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New York City Panel on Climate Change 2015 Report Chapter 2: Sea Level Rise and Coastal Storms

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Introduction

New York City's low-lying areas are home to a large population, critical infrastructure, and iconic natural, economic and cultural resources. These areas are currently exposed to coastal flooding by warm-season tropical storms such as Hurricane Sandy[a] (Box 2.1) and cold-season nor'easters. Sea level rise increases the frequency and intensity of coastal flooding. For example, the ∼12 inches of sea level rise in New York City since 1900 may have expanded Hurricane Sandy's flood area by approximately 25 square miles, flooding the homes of more than 80,000 *additional* people[b] in New York and New Jersey alone (Climate Central 2013, as reported in Miller *et al.*, 2013; see also Chapter 3, NPCC, 2015).

This chapter presents an overview of observed sea level rise and coastal storms for the New York metropolitan region, sea level rise projection methods and results, coastal storm projections, and recommendations for future research.

2.1 Observed changes

This section describes observed sea level rise and coastal storms.

Sea level rise

Since 1900, the global rate of sea level rise has averaged 0.5 to 0.7 inches per decade (Church *et al.*, 2013; Hay *et al.*, 2015; Church and White, 2011). As with temperature, the long-term upward trend in sea level has varied over the decades. For example, there were lower rates of increase during the early part of the 20th century and much of the 1960s and 1970s; sea level rise increased more rapidly during the 1930s through the 1950s. Since 1993, satellite observations and tide gauges show a global sea level rise of ∼1.3 ± 0.1 inches per decade (Church *et al.*, 2013; Nerem *et al.*, 2010). There may be a small, yet statistically significant global sea level acceleration of 0.004 ± 0.002 inches per decade between 1900 and 2009 (Church and White, 2011).

There are multiple processes that contribute to sea level rise, including changes in ocean mass distribution and density; changes in the mass of glaciers, ice caps, and ice sheets; water storage on land; vertical land movements; and gravitational, elastic, and rotational effects resulting from ice mass loss. Historically, the majority of the observed rise in global mean sea level has been attributed to thermal expansion. More recently, the contribution of land-based ice loss to global mean sea level rise has begun to rival that of thermal expansion (Church *et al.*, 2011; 2013).

Each of these processes has a unique local signature. Sea level rise in New York City has averaged 1.2 inches per decade since 1900 (Fig. 2.1).

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[a] We hereafter refer to Sandy as a hurricane or tropical cyclone, although it also can be referred to as a hybrid storm. The storm completed its transition to an extratropical storm just prior to making landfall in New Jersey (Blake *et al.*, 2013).

[b] Relative to the number of people who would have experienced flooding in the absence of the ∼12 inches of sea level rise since 1900.

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Box 2.1. Hurricane Sandy

Hurricane Sandy was directly responsible for approximately 150 deaths (Blake *et al.*, 2013) and $70 billion in losses (NOAA, 2013). About half of the deaths occurred in the Caribbean and half in the United States, including 44 in New York City (Blake *et al.*, 2013). Sandy's 14.1-foot elevation (above mean low low water; MLLW) set the record at the Battery tide gauge (Blake *et al.*, 2013). Several factors caused the extreme surge. Sandy's minimum pressure was the lowest ever recorded[c] at landfall north of Cape Hatteras, NC. With a tropical storm-force wind field of close to 1000 miles in diameter, Sandy was among the largest storms as well. Hurricane Sandy's unusual westward-turning track also concentrated storm surge, wind, and waves in the New York metropolitan region. Part of the extensive coastal flooding was due to the fact that Sandy's peak surge coincided with high tide.

This is nearly twice the observed global rate. In New York City, approximately 40% of the observed sea level rise is due to land subsidence,[d] with the remaining sea level rise driven by climate-related factors (Peltier, 2004; Engelhart and Horton, 2012).

A faster rate of *local* New York City sea level rise has also been observed in recent decades relative to earlier in the 20th century. Tide gauges along the Atlantic coast show a distinct regional sea level acceleration "hotspot" from Cape Cod to Cape Hatteras since the early 1990s (Sallenger *et al.*, 2012; Boon, 2012; Ezer and Corlett, 2012), although the acceleration is still too short to attribute to climate change because of high interannual-multidecadal ocean variability (Kopp, 2013).

Coastal storms

The two types of storms with the largest influence on the coastal areas of the New York metropolitan region are tropical cyclones (hurricanes and tropical storms) and nor'easters. Tropical cyclones strike New York City very infrequently, generally between July and October, and can produce large storm surges and wind damage (Lin *et al.*, 2010). Nor'easters, which tend to occur during the cold season (November to April), are generally associated with smaller surges and weaker winds than hurricanes. Nevertheless, nor'easters affect New York City more frequently (several times a year) than do hurricanes (Karvetski *et al.*, 2009), and their impacts can be large, in part because their lengthy duration leads to longer periods of high winds and high water than are experienced during tropical cyclones.

The greatest coastal inundation occurs when the surge caused by a storm's wind and wave effects coincides with high astronomical (or "non-storm") tides. At the Battery, the mean range of tide[e] is 4.5 feet but can be as large as 7.7 feet[f] during the most extreme spring tides[g] (NOAA Tides and Currents, 2013; Orton *et al.*, 2012).

Because of the complexity of the New York City coastline, there is often a large spatial variation in the extent and timing of flooding associated with any particular storm. High tides and waves associated with nor'easters can lead to significant flooding and beach erosion (Hondula and Dolan, 2010). In the case of Hurricane Sandy (see Box 2.1), one of the reasons coastal flooding was so devastating for southern parts of New York City was that the peak storm surge occurred near high tide. Had the storm struck a few hours earlier or later than it did, coastal flood damage would have been much higher elsewhere, including other parts of the city such as Hunts Point in the Bronx.

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[c] The 1938 hurricane probably had lower pressure at landfall, but it went unrecorded.

[d] Land can subside or "sink" for many reasons. At the Battery, the primary cause is a process known as glacial isostatic adjustment, whereby the land is still responding to the retreat of the ice sheets during the last ice age.

[e] The mean range of tide is defined as the difference in height between mean high water and mean low water (NOAA Tides and Currents, 2013).

[f] The maximum range of tide is defined as the difference in height between NOAA's highest astronomical tide (HAT) and lowest astronomical tide (LAT).

[g] A tide near the time of a new or full moon, when there is the greatest difference between high and low water.

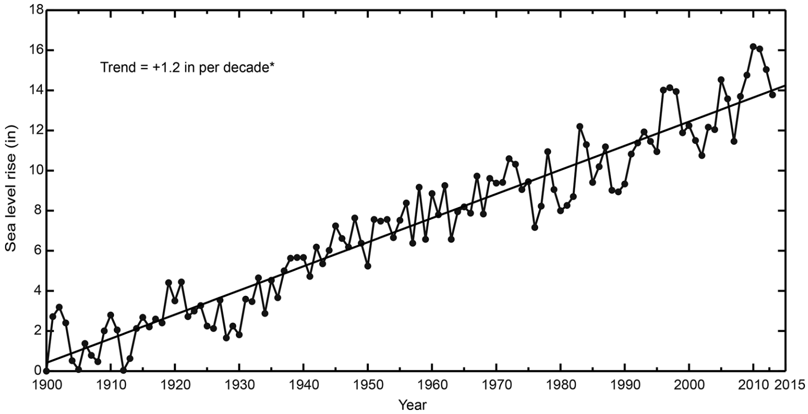

Figure 2.1. Observed sea level rise in New York City (the Battery) from 1900 to 2013. Data are from Permanent Service for Mean Sea Level (PSMSL). *Trend is significant at the 99% level.

Observed changes in the frequency and intensity of coastal storms can also be provided for large geographic regions. There has been an increase in the overall strength of hurricanes and in the number of strong (category 4 and 5) hurricanes in the North Atlantic Basin since the early 1980s (Melillo *et al.*, 2014). However, it is unclear how much of the observed trend is due to natural variability (Seneviratne *et al.*, 2012), increases in greenhouse gas (GHG) concentrations (Hegerl *et al.*, 2007), and/or other changes such as a reduction in aerosol pollution[h] in recent decades (Booth *et al.*, 2012). There is also some evidence of an overall increase in storm activity near the northeastern U.S. coastline during the second half of the 20th century from 1950 to 2010 (Melillo *et al.*, 2014). Studies have also noted increases in coastal flooding during the past century along the United States East Coast (Grinsted *et al.*, 2012) and in the New York metropolitan region (Talke *et al.*, 2014). Coastal flooding has been influenced by historical changes in sea level in addition to changes in storm frequency and intensity.

2.2 Sea level rise and coastal storm projections

This section describes the methods used to project future sea level rise for New York City and presents the projections (see Appendix I for infographics of projections and Appendix IIB for details of the methods (NPCC, 2015)).

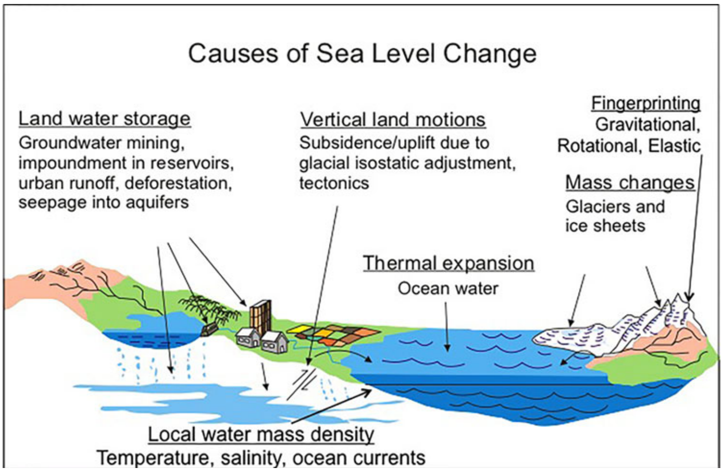

Figure 2.2. Causes of sea level change.

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[h] Aerosols can influence hurricanes both by blocking sunlight from heating the upper ocean and through local changes in cloud formation.

Table 2.1. Sea level rise projection components

Sea level rise component	Scale	Description	Method	Sources
Global thermal expansion	Global	Ocean water expands as it warms	Single globally-averaged value from CMIP5 models	http://cmip-pcmdi.llnl.gov/cmip5
Local changes in ocean height	Local	Changes in ocean water density and circulation	Local values from CMIP5 models	http://cmip-pcmdi.llnl.gov/cmip5
Loss of ice from Greenland and Antarctic ice sheets	Global	Addition of freshwater to the ocean	Bamber and Aspinall expert elicitation surveys of 26 ice sheet experts, with additional probabilistic analysis	Bamber and Aspinall, 2013
Loss of ice from glaciers and ice caps	Global	Addition of freshwater to the ocean	Range from two recent analyses	Radić *et al.*, 2014; Marzeion *et al.*, 2012
Gravitational, rotational, and elastic "fingerprints"* of ice loss	Local	Regional sea level changes due to ice mass change are modified by gravitational, rotational, and "fast" (elastic) isostatic responses	Ice loss from each ice sheet and the glaciers/ice caps is multiplied by a local NYC coefficient reflecting the aggregate effect	Mitrovica *et al.*, 2009; Perrette *et al.*, 2013; Gomez *et al.*, 2010
Vertical land movements/glacioisostatic adjustments (GIA)	Local	Local land subsidence is an ongoing slow response to the last deglaciation	Peltier's Glacial Isostatic Adjustment (GIA model)	Peltier, 2004
Land-water storage	Global	Addition or subtraction of freshwater stored in reservoirs and groundwater	Global estimates derived from recent literature	Church *et al.*, 2011; Milly *et al.*, 2010

* See Appendix IIB for a full description of the "fingerprints."

Sea level rise methods and components

The NPCC2 sea level rise projections for New York City have been developed using a component-by-component analysis (Fig. 2.2; Table 2.1).

Other published studies (e.g., Kopp *et al.*, 2014; Perrette *et al.*, 2013; Slangen *et al.*, 2012) have taken a similar regionalized approach to sea level rise projections using different sources of information (e.g., set of climate models) and assumptions (e.g., for vertical land motion and ice sheet mass loss).

For each of the components of sea level change, the NPCC2 estimated the 10th, 25th, 75th, and 90th percentiles of the distribution. The sum of all components at each percentile is assumed to give the aggregate sea level rise projection.

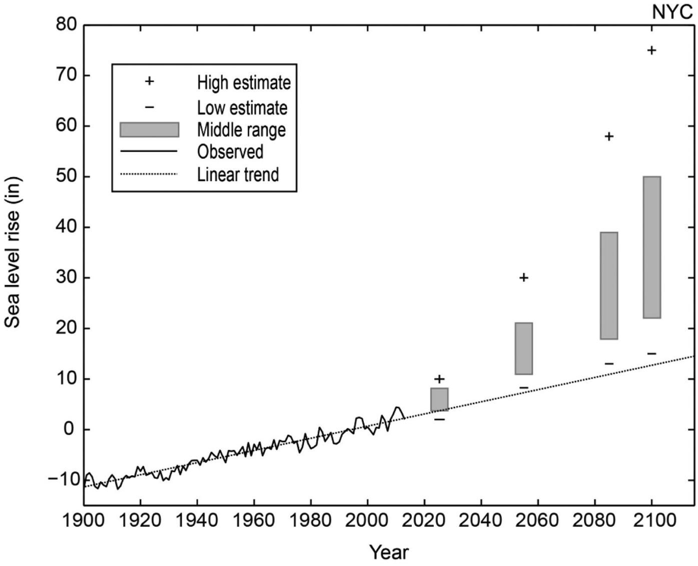

Figure 2.3. New York City sea level rise trends and projections. Projections shown are the low estimate (10th percentile), middle range (25th to 75th percentiles), and the high estimate (90th percentile). The historical trend is also included. Projections are relative to the 2000 to 2004 base period.

Projections for sea level rise are relative to the 2000 to 2004 base period. The three time slices for sea level rise (2020s, 2050s, 2080s) are centered on a given decade. For example, the 2050s time slice refers to the decadal period from 2050 to 2059. Decadal time slices were used for sea level rise (in contrast to the 30-year periods used for the climate variables; see Chapter 1) because natural variability of sea level is lower than that of temperature and precipitation. The sea level rise projections were also extended to 2100 (the methodology is described in Appendices IIA and IIB).

The NPCC2 90th percentile projections are generally comparable to the rapid ice melt scenario of NPCC 2010. Whereas NPCC 2010 included two sea level rise projection techniques, NPCC2 consolidates the projections for all percentiles into a single methodology.

Future sea level rise

As shown in Table 2.2 and Figure 2.3, the middle-range (25th to 75th percentile) sea level rise projection in New York City is an increase of 4 to 8 inches in the 2020s, 11 to 21 inches in the 2050s, 18 to 39 inches in the 2080s, and 22 to 50 inches by 2100. Sea level rise is projected to accelerate as the century progresses and could reach as high as 75 inches by 2100 under the high estimate (90th percentile). New York City's sea level rise projections exceed the global average, primarily due to local land subsidence and global climate model projections that ocean height along the Northeast coastline may increase faster than global average ocean height due in part to projected weakening of the Gulf Stream current (Yin *et al.*, 2009, 2010). The range of projected sea level rise grows as the century progresses, primarily because of uncertainties about how much the ice sheets will melt as temperatures rise.

At the 90th percentile, the NPCC2 late-century sea level rise projections are higher than those of Kopp *et al.* (2014). This is primarily due to (1) differing representation of the tail of the sea level rise distribution in Kopp *et al.*, which is based on a combination of Bamber and Aspinall's (2013) estimate and that of IPCC AR5 (Church *et al.*, 2013), and (2) the assumption by Kopp *et al.* that sea level rise components are independent.

Flood heights and recurrence intervals

Sea level rise is projected to yield large changes in the frequency and intensity of coastal flooding, even if storms themselves do not change at all (Table 2.3). By the 2050s, the middle range sea level rise projections are associated with approximately a doubling of the probability of the historical 100-year coastal flood (the 100-year coastal flood event refers to the

Table 2.2. New York City sea level rise projections

Baseline (2000–2004) 0 in	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2020s	2 in	4–8 in	10 in
2050s	8 in	11–21 in	30 in
2080s	13 in	18–39 in	58 in
2100	15 in	22–50 in	75 in

Note: Projections are based on a six-component approach that incorporates both local and global factors. The model-based components are from 24 global climate models and two representative concentration pathways. Projections are relative to the 2000–2004 base period.

Table 2.3. Future coastal flood heights and recurrence intervals at the Battery, New York

	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2020s			
Annual chance of today's 100-year flood (1%)	1.1%	1.1–1.4%	1.5%
Flood heights associated with 100-year flood (11.3 ft)	11.5 ft	11.6–12.0 ft	12.1 ft
2050s			
Annual chance of today's 100-year flood (1%)	1.4%	1.6–2.4%	3.6%
Flood heights associated with 100-year flood (11.3 ft)	12.0 ft	12.2–13.1 ft	13.8 ft
2080s			
Annual chance of today's 100-year flood (%)	1.7%	2.0–5.4%	12.7%
Flood heights heights associated with 100-year flood	12.4 ft	12.8–14.6 ft	16.1 ft

Note: Flood heights are derived by adding the sea level–rise projections for the corresponding percentiles to the baseline values. Baseline flood heights associated with the 100-year flood are based on the FEMA stillwater elevations (i.e., without wave height). Flood height elevations are referenced to the NAVD88 datum.

flood with a 1% annual chance of occurrence). By the 2080s under the middle range, the historical 100-year event is projected to occur approximately 2 to 4 times more often. Even under the low sea level rise estimate, coastal flood frequency would approximately double by the 2080s. Under the high sea level rise estimate, coastal flood frequency would increase more than ten-fold, turning the 100-year flood into an approximately once per eight year event. The next section addresses potential changes in coastal storms themselves.

Coastal storms

The balance of evidence suggests that the strongest hurricanes in the North Atlantic Basin may become more frequent in the future, although the total number of tropical storms may decrease slightly (Christensen *et al.*, 2013; see Table 2.4).[i] The implications for the New York metropolitan region, however, are unclear because individual storm tracks are highly variable, and potential changes in tropical cyclone tracks are poorly understood (Kozar *et al.*, 2013; Christensen *et al.*, 2013). As the ocean and atmosphere continue to warm, intense precipitation from

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[i] A few recent studies based on downscaled CMIP5 global climate models have projected an increase in the number of 21st-century tropical storms (Emanuel, 2013), at least through midcentury (Villarini and Vecchi, 2012; 2013).

Table 2.4. Projected changes in coastal storms

	Spatial scale of projection	Direction of change by the 2080s	Likelihood
Tropical cyclones			
Total number	North Atlantic Basin	Unknown	—
Number of intense hurricanes	North Atlantic Basin	Increase	More likely than not[a]
Extreme hurricane winds	North Atlantic Basin	Increase	More likely than not
Intense hurricane precipitation	North Atlantic Basin	Increase	More likely than not
Nor'easters (number and intensity)	New York City metropolitan region	Unknown	—

[a] >50% probability of occurrence

Sources: Melillo, 2014; IPCC, 2012; Colle et al., 2013.

hurricanes will more likely than not increase on a global scale (Knutson *et al.*, 2010; IPCC, 2012), although the implications for the more limited New York metropolitan region are unclear because so few tropical cyclones impact the region. It is unknown how nor'easters in the region may change in the future.[j]

2.3 Conclusions and recommendations

Sea level rise in the New York metropolitan region is projected to accelerate as the century progresses and could reach as high as 75 inches by 2100 under the NPCC2 high estimate. New York City's sea level rise is projected to exceed the global average due to land subsidence and changes in ocean circulation, increasing the hazard posed to the New York metropolitan region's coastal population, infrastructure, and other built and natural assets. Although projected changes in coastal storms are uncertain, it is virtually certain (>99% probability of occurrence) that sea level rise alone will lead to an increased frequency and intensity of coastal flooding as the century progresses.

Although these sea level rise projections are New York region specific, projections based on similar methods would not differ greatly throughout the coastal corridor from Boston to Washington, DC (see e.g., Tebaldi *et al.*, 2012; Kopp *et al.*, 2014). Exceptions would include locations experiencing more rapid changes in local land height, such as land subsidence due to excess groundwater extraction.

In the face of uncertainty about the future frequency and intensity of coastal storms, two critical messages are that (1) New York City is highly vulnerable to coastal storms today, and (2) even low-end sea level projections can be expected to increase the frequency and intensity of coastal flooding, absent any changes in storms themselves.

Although the NPCC projections have focused on the 21st century, sea level rise is projected to accelerate into the 22nd century even if heat-trapping GHG concentrations stabilize later this century. Reducing GHG emissions in the near term is critical to minimizing that long-term acceleration.

More research is needed on how the Greenland and West Antarctic ice sheets will respond to climate change because these ice sheets are the largest long-term source of "high-end" uncertainty. Future research efforts should also explore the relationship between the different sea level rise components as well as the relationship between those sea level rise components and coastal storm risk. For example, research is needed on the potential correlation between dynamic sea level along the northeastern U.S. coast and coastal storm risk (Horton and Liu, 2014).

As understanding grows of how coastal storms may change with climate change, it will become possible to combine changing storm and sea level hazards into integrated projections of coastal flood exposure. Another important area of research is how sea level rise may impact coastal flooding and wave damage associated with a given coastal storm.

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[j] One recent study (Colle *et al.*, 2013) using CMIP5 models projects that nor'easter tracks could shift to the west.

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