oscillation.

3. To what extent is local sea level rise influenced by global sea level rise?

In many of the most vulnerable coastal locations, the dominant causes of local sea level rise are natural oceanic and geologic processes and land use practices. Land use and engineering in the major coastal cities have brought on many of the worst problems, notably landfilling in coastal wetland areas and groundwater extraction.

4. How much will sea level rise in the 21st century?

Local sea level in many regions will continue to rise in the 21st century – independent of global climate change.

Emissions scenario choice exerts a great deal of influence on predicted sea level rise after 2050. If RCP8.5 is rejected as an extremely unlikely, if not impossible, scenario, then the appropriate range of sea level rise scenarios to consider for 2100 is 0.2–1.6 m [8 inches to 5 feet]. Values exceeding 2 feet are increasingly weakly justified. Values exceeding 5 feet require a cascade of extremely unlikely to impossible events, the joint likelihood of which is arguably impossible. Further, these values of sea level rise are contingent on the climate models predicting the correct amount of temperature increase. However, there are numerous reasons to think that the climate models are predicting too much warming for the 21st century.

Kopp et al. (2017) state:

> "The breadth of published projections, as well as of remaining structural uncertainties, highlight the fact that future sea-level rise remains an arena of deep uncertainty."

Climate-related decisions involve incomplete information from a fast-moving and irreducibly uncertain science. The challenges of understanding the causes of sea level rise and projecting future climate change and sea level rise are well-recognized by the international community of climate and sea level researchers, as summarized in the World Climate Research Programme (WCRP) Grand Challenges. The WCRP Grand Challenge on Regional Sea Level Change and Coastal Impacts states:

> "Despite considerable progress during the last decade, major gaps remain in our understanding of past and contemporary sea level change and their causes. These uncertainties arise from limitations in our current conceptual understanding of relevant physical processes, deficiencies in our observing and monitoring systems, and inaccuracies in statistical and numerical modelling approaches to simulate or forecast sea level."

> "A significant part of this large uncertainty arises from inappropriate (or sometimes missing) model representations of some physical processes that affect sea level and needs to be reduced for more accurate sea level projections."

> "Improved sea level predictions/projections, particularly over the next decades, are critically dependent on understanding observed natural variability, accurately reproducing it in models, and mapping its future behavior under climate change."

References

Ablain, M, JF Legeais, P Prandi et al. (2016) Satellite Altimetry-Based Sea Level at Global and Regional Scales. *Surv. Geophysics,* DOI 10.1007/s10712-016-9389-8

Accordi, G, F Carbone (2016) Evolution of the siliciclastic-carbonate shelf system of the northern Kenyan coastal belt in response to Late Pleistocene-Holocene relative sea level changes. *Journal of African Earth Sciences*, 123, 234-257.

Baki Iz, H, CK Shum, C Zhang and CY Kuo (2017) Inferring regional vertical crustal velocities from averaged relative sea level trends: A proof of concept. *J. Geod. Sci.* 7, 59–67

Bamber, J. L., & Aspinall, W. P. (2013). An expert judgement assessment of future sea level rise from the ice sheets. *Nature Climate Change*, *3*, 424–427.

Bamber, JL, RM Westaway, B Marzeion, B Wouters (2018) The land ice contribution to sea level in the satellite era. *Environ. Res. Lett.,* 13, 06308

Barletta, V, M Bevis, BE Smith et al. (2018) Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability. *Science,* 360, 1335-1339.

Becker M, Karpytchev M, Lennartz-Sassinek S (2014) Long-term sea level trends: natural or anthropogenic? *Geophys Res Lett.,* 41, 5571–5580.

Betz, G. (2010) What's the worst case? The method of possibilistic prediction. *Analyse & Kritik* 01, 87-106

Bilbao RAF, Gregory JM, Bouttes N (2015) Analysis of the regional pattern of sea level change due to ocean dynamics and density change for 1993–2099 in observations and CMIP5 AOGCMs. *Clim Dyn.* doi:10.1007/s00382-015-2499-z

Bradley, SL, GA Milne, BP Horton, Y Zong (2016) Modelling sea level data from China and Malay-Thailand to estimate Holocene ice-volume equivalent sea level change. *Quaternary Science Reviews*, 137, 54-68.

CCSR (2017): Sea level rise. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program, Washington, DC, USA, pp. 333-363, doi: 10.7930/J0VM49F2.

CDIAC (2014) Annual Global Fossil Fuel Emissions. Carbon Dioxide Information Analysis Center. http://cdiac.ess-dive.lbl.gov/trends/emis/glo_2014.html

Chambers, DP, MA Merrifield, SR Nerem (2012) Is there a 60-year oscillation in global mean sea level? *Geophysical Research Letters*, 39, L18607.

Charney, JG et al. (1979) *Carbon Dioxide and Climate: A Scientific Assessment*. The National Academies Press. http://nap.edu/12181

Chen, X, X Zhang, JA Church et al. (2017) The increasing rate of global mean sea level rise during 1993-2014. *Nature Climate Change*, DOI: 10.1038/NCLIMATE3325

Chiba, T, S Sugihara, Y Matsushima et al. (2016) Reconstruction of Holocene relative sea-level change and residual upift in the Lake Inba area, Japan. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 441, 982-996

Clark, PU, AC Mix, M Eby et al. (2018) Sea-level commitment as a gauge for climate policy. *Nature Climate Change*, 8, 653-655.

Cronin, T. M. (2012), Rapid sea-level rise, *Quat. Sci. Rev.*, *56*, 11–30.

CU (2011) What is glacial isostatic adjustment and why do you correct it? http://sealevel.colorado.edu/content/what-glacial-isostatic-adjustment-gia-and-why-do-you-correct-it

Curry, JA (2018) Climate Uncertainty and Risk, *CLIVAR Variations*, Volume 16, Number 3 https://indd.adobe.com/view/da3d0bde-1848-474d-b080-f07200293f91

Curry, JA, PJ Webster (2011) Climate Science and the Uncertainty Monster. *Bull. American Meteorological Society.* 92, 1667-1682.

Dangendorf, S, D Rybski, C Mudersbach et al. (2014), Evidence for long-term memory in sea level, *Geophys. Res. Lett.,* 41, 5530–5537, doi:10.1002/ 2014GL060538.

Dangendorf S, M Marcos, A Muller et al. (2015) Detecting anthropogenic footprints in sea level rise. *Nature Communications*. doi:10.1038/ncomms8849
Dangendorf, S, M Marcos, G. Woppelman et al. (2017) Reassessment of 20th century global sea level rise. *Proc. Nat. Acad. Sci,* 114, 5946-5951.
Dangendorf, S, M Marcos (2018) A reconciled estimate of 20th century global mean sea level rise. *CLIVAR Exchanges*, Vol 16, No. 1http://www.clivar.org/sites/default/files/documents/Variations-Exhanges-Winter2018.pdf
DeConto, RM, D Pollard (2016) Contribution of Antarctica to past and future sea-level rise. *Nature*, **531** (7596), 591-597.
De Vries, VW et al. (2018) A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. Geological Society, London, Special Publications, 461, 231. https://doi.org/10.1144/SP461.7
Dieng HB, A Cazenave, B Meyssignac,M Ablain (2017) New estimate of the current rate of sea level rise from a sea level budget approach *Geophys. Res. Lett.,* 44, 3744-3751.
Domack, E, et al. (2005) Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. *Nature*, **436**, 681.
Eggleston J and J Pope (2013) Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region. U.S. Geological Survey Circular 1392, 30 p. http://dx.doi.org/10.3133/cir1392.
Fasullo, JT, C Boening, FW Landerer, RS Nerem (2013) Australia's unique influence on logal sea level in 2010-2011. *Geophys. Res. Lett,* 40, 4368-4373.
Fettweiss, X, E Hanna, H Gallee et al. (2008) Estimation of the Greenland ice sheet surface mass balance for the 20th and 21st centuries. *The Cryosphere,* 2, 117-129.
Fettweis, X et al.(2013) Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR. *The Cryosphere*, **7**, 469-489.
Gomez, N., D. Pollard, D. Holland (2015) Sea-level feedback lowers projections of future Antarctic ice sheet loss. *Nature Comm.,* 6, 8798.
Gregory, JM, NJ White, JA Church et al. (2013) Twentieth-Century Global-Mean Sea Level Budget: Is the Whole Greater than the Sum of the Parts? *J. Climate,* https://doi.org/10.1175/JCLI-D-12-00319.1
Griggs, G, et al. (2017) *Rising Seas in California: An Update on Sea-Level Rise Science.* California Ocean Science Trust, April 2017.
Grinsted, A, JC Moore, S Jevrejeva (2009) Reconstructing sea level from paleo and projected temperatures, 200 to 2100 AD. *Climate Dynamics,* DOI 10.1007/s00382-008-0507-2
Hahn, L et al. (2018) North Atlantic natural variability modulates emergence of widespread Greenland melt in a warming climate. *Geophys. Res. Lett, 45,* 9171-9178.
Hallegatte, S, C Green, RK Nicholls, and J Corfee-Morlot (2013) Future Flood Losses in Major Coastal Cities, *Nature Climate Change* (3), 802-806 pp.
Hamlington, BD, PR Thompson (2015) Considerations for estimating the 20th century trend in global mean sea level. *Geophysical Research Letters,* 42, 4102–4109.
Hamlington BD, Cheon SH, Thompson PR, Merrifield MA, Nerem RS, et al. 2016. An ongoing shift in Pacific Ocean sea level. *J. Geophys. Res. Oceans* 121, 5084–97
Hanna, E, JM Jones, J Cappelen et al. (2013) The influence of North Atlantic atmospheric and oceanic forcing effects on 1900-2010 Greenland summer climate and ice melt runoff. *Int. J. Climatol.* **33**: 862–880.
Hansen, J, M Sato, P Hearty et al. (2016) Ice melt, sea level rise, and superstorms: evidence from paleoclimate data, climate modeling and modern observations that 2°C global warming could be dangerous. *Atmos. Chem. Phys.,* 16, 3761–3812
Hawkins, E (2018) Comparing CMIP5 and Observations. Climate Lab Book https://www.climate-lab-book.ac.uk/comparing-cmip5-observations/

Hay, CC, E Morrow, RE Kopp, JX Mitrovica (2015) Probabilistic reanalysis of twentieth century sea-level rise. *Nature,* doi:10.1038/nature14093

Hegerl, GC, et al. (2010) Good practice guidance paper on detection and attribution related to anthropogenic climate change. In: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change*, IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.

Hofer, S, AJ Tedstone, X Fettweis, JL Bamber (2017) Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet. *Science Advances,* 3, e1700584

Horton, BP, S Rahmstorf, SE Englehart, AC Kemp (2014) Expert assessment of sea-level rise by AD2100. Quaternary Science Review, 84, 1-6.

Horton, BP, RE Kopp, AJ Garner, et al. (2018) Mapping sea-level change in time, space and probability. *Ann. Rev. Environ. Resourc.,* 43, 481-521.

Houston, J. R. and Dean R. G. (2011). Sea level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses. *J. Coastal Res*., 27(3): 409–417.

Howell, S, B Smith-Konter, N Frazer et al. (2016) The vertical fingerprint of earthquake cycle loading in Southern California. *Nature Geoscience*, DOI: 10.1038

JASON (2017) The Jason Products Handbook, NOAA NESDIS https://www.nodc.noaa.gov/media/pdf/jason2/j3_user_handbook.pdf

Jenkins, A, D Shoosmith, P Dutrieux et al. (2018) West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability. *Nature Geoscience*, 2018; DOI: 10.1038/s41561-018-0207-4

Jevrejeva, S, A Grinsted, JC Moore (2009) Anthropogenic forcing dominates sea level rise since 1850. *Geophys. Res. Lett,* **https://doi.org/10.1029/2009GL040216**

Jevrejeva, S., JC Moore, A Grinsted, A.Matthews, G Spada (2014) Trends and acceleration in global and regional sea levels since 1807. *Global and Planetary Change*, 113. 11-22. https://doi.org/10.1016/j.gloplacha.2013.12.004

Jorda` G (2014) Detection time for global and regional sea level trends and accelerations. *J Geophys Res Oceans* 119,7164–7174. doi:10.1002/2014JC010005

Karegar, MA, TH Dixon, SE Engelhart (2016), Subsidence along the Atlantic Coast of North America: Insights from GPS and late Holocene relative sea level data, *Geophys. Res. Lett.,* 43, 3126–3133, doi:10.1002/2016GL068015.

Kasmarek, M.C., and Ramage, J.K., 2017, Water-level altitudes 2017 and water-level changes in the Chicot, Evangeline, and Jasper aquifers and compaction 1973–2016 in the Chicot and Evangeline aquifers, Houston-Galveston region, Texas: U.S. Geological Survey Scientific Investigations Report 2017–5080, 32 p., https://doi.org/10.3133/sir20175080.

Kemp, A.C., A.J. Wright, R.J. Edwards (2018) Relative sea-level change in Newfoundland, Canada, during the past ~3000 years. *Quaternary Science Reviews,* 201, 89-110.

Kennedy, AJ, ML Griffin, SL Morey et al (2007) Effects of El Niño-Southern Oscillation on sea level anomalies along the Gulf of Mexico coast*.* *J. Geophys. Res.,* 112, C05047

Kingslake, J, RP Scherer T Albrecht et al. (2018) Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene. *Nature***, 558**, pages430–434

Kolker, AS, AM Dausman, GL Brown et al. (2018) Rethinking the river, *EOS, 99,* https://doi.org/10.1029/2018EO101169

Kopp, RE, AC Kemp, K Bitterman et al (2016) Temperature-driven global sea-level variability in the Common Era. *Proc. Nat. Acad. Sci,* E1434–E1441 http://www.pnas.org/content/early/2016/02/17/1517056113.full

Kopp, R. E., DeConto, R. M., Bader, D. A et al. (2017). Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections, *Earth's Future*, *5*, 1217–1233, https://doi.org/10.1002/ 2017EF000663

Lamb, HH (1995) *Climate, History and the Modern World.* Routledge, 464 pp.
Leclercq, P.W.; Oerlemans, J.; Basagic, H.J.; et al. (2014) A data set of worldwide glacier fluctuations. *The Cryosphere,* 8, 659 – 672
LeCozannet, G, JC Manceau, J Rohmer (2017) Bounding probabilistic sea-level projec- tions within the framework of the possibility theory. *Environmental Research Letters*, 12, 014012.
Letetrel, C, M Karpytchev, MN Bouin et al (2015) Estimation of vertical land movement rates along the coasts of the Gulf of Mexico over the past decades. *Continental Shelf Research,* 111, 42-51.
Lewis, N, JA Curry (2015) The implications for climate sensitivity of AR5 forcing and heat uptake estimates. *Climate Dynamics,* 45, 1009-1023
Lewis, N, JA Curry (2018) The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *J. Climate,* *https://doi.org/10.1175/JCLI-D-17-0667.1*
Little, CM, RM Horton, RE Kopp et al. (2014) Uncertainty in 21st Century CMIP5 Sea Level Projections. *Journal of Climate,* 28, 838-852.
Lim, YK, SD Schubert, SM Nowicki (2016) Atmospheric summer teleconnections and Greenland surface mass variations: insights from MERRA-2. *Environ. Res. Lett,* 11, 0204.
Loehle, C. (2018) The epistemological status of general circulation models. *Climate Dynamics,* 50, 1719-1731.
Loose, B., A.C.Naveira Garabato, P. Schlosser et al. (2018) Evidence of an active volcanic heat source beneath the Pine Island Glacier. *Nature Communications*, 9, Article number: 2431 (2018)
Lyu K., X. Zhang, J.A. Church et al. (2014) Time of emergence for regional sea-level change. *Nature Climate Change* 4, 1006–1010.
Marcos, M, B Marzeion, S Dangendorf (2016) Internal Variability Versus Anthropogenic Forcing on Sea Level and Its Components. *Surv. Geophysics*, DOI 10.1007/s10712-016-9373-3
Marcos, YM, M Catalan, TA Jordan et al. (2017) Heat flux distribution of Antarctica unveiled. Geophys. Res. Lett, https://doi.org/10.1002/2017GL075609
MacIntosh, CR, CJ Merchant, K von Schuckmann (2018) Uncertainties in Steric Sea Level Change Estimation During the Satellite Altimeter Era: Concepts and Practices. *Surv Geophysics*, 38, 59–87 DOI 10.1007/s10712-016-9387-x
Maloney, JM, SJ Bentley, K Xu et al. Mississippi River Subaqueous delta is entering a stage of retrogradation. *Marine Geology*, 400, 12-23.
Mauritsen, E, B Stevens, E Roeckner et al (2013) Tuning the climate of a global model. *J. Adv. Modelling Earth Systems.* https://doi.org/10.1029/2012MS000154
McCarthy, GD, ID Haigh, JJM Hirschi et al. (2015) Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature*, 521, 508-510.
Mernild, SH GE Liston (2012) Greenland Freshwater Runoff: Distribution and Trends, 1960-2010. *J. Climate,* https://doi.org/10.1175/JCLI-D-11-00592.1
Mernild, SH, GE Liston, AP Beckerman, JC Yde (2017) Reconstruction of the Greenland Ice Sheet surface mass balance and the spatiotemporal distribution of freshwater ruoff from Greenland to surrounding seas. *The Cryosphere,* https://doi.org/10.5194/tc-2017-234
Merrifield, MA, ST Merrifield, GT Mitchum (2009) An Anomalous Recent Acceleration of Global Sea Level Rise. *J. Climate* https://doi.org/10.1175/2009JCLI2985.1
Miller, KG, RE Kopp, BP Horton et al. (2013) A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast, *Earth's Future*, *1*, 3–18.
Mitrovica, JX, CC Hay, E Morrow et al. (2015) Reconciling past changes in Earth's rotation rate with 20th century global sea-level rise: Resolving Munk's enigma. *Science Advances*, 1, e1500679
Montillet, JP, TI Melbourne, WM Szeliga (2017) GPS vertical land motion corrections to sea-

level rise in the Pacific Northwest. *J. Geophys. Res. Oceans*, DOI 10.1002/2017JC013257
Munk, W (2007) Sea level rise: an enigma. *Proc. Nat. Acad. Sci.,* 99, 6550-6555.
NAS (2012) *Sea-Level Rise for the Coasts of California, Oregon and Washington: Past, Present, and Future.* Appendix A: Vertical Land Motion and Sea-Level Data Along the West Coast of the United States. National Academies Press, NAP.edu/10766.
Nerem, RS, A Cazenave, DP Chambers et al. (2007) Comment on "Estimating future sea level change from past records" by Axel Morner. *Global and Planetary Change,* 55, 358-360.
Nerem, RS, BD Beckley, JT Fasullo et al. (2018) Climate-change-driven accelerated sea level rise detected in the altimeter era. *Proc. Nat. Acad. Sci,* https://doi.org/10.1073/pnas.1717312115
Nienhuis, JA (2017). A New Subsidence Map for Coastal Louisiana, *GSA Today*. DOI: 10.1130/GSATG337GW.1
NOAA (2013) Estimating Vertical Land Motion from Long-Term Tide Gauge Records. NOAA Technical Report NOS CO-OPS 065.
NOAA (2017) *Global and regional sea level rise scenarios for the United States*. NOAA Technical Report NOS CO-OPS 083.
NOAA (2018) *Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold.* NOAA Technical Report NOS CO-OPS 087
Munneke, K, P., Luckman, A. J., Bevan. et al. (2018) Intense winter surface melt on an Antarctic ice shelf. *Geophysical Research Letters*, *45* https://doi.org/10.1029/2018GL077899
Nicolas, JP, DH Bromwich (2014) New reconstruction of Antarctic near-surface temperatures: Multidecadal trends and reliability of global reanalyses. *Journal of Climate*, **27** (21), 8070-8093, doi:10.1175/JCLI-D-13- 00733.1.
Parker, WS (2010) Predicting weather and climate: Uncertainty, ensembles and probability. *Studies in History and Philosophy of Science Part B,* 41, 263-272.
Parker, WS (2011) When Climate Models Agree: The Significance of Robust Model Predictions. *Philosophy of Science* 78 (4): 579–600.
Parris, A., P. Bromirski, V. Burkett, et al. (2012). *Global Sea Level Rise Scenarios for the US National Climate Assessment.* NOAA Tech Memo OAR CPO-1. 37 pp.
Prieto, AR, D Mourelle, WR Peltier et al. (2016) Relative sea-level changes during the Holocene in the Rio de la Plata Argentina and Uruguay: A review. *Quaternary International,* DOI: 10.1016/j.quaint.2016.02.044
Rignot, E, et al (2014) Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters*, **41** (10), 3502-3509.
Ritchie, J, H. Dowlatabadi (2017) Why do climate change scenarios return to coal? *Energy*, 140, 1276-1291.
Ritz, C., Edwards, T. L., Durand, G., Payne, A. J., Peyaud, V., & Hindmarsh, R. C. (2015). Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. *Nature*, *528*(7580), 115–118.
Rogozhina, I, AG Petrunin, APM Vaughan, et al. (2016) Melting at the base of the Greenland ice sheet explained by Iceland hotspot history. *Nature Geoscience,* DOI: 10.1038/NGEO2689
Rohling, EJ, ID Haigh, GL Foster et al. (2013) A geological perspective on future sea level rise. *Scientific Reports,* 3, 3461 DOI: 10.1038/srep03461
Rovere, A, P Stocchi, M Vacchi (2016) Eustatic and relative sea level changes. *Current Climate Change Reports,* 2, 221-231.
Rysgaard, S, J Bendtsen, J Mortensen, MK Sejr (2018) High geothermal heat flux in proximity to the Northern Greenland ice stream. *Scientific Reports,* 8, 1344. https://www.nature.com/articles/s41598-018-19244-x
Schroeder, DM, DD Blankenship, DA Young, E Quartini (2014) Evidence for elevated and

spatially variabile geothermal flux beneath the West Antarctic Ice Sheet. *Proc. Nat. Acad. Sci,* 111, 9070-9072.

Schwannwell, C, S Cornford, D Pollard, NE Barrand (2018) Dynamic response of Antarctic Peninsula Ice Sheet to potential collapse of Larsen C and George VI ice shelves *The Cryosphere,* 12, 2307–2326.

Shirzaei, M, R Burgmann (2018) Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area**.** *Science Advances,* 4, eaap9234

Slangen ABA, Church JA, Agosta C, et al. (2016) Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change.* doi:10.1038/nclimate2991

Smith, LA, N Stern (2011) Uncertainty in Science and Its Role in Climate Policy. *Phil. Trans. R. Soc. A,* 369, 4818–4841.

Smith, KL, LM Polvani (2017) Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models. *Climate Dynamics*, **48** (7-8), 2653-2670.

Stainforth DA, MR Allen, ER Tredger, L. Smith (2007) Confidence, uncertainty, and decision-support relevance in climate prediction. *Phil. Trans. Roy. Soc.* A, 365, 2145-2161.

Steig, EJ, et al. (2013) Recent climate and ice-sheet changes in West Antarctica compared with the past 2,000 years. *Nature Geoscience*, **6** (5), 372-375.

Thompson, PR, BD Hamlington, FW Landerer, S Adhikari (2016) Are Long Tide Gauge Records in the Wrong Place to Measure Global Sea Level Rise? *Geophys. Res. Lett.*, *43*, 10,403–10,411, doi:10.1002/2016GL070552.

Turner, J, et al., (2016) Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. *Nature*, **535** (7612), 411-415.

Valle-Levinson, A, A Dutton, JB Martin (2017) Spatial and temporal variability of sea level rise in the eastern United States. *Geophys. Res. Lett.,* https://doi.org/10.1002/2017GL073926

Van den Broeke, M, J Box, X Fettweis et al. (2017) Greenand ice sheet surface mass loss: recent developments in observation and modeling. *Curr Clim Change Rep*, 3, 345–356

van Vuuren DP, J Edmonds, M Kainuma, K Riahi, A Thomson et al. (2011) The representative concentration pathways: an overview. *Climatic Change,* 109, 5-31.

Wada, Y, et al. (2017) Recent Changes in Land Water Storage and its Contribution to Sea Level Variations. *Surveys in Geophysics*, **38** (1), 131-152.

Wang, W, CS Zender, D van As (2018) Temporal characteristics of cloud radiative effects on the Greenland ice sheet: discoveries from multiyear automatic weather station measurements. *J. Geophys. Res.,* https://doi.org/10.1029/2018JDO28540

Watson, PJ (2016) A new perspective on global mean sea level (GMSL) acceleration. *Geophysical Research Letters*, **43** (12), 6478-6484.

Watson, PJ (2016) Acceleration in U.S. mean sea level? A new insight using improved tools. *J. Coastal Res.,* 32, 1247-1261.

Watson, PJ (2017) Acceleration in European Mean Sea Level? A new insight using improved tools. *J. Coastal Research*, 33, 23-38.

WCRP (2017a) The World Climate Research Programme (WCRP) Grand Challenge on Regional Sea-level Change and Coastal Impacts https://www.wcrp-climate.org/component/content/article/687-gc-sealevel-regional-impacts-overview?catid=28&Itemid=264

WCRP (2017b) The World Climate Research Programme (WCRP) Conference Report on Regional Sea Level Changes and Coastal Impacts https://www.wcrp-climate.org/WCRP-publications/2018/WCRP-Report-No8-2018-SLC2017.pdf

WCRP (2017c) The World Climate Research Programme (WCRP) Grand Challenge on Clouds, Circulation and Climate Sensitivity https://www.wcrp-climate.org/images/documents/grand_challenges/GC4_Clouds_14nov2012.pdf

WCRP (2017d) The World Climate Research Programme (WCRP) Grand Challenges on Melting Ice and Global Consequences https://www.wcrp-climate.org/images/documents/grand_challenges/GC_cryo.pdf

WCRP (2018) Global sea-level budget 1993-present. Earth Syst. Sci. Data, 10, 1551–1590.

Woodworth, P.L.; White, N.J.; Jevrejeva,et al. (2009). Evidence for the accelerations of sea level rise on multi-decade and century timescales. *International Journal of Climatology,* 29, 777–789, doi:10.1002/joc. 1771.

Wunsch, C. (2018): Towards determining uncertainties in global oceanic mean values of heat, salt, and surface elevation. *Tellus Series A*, 70, 1445379, https://doi.org/10.1080/16000870.2018.1471911.