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New York City Panel on Climate Change 2019 Report Chapter 4: Coastal Flooding

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Introduction

Coastal flooding from storm surge is one of the most dangerous and damaging natural hazards that societies face. It was responsible for half of all hurricane-related mortalities in the United States from 1963 to 2012, far more than any other factor (Rappaport, 2014). Coastal extreme water levels are increasing globally, mainly driven by rises in mean sea level (MSL; e.g., Marcos *et al.*, 2015; Marcos and Woodworth, 2017; Menéndez and Woodworth, 2010). Sea level rise is also causing rapid increases in the annual number of shallow "nuisance floods" for low-lying neighborhoods (e.g., Strauss *et al.*, 2016; Sweet and Marra, 2014).

The objectives of this chapter are to review the latest knowledge on New York City flood risk from storms and tides, and to evaluate how climate change will affect this risk between now and the end of the century. Methods used by NPCC (2015) for assessing storm-driven extreme floods are generally repeated here, including the use of the Federal Emergency Management Agency (FEMA, 2013) baseline flood hazards (e.g., the 100-year flood[a]) and the methods for adding sea level rise and mapping the resulting hazard (Horton *et al.*, 2015b; Patrick *et al.*, 2015). New advancements include an innovative analysis of monthly tidal flooding based on a dynamic model, a broadened set of sea level rise scenarios supplemented with the Antarctic Rapid Ice Melt (ARIM) scenario (see Chapter 3), and sensitivity analyses that show how differing methods would affect our results. Wind is a primary factor for coastal storm surge, and a brief review is given in Appendix 4.A, with the latest scientific knowledge on what drives extreme wind events in the New York City area and how they may change in the future.

4.1. Key processes

Coastal storms have historically flooded New York City's lowest lying neighborhoods many times, and even a water level 5 ft below that of record-setting Hurricane Sandy is sufficient to begin flooding several neighborhoods (Fig. 4.1). The worst four known coastal floods were all caused by tropical cyclones (1788, 1821, 1960, and 2012), whereas the fifth worst was caused by an extratropical cyclone in 1992 (Orton *et al.*, 2016b). Sandy in 2012 was a "hybrid" storm type, in that it was transitioning from a tropical to an extratropical cyclone while approaching landfall. It generated the highest recorded water level at New York Harbor in at least 300 years, due to sustained strong easterly winds and a storm surge maximum coinciding with high tide (Colle *et al.*, 2015; Orton *et al.*, 2016b).

Wind is the primary factor governing storm surge, through its speed and the distance over which it blows, the wind fetch. The height and timing of high tide relative to the peak storm surge is also an

[a]The coastal flood that has a 1/100 or 1% chance of occurring in each year.

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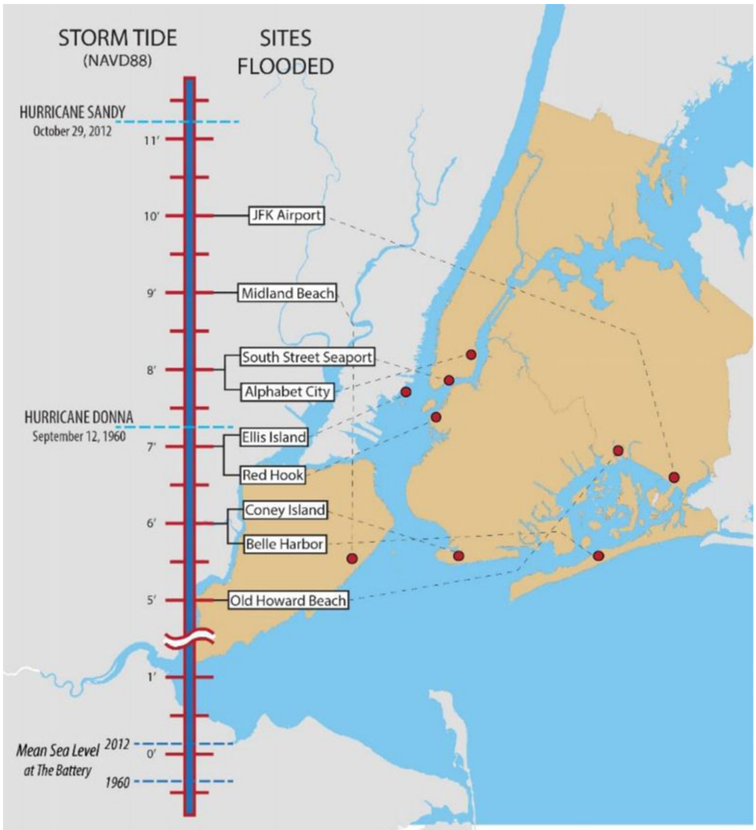

Figure 4.1. Vertical scale bar illustrating approximate breach elevations for the water level (in feet) that floods various New York City locations and neighborhoods. Hurricanes Sandy and Donna peak water levels are shown for comparison. Water levels are assumed spatially constant. Breach, or critical, elevations estimated using a 1-ft resolution 2010 LIDAR-based DEM, with static mapping (Patrick *et al.*, 2015) and 0.5-ft vertical increments of water level.

important factor for New York City coastal flooding (e.g., Colle *et al.*, 2015; Colle *et al.*, 2008; Georgas *et al.*, 2014; Kemp and Horton, 2013). Storm tide can be defined as the combination of tide level and storm surge, measured as a value above a given year's MSL. The total water level is the storm tide plus MSL and can be measured with respect to the geodetic North American Vertical Datum of 1988 (NAVD88). In addition to storm surge and tide, waves can also raise water levels at some coastal neighborhoods of New York City (e.g., Van Verseveld *et al.*, 2015), and are incorporated into FEMA's "base flood elevation" (FEMA, 2013).

This section hereafter refers to storm tide and total water level (called "still water elevation" by FEMA), neither of which includes the oscillations caused by waves. Rainfall typically has a negligible effect on storm-maximum coastal and estuarine water levels surrounding New York City (Orton *et al.*, 2012), though it can directly cause street and neighborhood flooding (e.g., NYC-DEP, 2010).

Of the top 22 known historical storm tide events in New York City history, 15 have been caused by extratropical cyclones, which impact the region far more often than hurricanes (Booth *et al.*, 2015; Catalano and Broccoli, 2018). However, extratropical cyclones appear to have a lower maximum storm tide potential because their maximum wind speeds (based on observations) are much lower than those for hurricanes or hybrids (Orton *et al.* 2016b). In storm tide data going back to 1844 (Talke *et al.*, 2014) and news reports back to the 1700s (Orton *et al.*, 2016b), no extratropical cyclone-driven storm tide has exceeded 7.2 ft MSL and the 1000-year return period extratropical storm tide was recently estimated to be only 8.5 ft MSL (Orton *et al.*, 2016b).

Table 4.1. Comparison of storm tides (in feet)[a] at various return periods (in years) for The Battery, New York City, from various studies and sources

		Return period			
		1	10	100	500
Study	Study type				
FEMA (2007)	Model		6.4	8.6	10.8
Lin *et al.* (2012)[b]	Model			6.7	10.2
FEMA (2013)	Model		7.0	11.3	14.8
Lopeman *et al.* (2015)	Historical Monte Carlo		6.5	11.1	
Nadal-Caraballo *et al.* (2016)	Historical Monte Carlo		6.1	8.0	
Cialone *et al.* (2015)	Model	4.7	7.5	11.2	14.9
Buchanan *et al.* (2016)	Historical	4.7	6.1	8.4	10.7
Orton *et al.* (2016b)	Model		6.4	8.9	12.8
NOAA (2017)	Historical	4.0	6.1	8.0	
Range over studies		4.0–4.7	6.1–7.5	6.7–11.3	10.2–14.9

[a]Values are given in feet above any given year's mean sea level (MSL).
[b]Lin *et al.* (2012) analyzed only tropical cyclones based on the period 1980–2000, and is included for comparison to the longer 100- and 500-year return period storm tides.

For comparison, Sandy's storm tide was 11.1 ft MSL (relative to the 2012 MSL).

Climate change is an increasingly important factor for storm-driven floods and "sunny-day" nuisance floods worldwide. It has increased the height of New York City coastal floods by causing sea levels to rise (Kemp and Horton, 2013; Talke *et al.*, 2014), and this effect is expected to worsen in future decades (e.g., Garner *et al.*, 2017; Orton *et al.*, 2015). Although intensities of tropical and perhaps extratropical cyclones are expected to strengthen in this region, cyclone track changes are difficult to project, and studies have shown mixed results for the effects on New York City storm tides. Uncertainty in this area of research is still high (Garner *et al.*, 2017; Lin *et al.*, 2012; Roberts *et al.*, 2016).

4.2. Current coastal flood risks: observations and trends

"Present-day" flood risk studies typically use past storm events or analysis of their characteristics to represent the present-day hazard, assuming no change to storm climatology. Several academic and governmental studies have found 100-year storm tide estimates in New York City ranging from 6.7 to 11.3 ft (Table 4.1). FEMA's standard map products show contours of the 100- and 500-year return period flood zones, among other metrics, and these return periods have been a common focus of past NPCC flood mapping assessments of sea level rise impacts (Orton *et al.*, 2015; Patrick *et al.*, 2015). These can be referred to as the 1% and 0.2% annual chance floods, respectively, corresponding to the percentage chance of each occurring in a given year. The most recent FEMA (2013) estimates of 100- and 500-year floods are 11.3 and 14.8 ft NAVD88, respectively, and are presently used for planning and building codes but not for insurance purposes because of a successful appeal by New York City (FEMA, 2016).

One source of differences between studies in Table 4.1 involves the use of historical storm tide data versus model-based data. Model-based studies can include synthetic tropical cyclones that have never occurred, with the goal of representing all possible events and surge–tide combinations beyond those observed in the limited historical record (Lin *et al.*, 2014).

Additional reasons for differences can include the particular choice of models, probability distributions, and probabilistic frameworks used to derive storm sets (see discussion in Orton *et al.*, 2016b; Wahl *et al.*, 2017). The Monte Carlo approaches of Lopeman *et al.* (2015) and Nadal-Caraballo *et al.* (2016) are based on historical storm tide data, but also show strong differences for the 100-year event, likely due to their use of different methods for synthesizing water-level time series from storm surge and tide data. Considering the very wide range of storm tide estimates at all return periods shown in Table 4.1, flood hazard assessments should be

Figure 4.2. **Nuisance flooding occurs several times per year due to spring tides with small storm surges (e.g., 1–2 ft), (left) on Rockaway Peninsula and (right) in Hamilton Beach. Photos are from 9:49 am dated 9/10/2018 (credit: Jeanne DuPont) and 11:06 am dated 10/8/2017 (credit: Nathan Kensinger), respectively. The Rockaway Peninsula location frequently floods from saltwater coming up through sewers and rain that will not drain through sewers blocked by high sea levels.**

evaluated using comparisons of both observed and model-based estimates (Orton *et al.*, 2016b).

Coastal flooding for the New York City region has already been worsened by sea level rise. For example, Sandy's peak water level rose higher, and its return period decreased by a factor of three because of the historic sea level rise of 1.64 ft between 1800 and 2000 (Lin *et al.*, 2016). An early sign of sea level rise readily experienced by the public is an increasing frequency of nuisance flooding, which increased substantially in the United States between 1950 and 2013 (Sweet and Marra, 2014; Sweet *et al.*, 2014). Strauss *et al.* (2016) attribute two-thirds of U.S. nuisance flood days since 1950 to global warming.[b]

Nationwide, the number of such flood days has increased by over 80% for the period 1985–2014 relative to 1955–1984. In New York City, the total number of flood days has grown from 32 to 63 over these two 30-year periods. Thirty-four of the 63 flood days can be linked to anthropogenic sea level rise over the study period (Strauss *et al.*, 2016).[c]

The increasing incidence of coastal flooding creates a growing public inconvenience because of potential damages to low-lying infrastructure and private homes, which would face more frequent street, driveway, and basement flooding without adaptive measures. Already affected New York City areas include several neighborhoods around Jamaica Bay, including parts of Old Howard Beach (Fig. 4.1) and nearby Hamilton Beach, Broad Channel, and Rockaway Peninsula (Fig. 4.2).

New York City flood risk may also have risen due to climate change–related influences on storms (e.g., intensity, frequency, or storm track), as well as changes in the water flow behavior in New York Harbor caused by dredging of ship channels and filling of wetlands. The latter has been shown to have raised the 100-year flood for the Jamaica Bay region of New York City by 1.44 ft since the late 1800s (Orton *et al.*, 2016a). Since the mid-1800s, the 10-year flood height at The Battery has risen by 2.36 ± 0.82 ft, 1.44 ft of this resulting from sea level rise and the remaining 0.92 ft from other sources, such as storm changes or anthropogenic harbor modifications (Talke *et al.*, 2014).

Studies of historical data have not found significant evidence in this region for larger storm tides due to the effect of climate change on storms (e.g., Marcos and Woodworth, 2017; Wahl and Chambers, 2016). Moreover, no quantitative evidence has been presented demonstrating that Hurricane Sandy was intensified or its storm tide was increased or made more likely by climate change (Lackmann, 2015; Mattingly *et al.*, 2015). Sandy had hybrid cyclone characteristics as it

[b]Sea level rise due to increasing global temperature. Not considered are land subsidence (GIA, subsurface fluid extraction), spatial fingerprints of land–ice mass change, or ocean dynamics.

[c]The "nuisance flood" level at The Battery in New York City is 26 inches (0.65 m) above Mean Higher-High Water (MHHW; Sweet *et al.*, 2014).

approached the region and therefore represents a relatively complex case study (Galarneau *et al.*, 2013; Zambon *et al.*, 2014).

4.3. Future coastal flood risk under climate projections

In this section, we assess how sea level rise will affect storm-driven and tidally driven coastal flooding over the 21st century. The assessment and mapping of storm-driven floods with the NPCC (2015) high-estimate (90th percentile) scenarios conservatively[d] captures the possible future extreme event contribution to coastal flood risk (Horton *et al.*, 2015b; Patrick *et al.*, 2015). These results are repeated here, as they are now being used for planning purposes by New York City (e.g., NYC-DCP, 2018a, 2018b, 2018c).

The assessment of tidal flooding is an important advancement over NPCC (2015), as more frequently recurring nuisance floods are one of the earliest manifestations of sea level rise and can be a more important driver of flood adaptation (Moftakhari *et al.*, 2017; Sweet and Park, 2014). The water levels and flood mapping of ARIM, a higher impact, lower probability sea level rise scenario, are included for both storm- and tide-driven flooding to raise awareness, but not for planning purposes.

Static mapping approaches simply superimpose sea level rise on water levels for various return period floods and extrapolate ("bathtub") the water level horizontally over the floodplain (Patrick *et al.*, 2015). On the other hand, dynamic flood modeling explicitly accounts for all the forces acting on the water and the resulting water movement, yet is computationally expensive (Orton *et al.*, 2015). Static mapping is used here for the storm-driven flood assessment, and a hybrid dynamic/static approach is used for tidally driven flooding, as described and discussed below.

All flood mapping in this report uses the static approach to project water levels onto inland flood zones, and these static mapping methods are given in Chapter 5 of this report. The flood hazard assessments and mapping assume no future changes in the shoreline due to either coastal erosion or coastal flood protection, for example, and therefore may over- or underestimate flood area. New York City is implementing a $20 billion adaptation plan developed after Hurricane Sandy (City of New York, 2013). Moreover, recent work has demonstrated that while extreme water levels around the United Kingdom have increased due to sea level rise, this has not led to a corresponding increase in coastal flooding, due to improved coastal protection measures, forecasts, and emergency planning (Haigh and Nicholls, 2017; Stevens *et al.*, 2016).

4.3.1 Future storm tide flooding. NPCC (2015) research compared the results of static and dynamic flood modeling of sea level rise using FEMA (2013) storm tide scenarios as a present-day baseline, and found that they were similar for most locations. Differences were usually within ±0.5 ft, and therefore using static mapping leads to a relatively small additional uncertainty compared to the large uncertainty in storm tide probabilities and sea level rise projections (Orton *et al.*, 2015).

Section 4.3.2 uses dynamic modeling to address possible changes to tides with sea level rise, and shows these are also relatively small. Due to these findings and the high expense of performing hundreds of storm simulations for each sea level rise scenario, here we utilize static methods to assess future storm-driven flooding.

We also follow NPCC (2015) precedent by not including the possible effects of storm climatology changes on flooding, but this is partially addressed with a sensitivity analysis (see "Sensitivity tests" section). Studies have shown that atmospheric warming will likely intensify tropical cyclones in the future (Emanuel, 2005; Garner *et al.*, 2017; Knutson *et al.*, 2010; Lin *et al.*, 2012). However, changes in storm tracks could offset the intensity increase, resulting in little change in storm tides at The Battery (Garner *et al.*, 2017).

Most studies suggest there will be a future decrease in the frequency of extratropical cyclones over the North Atlantic (Bengtsson *et al.*, 2006; Chang, 2013; Zappa *et al.*, 2013), although little decrease near the coast (Colle *et al.*, 2013). Some studies have shown an increase in intensity for extratropical cyclones over the next 100 years (Marciano *et al.*, 2015; Michaelis *et al.*, 2017) resulting from additional condensational heating in a warmer

[d]Conservative from an adaptation perspective, that is, erring on the side of a high-risk bias and therefore leading to a more risk-averse response.

Table 4.2. **Water levels (feet NAVD88) for (top) 100-year floods and (bottom) 500-year floods at The Battery for NPCC (2015) (10th–90th percentiles) and ARIM sea level rise scenarios, using static superposition (with unchanged storm climatology)**

		NPCC2 2015 Coastal flooding projections Current projections of record for planning			NPCC3 ARIM scenario Growing awareness of long-term risk
	Time horizon	Low estimate (10th percentile)	Middle range (25th–75th percentile)	High estimate (90th percentile)	ARIM scenario
100-year flood	2020s	11.5 ft	11.6 to 12.0 ft	12.1 ft	–
	2050s	12.0 ft	12.2 to 13.0 ft	13.8 ft	–
	2080s	12.4 ft	12.8 to 14.5 ft	16.1 ft	18.0 ft
	2100	12.5 ft	13.1 to 15.5 ft	17.6 ft	20.7 ft
500-year flood	2020s	15.0 ft	15.1 to 15.5 ft	15.6 ft	–
	2050s	15.5 ft	15.7 to 16.5 ft	17.3 ft	–
	2080s	15.9 ft	16.3 to 18.0 ft	19.6 ft	21.5 ft
	2100	16.0 ft	16.6 to 19.0 ft	21.1 ft	24.2 ft

Notes: The baseline 100- and 500-year water levels are 11.3 and 14.8 ft, respectively (FEMA, 2013; Horton *et al.*, 2015b). ARIM represents a new, physically plausible upper end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from improved modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections.

(and more moist) climate; however, not all models agree with this change (Seiler and Zwiers, 2016).

There is currently little understanding of how hybrid storms like Sandy will change in the future, and more work is needed looking at tropical and extratropical cyclone changes as well.

Methods. The NPCC (2015) coastal flood scenarios took the FEMA (2013) study as a baseline, focused only on the 90th percentile sea level rise scenario, and used static methods for the primary map and flood-level products (Horton *et al.*, 2015b; Patrick *et al.*, 2015). Those results are now being used for planning purposes by New York City (e.g., NYC-DCP, 2018a, 2018b, 2018c). The sea level rise projections were based on an ensemble of 24 global climate models and two emissions scenarios (RCP4.5 and RCP8.5), along with literature review and expert judgement (see Chapter 3) to reflect uncertainty in future emissions as well as in the ocean, cryosphere, and climate system. The sea level rise projections were presented for the 10th, 25th, 75th, and 90th percentiles, for the 2020s, 2050s, 2080s, and 2100 (Table 3.1).

We keep the same static flood scenario approach, superimposing the percentiles of sea level rise on the 100- and 500-year storm tide of the FEMA (2013) baseline. In addition, we expand the calculation to include this report's new upper-end ARIM projections that are available for the 2080s and 2100 (see Chapter 3, Section 3.6, Table 3.2).

Results. Results for 100- and 500-year flood water levels for a range of sea level rise scenarios and time horizons are shown in Table 4.2. For example, the 100-year water level for the 2080s ranges from 12.4 to 16.1 ft NAVD88 for the 10th–90th percentile sea level rise scenarios. This rises to 18.0 ft NAVD88 in the ARIM scenario.

Table 4.3 shows estimated future return periods for the baseline 100- and 500-year floods of 11.3 and 14.8 ft NAVD88, respectively. Today's 100-year flood will become more frequent, occurring on average every 28–71 years in the 2050s, and every 8–59 years in the 2080s (90th and 10th percentiles). If the ARIM projection is reached at 2100, today's 500-year flood of 14.8 ft will have a return period below 5 years. Results for a full range of return periods are plotted in Appendix 4.B, Figure 4.B.1.

A 100-year flood map with the 90th percentile and ARIM sea level rise scenarios, for the Jamaica Bay and Coney Island areas of the city, is shown in Figure 4.3. A similar city-wide map is presented in Chapter 5 of this report (Mapping Climate Risk), but here we zoom in on this localized region due to its having a significant proportion of the city's total floodplain area. The maps clearly illustrate the expansion of the area at risk of flooding for each

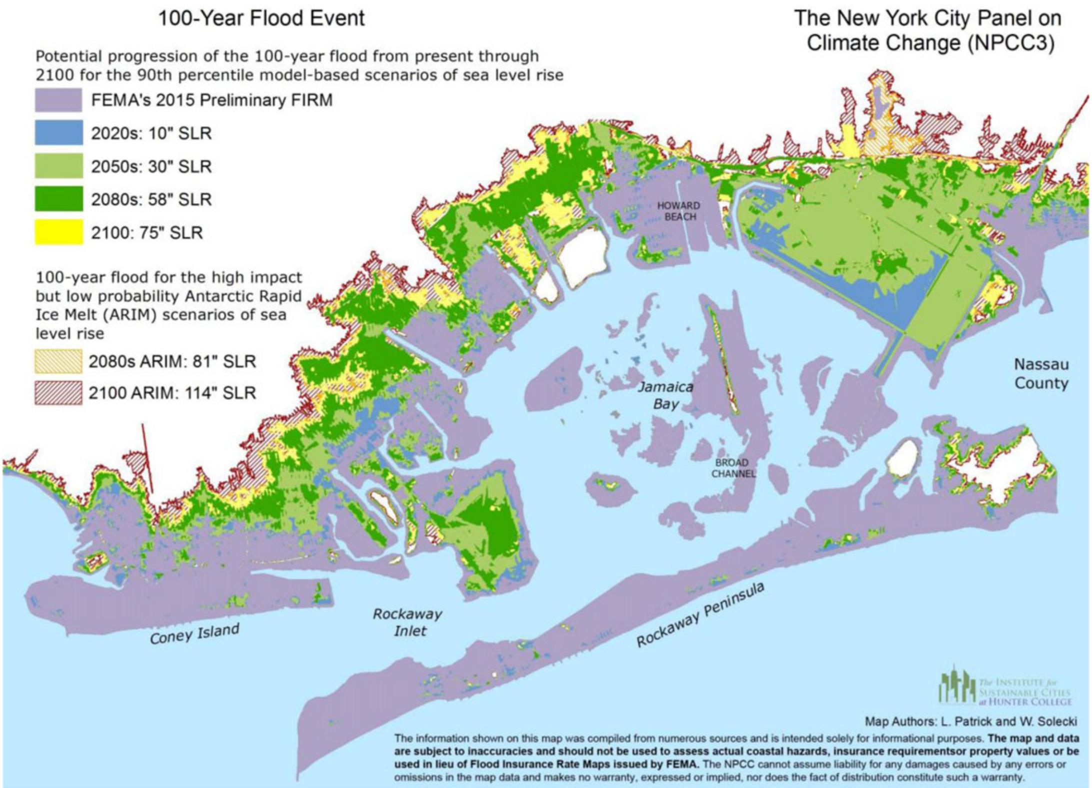

Figure 4.3. Expansion of the 100-year return period floodplain over time in the Jamaica Bay and Coney Island areas of New York City for the NPCC (2015) 90th percentile sea level rise and ARIM scenarios. Results assume no future changes in the shoreline due to either coastal erosion or coastal flood protection, for example, and therefore may over- or underestimate flood area.
NOTE: ARIM represents a new, physically plausible upper end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections. It is included to raise awareness but not for planning purposes.

mapped sea level rise scenario, progressing into the future. However, only Tables 4.2 and 4.3 show the range of uncertainty across the sea level rise projections. The 100-year flood baseline of FEMA (2013) covers a similar area to that which was flooded during Hurricane Sandy (Orton *et al.*, 2015), and this is compared with future tidal flooding at the end of Section 4.3.2.

Sensitivity tests. Detailed analyses of the sensitivity of these results to three key underlying assumptions are given below. First, we evaluate the sensitivity to assumptions on future emissions, which can cause large differences in sea level rise projections. Second, the choice of superimposing a single sea level rise percentile is analyzed, as for certain applications it may be more appropriate to incorporate the full probability distribution of projected sea level rise through mathematical convolution[e] (Lin *et al.*, 2016; Lin and Shullman, 2017; Ruckert *et al.*, 2017). In the third sensitivity test, we examine the possible influence of changing storm characteristics due to climate change, for which there remains substantial uncertainty.

The results presented in Tables 4.2 and 4.3 are based on NPCC (2015) sea level rise projections (Chapter 3, Section 3.4.2) that combine projections for both the lower emission RCP4.5 and higher emission RCP8.5 pathways (Horton *et al.*, 2015a, 2015b). Applying a higher emission scenario would result in higher projected flood levels. For example, applying the 90th percentile sea level rise for an

[e] A convolution is an integral that expresses the amount of overlap of one distribution as it is shifted over another. It therefore “blends” one distribution with the other.

Table 4.3. Future return periods (in years) for today's 100-year flood of 11.3 ft (top), and 500-year flood of 14.8 ft (bottom), for the NPCC (2015) sea level rise projections

		NPCC2 2015 coastal flooding projections Current projections of record for planning			NPCC3 ARIM scenario Growing awareness of long-term risk
	Time horizon	Low estimate (10th percentile)	Middle range (25th–75th percentile)	High estimate (90th percentile)	ARIM scenario
100-year flood	2020s	93 years	85–71 years	66 years	–
	2050s	71 years	64–42 years	28 years	–
	2080s	59 years	47–19 years	8 years	<5 years
	2100	54 years	40–11 years	<5 years	1 day
500-year flood	2020s	457 years	429–374 years	346 years	–
	2050s	374 years	332–228 years	161 years	–
	2080s	304 years	255–112 years	53 years	19 years
	2100	282 years	219–72 years	25 years	<5 years

Notes: The FEMA (2013) baseline flood exceedance curve data do not extend to lower return periods than 5 years (therefore, "<5" is designated), but tidal flood modeling with sea level rise helps estimate a return period of 1 day for one case. The ARIM scenario is shown to raise awareness of potential long-term risk. ARIM represents a new, physically plausible upper-end, low-probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from improved modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections.

RCP8.5 projection (Kopp *et al.*, 2017) that considers rapid ice melt (DeConto and Pollard, 2016) leads to an estimated 100-year flood by the 2080s that is 2.4 ft higher than that based on the NPCC (2015) 90th percentile sea level rise projection (16.1 ft). On the other hand, applying a lower emission scenario would result in lower projected flood levels. Estimated flood levels based on the considered percentiles of RCP8.5, RCP4.5, and RCP2.6 sea level rise projections from Kopp *et al.* (2017) are shown in Figures 4.B.2–4.B.4, respectively.

The alternative approach of combining a full sea level rise distribution with the storm tide distribution through convolution leads to a 100-year flood in the 2080s of 16.7 ft (for the case where the RCP 8.5 sea level rise distribution (Kopp *et al.*, 2017) is applied to the FEMA baseline). This approach estimates the "expected" flood level (integrating all sea level rise percentiles; Lin *et al.*, 2016), but, in this case, the estimated flood level is slightly above the result from superposition with the 50th percentile of the same sea level rise distribution.

Results for various sea level rise distributions are compared in Figures 4.B.2–4.B.4. In the cases where the sea level rise distribution is broader (i.e., the sea level rise projection less certain) such as with the high emissions scenarios for 2100, the result of incorporating the full sea level rise distribution can be well above the result from superposition with the 50th percentile. Future projections of the effect of sea level rise on coastal floods may incorporate full sea level rise distributions, in addition to superposition with specific percentiles, to provide a more integrated account of the uncertainties in sea level rise projections.

Finally, the above results neglect climate-driven changes to storms, which could also increase future flood risk. To test sensitivity to changing tropical cyclones, we estimated future tropical cyclone storm tide probabilities using storm projections based on four IPCC (2007) climate models (Lin *et al.*, 2012). Results show a weighted average increase of 3.4/7.3% in the 100-/500-year storm tides in the 2080s, relative to the assessment considering only sea level rise and no storm changes. Additional details of this analysis are given in Figure 4.B.5.

Results using these climate models suggest that tropical cyclone changes will lead to slightly higher storm tides, yet similar studies elsewhere using IPCC (2013) climate models found no changes in tropical (Garner *et al.*, 2017) and extratropical cyclone (Roberts *et al.*, 2015) storm tides. The spread among different climate models in these studies is often large, and some models indicate that surges could possibly get significantly worse (Lin *et al.*, 2012). Therefore, further research on this topic should be undertaken. One potentially important additional factor that needs more study is the possible correlation between future sea level rise and storm changes (Little *et al.*, 2015).

4.3.2 Future monthly tidal flooding. Tides are far more predictable than storm surges, and modeling their potential flooding therefore requires a much smaller number of simulations and computational expense than storms. As a result, we use dynamic model simulations with sea level projections to quantify the future evolution of tides, though we subsequently use static mapping to map these water levels onto topography. Presently, monthly tidal flooding threatens the lowest lying streets in a few city neighborhoods (e.g., Hamilton Beach).

NPCC has not previously evaluated how sea level rise will affect tidally driven nuisance flooding. However, regular tidal flooding can lead to a tipping point in the advancement of impacts, hypothesized to occur at a threshold of perhaps ∼30 nuisance floods per year (Sweet and Park, 2014). As a result, the city has become interested in seeing projections of future tidal flooding (see Chapter 3 for description of flooding impacts).

Methods. An innovation here is that we map monthly tidal flooding, which can be a useful threshold indicator of repeated flooding that is sufficient to trigger large-scale adaptation investments. Specifically, we model and map the Mean Monthly High Water (MMHW), which is the average of all monthly maxima in predicted astronomical tide levels. MMHW is not a standard tidal datum used by NOAA, such as MSL or MHHW. It is typically exceeded by observed water levels about 25–35 times per year at New York City, based on examination of observed water levels at The Battery, Kings Point, and Jamaica Bay (Inwood, Long Island), closely approximating the aforementioned tipping point of 30 floods per year (Sweet and Park, 2014).

Three-dimensional dynamic simulations of tides are performed using the Stevens Institute of Technology Estuarine and Coastal Ocean Model using the New York Harbor Observing and Prediction System (NYHOPS) operational model setup and grid (Georgas and Blumberg, 2010; Orton *et al.*, 2016b). Simulations cover a 35-day period beginning August 1, 2015, under tide and streamflow forcing (no wind). Modeled water-level time series at all model grid cells are subjected to tidal harmonic analysis (Pawlowicz *et al.*, 2002) to create 19-year tide time series that capture all the periodicities therein, and monthly maxima are computed and averaged.

Resulting tide datum estimates are bias-corrected using observation-based estimates from several sites around New York City (the mean magnitude of model bias for MMHW was only 1 inch). The biases for this zero sea level rise case are then applied to all results for six sea level rise scenarios.

This approach for modeling tides with sea level rise was used recently by this chapter's lead author in studies of Long Island Sound and Jamaica Bay (Fischbach *et al.*, 2018; Kemp *et al.*, 2017). Static mapping methods for using these dynamically modeled estuary tide data to map monthly tidal floodplains are described in Chapter 5 (Mapping Climate Risk).

Results and discussion. Figure 4.4 presents the map of monthly tidal flooding for the Jamaica Bay area of New York City, based on six projections of 90th percentile and low-probability ARIM sea level rise. A similar citywide monthly tidal flood map is presented in the Mapping Climate Risk chapter (Chapter 5). Under the conservative 90th percentile sea level rise scenario, monthly tidal flooding by the 2050s is moderately widespread, including large swaths of low-lying areas like Rockaway Peninsula. At 2100 under this 90th percentile scenario, flooding is very widespread across all neighborhoods around the bay and includes portions of John F. Kennedy Airport (Fig. 4.4, top right). In the more extreme ARIM scenario, the flooding is extremely widespread at 2100.

The new concept of a monthly tidal flood datum MMHW is presented here as a useful metric of chronic flooding. Mapping the effect of sea level rise on monthly tidal flooding (MMHW) has several advantages compared with mapping daily tidal flooding (MHHW), which has become common practice (e.g., Climate Central, 2018; NYC-DCP, 2018b).

Depending on location around New York City, MMHW exceeds MHHW by 0.6–1.0 ft (Fig. 4.B.6), and therefore is a substantially higher metric of tidal flooding, reaching a larger area of the city sooner as sea level rises. While MHHW is exceeded hundreds of times per year, MMHW has only 25–35 exceedances per year, and is more useful as a threshold indicator for when sea level rise will first affect neighborhood habitability and require adaptation (e.g., elevated seawalls).

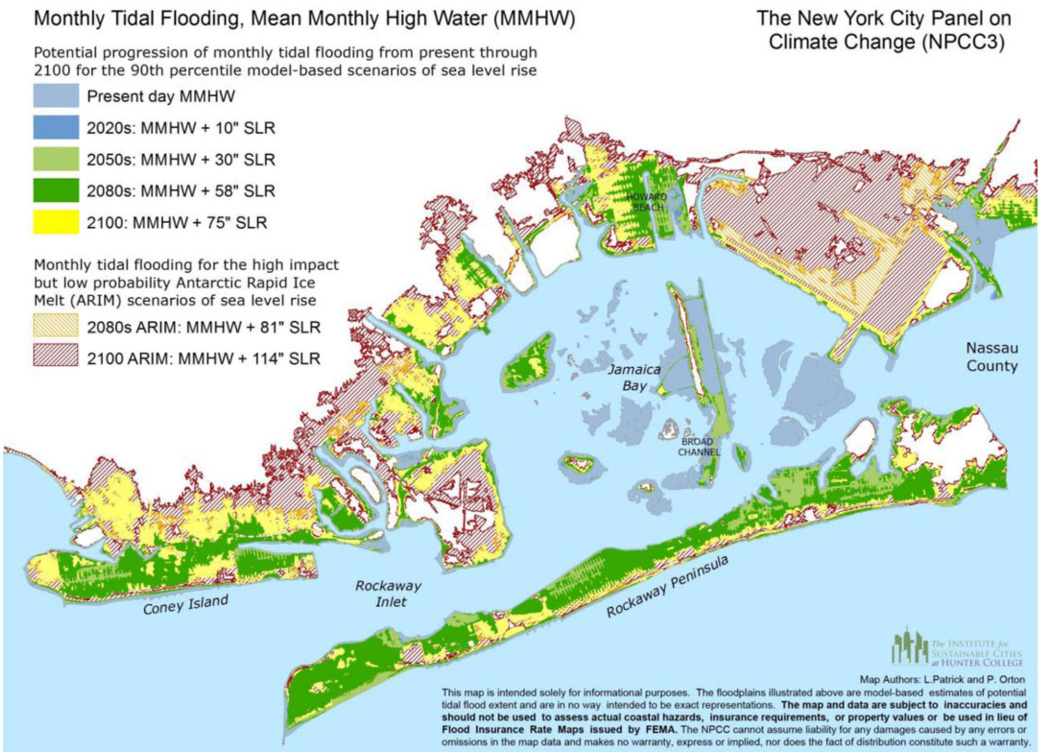

Figure 4.4. Expansion of area affected by monthly tidal flooding for Jamaica Bay and Coney Island areas of New York City for NPCC (2015) 90th percentile sea level rise and ARIM scenarios. Results assume no future changes in the shoreline due to either coastal erosion or coastal flood protection, for example, and therefore may over- or underestimate flood area.
NOTE: ARIM represents a new, physically plausible upper end, low-probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections. It is included to raise awareness but not for planning purposes.

Monthly tidal flooding is already occurring on some low-lying streets of New York City, and citizen observations with time-stamped photographs are helping validate the modeling and mapping (e.g., Fig. 4.2). Moreover, mapping the relatively frequent and observable monthly tidal flooding may be more helpful than mapping the rare 100-year flood, for communicating flood risk and its advancement with sea level rise.

A comparison of dynamic modeling results to simple superposition of tides and sea level rise (Fig. 4.B.7) demonstrates that the difference is relatively small around New York Harbor and moderate for western Long Island Sound (southeast Bronx and northern Queens), adding about 2% and 7% of the amount of sea level rise to MMHW levels, respectively. Similar to previous results where dynamic and static storm tide modeling were compared (Orton *et al.*, 2015), the differences between them here are within ±0.5 ft. Using the 90th percentile 2100 sea level rise (6.25 ft) as an example, the additional increase in monthly high tides at The Battery is 0.15 ft, and at western Long Island Sound is 0.45 ft (Fig. 4.B.7). That is, sea level rise adds 6.25 ft, while the dynamic response of the tides adds another 0.15–0.45 ft to MMHW.

The ARIM sea level rise at 2100 has a very low probability, significantly less than 10%, but provides insights into the impacts of extreme sea level rise that may occur in centuries beyond 2100 (see Chapter 3, Sea Level Rise). In the long term, sea level rise could eventually raise tidal flooding to levels even more severe than those that occurred during Hurricane Sandy. For example, with the ARIM scenario of 9.5 ft of sea level rise at 2100, even the daily maximum tidal water levels are worse than the maximum water levels during Sandy (Fig. 4.B.8).

4.4 Conclusions and recommendations

In this update to the NPCC (2015) coastal flood projections for New York City, NPCC3 has reviewed key processes, summarized historical trends and present-day flood hazards, and assessed how sea level rise will affect storm- and tide-driven future flooding.

A combined dynamic/static analysis shows that monthly flooding will not be a widespread problem until the 2050s or later, but by late in the century it could impact most of the neighborhoods immediately surrounding Jamaica Bay, as well as several other low-lying neighborhoods of the city. Areas particularly susceptible to this monthly tidal flooding include Rockaway Peninsula, Howard Beach, and Coney Island and areas immediately to the north. Under the new ARIM scenarios, sea level rise by the end of this century could raise daily tidal flooding to levels even more severe than that which occurred during Hurricane Sandy.

A static assessment of storm-driven flooding shows how extreme events such as the 100- and 500-year floods will rise with a variety of sea level rise projections, ranging from 10th to 90th percentiles for the 2020s, 2050s, 2080s, and 2100 and including the ARIM scenarios for the 2080s and 2100. Assumptions on future emissions pathways are shown to cause large differences in the sea level rise projections, and as a result, the flood projections. Moderate differences can also arise from differing methods for combining probabilities of storm tides and sea level rise.

An improved understanding of present and future flood risk should be helpful to New York City for optimal long-term planning. NPCC3 therefore makes the following recommendations for continued research to address coastal flooding risks in the New York metropolitan region:

Recommendations for research

- Given the wide range of estimates of storm tide at different return periods, continued research is needed on flood hazards in the New York metropolitan region, including investigations of historical or sedimentary archives, flood modeling, storm modeling, and analyses of how and why the range of hazard assessments differ.
- There remains substantial uncertainty regarding the potential influences of future changes to tropical, extratropical, and hybrid cyclones, and more research should be conducted into future changes to each of these storm types.

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Appendix 4.A. Extreme winds and possible future trends

None of the chapters in this report specifically address the related topic of extreme wind events and how they may change across the region in the future, so here we briefly review the latest science on this related topic. Extreme winds at New York City and the New York Bight are associated with nearby extratropical cyclones, cold and warm fronts, convective storms, and tropical cyclones (tropical storms and hurricanes). High winds during the cool season can be separated in pre-cold frontal (PRF), post-cold frontal (POF), and strong pressure gradients near a coastal northeast winter storm (NEC).

Layer and Colle (2015) showed that NECs and PRFs peak in December, while POFs peak in January and February. During the warm season, there can be severe small-scale convective wind gusts (Colle *et al.*, 2012), quasi-linear convective systems and squall lines (Lombardo and Colle, 2010), and tropical cyclones undergoing extratropical transition such as Sandy (2012; Colle *et al.*, 2015) and Floyd (1999; Colle, 2003).

With regard to extratropical cyclones, most studies suggest there will be a future decrease in their frequency over the North Atlantic (Bengtsson *et al.*, 2006; Chang, 2013; Zappa *et al.*, 2013), although little decrease near the coast (Colle *et al.*, 2013). Some studies have found that there will be an increase in intensity for extratropical cyclones over the next 100 years over the northern Atlantic (Marciano *et al.*, 2015; Michaelis *et al.*, 2017) resulting from additional condensational heating in a warmer (and more moist) climate; however, not all models agree with this change (Seiler and Zwiers, 2016). Extratropical cyclones that cause wind extremes tend to follow a preferred track (Booth *et al.*, 2015), and climate models suggest that there has been an increase in the occurrence of strongly intensifying cyclones along this preferred track (Colle *et al.*, 2013). However, these two studies were not focused on the exact same types of storms, and so more work is needed.

Future trends in tropical cyclones, squall lines, and convective systems are even less certain because climate models cannot resolve convective storm events. Therefore, statistical approaches have been attempted by using future changes in the ambient conditions from CMIP5 models to predict future convective storm changes. For example, Li and Colle (2015) showed that there will be a 50–80% increase in the number of convective storm days for the New York region by the end of the century, from which one can infer a significant increase in the number of convective wind gusts. However, higher resolution models will need to be used in future studies to confirm these results.

Several studies have shown that atmospheric warming will likely intensify tropical cyclones in the future (Emanuel, 2005; Garner *et al.*, 2017; Knutson *et al.*, 2010; Lin *et al.*, 2012). There is currently little understanding of how hybrid storms like Sandy will change in the future, and more work is needed to examine both tropical and extratropical cyclone changes.

Appendix 4.B. Coastal flooding supplemental figures

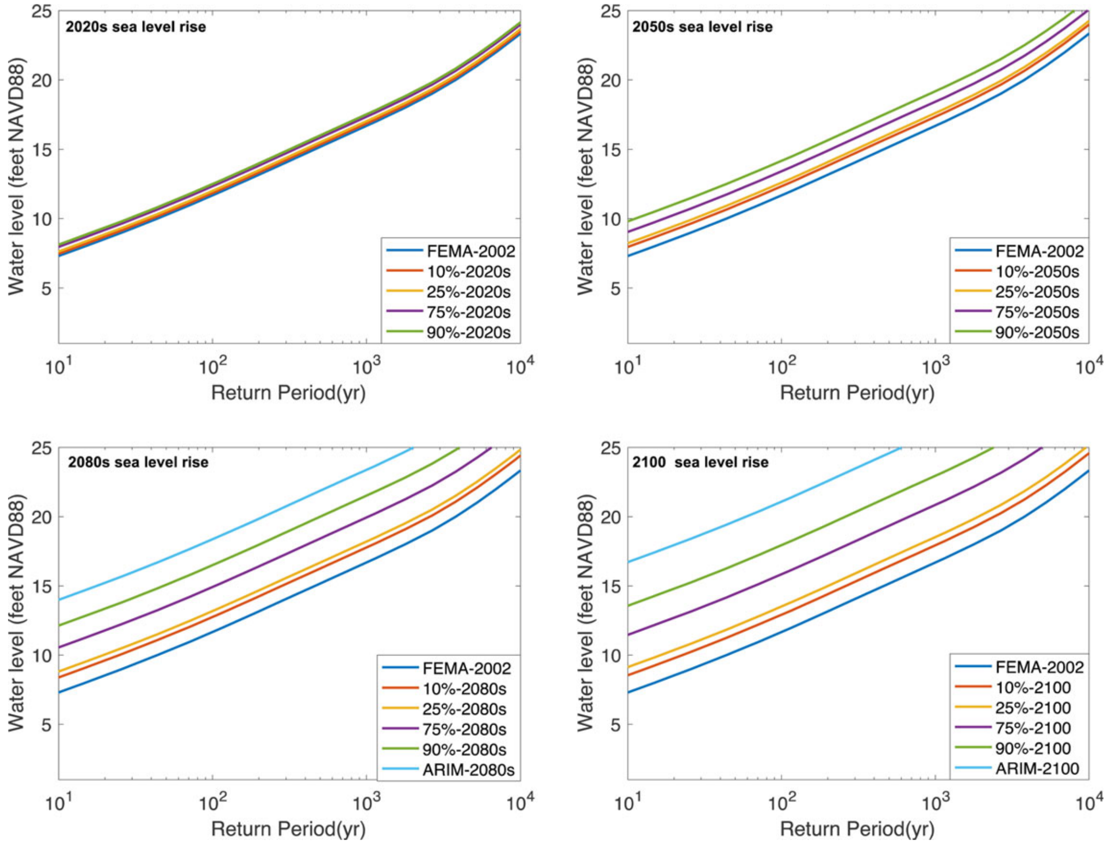

Figure 4.B.1. Estimated flood return periods based on FEMA (2013) storm tide probability distribution ("2002" baseline, i.e., 2000–2004 mean sea level) and NPCC (2015) and ARIM sea level rise scenarios. Particular percentiles (%) of the NPCC sea level rise are considered. Top left: sea level rise for the 2020s; top right: sea level rise for the 2050s; bottom left: sea level rise for the 2080s; bottom right: sea level rise for 2100. Results for 100- and 500-year flood levels are presented in Table 4.2.

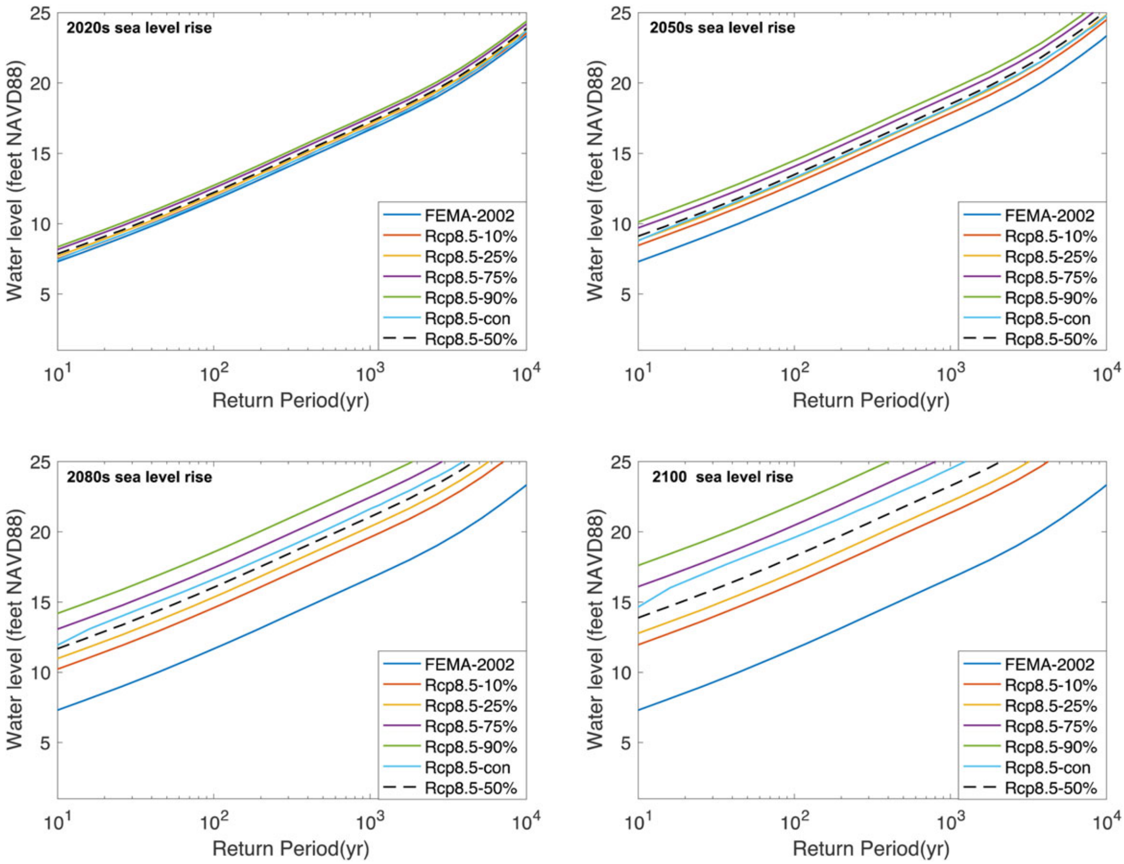

Figure 4.B.2. Estimated flood return periods based on FEMA (2013) storm tide probability distribution ("2002" baseline, i.e., 2000–2004 mean sea level) and RCP8.5 sea level rise probability distribution of Kopp *et al.* (2017). In addition to estimates based on superposition of particular percentiles (%) of the sea level rise to the storm tide return levels, estimates based on convolution with the full distribution of sea level rise ("con") are also shown.

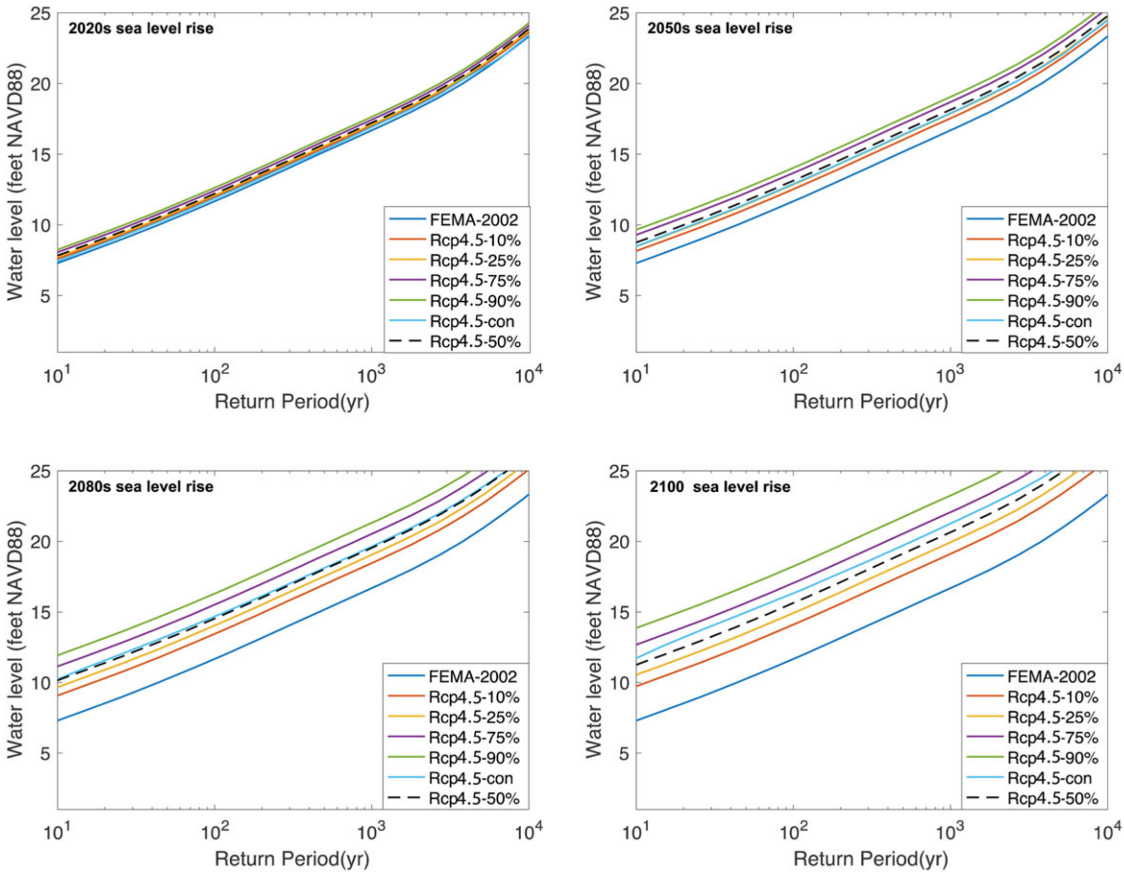

Figure 4.B.3. Same as Figure 4.B.2 but using the RCP4.5 sea level rise probabilities of Kopp *et al.* (2017).

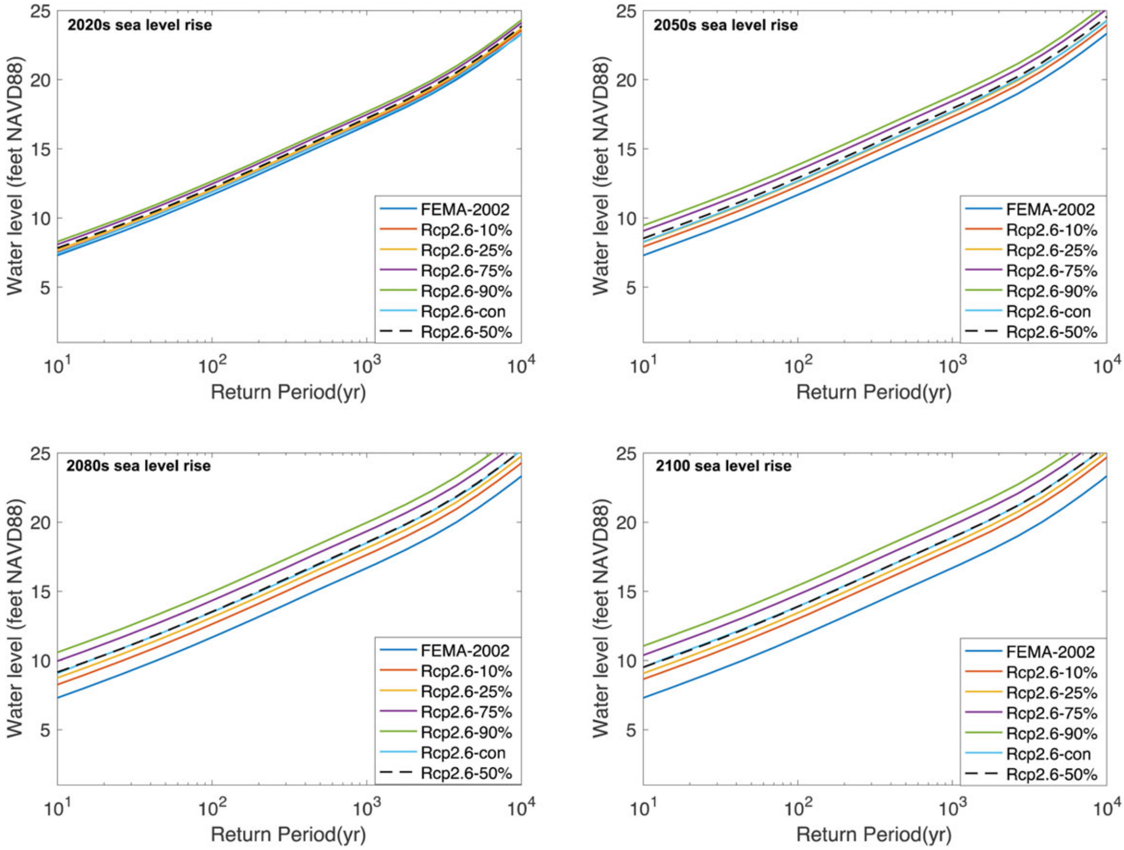

Figure 4.B.4. Same as Figure 4.B.2 but using the RCP2.6 sea level rise probabilities of Kopp *et al.* (2017).

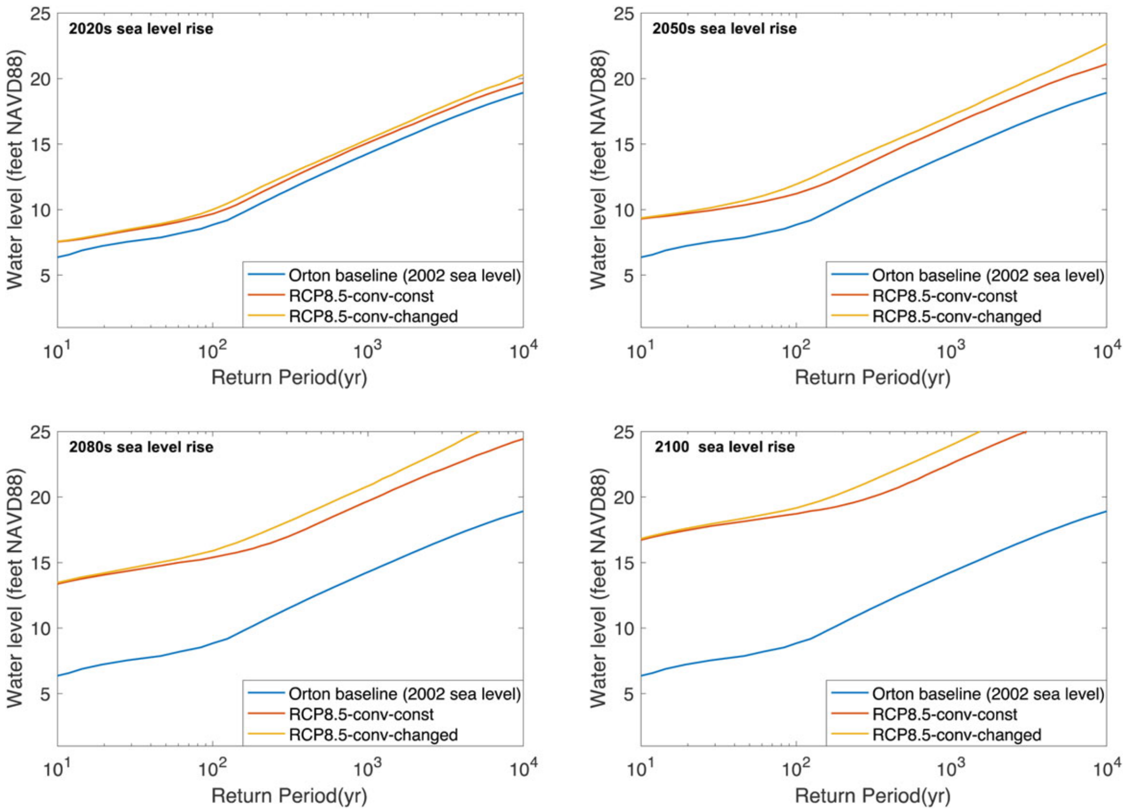

Figure 4.B.5. Estimated water-level return periods based on the storm tide probability distribution of Orton *et al.* (2016b) and RCP8.5 sea level rise probabilities of Kopp *et al.* (2017), with (changed) and without (constant) considering tropical cyclone changes (Lin *et al.*, 2012). The effect of tropical cyclone changes is estimated as a weighted average based on four IPCC (2007) climate model projections in Lin *et al.* (2012). Orton *et al.* (2016b) is used as the storm tide baseline in this analysis of the effect of tropical cyclone changes, as it depicts more appropriate relative contributions of tropical cyclones and extratropical cyclones to the surge probabilities than the FEMA baseline.

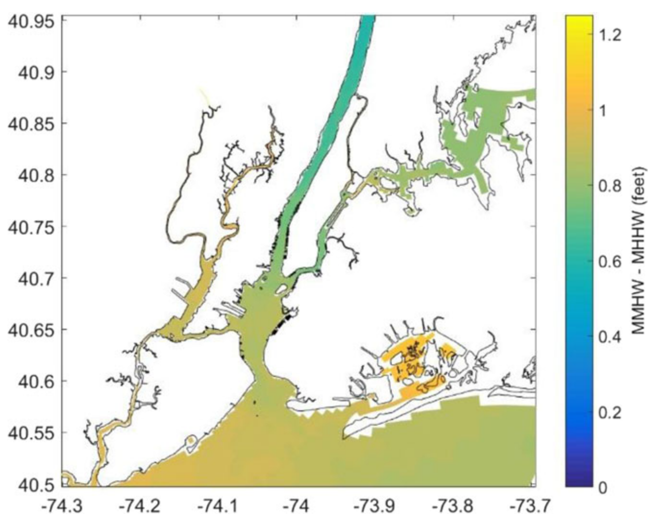

Figure 4.B.6. Map (versus longitude, latitude) showing the difference between present-day tidal MMHW (monthly maximum) and MHHW (daily maximum) water levels.

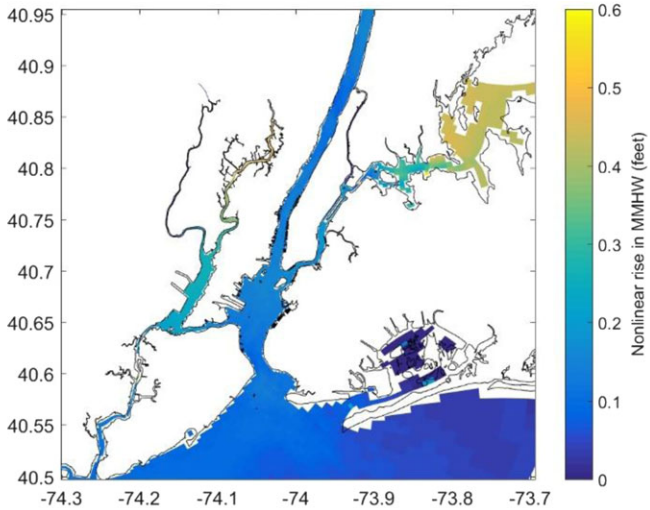

Figure 4.B.7. Map (versus longitude, latitude) showing the difference between the water levels for the dynamic and static superposition approaches for the 90th percentile SLR in 2100 (after NPCC, 2015). In the dynamic approach, nonlinear effects are captured with modeling.

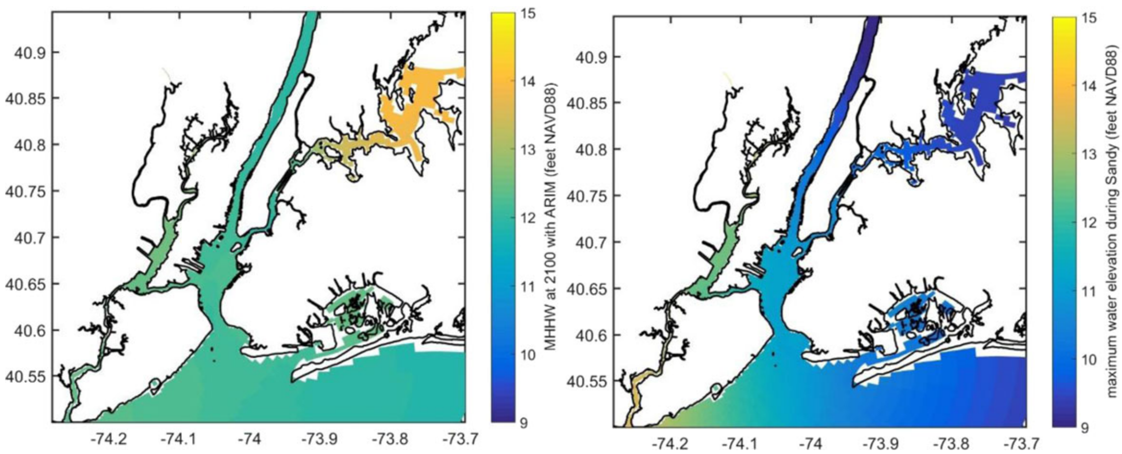

Figure 4.B.8. Comparison of (left) MHHW water levels under the ARIM sea level rise scenario at 2100, with (right) Hurricane Sandy water levels. These are raw model results, and the model is not gridded over land. As a result, no overland flooding is shown.