Sea-level Rise, Storm Surges, and Extreme Precipitation in Coastal New Hampshire: Analysis of Past and Projected Future Trends

Prepared by

Science and Technical Advisory Panel
New Hampshire Coastal Risks and Hazards Commission
(RSA 483-E)

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Executive Summary

Climate change is expected to have significant impacts on critical infrastructure, and natural and cultural resources in our seacoast region over the next century and beyond. In 2013 the New Hampshire Legislature created the New Hampshire Coastal Risks and Hazards Commission to consider key scientific research concerning future risks and provide recommendations to help New Hampshire communities and businesses prepare for these effects. In undertaking this work, the New Hampshire Coastal Risks and Hazards Commission established a Science and Technical Advisory Panel to distill the most important of the large volume of published scientific research pertaining to climate change and coastal flood risk, and advise the Coastal Risks and Hazards Commission on the data and projections that should be used in developing its guidance and recommendations.

The Panel followed the intent of the bill establishing the Commission (SB 163) in the selecting research to review.
"I. The commission shall review National Oceanic and Atmospheric Administration (NOAA) and other scientific agency projections of coastal storm inundation, and flood risk to determine the appropriate information, data, and property risks."

Thus while there are many websites and blogs on the science of climate change, we limited our review to NOAA and other peer-reviewed scientific reports and papers. Responses to points raised during the Commission review of our report on whether and to what extent temperatures are really rising or ice on land melting can be found in the US 2014 National Climate Assessment Frequently Asked Questions (Appendix 4, http://www.globalchange.gov/ncadac).

This document is the Science and Technical Advisory Panel's (Panel) report to the Coastal Risks and Hazards Commission (Commission). It outlines the projected impacts we will likely experience in the next few decades and out into the end of the century and recommends a number of assumptions and projections for the Commission to use. It is intended to specifically advise the Commission which will in turn develop specific recommendations to assist in planning and preparation for the changing climatic conditions.

Sea-level Rise. Global sea levels have been rising for decades and are expected to continue to rise well beyond the end of the 21st century. Rising seas pose significant risks to coastal areas around the globe and here in New England and New Hampshire. This includes risks to our coastal communities and ecosystems, cultural resources, Portsmouth Naval Shipyard, power plants, and other coastal infrastructure.

There are a wide variety of processes that cause sea level to change. Sea level varies as the ocean warms or cools, as water is transferred between the oceans and glaciers/ice sheets and between the oceans and continents, from vertical land movements, and by shifts in Earth's gravity field and ocean dynamics. Any reliable projections of future sea-level rise on a local to regional level require an assessment of the combined impact of all of these processes.

Recent estimates of sea-level rise have been provided by satellite altimetry data. Published studies conclude that since 1993 the global mean sea level has risen at a rate of 3.3 ±0.4 mm per year, or approximately double the longer-term rate over the 20th century. Detailed analysis indicates that since 1993, ocean warming (thermal expansion) is responsible for about 40% of global mean sea-level rise, melting glaciers (not including the Greenland and Antarctic ice sheets) are responsible for about 30%, and each of the Greenland and Antarctic ice sheets and transfer of land water storage to the oceans are each responsible for about 10%. These results indicate that loss of land based ice has provided a greater contribution to global sea-level rise compared to thermal expansion over the past two decades.

There are scores of recent papers published in the peer-reviewed scientific literature that provide projections of future global mean sea-level rise. We reviewed scenarios of future sea-level rise provided in three recent high profile and well regarded assessments: the 2012 National Research Council report[1], the 2013 Intergovernmental Panel on Climate Change report,[2] and the 2012-2014 National Climate Assessment.[3] All of these assessments (based on results in the peer-reviewed scientific literature) conclude that sea -level will continue to rise over the 21st century (and beyond), and the greatest uncertainty in the sea-level rise projections (especially out to 2100) is the rate and magnitude of ice loss from the Greenland and West Antarctic ice sheets. Projections of sea-level rise from these assessments range from 8 inches to 6.6 feet by 2100 (more detail provided in the report). The higher projections should be considered in situations where there is very low tolerance for risk or loss, while the lower estimate can be considered where there is a high tolerance for risk or loss.

The range of the estimates from the different assessments is closely related to the level of confidence placed on that estimate. In other words, the higher level of confidence (expressed as probability), the broader range of the estimate. For example, the 2013 Intergovernmental Panel on Climate Change estimate of 21-29 inches of sea-level rise by 2100 (range from 14 to 39 inches) from process-based models is deemed "likely", meaning there is a 66% probability of that amount of sea-level rise occurring. The National Climate Assessment report on sea-level rise provides a very high confidence (greater than 90% probability) that the global mean sea level will rise from the 1992 level at least 8 inches but no more than 6.6 feet by 2100. The larger the range, the higher the confidence that reality will fall within that range. The range for potential sea-level rise from the National Research Council falls between the Intergovernmental Panel on Climate Change and National Climate Assessment estimates.

In planning for a future condition a relatively narrow range of numbers is the most useful, yet if we want relative certainty that the estimate will be right, we have to accept a wide range, which is much harder to plan for.

Storm Surges. The New Hampshire coast is threatened by both extratropical storms (known locally as nor'easters) and tropical storms (locally known as hurricanes when they become

[1] NRC (2012) Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: The National Academies Press. http://www.nap.edu/catalog.php?record_id=13389

[2] Church, J.A., P.U. Clark, and others (2013) Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.climatechange2013.org/images/report/WG1AR5_Chapter13_FINAL.pdf

[3] Parris, A., and others (2012) Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1. 37 pp. http://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf

particularly strong). The counterclockwise (in the northern hemisphere) winds from nor'easters and hurricanes can drive ocean water towards the land resulting in the short-term rise in water levels (called surge). The actual size of a surge depends upon such features as storm intensity, forward speed, storm area size, the characteristics of the coast line and bathymetry, and the angle of approach to the coast.

Given the infrequent occurrence of major hurricane landfall further north along the New England coast, nor'easters account for the majority of storm surge events, particularly within the Gulf of Maine. Over the past ten years, the largest storm surges observed at Fort Point, New Hampshire occurred during nor'easters, which may impact the region for several days and produce a storm surge with or without the addition of inland runoff from heavy precipitation.

No research consistently finds a trend in the frequency and/or intensity of nor'easters over the period of record. While there has been a significant increase in hurricane losses nationwide over the 20th century, there continues to be some uncertainty in the trends in hurricane frequency and intensity within any given region.

There is also considerable uncertainty concerning projections of changes in nor'easters in the future. There is some suggestion they may be less frequent and less intense. Over the next century there may be fewer but more intense tropical storms with a possible poleward shift in storm tracks. The possible change in frequency particularly is far from resolved by experts. At this time the Panel concludes that there is insufficient basis to draw a specific conclusion whether larger storm surges will occur in the future but emphasize that future storm surges will occur on top of higher sea levels (Table ES.1). Considering changes in surge high water levels due to sea-level rise alone, today's extreme surge events (i.e. 100-year surge) will have a greater inundation extent and a shorter return period by 2100.

Precipitation. The mean annual precipitation in the Northeast has increased by approximately 5 inches, more than 10 %, from 1895 and 2011. The region also had a large increase in extreme precipitation between 1901 and 2012; for example, there has been a greater than 50 % increase in the annual amount of precipitation from storms classified as extreme events. Projected increases in annual precipitation are uncertain but could be as high as 20 % in the period 2071-2099 compared to 1970-1999, with most of the increases in winter and spring with less increase in the fall and perhaps none in the summer. Extreme precipitation is also projected to increase with the occurrence of extreme rainfall events during summer and fall influenced by changes in tropical storm activity as the rainfall amounts produced by tropical storms is projected to increase. In general, total annual precipitation is expected to increase as is extreme precipitation.

Application of Findings for Municipalities and the State. The recommendations presented here are based upon our collective analysis of the information provided in this report combined with our expert assessment. The information used to make this assessment is dynamic and based on frequently updated data and research. Therefore we suggest the assessment be updated periodically, and at least every two years.

- <u>Sea-level Rise.</u> We believe the range that best covers plausible sea-level rise increases to 2050 and 2100 are those prepared for the US National Climate Assessment and include the "Highest" and "Intermediate Low" scenarios (Table ES.1). For simplicity, we have only provided values for 2050 and 2100 (using a reference year for mean sea level of 1992). If a finer time scale is needed, it can be provided. Local and regional influences from land subsidence and gravity effects are not expected to be significant compared to the global sea-level rise changes. However, dynamic changes in ocean circulation (which are difficult to predict) may increase coastal New England sea-level rise projections by as much as eight to twelve inches by 2100.

Time Period*	**"Intermediate Low**	**"Intermediate High"**	**"Highest"**
2050	0.6 ft.	1.3 ft.	2.0 ft.
2100	1.6 ft.	3.9 ft.	6.60 ft.

*using mean sea level in 1992 as a reference (Parris et al., 2012)

Table ES.1. Sea-Level Rise Scenarios (in feet) Provided by the National Climate Assessment (Parris et al., 2012).

We recommend, however, that for coastal locations where there is little tolerance for risk in protecting new infrastructure or existing coastal settlements, infrastructure or ecosystems, that the range include that from the Intermediate High to the Highest (Table ES.1) and that the range be applied as follows:

1. **Determine** the time period over which the system is designed to serve (either in the range 2014 to 2050, or 2051 to 2100).

2. **Commit** to manage to the Intermediate High condition, but be **prepared** to manage and adapt to the Highest condition if necessary.

3. Be **aware** that the projected sea-level rise ranges may change and adjust if necessary.

For example, for a project with a lifetime past 2050, a flood wall could be constructed for the highest scenario (6.6 feet) now, which would be the most robust approach, or constructed for 2 feet of future sea-level rise now but in a manner that would facilitate expanding and raising the wall to protect against 3.9 or 6.6 feet of sea-level rise, if future assessments indicate that is necessary. This could be accomplished by designing and constructing the wall foundation for the 6.6 feet sea-level rise scenario while only constructing the wall for a 2-foot sea-level rise scenario. The choice of management strategies can include strategies to protect, accommodate or retreat from the threat.

We anticipate that specific recommendations and standards for implementing this approach will be further developed in the Commission's subsequent reports.

- Storm Surge. Given the uncertainties associated with future storm surge changes, we recommend that projects continue to use the present frequency distributions for storm surge heights and these be added to sea-level rise conditions. The flood area of the current 100-year storm surge will increase as sea level rises. Similarly, the area flooded by a 100 year surge today will be flooded more frequently by smaller surges as sea level rises. Higher sea level (resulting from a combination of storm surge and sea-level rise) will also result in longer durations of flooding.

- Extreme Precipitation. Extreme precipitation events are projected to increase in frequency and amount of precipitation produced; however, we are unable at present to confidently quantify exact future changes in extreme precipitation events, We do, however, recommend at a minimum that all related infrastructure be designed with storm intensities based on the current Northeast Regional Climate Center (Cornell) atlas to represent current precipitation conditions and infrastructure should be designed to manage a 15 % increase in extreme precipitation events after 2050 and that a review of these projections be continued.

1. Introduction

The New Hampshire Coastal Risks and Hazards Commission (Commission) was established by the New Hampshire Legislature effective July 2, 2013. The Commission was charged with recommending legislation, rules and other actions to prepare for projected sea-level rise and other coastal and coastal watershed hazards such as storms, increased river flooding, and storm water runoff, and the risks such hazards pose to municipalities and state assets in New Hampshire. The Commission was also charged with reviewing National Oceanic and Atmospheric Administration (NOAA) and other scientific agency projections of coastal storm inundation and flood risk to determine the appropriate information, data and property risk. The Commission requested the Chair to organize and provide a charge to a Science and Technical Advisory Panel (Panel) to help address this task. Specifically, the charge to the Panel was to:

1. Ensure the Commission is aware of and using the best available and relevant scientific and technical information to inform our recommendations;
2. Assist the Commission in interpreting and reconciling conflicting projections, scenarios and probabilities about future conditions; and
3. Review, evaluate, and respond to any major theory and supporting evidence put forward refuting the high likelihood of continued, accelerated sea-level rise and increased coastal risks and hazards.

This report addresses these issues by analyzing trends and projections for 2050 and 2100 of sea-level rise coastal storms, and extreme precipitation.

The Panel followed the intent of the bill establishing the Commission (SB 163) in the selecting research to review.

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Thus while there are many websites and blogs on the science of climate change, the Science and Technical Advisory Panel limited our review to National Oceanic Atmospheric Administration and other peer-reviewed scientific reports and papers. Responses to points raised during the Commission review of our report on whether temperatures are really rising and ice on land melting can be found in the US 2014 National Climate Assessment Frequently Asked Questions. (Appendix 4, www.globalchange.gov/ncadac).

2. Sea-level Rise

2.1 Processes that Contribute to Global and Regional Sea-level Rise

There are a wide variety of processes that cause sea level to change on time scales ranging from hours to millennia, and spatial scales ranging from regional to global. Sea level varies as:

- the ocean warms or cools (because the density of water is closely related to its temperature),
- water is transferred between the ocean and glaciers/ice sheets,
- water is transferred between the ocean and continents,
- a result of vertical land movements associated with glacial isostatic adjustment, tectonic activity, groundwater mining, or hydrocarbon extraction,
- shifts in Earth's gravity field are induced by changes in the mass distribution on land (self-gravitation or static effect), and ocean and atmosphere dynamics (the dynamics effect).

Here we provide a brief review of these processes as it is the sum of these processes that will drive future changes in relative sea level on New Hampshire's coast. The processes are summarized in Figure 2.1 with values in Table 2.1.

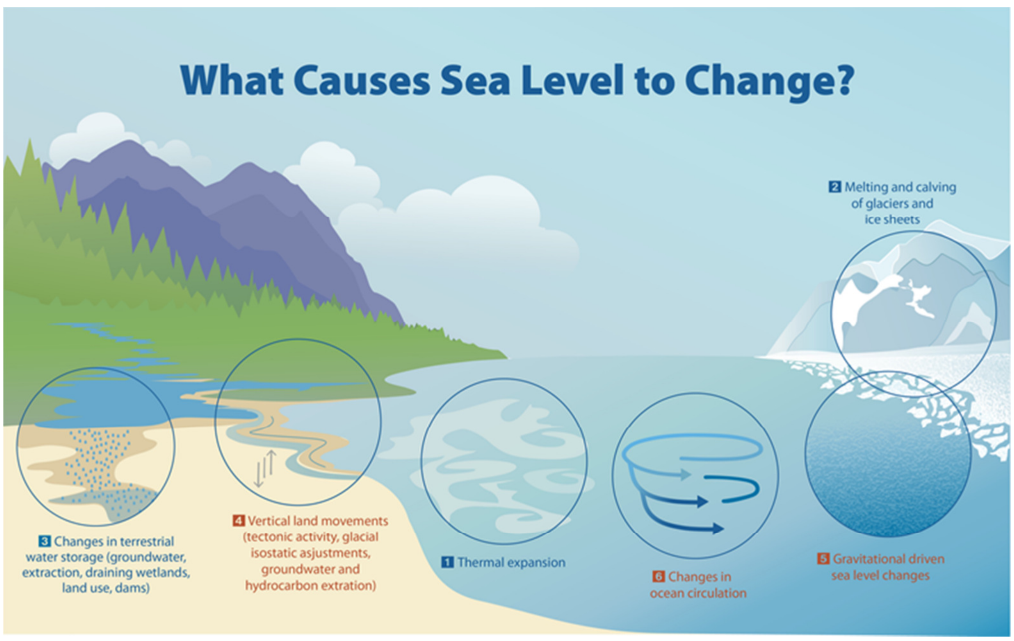


Figure 2.1. Six processes contributing to global and regional changes in relative sea level. Numbers and text in blue (1, 2, 3) represent processes that change global mean sea level; those in red (4, 5, 6) represent processes that change sea level on a regional scale. Each of the six processes referred to in this figure are explained in the text. Figure modified from Griggs (2001).

1. Thermal Expansion: Changes in the temperature of salt water in the oceans contributes to changes in the volume of water in the oceans due to thermal expansion or contraction. Seawater reaches a maximum density at its freezing point, which is usually below 0^{o}C because of its salinity. As a result, when the ocean warms, seawater becomes less dense and expands, raising sea levels. This is commonly referred to as the steric or thermosteric component of sea-level rise. Detailed analysis of historical ocean temperature data from 1955-2010 conclude that the world's oceans over a depth range from 0-2000 meters experienced a warming of 0.09^{o}C (Levitus et al., 2012). Based on a heat content calculation, this represents approximately 93% of the warming of the earth system that has occurred since 1955 and corresponds to a thermal expansion of 0.54±0.05 mm per year for the 0-2000 meter layer, or approximately one-third of total global mean seal level rise over that time period. Since 1992, thermal expansion has accounted for approximately 40% of the observed sea-level rise.

2. Glaciers and Ice Sheets: Melting and calving of land-based ice results in a transfer of water and ice from the land into the oceans and is a major contributor to global mean sea-level rise equivalent to or exceeding the contribution from thermal expansion over the past two decades (NRC, 2012; Church et al., 2013). While ice sheets are technically also glaciers, contributions from the Greenland and Antarctic ice sheets are commonly treated separately from the contribution of other glaciers. This is primarily the result of the rather large amount of water stored in the ice sheets. The Antarctic and Greenland ice sheets store the equivalent of about 190 feet and 20 feet of sea level rise, respectively (Bamber et al., 2001; NSIDC, 2014). Since 1992; glaciers (not including the Greenland and Antarctic ice sheets) are responsible to about 30% of the observed sea-level rise, and the Greenland and Antarctic ice sheets are responsible for about 10% each (details provided in Table 2.3).

3. Terrestrial Water Storage: A decrease in the amount of water stored on continents generally results in a similar amount of increase of water stored in the oceans (and vice versa). Groundwater extraction, draining wetlands, or changes in land cover that reduce water storage in soils (e.g., deforestation) eventually results in additional water flowing into the ocean and causing sea levels to rise. Conversely, water stored behind dams serves to reduce the volume of water in the oceans. While the construction of dams during the 20th century significantly increased terrestrial storage of water, groundwater extraction is now equivalent to or larger than expanded surface water storage, resulting in a net zero or small positive contribution to sea-level rise in recent years from changes in terrestrial water storage (NRC, 2012; Church et al., 2013). The transfer of land water storage to the oceans is responsible for about 10% of the observed global mean sea level rise since 1992 (details provided in Table 2.3).

4. Vertical Land Movements: Local and regional vertical land movements also result in regional changes in relative sea level. These vertical land movements are related to regional-specific processes such as tectonic activity, glacial isostatic adjustment, land surface changes due to compaction, groundwater mining, and hydrocarbon extraction (e.g., Peltier, 1998; Wöppelmann et al., 2009; King et al., 2012). Along the northeastern U.S. coast, vertical land movements are driven primarily by glacial isostatic adjustment and range from less than 0.3 inches per decade along the Maine coast to 0.7 inches per decade in Delaware (Brown, 1978; Anderson et al., 1984; Kirshen et al., 2008; Koohzare et al., 2008; Engelhart et al., 2009; Zervas, 2001).

5. Gravity Effects: Since ice and water have mass, ice and water on land will attract ocean water, literally pulling the ocean toward, for example, an ice sheet. Consequently sea level is higher near an ice sheet rather than further away from it, everything else being equal. When land ice melts and the water mass is added to the ocean, it raises sea level by a small amount averaged over the whole globe, but close to the ice mass (within about 2000 miles) it may actually cause a sea level fall by a reduction in the self-gravitation effect. This is shown in Figure 2. 2.

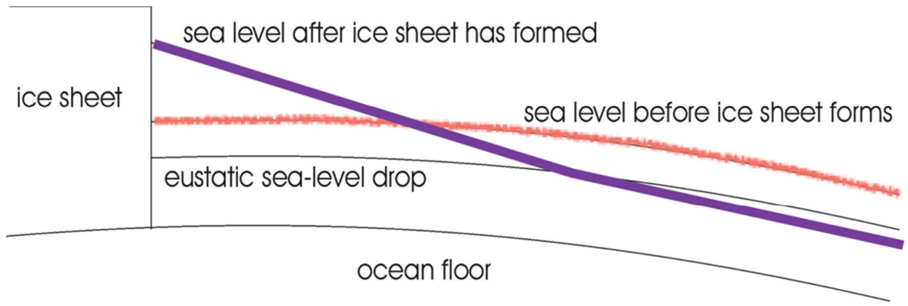


Figure 2.2. Schematic of the self-gravitation effect. The ocean is pulled toward the mass of an ice sheet which raises sea level locally. A reduction in the ice sheet mass causes a local lowering of sea level although sea level is raised significantly away from the ice sheet.

The impact of the self-gravitation effect on future sea level projections was ignored in early Intergovernmental Panel on Climate Change assessment reports and in the associated scientific literature, even though the effect has been known since the 1800s and its impact had been studied in paleoclimate contexts (Woodward, 1886; Upham, 1895; Clark 1976). Mitrovica et al (2001) provided a reminder to the community of the importance of this effect within a future and past climate change context. Loss of ice mass in Antarctica causes a reduction of sea level due to the self-gravitation effect, locally along the Antarctic coast, but enhanced increases throughout the Northern Hemisphere, and losses in Greenland has the opposite impact. The effect of smaller, isolated, glaciers is patchier and of smaller magnitude. Much subsequent effort has been expended to parse out the role of self-gravitation in explaining vexing spatial differences in past sea level records as well as working out the details of its impact in the future. Incorporating these patterns, called 'fingerprints' into interpretations of paleo-sea level records has enabled a great leap forward in integrating and understanding records that were previously difficult to reconcile.

Importantly for our purposes here, the impact of West Antarctic Ice Sheet melt through self-gravitation and other effects is maximized along the eastern and western seaboards of North America at approximately 40 degrees north latitude. Under a fast melt scenario, this will lead to a 25% increase locally by 2100 of the sea level effect over the amount expected over the global mean (Bamber et al, 2009). It is difficult to predict with accuracy whether or not the West Antarctic Ice Sheet eventually melts and the time scale of this melt, although recent results suggest the process is underway and potentially unstoppable at this point (Joughin et al., 2014; Mouginot et al., 2014).

6. Dynamic component: The dynamic component is best thought of with reference to meteorological phenomena that people are familiar with. Just as winds flow around masses of air, which we call highs and lows, current systems in the ocean are found in association with hills and valleys in sea level height (called steric height variations or 'dynamic topography'). This current system arises through a complex interplay between global and local features including winds, topography, and fluxes of heat and salt.

The Gulf Stream is a vigorous current system that is associated with the largest of these highs in dynamic topography that lies just to the south of New Hampshire's seacoast. As a consequence of the complex interactions that go into predicting the location and strength of the Gulf Stream, this is a difficult system to model (Griffies and Greatbatch, 2012), consequently simulations in the region tend to be relatively poor (Landerer et al., 2013) and predictions for the future have a greater degree of uncertainty associated with them (Yin, 2012) than is true for some other elements of sea level prediction (such as the global thermal expansion).

Nevertheless, some aspects of the system are at least boundable. Over the next couple of decades the regional pattern of sea level change will be influenced by dynamical changes in the ocean-atmosphere system associated with natural modes of variation (including the El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation). All these natural oscillations have large local-to-regional scale impacts on sea level in time scales of years to decades.

General Circulation Models (also referred to as Global Climate Models, GCM) tend to predict some trends in regional, dynamically-driven sea level variations that emerge through this noise of natural variability in the latter half of the 21st century. The most relevant of which for the New Hampshire seacoast is a poleward movement and weakening of the Gulf Stream in some models (Yin, 2012) associated with large scale changes in winds and air-sea fluxes of heat and moisture and changes in formation of North Atlantic deep water (Bouttes et al., 2013). Some models do not predict such a shift, but among the ones that do it is associated with an increase in local sea level of several inches. Whether a long term trend in the dynamical component of sea level ever emerges in the New Hampshire seacoast is beyond the current capability of GCMs because natural variability is large and models produce diverging results for the future (Yin, 2012; Bouttes et al., 2013). So it is reasonable to assume that a middle-of-the-road handling of the dynamic effect is that it is 8 to 12 inches locally, but that the uncertainty is weighted toward higher positive (i.e. net sea-level rise) values by 2100.

2.2 Past Sea-level Rise

Changes in Sea Level over the Past 400,000 years

Sea level has been naturally rising and falling in a cyclic manner throughout the earth's history. This rise and fall of sea level has been associated with periods of glaciation and deglaciation of the earth, of which there have been four major cycles (and numerous smaller cycles) over the past 400,000 years (Figure 2.3). At the peak of the last interglacial warm period, approximately 125,000 years ago, mean sea level on the Earth was approximately 13 to 30 feet higher than it is today (Huybrechts, 2002; Kopp et al., 2009, 2013; Dutton & Lambeck, 2012). Since that time, sea level generally fell until the last glacial maximum, approximately 20,000 years ago, and has been rising ever since.

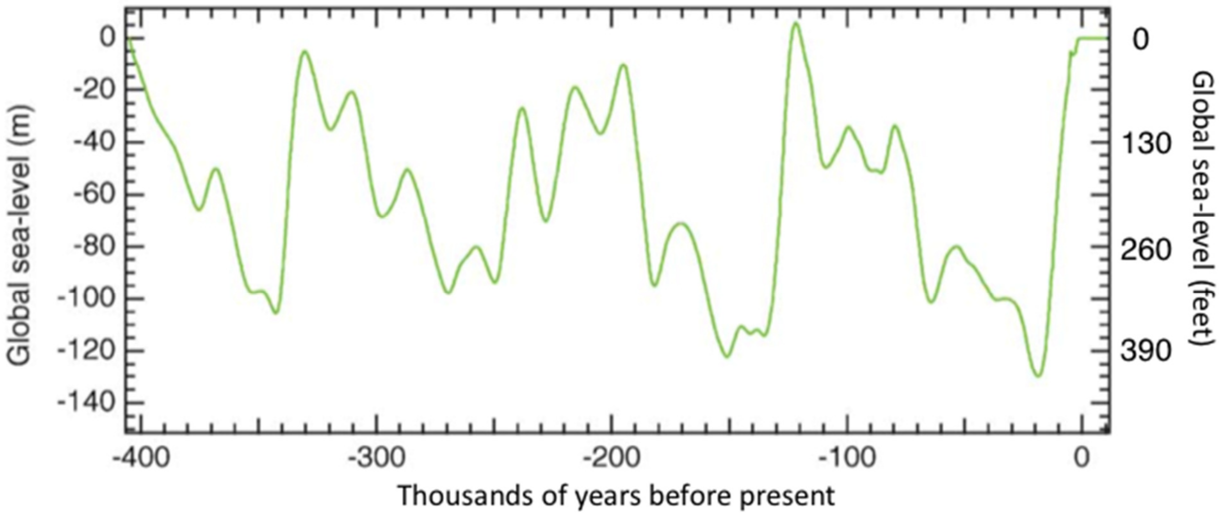


Figure 2.3. Changes in global sea-level over the past 400,000 years. Figure from Huybrechts (2002).

During periods of sea-level rise associated with deglaciation, sea level generally rose at a steady rate for several thousand years. These periods of steady rise, however, were periodically interrupted by periods (less than 1,000 years in length) of extremely fast sea-level rise. Global geologic records have identified two periods of extremely fast sea-level rise since the last glacial maximum, one of which occurred approximately 14,600 years ago and the other of which occurred approximately 11,300 years ago. During these two pulses, global sea level rose at rates greater than 20 mm per year, and perhaps as high as 50 mm per year, for several centuries (Fairbanks, 1989; Peltier and Fairbanks, 2006; Carlson and Clark, 2012; Deschamps, et al 2012), or rates that were significantly greater than the global average rate for the 20th century.

Sea-level can rise and fall at rates that vary across the Earth so it is important to know how applicable the extreme rates of sea-level rise described above are to coastal New Hampshire. Is there a historic precedence for extreme rates of sea-level rise in New Hampshire or are these rates irrelevant here? While there have been no rigorous studies of long-term sea-level rise in New Hampshire, the University of Maine and Maine Geological Survey did conduct a study in Wells, Maine, less than 20 miles north of Portsmouth, New Hampshire. This study concluded that southern Maine had experienced geologically recent (during the current or Holocene epoch) periods of extremely fast sea-level rise with rates of approximately 22 mm/year (Kelley et al., 1996). While less than the global extreme rates measured at other locations, this rate is still over ten times greater than the average sea-level rise rate for New Hampshire for the 20th century and provides evidence that an acceleration in the rate of sea-level rise from the current rate is not only physically possible, but has happened before.

20th Century Sea-Level Rise

Data from tide gauges around the world provide reliable records of changes in relative sea-level at many locations around the globe over the 20th century (PSMSL 2014) and provide a measure of the combined effects of changes in the volume of water in the ocean and vertical land motion. A variety of approaches have been employed to estimate the rate of 20th century global mean sea-level rise from the tide gauge records including: analysis of only nearly continuous, very long records (Holgate, 2007), using shorter but more numerous records and filters to compute longer term trends (Jevrejeva et al., 2006, 2008), analysis using neural networks (Wenzel and Schroeter, 2010), or performing empirical orthogonal functions analysis (Church and White, 2006; 2011; Ray and Douglas, 2011). The different analytical approaches show very similar century scale trends of about 1.7$\pm$0.3 mm per year over the 20th century (Table 2.1; Figure 2.4).

Various estimates of sea-level rise since 1992 have also been developed based upon satellite altimetry data collected from the TOPEX/Poseidon satellite and its successors (Jason-1, Jason-2). Published studies conclude that the global mean sea level since 1992 has risen at a rate of 3.3 $\pm$0.4 mm per year, as shown in Table 2.2.

It should be noted that the satellite data set from which this rate is derived covers a relatively short period, about 20 years in duration, which is not sufficient to base conclusions about current rates of global sea level rise.

In general, the Army Corps of Engineers and National Oceanic and Atmospheric Administration recommend against using data records shorter than 40 years when determining sea level trends, for the following reasons:

1) A 19-year period is used by the Army Corps of Engineers and National Oceanic and Atmospheric Administration to describe tidal cycles around the world (a 19-year period allows us to include the 18.6 year period for the regression of the lunar nodes). At least two full cycles are generally needed to determine a reasonable trend.

2) There are very long period oscillations in the large ocean basins that, in some instances, are multiple decades in length. A 40-year period of record allows an accounting for the variations in sea-surface height that are associated with these multi-decadal oscillations.

3) Analyses by the National Oceanic and Atmospheric Administration and in the Army Corps of Engineers sea level guidance indicate the standard error of the estimate of the sea-level rise trend decreases significantly with periods of record longer than 40 years.

What can be said definitively is that the global rate of sea-level rise for the 20th century, as measured from tide gauges, was ~1.7 mm/yr. and that the satellite record shows a mean trend of ~3.2 mm/yr. for its 20-year period of record. As the satellite data set deepens over time it will provide a stronger basis for estimating current rates of sea level rise and the degree to which it is accelerating.

The various contributions from thermal expansion, glaciers and ice sheets, and changes in land water storage are provided in Table 2.3 for two time periods (1970 – 2010 and 1993 – 2010). The results indicate that since 1992, thermal expansion is responsible for about 40% of global mean sea-level rise, glaciers (not including the Greenland and Antarctic ice sheets) are responsible to about 30%, and each of the ice sheets and transfer of land water storage to the oceans are responsible for about 10%. These results indicate that loss of land based ice has provided a greater contribution to global sea-level rise compared to thermal expansion over the past two decades.

Coastal New Hampshire

Relative sea level has been rising on the New Hampshire coast for the past 10,000 years (Kelly et al., 1995; Ward and Adams, 2001). However, direct measurements of relative sea level have been recorded at the Portsmouth Naval Shipyard (Seavey Island, Maine) tide gauge only since 1926 (NOAA, 2014).[4] For the period 1927 to 2001, sea level rose nearly half a foot (5.3 inches), at a rate of about 0.7 inches per decade (1.76±0.30 mm/yr.) (Figure 2.5). This rate of sea-level rise is very close to the global mean sea-level rise of about 1.7±0.3 mm per year over the 20th century described above, suggesting that processes that cause regional changes in relative seal-level (such as glacial isostatic adjustment or changes in regional ocean dynamics or gravitational influences) have had negligible influences on relative sea-level rise in coastal New Hampshire. The rate of sea-level rise from the Portland Maine tide gauge (Figure 2.5) is also similar to Seavey Island (1.82±0.18 mm/yr.), suggesting a similar lack of influence of vertical land movements and other influences over the 20th century in the coastal regions of southern Maine. In contrast, the Boston tide gauge record (Figure 2.5) shows a higher rate of sea-level rise of 2.63±0.18 mm/yr. This higher rate is most likely due to coastal subsidence that is a significant factor in the higher rates of sea-level rise observed from Boston south to the mid-Atlantic (Kirshen et al., 2008; CCSP, 2009).

Reference	GMSL rise (mm per year)	range (5-95%) (mm per year)	Period
Church & White 2006	1.7	1.4 to 2.0	1900-1999
Holgate 2007	1.74	1.58 to 1.90	1904-2003
Jevrejeva et al. 2008	1.9	NA	1900-1999
Wenzel & Schroter 2010	1.56	1.31 to 1.81	1900-2006
Church & White 2011	1.7	1.5 to 1.9	1900-2009
Ray & Douglas 2011	1.70	1.44 to 1.96	1900-2010

Table 2.1. Summary of global mean sea-level (GMSL) rise during the 20th century estimated from tide gauge records.

Reference	**GMSL rise (mm per year)**	**Range (5-95%)**	**Period**
Beckley et al. 2010	3.3	2.9 to 3.7	1993-2010
Nerem et al. 2010	3.4	3.0 to 3.8	1993-2009
Church & White 2011	3.2	2.8 to 3.6	1993-2009

Table 2.2. Summary of results of global mean sea-level (GMSL) rise since 1992 from tide gauge and satellite altimetry measurements.

[4] In 2003, the Fort Point tide gauge replaced the Seavey Island gauge, but this new gauge does not have a long enough record from which to examine changes in relative sea level.

GMSL Rise Component	1971-2010		1993-2010	
	median	range (5-95%)	median	range (5-95%)
Thermal expansion	0.8	0.5 to 1.1	1.1	0.8 to 1.4
Glaciers (not including Greenland and Antarctic ice Sheets)	0.68	0.22 to 1.08	0.86	0.32 to 1.26
Greenland Ice Sheet	na	na	0.33	0.25 to 0.41
Antarctic Ice Sheet	na	na	0.27	0.16 to 0.38
Land water storage	0.12	0.03-0.22	0.38	0.26 to 0.49
Total contributions			2.8	2.3 to 3.4
Observed GMSL rise			3.2	2.8 to 3.6

Table 2.3. Estimated contributions to global mean sea-level (GMSL) rise (mm per year). Data from Church et al. (2013, Table 13.1).

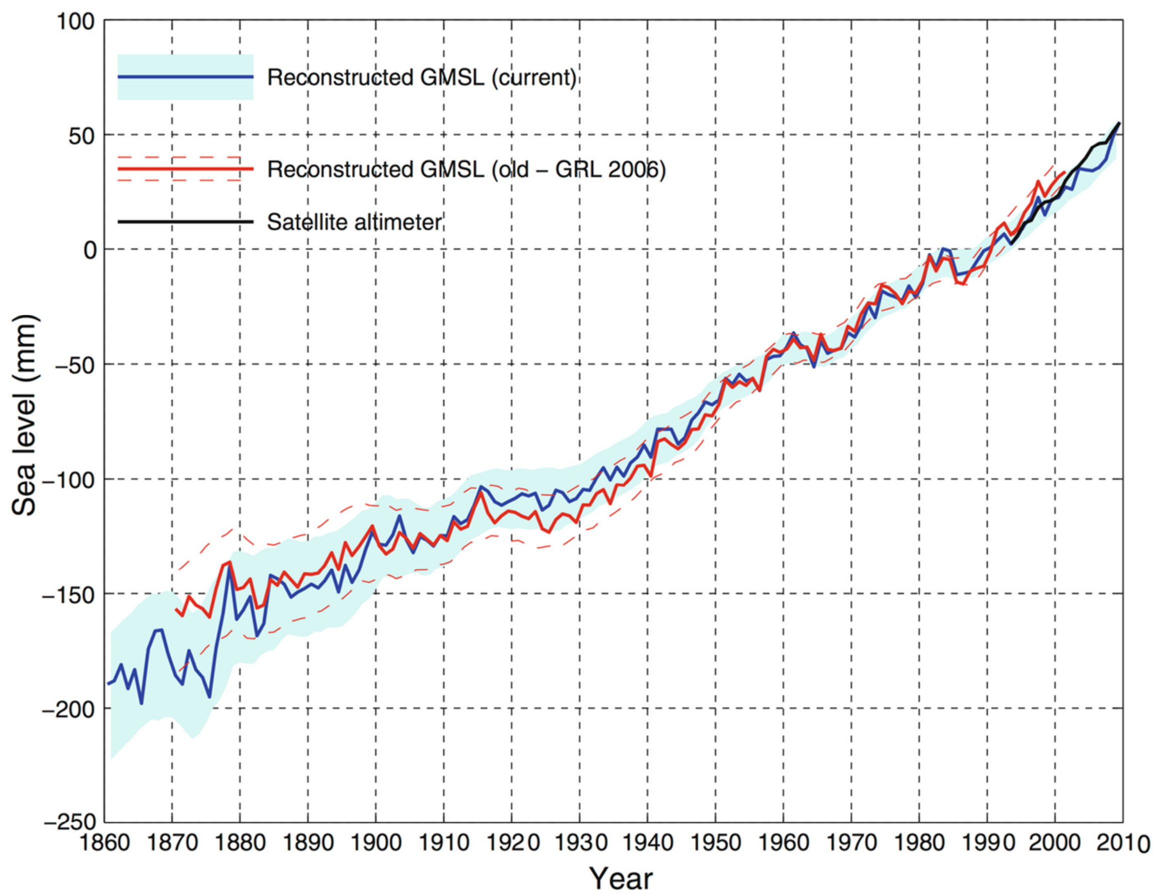


Figure 2.4. Global mean sea-level (GMSL) rise from 1860 to 2010 from Church and White (2011). Estimates from an earlier paper (Church and White, 2006) and satellite altimeter data are also included.

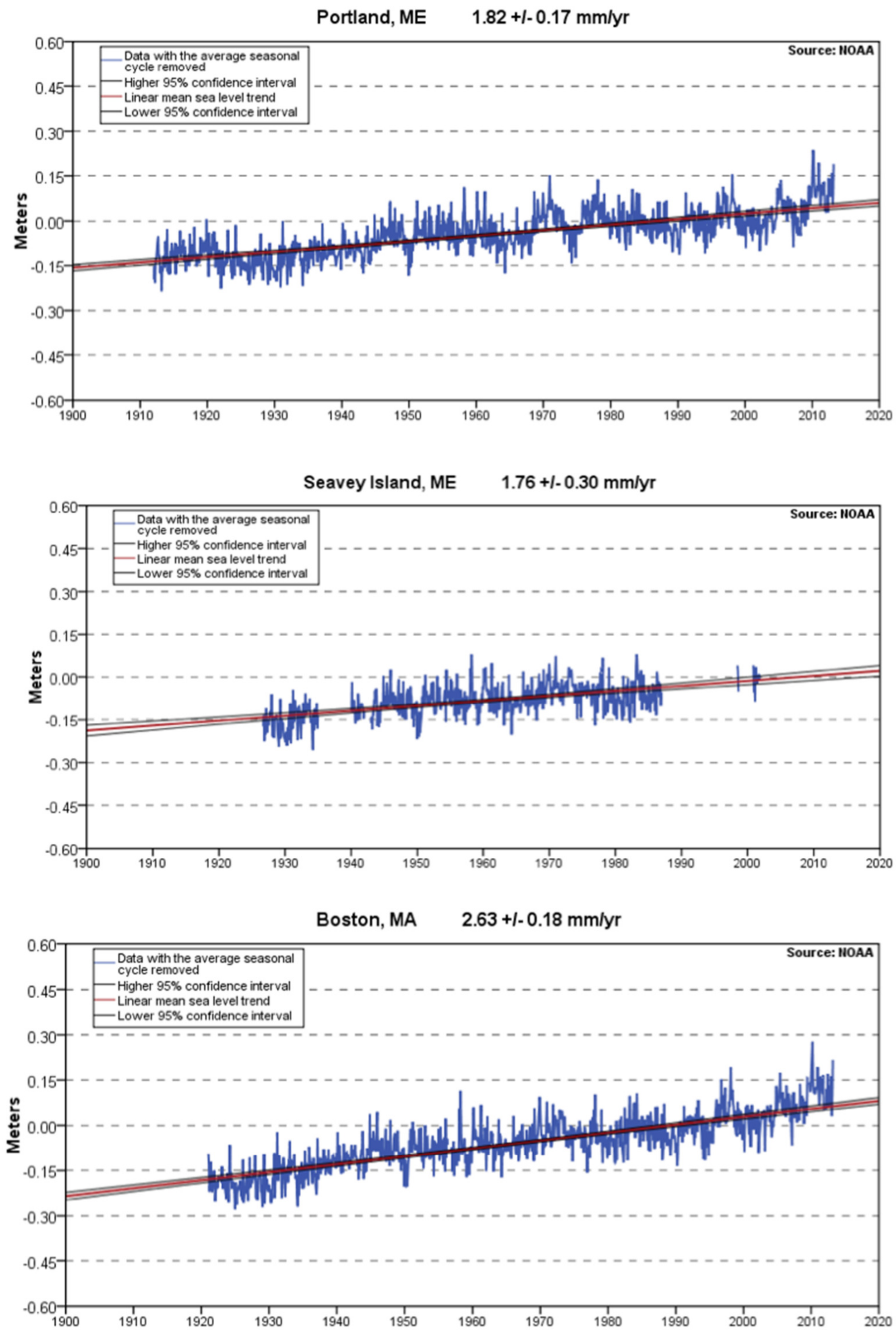


Figure 2.5. Mean sea level trends from Portland, Maine; Seavey Island (Portsmouth Naval Shipyard), Maine; and Boston Massachusetts based on observed monthly mean sea level data from NOAA tide gauges (NOAA 2014).

2.3. Projected Sea-level Rise

There are many papers published in the peer-reviewed scientific literature over the past decade that provide a set of scenarios of future sea-level rise (see bibliography for citations to specific papers). Instead of detailing the results from the scores of specific published papers, we reviewed scenarios of future sea-level rise provided in three recent high profile and well regarded assessments: the National Research Council assessment of sea-level rise (NRC, 2012), the Intergovernmental Panel on Climate Change assessment of sea-level rise (Church et al, 2013), and global sea-level rise scenarios developed for the National Climate Assessment (NCA) (Parris et al., 2012; Mellilio et al., 2014). Scenarios do not provide a prediction of future change, but rather describe plausible potential future conditions in a way that supports decision making under conditions of uncertainty (Moss et al 2010, Gray 2011, Weeks et al 2011). This approach allows for the analysis of vulnerabilities, potential impacts, and adaptation strategies associated with possible, uncertain futures.

Projections of global sea-level rise are commonly made using: (1) models of the ocean-atmosphere-climate system (GCMs, these are also referred to as process based models); (2) semi-empirical models, (3) extrapolations, or (4) some combination of these methods.

Ocean-atmosphere-climate system models are based on the mathematical simulation of the physical processes that govern the climate system and changes in sea level, and they are used to project the response of those processes to different greenhouse gas emission scenarios. This approach provides a reliable estimate of the thermal expansion of sea-level rise, but the models tend to underestimate the contributions to sea-level rise from melting ice as they do not account fully for the dynamic and rapid response of ice sheets and glaciers to increases in global atmospheric and sea surface temperatures (NRC, 2012). The 2007 Intergovernmental Panel on Climate Change projections were made using this method and they are likely too low. In contrast, semi-empirical methods rely on modeling the past relationship between sea level and atmospheric temperature, and then extrapolating future sea level based on projections of atmospheric temperature. The widely cited sea-level rise estimates of Vermeer and Rahmstrof (2009) used the semi-empirical methods. Estimates of the total contribution from melting land ice have been developed by extrapolating observations of recent ice loss into the future (e.g., Pfeffer et al., 2008). Finally, the recent 2013 Intergovernmental Panel on Climate Change sea-level rise assessments include a review of both process-based and semi-empirical models (although their final estimates of sea-level rise are based on the process based models), while the National Research Council (2012) and the National Climate Assessment (Parris et al., 2012; Mellilio et al., 2014) use a combination of approaches for their projections.

National Research Council (2012)

The National Research Council (2012) provided a thorough review of past and future global sea-level rise and considered results from process based models, semi-empirical methods, and expert assessment. They used global climate model simulations from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) to estimate the thermal contribution and extrapolation techniques to estimate the cryospheric contribution. The terrestrial land storage component was assumed to be near zero and was not factored into their projections.

The NRC (2012) report estimates that global sea level will rise 3-9 inches by 2030, 7-19 inches by 2050, and 20-55 inches by 2100, relative to 2000 levels (Figure 2.6). These global sea-level rise projections for 2100 are substantially higher than the Intergovernmental Panel on Climate Change's (2007) projection (mainly due to the observed more rapidly growing contributions from ice sheets) and are somewhat lower than the Vermeer and Rahmstorf (2009) semi-empirical projections. Note that for time periods further in the future (e.g., end of the century) the uncertainties grow as the ranges of projected sea-level rise widen. The major sources of uncertainty are related to the estimated contributions from ice sheets and the growth of future greenhouse gas emissions.

Intergovernmental Panel on Climate Change Fifth Assessment Report (2013)

The Intergovernmental Panel on Climate Change Fifth Assessment Report provides an extensive review of the results of papers published in the scientific literature for projections of sea-level rise based on GCM simulations. The global climate models were driven by three different scenarios of the emissions of heat trapping gases (called Representative Concentration Pathways 4.5, 6.0, and 8.5; Moss et al., 2010). The numbers refer to the total radiative forcing in 2100 due to anthropogenic greenhouse gas emissions in watts/square meter (http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html, accessed May 25, 2014).

The results from the global climate models provide an estimate of the sea-level rise due to thermal expansion and, when combined with estimates of the contribution from glaciers and changes in terrestrial water, provide an overall projection of sea-level rise for three different scenarios for two time periods (2046-2065 and 2081-2100) and for 2100 (relative to 1986-2005) (Table 2.4). Sea-level rise projections across the three scenarios are 10-12 inches (range of 7-38 inches) by the middle of the century, and 21-29 inches (range from 14-39 inches) by the end of the century.

The results from the semi-empirical models reviewed by the Intergovernmental Panel on Climate Change are slightly greater, from 22 to 38 inches (range of 17 to 44 inches) by the time period 2081-2100 (again, relative to 1986-2005) (Table 2.5).

The Intergovernmental Panel on Climate Change (2013) concludes that for the period 2081-2100 (compared to 1986-2001), global mean sea level is *likely* to be in the 5-95% range of projections from processed based models (Table 2.4), with medium confidence. For Representative Concentration Pathway 8.5 scenario (which represents the global emission scenario we are currently on), this translates to an end-of-century sea-level rise of between 21 to 39 inches. However, it is critical to note that the likelihood scale (i.e. *likely* in this case) means the Intergovernmental Panel on Climate Change has concluded there is at least a 66% probability that sea-level will rise 21 to 39 inches if we follow a high emissions scenario. Their conclusion also means there is up to a 34% probability that sea-level rise will not fall in this range.

Finally, the Intergovernmental Panel on Climate Change (2013) notes that "We have considered the evidence for higher projections and have concluded that there is currently insufficient evidence to evaluate the probability of specific levels above the assessed *likely* range. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century”. Recently a series of two papers (Joughin et al., 2014; Rignot et al., 2014) suggest the West Antarctic ice sheet is not as stable as previously thought, and its melting may be inevitable.

U.S. National Climate Assessment (NCA)

The National Climate Assessment (Parris et al., 2012; Mellilio et al., 2014) provides four scenarios of global mean sea-level rise that reflect different degrees of ocean warming and ice sheet loss (Table 2.6; Figure 2.7) and are based upon analysis and expert assessment of physical evidence (e.g. observations of sea level and land ice variability), general circulation model simulations, and from semi-empirical methods that utilize both observations and general circulation models. The report includes input from national experts in climate science, physical coastal processes, and coastal management. The large range in the National Climate Assessment sea level scenarios is due to uncertainty in the rate and magnitude of ice loss from the Greenland and West Antarctic ice sheets. The National Climate Assessment report provides a synthesis of the scientific literature and a set of four scenarios of future global sea-level rise.

The *Highest Scenario* (6.6 feet by 2100) is based on estimated ocean warming from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) combined with a calculation of the maximum possible contribution to sea level from the glacier and ice sheet loss.

The *Intermediate-High Scenario* (3.9 feet by 2100) represents an average of the high end of published, semi-empirical global sea-level rise projections that are based on statistical relationships between observed air temperature and global sea level change (including ice sheet loss). It includes limited ice sheet loss.

The I*ntermediate-Low Scenario* (1.6 feet by 2100) reflects an average of the upper end of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) global sea-level rise projections based on process based modeling (i.e. general circulation models) using a lower emissions scenario (B1).

The *Lowest Scenario* (0.7 feet by 2100) assumes the rate of sea-level rise over the past century continues into the future and was calculated using a linear extrapolation of the historical sea-level rise rate derived from tide gauge records beginning in 1900 (1.7 mm/year.). Using the historical rate of sea-level rise since 1900 to extrapolate future sea-level rise over the remainder of the 21st century does not account for projected rapid changes in atmospheric and ocean temperatures over the 21st century (Stocker et al., 2013; Mellilo et al., 2014), nor the projected rapid loss of ice from the Greenland and West Antarctic Ice sheets (e.g., Holland et al., 2008; Khan et al., 2014; Joughin et al., 2014; Rignot et al., 2008, 2011, 2014).

Guidance from the Parris et al (2012) states that the Highest Scenario should be considered in situations where there is little tolerance for risk, for example new or rebuilt infrastructure with a long anticipated life cycle such as a major bridge or power plant. The Intermediate-High

Scenario provides a basis to assess the risk of sea-level rise associated with limited ice-sheet loss. The Intermediate-Low Scenario allows experts and decision makers to assess risk of sea-level rise associated primarily with ocean warming. The Lowest Scenario should be considered where there is a great tolerance for risk. The National Climate Assessment sea-level rise team report (Parris et al., 2012) assigned a very high confidence that sea-level rise by 2100 would fall within the range of 0.7 to 6.6 feet (Table 2.6) compared to mean seal level in 1992 (which represent mean sea level based on a mean value over 19 years extending from 1983 – 2001 (Parris et al., 2012; Flick et al., 2013). While the final National Climate Assessment report (Melillo et al., 2014) chose a more narrow range of 1 to 4 feet of sea-level rise by 2100 as "plausible", they also clearly state that in the context of risk-based analysis, some decision makers should consider the wider range of scenarios presented in Parris et al. (2012).

GMSL Rise Component	RCP4.5		RCP6.0		RCP8.5	
	Median	Range	Median	Range	Median	Range
Thermal expansion	7.5	5.5 to 9.1	7.5	5.9 to 9.4	10.6	8.3 to 13.0
Glaciers (not including Greenland & Anatrctic ice	4.7	2.4 to 7.5	4.7	2.4 to 7.5	6.3	3.5 to 9.1
Greenland ice sheet						
Surface mass balance	1.6	0.4 to 3.5	1.6	0.4 to 3.5	2.8	1.2 to 6.3
Rapid dynamics	1.6	0.4 to 2.4	1.6	0.4 to 2.4	2.0	0.8 to 2.8
Antarctic ice sheet						
Surface mass balance	-0.8	-2.0 to 0.04	-0.8	-2.0 to 0.04	-1.6	-2.8 to -0.4
Rapid dynamics	2.8	-0.4 to 6.3	2.8	-0.4 to 6.3	2.8	-0.4 to 6.3
Land water storage	1.6	-0.4 to 3.5	1.6	-0.4 to 3.5	1.6	-0.4 to 3.5
GMSL rise in 2081-2100	18.5	12.6 to 24.8	18.9	13.0 to 24.8	24.8	17.7 to 32.3
GMSL rise in 2046-2065	10.2	7.5 to 13.0	9.8	7.1 to 12.6	11.8	8.7 to 15.0
GMSL rise in 2100	**20.9**	14.2 to 28.0	**21.7**	15.0 to 28.7	**29.1**	20.5 to 38.6

Table 2.4. Median values and ranges for projections of global sea-level rise in inches from 2081-2100, from 2046-2065, and in 2100 (relative to 1986-2005) from *process based models* based on three different global emission scenarios (RCP 4.5, RCP 6.0, RCP 8.5). Data from Church et al. (2013, Table 13.5).

Grinsted et al. (2010) calibrated with Moberg et al. (2005) temperature	34.6	24.8 to 44.9
Rahmstorf et al. (2012b) calibrated with Church and White (2006) GMSL	33.9	31.1 to 36.6
Rahmstorf et al. (2012b) calibrated with Church and White (2011) GMSL	24.8	22.4 to 26.8
Rahmstorf et al. (2012b) calibrated with Jevrejeva et al. (2008) GMSL	38.2	32.3 to 44.1
Rahmstorf et al. (2012b) calibrated with proxy data	34.6	22.0 to 48.8
Jevrejeva et al. (2012a) calibrated with Goosse et al. (2005) radiative forcing	22.0	16.9 to 27.2
Jevrejeva et al. (2012a) calibrated with Crow- ley et al. (2003) radiative forcing	25.6	18.9 to 31.5
Jevrejeva et al. (2012a) calibrated with Tett et al. (2007) radiative forcing	33.5	25.6 to 41.3
Schaeffer et al. (2012)	31.5	22.8 to 41.3

Table 2.5. Median values and ranges for projections of global meal sea-level rise in inches in 2081-2100 (relative to 1986-2005) from *semi-empirical based models* using Intergovernmental Panel on Climate Change RCP4.5 emissions scenario. Data from Church et al. (2013, Table 13.6).

Scenario	SLR by 2100*	
	meters	feet
Highest	2.0	6.6
Intermediate-High	1.2	3.9
Intermediate-Low	0.5	1.6
Lowest	0.2	0.7
*using mean sea level in 1992 as reference		

Table 2.6. Global sea-level rise (SLR) scenarios developed for the U.S. National Climate Assessment (Parris et al., 2012).

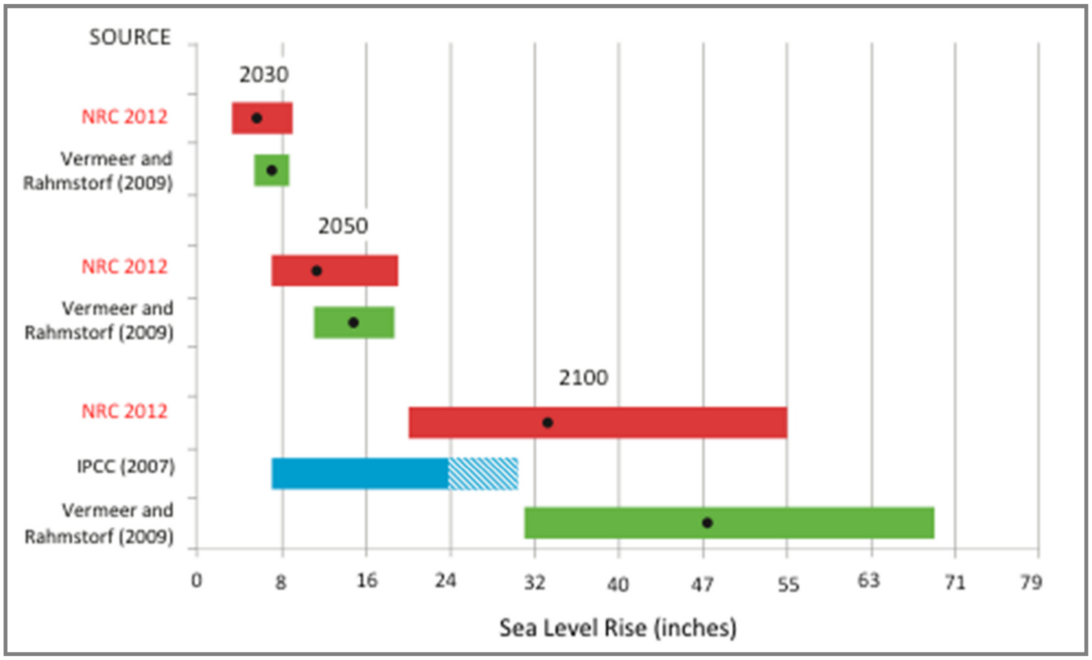


Figure 2.6. Global sea-level rise for 2030, 2050, and 2100 projected by National Research Council 2012 (red), Vermeer and Rahmstorf (2009; green), and Intergovernmental Panel on Climate Change (2007; blue). The dots are the projected mean values and the colored bars represent the range. The Intergovernmental Panel on Climate Change value includes the sea level projection (blue) plus a scaled-up ice sheet discharge component (blue diagonal lines). Figure modified from National Research Council (2012).

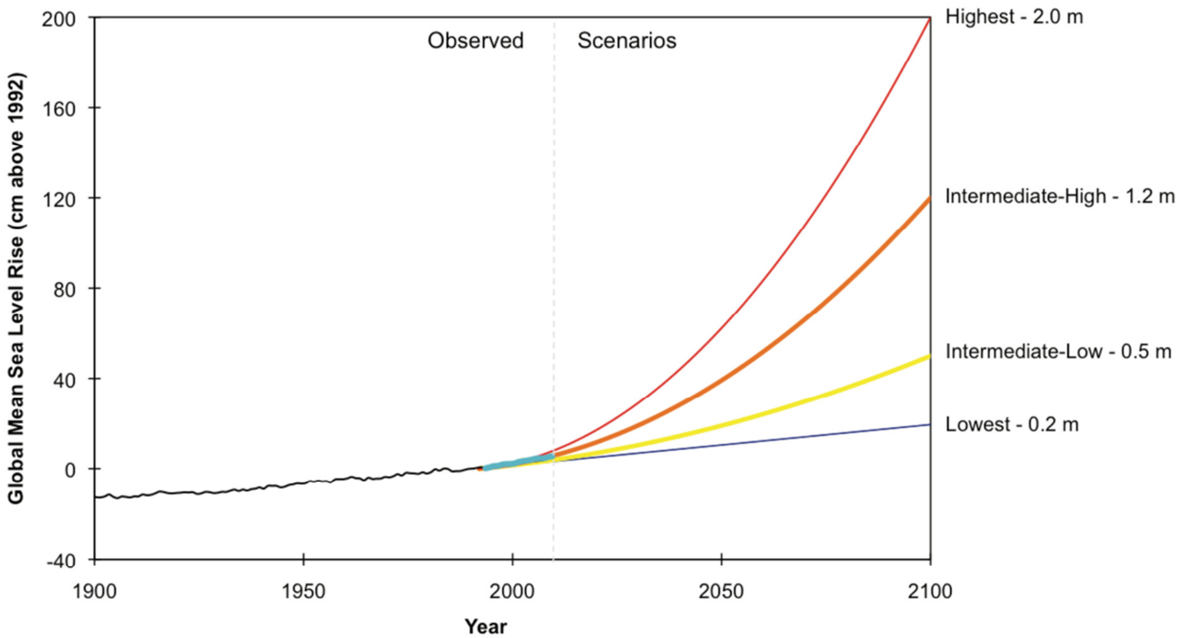


Figure 2.7. Global mean sea-level rise scenarios from 1992 from the U.S. National Climate Assessment. Figure from Parris et al.(2012).

Recently analyses have been performed in which all the various mechanisms have been combined. One such analysis is the recent work of Slangen et al. (2014) (Figure 2.8). A more detailed quantitative analysis for the specific regions of importance along the seacoast would be necessary to derive more refined values, but on the other hand the broad strokes painted by examination of these kinds of global analyses provides information about the spatial structure of the physical processes that go into such estimates and their uncertainties.

There is still considerable scientific support for a maximum value for sea level rise of close to 2 meters (6.6 ft.) by 2100. A recent survey of exceptional seal-level rise experts by Horton et al (2014) of possible changes in sea-level rise under a high CMIP5 scenario (RCP 8.5, resulting in a temperature increase of 4.5 C above preindustrial temperatures by 2100) is shown in Figure 2.9. There are many ways to interpret the data, but the paper itself notes that "Thirteen experts (out of ~ 90) estimated a 17 % probability of exceeding 2 meters of sea-level rise by 2100. In addition, US Army Corps of Engineers Circular No 1165-2-212, 10 1 12, Sea-Level Change Considerations for Civil Works Programs (most recent, October 1, 2011) on page B-11 states that a reasonable credible upper bound for 21st century global mean sea-level rise is 2 meters (6.6 ft).

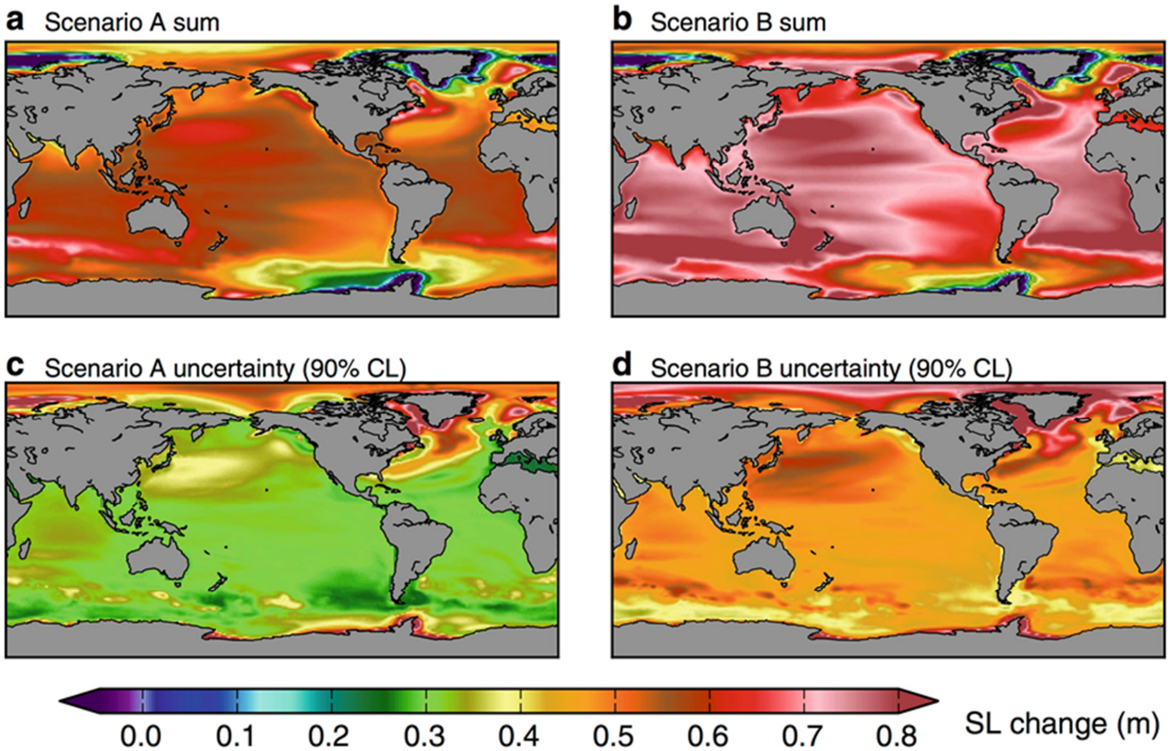
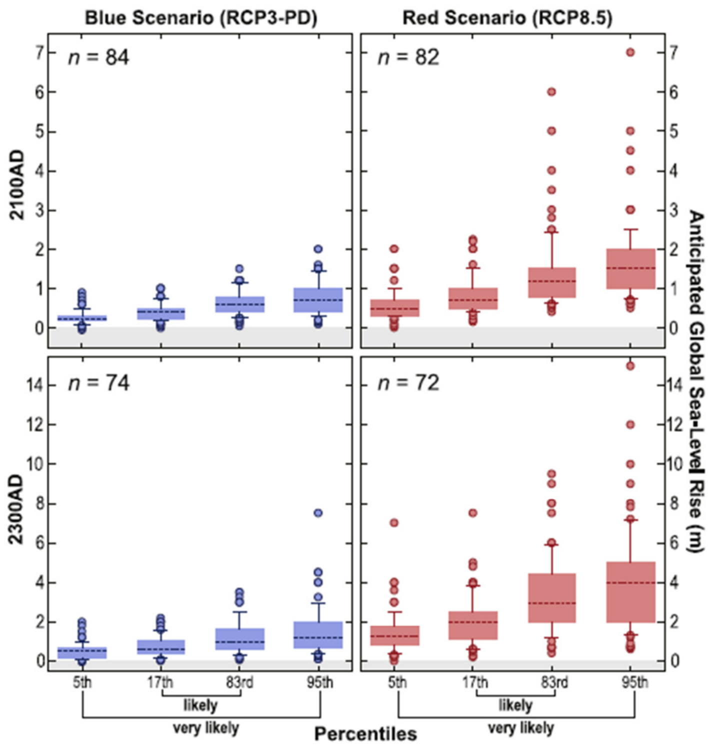


Figure 2.8. Patterns of regional sea-level rise (a and b) and uncertainties (c and d) over the period from 1986-2005 to 2081-2100 for Scenario A (RCP 4.5 plus other contributions; global mean sea-level rise is 1.8 feet) and Scenario B (RCP 8.5 plus other contributions; global mean sea-level rise is 2.3 feet). Note relatively high sea-level rise on eastern seaboard of the U.S. Figure from Slangen et al., (2014).



Horton (2013) Fig.2. Box plots of survey results from all experts who provided at least partial responses to questions. The number of respondents for each of the four questions is shown in the top left corner; it is thus the total of 90 participants since not all answered each question. Participants were asked to estimate likely (17th-83rd percentiles) and very likely (5th-95th percentiles) sea-level rise under two temperature scenarios and at two time points (AD 2100 and AD 2300), resulting in four sets of responses. Shaded boxes represent the range between the first and third quantiles of responses. Dashed horizontal line within the box is the median response. Whiskers (solid lines) represent two standard deviations of the responses. Filled circles show individual responses that are beyond two standard deviations of the median.

Figure 2.9. Results of expert survey of sea-level rise expectations, from Horton et al (2014).

3. Storm Surges

3.1 Cause of Surges

The New Hampshire coast is threatened by both extratropical storms (ETS, extra tropical storms, known locally as nor'easters) and tropical storms (TS, locally known as hurricanes when they become particularly strong). Extratropical storms result from the temperature contrast between high and low latitudes while tropical storms arise from the transfer of heat energy across the air-sea interface. Tropical storms are smaller in scale and more symmetric than extratropical storms and tend to be more intense (Wallace and Hobbs, 2006).

The counterclockwise (in the northern hemisphere) winds from extratropical storms and tropical storms can drive ocean water towards the land resulting in rise in the water level. The low pressure associated with these storms impacts the height of water rise minimally compared to wind forces. When combined with tidal influences, the event is known as a storm tide as in Figure 3.1 below. The actual size of a surge depends upon such features as storm intensity, forward speed, storm area size, the characteristics of the coast-line, and the angle of approach to the coast (http://www.nhc.noaa.gov/surge/, accessed May 23, 2014).

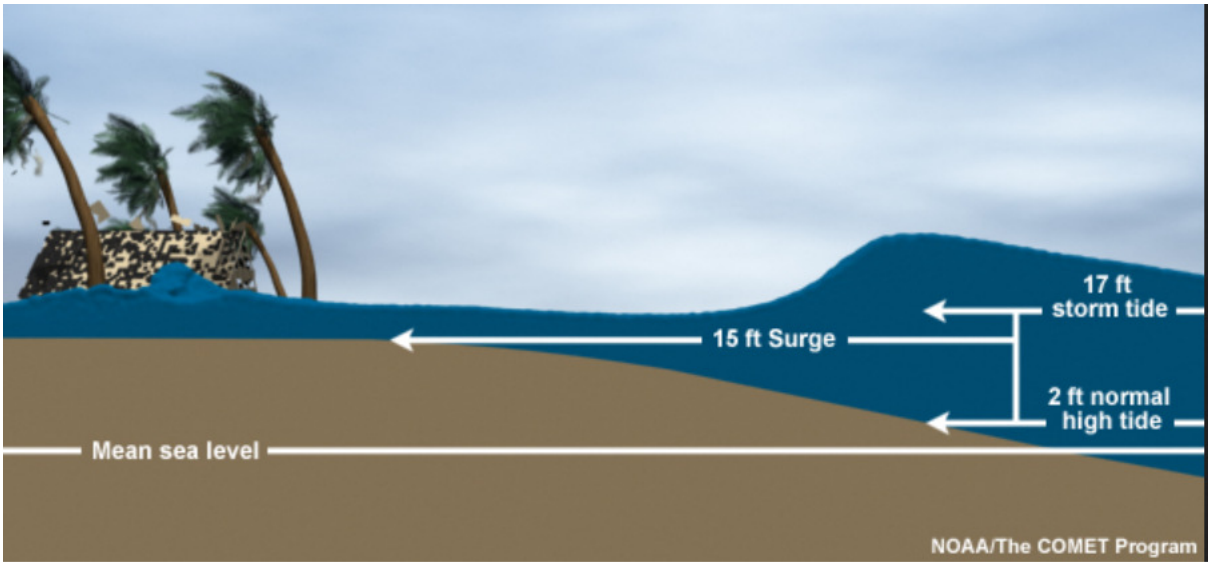


Figure 3.1. Storm Tide Components. from http://www.nhc.noaa.gov/surge/, accessed May 23, 2014).

In particular, storm surges along the New Hampshire coast are produced by easterly winds (meaning coming from the east) that occur within the northeast section of passing extratropical storms and tropical storms. Given the infrequent occurrence of major tropical storm landfall further north along the New England coast, the 10 largest storm surges observed at Fort Point, New Hampshire since 2003 occurred during extratropical storms. Extratropical storms may impact the region for several days and produce a storm surge with or without the addition of inland runoff from heavy precipitation.

Table 3.1 shows the ten highest water heights, all of which occurred during extratropical storm events, at Fort Point, New Hampshire since 2003. Reference water heights in feet on Station Datum (STND) for the National Tidal Datum Epoch (NTDE) 1983-2001 include: North American Vertical Datum of 1988 (NAVD-88) = 7.71 ft. (2.350 m), Mean High Water (MHW) = 11.69 ft. (3.564 m), and Mean Higher-High Water (MHHW) = 12.12 ft. (3.694m). Precipitation data are from the National Weather Service Cooperative Observer Program (NWS COOP) station in Greenland, New Hampshire. The numbers after the water heights rank the events; 14.99 ft. on STND ranks as the highest (#1) water height observed at Fort Point, New Hampshire since the station of record there was established in July of 2003.

Storm Date	Storm Type	Storm Total Precipitation (inches)	Water Height on STND (feet)
12/31/2009 – 01/04/2010	extratropical storm	9.3 inches snow 0.72 inches liquid	01/02/2010 – 14.99 (#1) 01/03/2010 – 14.83 (#6)
01/31/2006	extratropical storm	0.2 inches snow 0.02 inches liquid	01/31/2006 – 14.90 (#2)
04/15-18/2007	extratropical storm	5.2 inches rain	04/18/2007 – 14.87 (#3) 04/16/2007 – 14.77 (#8) 04/19/2007 – 14.74 (#10)
06/02-07/2012	extratropical storm	4.18 inches rain	06/05/2012 – 14.87 (#3) 06/04/2012 – 14.85 (#5)
01/18-22/2011	extratropical storm	13.2 inches snow 2.23 inches liquid	01/21/2011 – 14.82 (#7)
05/21-27/2005	extratropical storm	5.37 inches rain	05/25/2005 – 14.77 (#8)

Table 3.1. Highest Storm Heights at Fort Point NH since 2003.

Rising global sea levels will increase the baseline water level along New England's Gulf of Maine coast, having an additive effect on high water levels associated with storm surges (Grinsted et al. 2012 Tebaldi et al. 2012). Surge damages could also be impacted by changes in extratropical storm and tropical storm frequencies and intensities.

Table 3.2 on page 28 shows the maximum predicted and observed water levels (in feet above mean sea level (MSL)) at Fort Point, New Hampshire for the top ten highest water levels as well as for other recent, significant coastal storms. The observed water height is then added to the lower and upper boundary of the sea-level rise (SLR) estimates recommended for consideration in Table 4.1 to illustrate the potential impact similar storms may have on coastal water levels.

The coastal flood risk from storm surges as sea level rises depends on actual water level, relative to the land surface, which may vary in response to coastal geography and land use as well as local tide amplitude (Strauss et al., 2012).

Storm Type	Surge Date	Rank	Water Height above Mean Sea Level*		Storm Water Height Above Mean Sea Level* + Sea Level Rise**					
					2050			2100		
			Predicted Water Height (feet)	Observed Water Height (feet)	Inter-mediate Low (+0.6 feet)	Inter-mediate High (+1.3 feet)	Highest (+2 feet)	Inter-mediate Low (+1.6 feet)	Inter-mediate High (+3.9 feet)	Highest (+6.6 feet)
ETS	5/25/05	8	5.411	7.428	8.028	8.728	9.428	9.028	11.328	14.028
TS "Cindy"	7/9/05		4.476	4.967	5.567	6.267	6.967	6.567	8.867	11.567
ETS	1/31/06	2	6.206	7.510	8.110	8.810	9.510	9.110	11.410	14.110
ETS	5/16/06		5.055	5.656	6.256	6.956	7.656	7.256	9.556	12.256
ETS	4/16/07	8	5.851	7.362	7.962	8.662	9.362	8.962	11.262	13.962
	4/18/07	3	6.414	7.470	8.070	8.770	9.470	9.070	11.370	14.070
	4/19/07	10	6.537	7.346	7.946	8.646	9.346	8.946	11.246	13.946
TS "Barry"	6/5/07		4.705	5.797	6.398	7.097	7.797	7.398	9.697	12.397
TS "Hanna"	9/7/08		2.581	3.520	4.120	4.820	5.520	5.120	7.420	10.120
ETS	1/02/10	1	6.215	7.559	8.159	8.859	9.559	9.159	11.459	14.159
	1/03/10	6	6.133	7.418	8.018	8.718	9.418	9.018	11.318	14.018
ETS	1/21/11	7	5.840	7.438	8.038	8.738	9.438	9.038	11.338	14.038
ETS	6/05/12	3	6.622	7.441	8.042	8.741	9.441	9.042	11.341	14.041
	6/04/12	5	6.544	7.434	8.034	8.734	9.434	9.034	11.334	14.034
TS "Irene"	8/28/11		4.664	5.598	6.199	6.898	7.598	7.199	9.498	12.198
	8/29/11		5.709	6.276	6.876	7.576	8.276	7.876	10.176	12.876
TS "Sandy"	10/29/12		4.850	6.706	7.306	8.006	8.706	8.306	10.606	13.306

* Mean Sea Level (MSL) = 0.30 ft. (0.091 m) NAVD-88 or 7.41 ft. (2.259 m) on STND at Fort Point, New Hampshire for NTDE 1983-2001.
** Recommended range for SLR (Table 4.1) based on the scenarios prepared by the US National Climate Assessment (Parris et al., 2012).

Table 3.2 Maximum Observed and Predicted Water Levels at Fort Point, NH

3.2 Present Recurrence Intervals of New Hampshire Surges

We suggest these be based upon the preliminary floodplain maps prepared for coastal NH by the Federal Emergency Management Agency (FEMA).

3.3 Present Trends

Extratropical Storms (ETS) or Nor'easters

Extratropical Storms can result in heavy precipitation, high winds, and severe icing (Vose et al, 2014). U.S. Global e Change Research Program (USGCRP 2008) suggested a decrease in frequency but an increase in the intensity of winter storms over the mid-latitude northern hemisphere (30° to 60°N) along with a poleward shift of extratropical storm activity. Specifically related to extratropical storms that impact the northeastern U.S. and southeastern Canada, Hirsch et al. (2001) found no statistically significant trend in frequency and a marginal weakening trend in these systems between 1951 and 1997. Kunkel et al (2013) and Intergovernmental Panel on Climate Change (2012) report no research consistently finding a trend in the frequency and/or intensity of extratropical storms and the Intergovernmental Panel on Climate Change (2012) reports a poleward shift in extratropical storm tracks**.** Vose et al (2014) report "there is at least some indication of an increase in extreme extratropical storm activity during the cold season in the Northern Hemisphere since 1950, but the evidence overall is limited and thus inconclusive" (page 5).

Tropical Storms (TS) or Hurricanes

During the 20th century, landfalling tropical storms produced the majority of high surge events along the US east coast (Grinstead et al. 2012). Basin-scale analyses of 20th century Atlantic tropical cyclone activity indicate that the total number of Atlantic hurricanes increased (Knutson et al. 2010) along with an increase in the intensity and duration of tropical storms (Emanuel 2007; Bender et al. 2010; Bell et al. 2012). Biases in the historical record due to changes in methods of observation, which have improved for non-landfalling tropical storms over the period of record, precludes a direct link between 20th century trends in tropical storm frequency and anthropogenic climate change at this time (Landsea et al 2006; Mann and Emanuel 2006; Vecchi and Soden 2007; Crompton et al. 2011; Knutson et al. 2010; Grinstead et al. 2012; Landsea and Franklin 2013). However atmospheric warming related increases in sea surface temperatures (Ting et al. 2009; Knutson et al. 2010; Strazzo et al. 2013) as well as teleconnection (Pielke et al. 1999; Jagger and Elsner 2006; Moore et al. 2008; Kossin et al 2010; Camargo et al. 2013), tropical temperature and moisture patterns (Grinsted et al. 2013; Kossin et al. 2014) have all been cited as influences on Atlantic tropical storm activity (Bender et al. 2010; Emanuel and Sobel 2013).

Since 1970, the trend in North Atlantic tropical storm frequency has increased (IPCC 2012; IPCC 2013; Knunkle et al. 2013) and this trend is projected to continue within the northwestern sub-basin of the North Atlantic (Murakami and Wang 2010). Changes in North Atlantic tropical storm tracks as well as landfall rates and locations have been linked to changes in North Atlantic sea surface temperatures, which influences the location of hurricane formation and the atmospheric steering mechanisms that direct storm movement (Kossin et al. 2010; Murakami and

Wang 2010; Wang et al. 2011; Villarnini et al 2012). Presently, return periods for landfalling tropical storms along the Gulf of Maine coast range from 10-12 years, although estimates vary by study due to the period of record evaluated (Keim et al. 2007). Major hurricanes (Category ≥3) have a 100+ year return period along the New Hampshire coast north to Bar Harbor, ME (Keim et al. 2007) and are capable of producing 3.3 to 6.6 foot storm surges between Boston, MA and Eastport, ME (Tebaldi et al. 2012).

There is also the possibility of tropical and extratropical storms merging creating situations similar to Hurricane Sandy in 2012.

3.4. Future Projections

Extratropical Storms (ETS) or Nor'easters

Intergovernmental Panel on Climate Change (2012) reports with "medium confidence" there will be reduction in the number of extratropical storms in mid-latitudes in the future and a continued poleward shift of storm tracks. Wuebbles et al (2014) using the new CMIP5 models found similar results in the western Atlantic off of New England – less frequent and less intense. While CMIP5 results suggest that relatively weak extratropical storms are projected to decrease and stronger extratropical storms are projected to increase along the U.S. eastern seaboard, there is a broad range of uncertainty in these results (Wuebbles et al., 2014). Chang (2013) reports that CMIP5 models project a significant decrease in North American storm-track activity, with the largest decrease in summer and the smallest decrease in spring. Furthermore, CMIP5 projections indicate a coincident decrease in the frequency of breaking cyclonic wave patterns and blocking anticyclones over the western Atlantic, which will lead to a reduction in the intensity of post-tropical storms (Barns et al 2013). Vose et al (2014) report no firm conclusions can be drawn on future extratropical storm trends due to lack of adequate knowledge of the mechanisms causing changes.

The latest Intergovernmental Panel on Climate Change climate report (Stocker et al, 2013) supports the above findings. The National Climate Assessment Northeast (Chapter 16), Climate Change (Chapter 2) and the Coasts (Chapter 25) sections do not include extratropical storms trends or projections with the exception of citing Vose et al. (2014).

Tropical Storms (TS) or Hurricanes

Intergovernmental Panel on Climate Change (2012) reports that the frequency of Atlantic tropical storms is likely to decrease or stay the same by 2100 (Knutson et al., 2010, 2013; Seneviratne et al., 2012; Moser et al, 2012; Walsh et al. 2014) although it has also been argued by some that the frequency will increase over part or all of the 21st century (Emanuel, 2013). The projected change in Atlantic tropical storm frequency varies between studies due to differences in the models and downscaling techniques used (Emanuel, 2013). There is much greater agreement between models on the projected increase in tropical storm intensity and rainfall rates (Seneviratne et al., 2012; Knutson et al., 2013; Walsh et al. 2014). Studies show that tropical storm intensity is particularly sensitive to warming and Atlantic hurricanes are expected to become more intense and produce more rain than that observed over the 20th century (Seneviratne et al., 2012; Grinsted et al., 2013; Knutson et al. 2013; Villarini and Vecchi, 2013). The projected increase in tropical storm intensity means that the frequency of major hurricanes

(Category ≥3) is likely to increase (Grinsted et al., 2013; Knutson et al. 2013; Villarini and Vecchi, 2013).

A projected shift in storm tracks toward the western North Atlantic (Kossin et al., 2010; Murakami and Wang 2010) with the observed increase in the northern extent of maximum storm intensity (Kossin et al. 2014) increases the chance for tropical storm impacts along the New England coast. Therefore, tropical storms may impact the region more frequently and storms may be more intense than present and tropical storm surge remains a significant threat even if the total number of hurricanes does not increase (Grinsted et al., 2012; Tebaldi et al. 2012). Storm surge combined with projected sea-level rise will result in increased, but still locally variable, inundation extent and shorter return periods for extreme surge events. Considering projected increases in sea level along the US east coast, Tebaldi et al. (2012) estimate that today's 100-year storm surge for the Gulf of Maine will occur more frequently by 2050, ranging from every 5 years at Portland, ME to 30 years at Boston, MA.

3.5 Precipitation

Since the National Climate Assessment covers precipitation so fully, it is the primary source cited for this section. Horton et al (2014) report that the mean annual precipitation in the northeastern US has increased by approximately 5 inches, more than 10 % between 1895 and 2011. The region also had a large increase in extreme precipitation between 1901 and 2012; for example, a more than 50 % increase in the annual amount of precipitation falling as extreme events (defined as the largest 1 % of daily events in a year, Walsh et al, 2014). Data from the NH State Climate Office indicates that the region experienced back-to-back 100-year storm events in spring of 2006 and 2007, commonly referred to as the Mother's Day Storm (May 10-17, 2006) and the Patriot's Day Storm (April 15-18, 2007) respectively. Total rainfall received along the Gulf of Maine coast during the Mother's Day and Patriot's Day storms are listed in Table 3.4. The heaviest rainfall during the Mother's Day Storm occurred on May 14 (Figure 3.1). The Patriot's Day Storm produced over five inches of rainfall along the coast, the majority of which fell on April 17 (Figure 3.2).

Station Location	Storm Total Precipitation (inches)	
	Mother's Day Storm May 10-17, 2006	**Patriot's Day Storm April 15-18, 2007**
Newburyport, MA	17.23	4.76
Cape Neddick, ME	16.26	5.69
Eliot, ME	14.10	8.42
Kennebunkport, ME	10.37	5.48
Sanford, ME	11.73	Missing
Durham, NH	10.40	6.54
Epping, NH	11.30	6.43
Greenland, NH	13.29	5.20
North Hampton, NH	17.05	4.52
Rochester, NH	11.12	6.25
West Hampstead, NH	10.79	5.61

Table 3.4: Data Source – Northeast Regional Climate Center

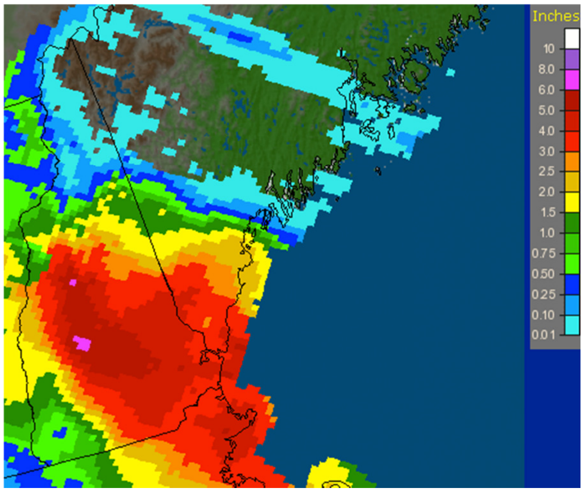


Figure 3.1: 24-hour rainfall totals for May 14, 2006. (Image source: NOAA-NWS Advanced Hydrologic Prediction Service)

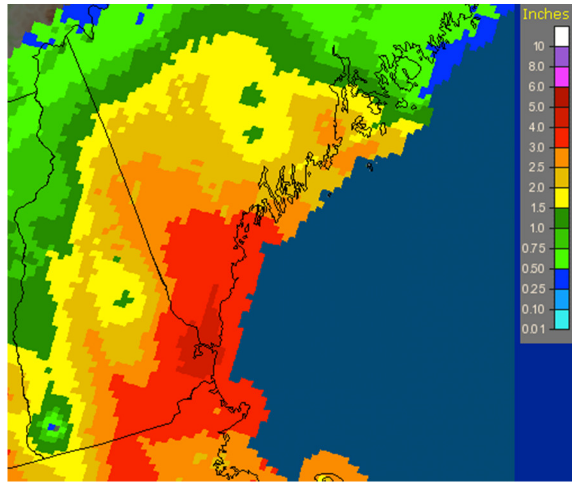


Figure 3.2: 24-hour rainfall totals for April 16, 2007. (Image source: NOAA-NWS Advanced Hydrologic Prediction Service)

Projected increases in annual precipitation could be as high as 20 % in the period 2071-2099 compared to 1970-1999 (Walsh et al, 2014), with most of the increases in Winter and Spring with less increase in the Fall and perhaps none in the Summer (Walsh et al, 2014, Horton et al, 2014). Extreme precipitation is also projected to increase. For example, the frequency of the occurrence of the daily rainfall that is presently equaled or exceeded every 20 years may increase by twice to four times as often in the period 2081-2100 compared to 1981-2000 (Walsh et al, 2014).

Additional analysis of past changes and projected future change in precipitation in coastal New Hampshire are provided in Wake et al. (2011; 2014).

An example of expected changes in frequencies of extreme events in a similar region as coastal New Hampshire is Boston Massachusetts. As part of the update of its Wastewater and Storm Drainage Facilities Plan, the Boston Water and Sewer Commission had prepared estimates of changes in extreme 24 hour precipitation using historical data, daily precipitation output for the future from 12 global climate models for two greenhouse gas emission scenarios (B2 (moderate) and A1Fi (Precautionary)), and extreme value theory (CH2M Hill, 2013). The present and future values are in Figure 3.3.

EXHIBIT 24

Observed and Forecasted 24-hour Rainfall for Medium (B2) and Precautionary (A1FI) Scenarios for 2035, 2060 and 2100 with Return Periods of 2 to 500 Years

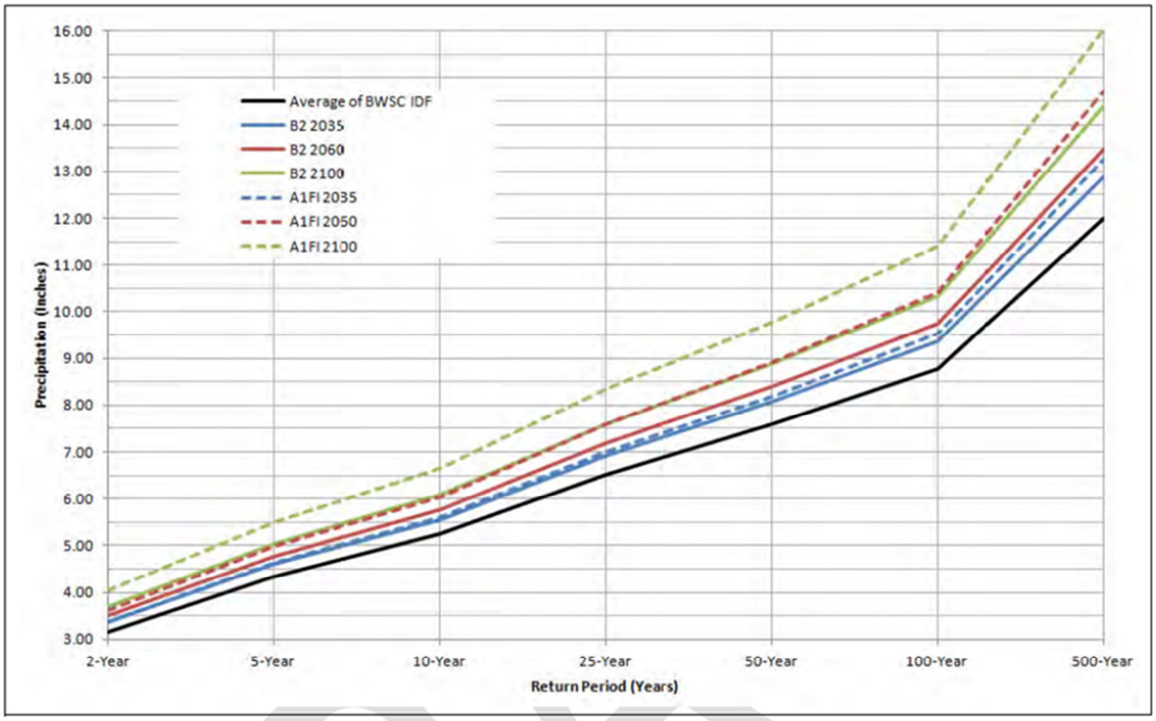


Figure 3.3. Present and projected changes in extreme precipitation frequencies in Boston MA (CH2M Hill, 2013).

4.0 Application of Findings for Municipalities and the State.

The recommendations presented here are based upon our collective analysis of the information provided in this report combined with our expert assessment. We suggest they be updated regularly, and at least every two years.

4.1 Sea-level Rise

Guidance to assist in decisions to adapt to global mean sea-level rise requires the assessment of the various contributions that drive local/regional relative sea-level rise (Figure 4.1). We have provided a brief review of the processes that cause sea level to rise (Section 2.1), past sea-level change (Section 2.2), projections of sea-level rise based on three high profile and well-regarded recent assessments of sea-level rise (Section 2.3), and an analysis of storm surges (Section 3). The information used to make this assessment is dynamic and based on frequently updated source data and research.

We believe the range that best covers plausible sea-level rise increases to 2050 and 2100 are those prepared for the US National Climate Assessment and include the “Highest” and “Intermediate Low” scenarios (Table 4.1). For simplicity, we have only provided values for 2050 and 2100 (using a reference year for mean sea level of 1992). If a finer time scale is needed, it can be provided. Local and regional influences from land subsidence and gravity effects are not expected to be significant compared to the global sea-level rise changes. However, dynamic changes in ocean circulation (which are difficult to predict) may increase coastal New England sea-level rise projections by as much as eight to twelve inches by 2100 (Yin et al, 2009) . Increases from 1992 are chosen because 1992 is the midpoint of the current National Tidal Datum Epoch (NTDE) of 1983- 2001

We fully acknowledge that in order for global mean sea-level to rise by 3.9 to 6.6 feet (1.2 to 2.0 meters) by the end of the century, there will be a large increase in the acceleration of the rate of sea-level rise over the remainder of the century. Under the National Oceanic Atmospheric Administration's Highest scenario, the average rate of sea-level rise over the period 2070 to 2100 would be 29.7 mm/year. Under the National Oceanic Atmospheric Administration's Intermediate High scenario, the average rate of sea-level rise over the period 2070 to 2100 would be 17.3 mm/year. Compared to the current long-term rate of approximately 1.7 mm/year, these are increases of 17 times and 10 times respectively. However, the increase in the rate of global mean sea-level rise over the 21st century is exactly what is projected to occur because of projected increases in atmospheric and ocean temperatures (Stocker et al., 2013; Mellilo et al., 2014) combined with projected rapid loss of ice from the Greenland and West Antarctic Ice Sheets (Holland et al., 2008; Khan et al., 2014; Joughin et al., 2014; Rignot et al., 2008, 2011, 2014). Other processes (vertical land movements, gravitational driven sea level changes, and changes in ocean circulation; Section 2.1) may result in even greater rates of sea-level rise in some regions.

Time Period*	"Intermediate Low	"Intermediate High"	"Highest"
2050	0.6 ft.	1.3 ft.	2.0 ft.
2100	1.6 ft.	3.9 ft.	6.60 ft.

*using mean sea level in 1992 as a reference (Parris et al., 2012)

Table 4.1. Sea-Level Rise Scenarios (in feet) Provided by the National Climate Assessment (Parris et al., 2012) and recommended to New Hampshire Coastal Risks and Hazards Commission as guidance on the plausible range of sea level rise to 2100.

We recommend, however, that for coastal locations where there is little tolerance for risk in protecting new infrastructure or existing coastal settlements, infrastructure or ecosystems, that the range include that from the Intermediate High to the Highest (Table 4.1) and that the range be applied as follows:

1. **Determine** the time period over which the system is designed to serve (either in the range 2014 to 2050, or 2051 to 2100).

2. **Commit** to manage to the Intermediate High condition, but be **prepared** to manage and adapt to the Highest condition if necessary.

3. Be **aware** that the projected sea-level rise ranges may change and adjust if necessary. (The scientific basis for these ranges should be reviewed regularly and the ranges updated as needed.)

For example, for a project with a lifetime past 2050, a flood wall could be constructed for the highest scenario (6.6 feet) now, which would be the most robust approach, or constructed for 2 feet of future sea-level rise now but in a manner that would facilitate expanding and raising the wall to protect against 3.9 or 6.6 feet of sea-level rise, if future assessment indicates that is necessary. This could be accomplished by designing and constructing the wall foundation for the 6.6 feet sea-level rise scenario while only constructing the wall for a 2-foot sea-level rise scenario. The choice of management strategies can include strategies to protect, accommodate or retreat from the threat.

We anticipate that specific recommendations and standards for implementing this approach will be further developed in the Commission's subsequent reports. Careful additional guidance will have to be provided on the locations and datums from which to measure changes in sea level (see Sidebar).

4.2 Storm Surge

Given the uncertainties associated with future storm surge changes, we recommend that projects continue to use the present frequency distributions for storm surges increased by sea level rise projections given in Section 4.1. Even if coastal storms do not increase in frequency and intensity, the storms will have more of an impact over time because storms ride on top of the tide and sea-level rise. Today's storm tide will have higher elevations relative to the land in the future given the same storm event of today. Storm surge events will result in not only higher levels of inundation above the land, but also in longer durations of inundation.

4.3 Extreme Precipitation

Data analysis shows that extreme precipitation is increasing across New Hampshire (Wake et al., 2011, 2014; Melillo et al., 2014). We are unable at present to assign with confidence future changes in extreme precipitation events. We do, however, recommend at a minimum that all related infrastructure be designed with storm volumes based on the current Northeast Regional Climate Center (Cornell) atlas to represent current precipitation conditions and infrastructure should be designed to manage a 15 % increase in extreme precipitation events after 2050 and that a review of these projections be continued.

****

SIDEBAR: Fixed and Tidal datum

"While planners and engineers will have to consider a future rise in sea level, they will have to relate that sea-level rise to a fixed vertical (geodetic) datum such as NAVD-88 for detailed planning and design. Planners and engineers should recognize that the relationship between tidal datums (MSL, MHW, MHHW) and a geodetic datum (NAVD-88) will vary with time and location. As a general rule of thumb, MSL (1983-2001 national tidal datum epoch) along the outer coast of New Hampshire is approximately -0.3 feet NAVD-88. MSL generally rises with respect to NAVD-88 as one moves into or up a harbor, estuary or river, but this can vary dramatically from location to location. Planners and engineers should properly determine the actual relationship between tidal datums and NAVD-88 for each specific project location."

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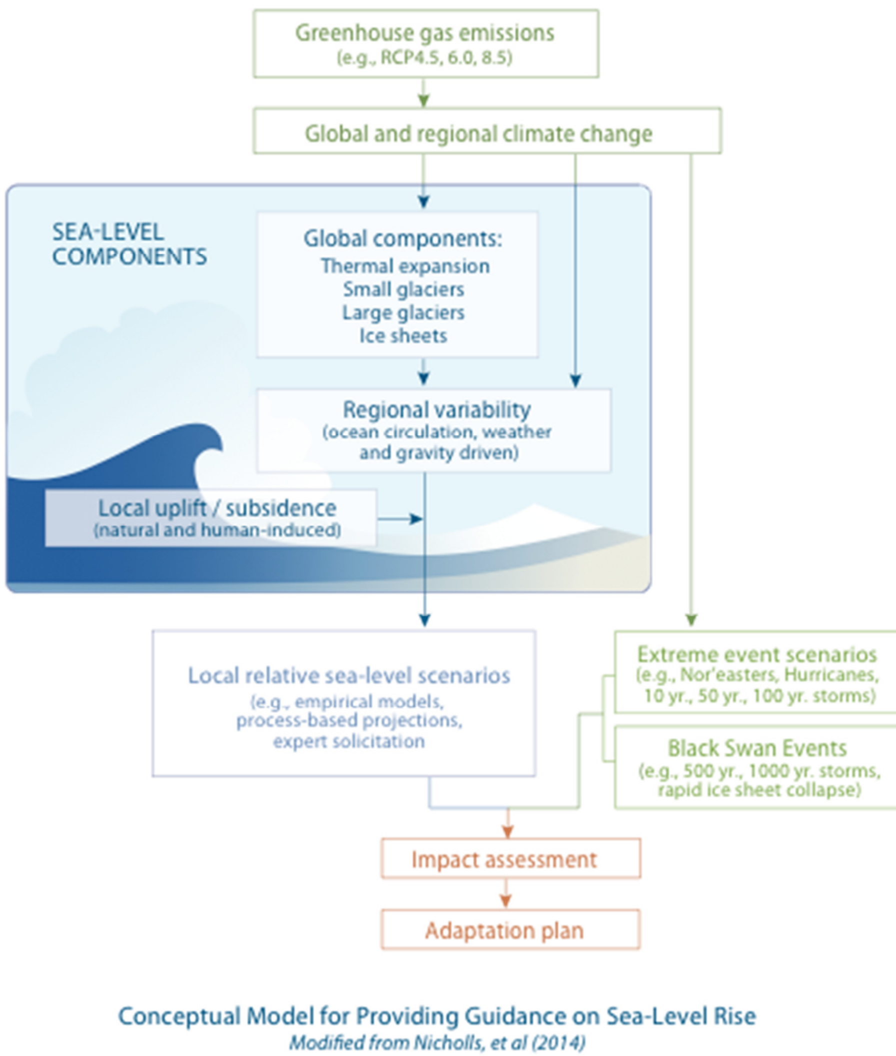

Figure 4.1. Conceptual model used to provide guidance regarding future sea-level rise for New Hampshire. Modified from Nicholls et al. (2014).

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