

The text below is modified and updated from the Sea Level Rise chapter in: Wake et al. (2011) Climate Change in the Piscataqua/Great Bay Region: Past, Present, and Future. <http://www.carbonsolutionsne.org/>

Sea Level Rise in coastal NH

Coastal NH Flood Mapping

The results of the analysis discussed in detail below indicates that we can expect the 100-year flood elevation at Fort Point in Newcastle, NH to increase from a current elevation of 11.2 feet to a range of 12.4 to 13.1 feet by 2050, and to range of 14.0 to 17.8 feet by 2100. Therefore, even under low greenhouse gas emissions scenarios, we can expect the 100-year flood elevation to increase several feet over the next 90 years. This increase in the 100-year flood elevation will result in more severe flooding in coastal New Hampshire in the future.

To illustrate the impact of the higher 100-year flood elevations in the future, we have produced a series of ten maps that cover the NH seacoast, Piscataqua River, and Great Bay. These maps show stillwater flood depths over land for flood elevations of six feet, nine feet, and twelve feet above mean higher high water (MHHW). (MHHW is the average of the higher high water elevation of each tidal day; values are provided by NOAA.)

These maps are based on detailed LiDAR (Light Detection and Ranging) topographic data that was collected during the spring of 2011. Note that the maps are provided for discussion and research purposes only. It is not appropriate to use the maps for detailed analysis (i.e., at the parcel level). Please contact Cameron Wake <cameron.wake@unh.edu> at Carbon Solutions New England <<http://carbonsolutionsne.org/>> for additional information on methodology and limitations.

MAKE A LIST OF MAPS HERE FOR DOWNLOAD:

12 FOOT FLOOD ELEVATION

list ten maps by location

9 FOOT FLOOD ELEVATION

list ten maps by location

6 FOOR FLOOD ELEVATION

list ten maps by location

Historical Sea Level Rise

An overwhelming body of scientific evidence indicates that “most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations” (Solomon et al., 2007). One of the impacts of this warming has been an increase in sea level resulting from melting of land-based ice (i.e., glaciers and ice sheets) combined with thermal expansion of the ocean. The sum of these two effects is known as *eustatic* sea level rise (SLR) (Pugh 2004). The long-term average rate of this eustatic global SLR has been estimated to be on the order of 0.67 inches per decade during the 20th century (Bindoff et al., 2007). Sea level rise during the latter half of the 20th century was estimated at 0.7 ± 0.1 inches per decade (Church et al., 2004). One study suggested that the rate of eustatic coastal SLR in the late 20th century was greater than the average eustatic SLR in the second half of the 20th century (Holgate and Woodward, 2004); this was later confirmed by sea level rise estimates of 1.2 inches per decade for the period 1993 to 2003 and 1.3 ± 0.2 inches per decade from 1993 to 2009 using satellite altimetry.

Rates of total or relative sea level rise (RSLR) which includes both climate and geologic influences measured at tide gauges along the United States coastline range from <0.4 to 3.9 inches per decade⁴⁵. Differences in RSLR are due to local variations in vertical land motion, which are related to regional-specific processes such as tectonic uplift and down dropping, isostatic rebound and depression, coastal subsidence, land surface changes due to compaction, dewatering, fluid extraction, and diagenetic processes. Specifically, along the northeastern U.S. coast, vertical land movement ranges from <0.3 inches per decade along the Maine coast to 0.67 inches per decade in Delaware⁴⁶, a range that is consistent with other estimates (Brown, 1978; Anderson et al., 1984; Kirshen et al., 2008; Koohzare et al., 2008).

The combined effects of thermal expansion, increases in meltwater, a subsiding coast, and potential changes in ocean circulation make coastal New Hampshire particularly vulnerable to rising sea level. Increases in relative sea level contribute to enhanced flooding of coastal infrastructure, increased coastal erosion, saltwater contamination of freshwater ecosystems and loss of salt marshes. Low-lying shorelines such as sandy beaches and marshes are likely to be the most vulnerable to rising seas.

Relative sea level has been rising on the New Hampshire coast for the past 10,000 years (Ward and Adams, 2001). However, relative sea level has been recorded at the Portsmouth Harbor (Seavey Island) tidal gauge only since 1926 (NOAA 2011). For the period 1926 to 2001, sea level rose nearly half a foot (5.3 inches), at a rate of about 0.693 inches per decade (Figure 1). 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. Analysis of recent trends in tidal gauge records in Portland and Boston suggest that trends of the late 20th century are similar to trends over the past decade. Here we assume that the rate of SLR at Fort Point over the past decade is the same as has been measured at the Seavey Island tide gauge over the time period from 1926 to 2001 - about 0.7 inches per decade.

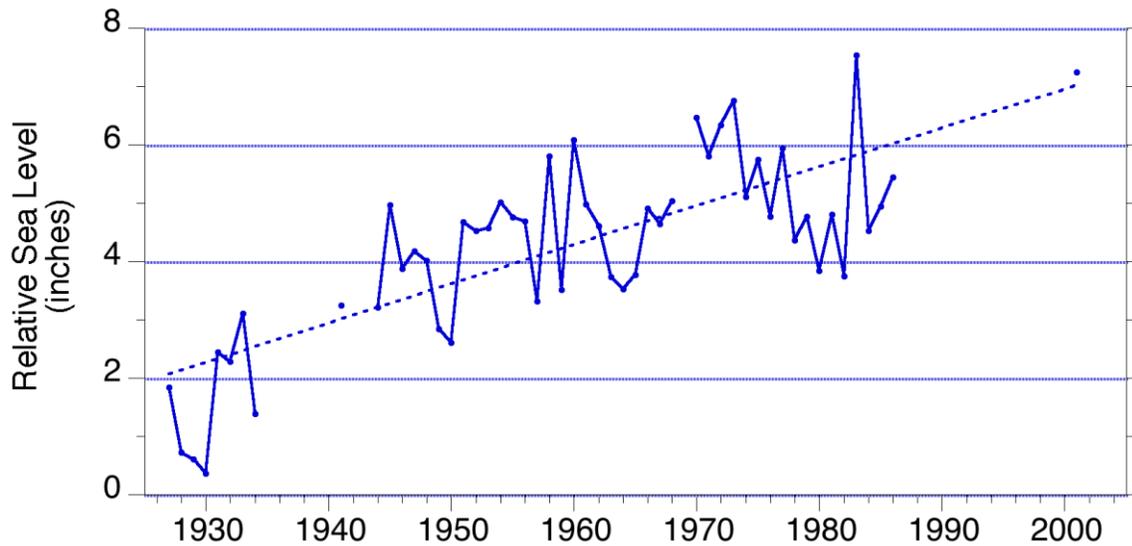


Figure 1 . Annual mean sea level measured at the Seavey Island tidal gauge, 1927-2001. Data from NOAA49. The annual values represent the annual mean of the monthly mean sea level data. The dashed blue line is the linear regression applied to the time series. The gaps represent years with missing data.

Estimates of Future Sea Level Rise and 100-Year Flood Elevations in Newcastle, NH.

Projections of global eustatic SLR produced for the 2007 Intergovernmental Panel on Climate Change report (Solomon et al., 2007) ranged from 7.1 to 23 inches by 2100, but were based only on thermal expansion because of a lack of reliable ice melt estimates at the time. Accounting for ice melt increased this range of projections to 31 inches (most plausible) - 79 inches (possible but unlikely)(Pfeffer et al., 2008) and 12 to 20 inches (moderate temperature scenario) to 16 to 31 inches (warm temperature scenario) (Katsman et al., 2008). Recent model projections of eustatic SLR (Vermeer and Rahmstorf, 2009) suggest a range in average sea level increase of 39 to 55 inches by 2100, with the range of uncertainty increasing from 31 to 75 inches. The large uncertainty is mainly due to the range of CO₂ emissions scenarios used in making these model-based projections.

For this report, we use the maximum extents of the range of global eustatic SLR by 2100 relative to 1990: 31 inches for the lower B1 SRES scenario, and 75 inches for the higher A1fi SRES scenario (Vermeer and Rahmstorf, 2009). These values were estimated using the SLR projection curve (Figure 2) and include a +7% uncertainty error. Projected values for eustatic SLR by the year 2050 under both lower and higher emissions scenarios were also estimated using the SLR projection curve shown in Figure 2.

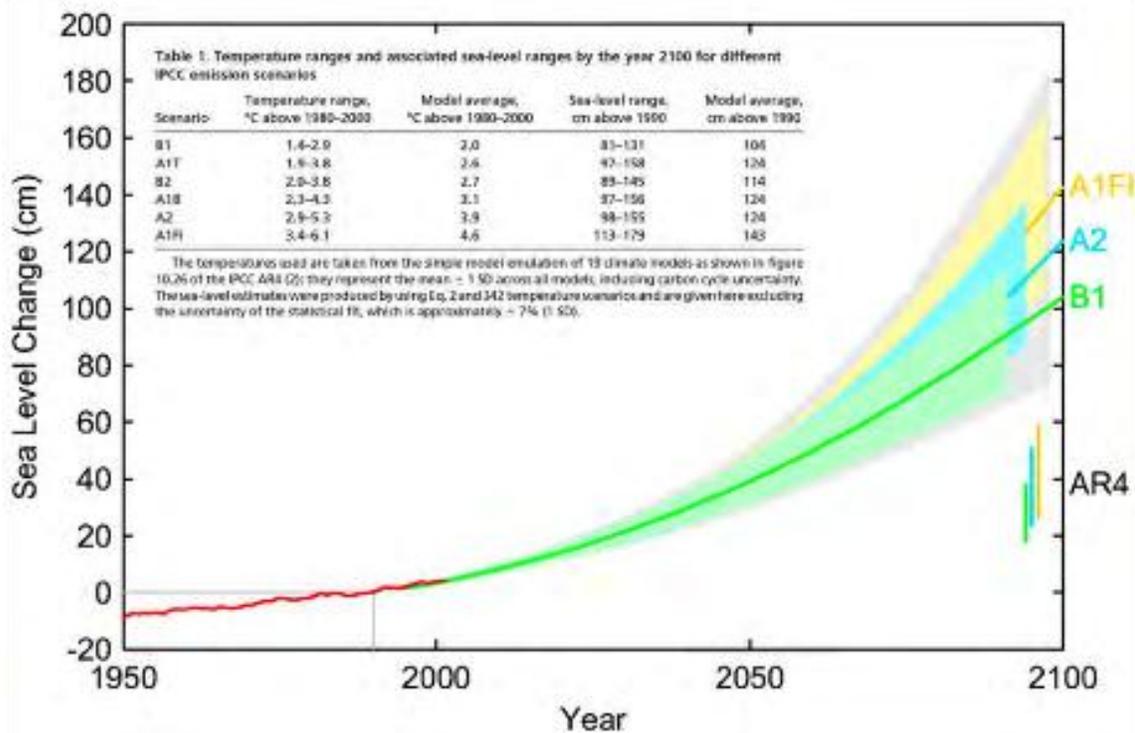


Figure 2. Projection of sea-level rise (SLR) from 1990 to 2100 (from Vermeer and Rahmstorf 2009), based on temperature projections for three different emission scenarios (Solomon et al., 2007). The sea-level range projected in the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4) for these scenarios is also shown for comparison in the vertical bars on the bottom right. Also shown is the observations-based annual global sea-level data (red) including artificial reservoir correction.

Future subsidence over the next century was estimated by assuming that current rates will continue (Kirshen et al., 2008). Eustatic SLR rate for the 20th century was estimated at 0.67 inches per decade (Chirch and White, 2006; Bindoff et al., 2007). Relative SLR at the Seavey Island gauge for the period 1926 to 2001 was calculated by the U.S. National Oceanographic and Atmospheric Administration (NOAA) to be 0.69 inches per decade (NOAA, 2011). Historical subsidence was estimated by assuming both historical eustatic SLR and historical RSLR are linear processes, and then subtracting historical eustatic SLR from the historical RSLR. We estimated local SLR due to subsidence at the Seavey Island gauge to be $0.02 + 0.26$ inches per decade, which results in average values of 0.14 inches by 2050 and 0.26 inches by 2100, relative to 1990. Although this calculated value for subsidence is lower than the range of values discussed above, we used this smaller value to be consistent with previous analyses (Kirshen et al., 2008). Additionally, for the purposes of this report, we assume that future subsidence over the next century for Fort Point will be the same as that measured at the Seavey Island tide gauge.

A summary of those components and their contribution to the preliminary estimates of future stillwater elevations is provided in Table 1. (Stillwater elevation is the elevation of the water surface that does not account for waves and run-up.). The estimated flood elevation is the result of our statistical analysis of the historical Seavey Island and Fort Point tide gauge data.

The 100-year flood elevation at the Fort Point tide gauge was estimated to be 6.8 feet. Adding this estimated flood elevation to the elevation of mean higher high water (MHHW, 4.4 ft), results in an estimate of the current 100-year coastal flood stillwater elevation of 11.2 feet relative to the North American Vertical Datum (NAVD). (MHHW is the average of the higher high water elevation of each tidal day; values are provided by NOAA). The NAVD is the current engineering standard for vertical datum and is used by FEMA for all new Flood Insurance Risk Maps.) By adding the estimated 100-year flood elevation to MHHW, our estimate represents a coastal flooding scenario that occurs during the highest daily tide. This serves as a valuable benchmark for future planning efforts as our largest nor'easters often result in storm surge that lasts for at least one, and sometimes several days.

The FEMA 100-year coastal flood stillwater elevation for New Castle, NH (where Fort Point is located) is 8.4 feet NAVD55 (Table 2). This elevation is 2.8 feet lower than our estimated 100-year coastal flood stillwater elevation of 11.2 feet NAVD. This difference is most likely due to several reasons: 1) our stillwater elevation estimate relies on a statistical analysis of observed tide gauge data, whereas the FEMA estimate is based on an analysis of a synthetic storm surge dataset generated by a computer model (FEMA 2005); 2) our stillwater elevation does not account for the hydrodynamic effects as the tide and storm surge move from the coast into Portsmouth harbor (according to the FEMA analysis, the stillwater elevation at Portsmouth is at least 0.3 feet lower than at the coast); 3), our stillwater elevation assumes that the maximum impact from the coastal flood event occurs during the bi-monthly astronomical high tide (spring tide).

Our analysis is based on the historical water level data from the Seavey Island and Fort Point tide gauges. There was missing data in the Seavey Island and Fort Point tidal records (Figure 1). Thus, there were a number of missing years in the water level time series developed for Portsmouth; these data gaps were filled using a regression model developed from tide gage data at Boston, Massachusetts and Portland, Maine. The root mean squared error for this regression model was 0.82 feet, which is nearly identical to the standard deviations of the Portsmouth, Boston, and Portland tide gage data. Although the specific limitations of the Seavey Island data cited by FEMA are unknown, we presume that these limitations include the data gaps discussed above.

Table 1. Estimates (in feet) of future 100-year flood stillwater elevations at Fort Point (New Castle, NH) relative to NAVD88 derived from statistical analysis presented in this report and for lower and higher emission scenarios for the years 2050 and 2100.

SLR component	2050		2100	
	Lower	Higher	Lower	Higher
Current Elevation of MHHW ^{a,b}	4.4	4.4	4.4	4.4
100-Year Flood Height	6.8	6.8	6.8	6.8
Subsidence	0.1	0.1	0.3	0.3
Eustatic Sea Level Rise	1.0	1.7	2.5	6.3
Total Stillwater Elevation (feet) ^{a,c}	12.4	13.1	14.0	17.8
a - NAVD88: North American Vertical Datum of 1988				
b - MHHW: Mean Higher High Water at Fort Point, Newcastle, NH				
c - Total stillwater elevation may not equal total of components due to rounding				

Table 2. Estimates (in feet) of future 100-year flood stillwater elevations at Fort Point (Newcastle, NH) relative to NAVD88 based on the FEMA stillwater elevation (FEMA 2005) for lower and higher emission scenarios for the years 2050 and 2100.

SLR component	2050		2100	
	Lower	Higher	Lower	Higher
100-Year Flood Elevation ^{a,b}	8.4	8.4	8.4	8.4
Subsidence	0.1	0.1	0.3	0.3
Eustatic Sea Level Rise	1.0	1.7	2.5	6.3
Total Stillwater Elevation (feet) ^{a,c}	9.5	10.3	11.2	15.0
a - NAVD88: North American Vertical Datum of 1988				
b - FEMA 100-Year flood elevation at New Castle, NH				
c - Total stillwater elevation may not equal total of components due to rounding				

References

- Anderson, W.A., J.T. Kelley, W.B. Thompson, and 10 others. 1984. Crustal warping in coastal Maine. *Geology* 12, 677-680.
- Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan, 2007: Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Brown, L.D., 1978, Recent vertical crustal movement along the east Coast of the United States. *Tectonophysics* 44, 205-231.
- Church, J.A., N. J. White, R. Coleman, K. Lambek, J. Mitrovica, 2004. Estimates of the Regional Distribution of Sea Level Rise over the 1950–2000 Period, *Journal of Climate* 17, 2609 – 2625
- Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, 33, L01602, doi:10.1029/2005GL024826.
- FEMA (2005) Flood Insurance Study, Rockingham County, New Hampshire, All Jurisdictions, Federal Emergency Management Agency, FIS Number 33015CV001A.
- Holgate, S.J, P.L. Woodworth, 2004, Evidence of enhanced coastal sea level rise during the 1990s, *Geophysical Research Letters*, 31:L07305
- Katsman, C.A, W.Hazeleger, S.S. Drijfhout, G.J. van Oldenborgh, G. Burgers (2008) Climate scenarios of sea level rise for the northeast Atlantic Ocean: a study including the effects of ocean dynamics and gravity changes induced by ice melt. *Climatic Change* 91:351–374
- Kirshen, P., C.J. Watson, E. Douglas, A. Gontz, J. Lee and Y. Tian (2008) Coastal flooding in the Northeastern United States due to climate change. *Mitigation and Adaptation Strategies for Global Change*. 13(5-6):437-451.
- Koohzare, A., P. Vaničeka, M. Santosa 2008 1994. Pattern of recent vertical crustal movements in Canada. *Journal of Geodynamics* 45, 133-145.
- NOAA, 2011, Mean Sea Level Trend, 8419870 Seavey Island, Maine.
http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid8419870
(accessed July 27, 2011).
- Pfeffer, W.T., J.T. Harper and S. O'Neel (2008) Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science* 321(5894):1340-1343.
- Pugh D (2004) *Changing sea levels: effects of tides, weather and climate*. Cambridge University Press, Cambridge, United Kingdom
- Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds) (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge University Press, Cambridge, UK.
http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html
- Ward, L. and J. Adams (2001) A Preliminary Assessment of Tidal Flooding along the New Hampshire Coast: Past, Present and Future. The New Hampshire Office of Emergency Management and the Office of State Planning Coastal Program http://des.nh.gov/organization/divisions/water/wmb/coastal/restoration/projects/documents/sea_level_rise_report.pdf
- Wake CP, E Burakowski, E Kelsey, K Hayhoe, A Stoner, C Watson, E Douglas (2011) Climate Change in the Piscataqua/Great Bay Region: Past, Present, and Future. Carbon Solutions New England Report for the Great Bay (New Hampshire) Stewards. <http://www.carbonsolutionsne.org/>
- Vermeer M. and S. Rahmstorf (2009) Global sea level linked to global temperature. *PNAS* 106:21527–21532.