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New York City Panel on Climate Change 2015 Report Chapter 4: Dynamic Coastal Flood Modeling

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Introduction

Storm surge is an increase in water level caused by winds and low atmospheric pressure and combines with tides to form the total water elevation during a storm, also known as the storm tide or stillwater elevation. Storm tides are among the world's most costly and deadly hazards, bringing floodwaters and waves capable of damaging and disabling infrastructure, homes, and property, as well as threatening human life and health. Sea level rise in the New York metropolitan region has already been increasing the number of coastal flood events (see e.g., Colle *et al.*, 2010; Sweet *et al.*, 2013; Talke *et al.*, 2014). Coastal flood heights are projected to increase and coastal flood zones to expand as sea levels continue to rise due to climate change, as documented in Chapters 2 and 3.

Until now, the New York City Panel on Climate Change (NPCC) has utilized a static mapping approach to assess future costal flood hazards (see NPCC, 2010; 2013; 2015). One assumption of static mapping is that the flood elevation is spatially uniform over inland flood areas, although peak water elevation for a major hurricane can have strong spatial variations (Fig. 4.1), potentially violating this assumption. In this chapter, the second NPCC (NPCC2) advances these methods by testing the use of a dynamic model that explicitly accounts for more of the forces acting on the water and the resulting water movement. The NPCC2 has undertaken dynamic modeling of future coastal flooding based on the Federal Emergency Management Agency's (FEMA) flood-mapping framework, which includes the effects of tides, storm surge, and wave setup (see Chapter 3, Box 3.1, NPCC, 2015) on water elevations and maps overland flood areas. This chapter presents the methods for the dynamic modeling of coastal flooding and compares results from the static approach (discussed in more detail in Chapter 3, NPCC, 2015) and dynamic modeling approaches.

The NPCC2's exploration of dynamic modeling was, in part, motivated by a desire to test whether there were considerable differences between dynamic modeling and static mapping outcomes. In addition, FEMA uses dynamic models for its flood-mapping studies (e.g., FEMA, 2014a), and the National Oceanic and Atmospheric Administration (NOAA) similarly uses dynamic models for forecasting neighborhood flooding during hurricanes. Further, prior studies of New York Harbor have shown that dynamic models can reproduce past storm-tide events with a typical accuracy of 0.5 ft (e.g., Colle *et al.*, 2008; Orton *et al.*, 2012; Georgas *et al.*, 2014).

In addition, under the Biggert-Waters Flood Insurance Reform Act of 2012, FEMA is required to convene a Technical Mapping Advisory Council to develop recommendations on "how to ensure that the Federal Emergency Management Agency

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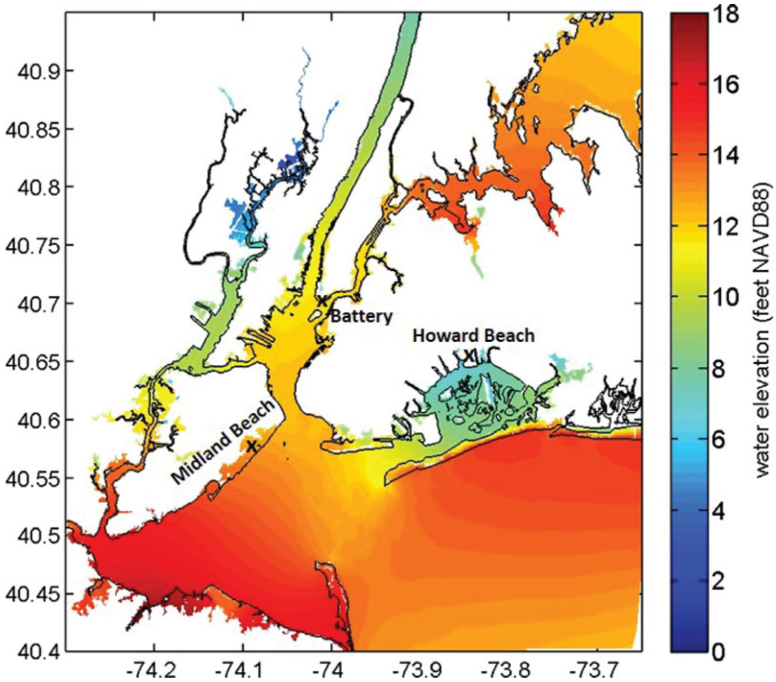

Figure 4.1. Study region for NPCC2 dynamic coastal flood modeling, with peak water elevation data for the synthetic tropical cyclone NJa_0007_006 shown in Figure 4.2.

uses the *best available methodology* to consider the impact of the rise in sea level."[b] New York City relies on FEMA's Flood Insurance Rate Maps (FIRMs) as the basis to understand current flood risk and to inform floodplain management regulations. Therefore New York City and the NPCC2 have an interest in developing methods for assessing future flood hazards that are consistent with FEMA's approach for mapping present-day flood zones.

Here, we set out to inform this discussion by utilizing both static and dynamic methods of calculating the effects of sea level rise on FEMA stillwater elevation estimates and then comparing results. The broader goal of this work is to contribute to the methods by which New York City and other coastal cities can evaluate and address the future impacts of sea level rise on coastal flooding.

4.1 Background

As discussed in Chapter 2 (NPCC, 2015), both tropical cyclones (e.g., hurricanes) and extratropical cyclones (e.g., nor'easters) strike the New York metropolitan region and are important to defining flood zones and elevations for the "100-year" and "500-year" floods, known respectively as the 1% and 0.2% annual chance floods (FEMA, 2014a, Chapter 2). Currently almost 400,000 New Yorkers live within the new 100-year FEMA flood zone, as defined by FEMA's Preliminary FIRMs (City of New York, 2013a; FEMA, 2014a), and Hurricane Sandy flooded many of these neighborhoods (see Chapter 2, FEMA, 2014a).

Hurricanes strike New York City infrequently but have produced the highest two flood events on record at the Battery at the southern tip of Manhattan—Hurricane Donna in 1960 (7.2 feet, NAVD88) and Hurricane Sandy in 2012 (11.3 feet, NAVD88). Extratropical cyclones such as nor'easters typically have small-to-moderate surges but occur more frequently. Their effects can be large because they can last for several days, leading to more extended periods with high storm surge. This makes it more likely for the storm surge to coincide with high tide, as occurred with the December 11–12, 1992 nor'easter (Colle *et al.*, 2010).

[b]42 USC 4101a(d) (emphasis added), available at http://www.law.cornell.edu/uscode/text/42/4101a.

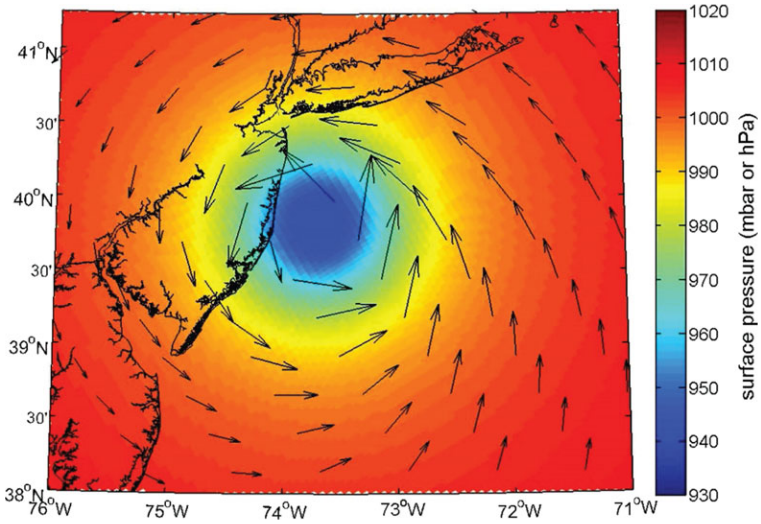

Figure 4.2. Atmospheric pressure and wind vectors for synthetic tropical cyclone NJa_0007_006, one of the worst in the FEMA storm set for New York metropolitan region flooding used in NPCC2 dynamic coastal flood modeling. The longest vector represents a maximum sustained wind speed of 124 mph, a Category-3 hurricane.

Flood-mapping methods for future sea levels

In Chapter 3 (NPCC, 2015), NPCC, 2010, and NPCC, 2013, static approaches were used to estimate the future impacts of sea level rise, adding sea level rise projections to FEMA's 100- and 500-year flood elevations, and to map flood zones with projected sea level rise (Horton *et al.*, 2010; NPCC, 2010; 2013). The static approach was applied to FEMA flood elevations for 100- and 500-year floods, with the additional criterion that low-elevation land areas must have direct connectivity to the open water in order to flood. Whereas the first NPCC maps relied on older FEMA flood elevations from the 2007 FIRMs, the NPCC2 updates use newer, higher flood elevations from the recently released FEMA Preliminary FIRMs and coastal flood study (FEMA, 2014a).

Dynamic flood modeling is a physics-based computer simulation technique that includes the effects of factors such as wind, atmospheric pressure, and friction in the calculation of flood elevations (this technique is also known as *hydrodynamic modeling*). A limited number of studies have compared static mapping and dynamic modeling to quantify the impact of sea level rise on coastal flooding. One study of low-lying populated regions around Miami found that dynamic modeling gave higher flood heights than static flood-mapping methods (Zhang *et al.*, 2013). A study of the New York metropolitan region that did not include overland flooding found that simple superposition of sea level rise on top of storm tide (used in the static mapping technique) was an excellent approximation to dynamic modeling results (Lin *et al.*, 2012). This NPCC2 study uses a hazard assessment framework, dynamically simulates water elevation (including the effects of tides, storm surge, and wave setup) and identifies overland flood areas.

4.2 Methods

The overall strategy of the NPCC2 dynamic modeling is to incorporate sea level rise projections into the dynamic coastal flood-modeling procedure used in the recent FEMA Region II Coastal Storm Surge Study (FEMA, 2014a). The aim is to produce compatible future flood exceedance curves and flood zones (see Appendix IID for details). The NPCC2 baseline simulations used the same dynamic model, grid parameters (e.g., bottom friction, bathymetry/land elevation), storm sets, and forcing data input files (wind, atmospheric pressure, and tide). Statistical methods were also similar between the NPCC2 dynamic modeling and the FEMA study, although there are small discrepancies in results that suggest minor differences in computation.

The study region for the NPCC2's dynamic coastal flood modeling is shown in Figure 4.1, with three areas that were highlighted for special focus: The Battery, Manhattan; the Midland Beach, Staten

Island neighborhood; and the Howard Beach, Queens neighborhood. The flood maps and hazard assessment presented in this chapter include the surrounding parts of New Jersey around the New York Harbor. These interconnected areas are a crucial part of the New York metropolitan region's transportation, energy, and food distribution systems.

The first step was to conduct a baseline reproduction of the FEMA (2014a) model simulations that do not include the effects of sea level rise. The ADCIRC (ADvanced CIRCulation)/SWAN (Simulating WAves Nearshore) (Booij *et al.*, 1996; Luettich *et al.*, 1992) computer model was used to conduct the storm-surge simulations. The NPCC2 baseline results were then compared to FEMA (2014a) results to test for consistency.

The storm set developed by FEMA for use in the Region 2 Coastal Storm Surge Study includes the 30 strongest extratropical cyclones from the period 1950–2009, based on ranking storm surge heights from tide gauges in the region. Tropical cyclones are harder to characterize because they are rare, so FEMA defined a set of 159 synthetic tropical cyclones that span a wider range of possible storms (see e.g., Fig. 4.2).

In the second step, the same modeling procedure was followed, incorporating NPCC2 sea level rise projections. Chapter 2 (NPCC, 2015) presents the NPCC2 sea level rise projections for the 10th, 25th, 75th and 90th percentiles for the 2020s, 2050s, 2080s and 2100. The NPCC2 dynamic coastal flood modeling used the 90th percentile sea level projections in order to focus on high-end risks. Time periods simulated were the 2020s, 2050s and 2080s (11, 31, and 58 inches of sea level rise, respectively[c]). Only a subset of the storms were simulated with sea level rise, focused on 100-year to 500-year events, but the final results take into account the full range of storms (see Appendix IID).

Dynamic coastal flood mapping

Temporal maximum water elevation data (e.g., Fig. 4.2) at each location over the entire domain for each storm were utilized for statistical analysis. For each of the 188,390 grid points in the study area that covers the spatial extent shown in Figure 4.2, probability distributions of water elevation were built separately for tropical cyclones (TCs) and extratropical cyclones (ETCs). A detailed description of the statistical methods utilized for converting these distributions to flood exceedance curves (return period versus water elevation; Fig. 4.3) is given in Appendix IID. As a consistency check, statistical codes and ADCIRC modeling outputs closely reproduced FEMA flood exceedance curves, generally within 2 inches (e.g., Fig. 4.3).

For dynamic flood maps of the baseline and future decades, the 100-year and 500-year stillwater elevation values were taken from the flood exceedance curves for each grid location. The resulting water elevation data were imported into ArcMAP and interpolated (inverse-distance weighting, IDW) to form a raster surface over the entire region (New York City and the New Jersey Harbor regions). The ADCIRC land surface elevation (essentially a coarse, 70-m-resolution digital elevation model) was also interpolated using IDW to the same cell size as the water elevation rasters. The land surface raster was subtracted from each water elevation raster to compute a map (raster) of flood depth, and the zero contour is the boundary of that event's floodplain. Static mapping methods were generally equivalent to those summarized in Chapter 3, but were performed using a 70-m-resolution digital elevation model (DEM) to enable equivalent comparison to the dynamic mapping results (see Appendix IID, NPCC, 2015 for details).

4.3 Results and discussion

This section presents the dynamic coastal flood modeling results and examines differences between the dynamic and static flood-mapping results. The sensitivity of the flood elevations to potential climate change–driven increases in the frequency of tropical cyclones is then analyzed. Finally, the section outlines and discusses some limitations of this study as well as how further research can address them.

Dynamic modeling of future coastal floods

Contours for the 100-year (1% annual chance) flood zone, baseline versus the 2080s, are shown in Figure 4.4. The regions where sea level rise will cause

[c]The values used here differ slightly from the 10, 30, and 58 inches presented in Chapter 2 (NPCC, 2015); the Chapter 2 values include additional information incorporated after the release of the IPCC Fifth Assessment Report. The small differences are within the bounds of climate uncertainty in the long-term projections.

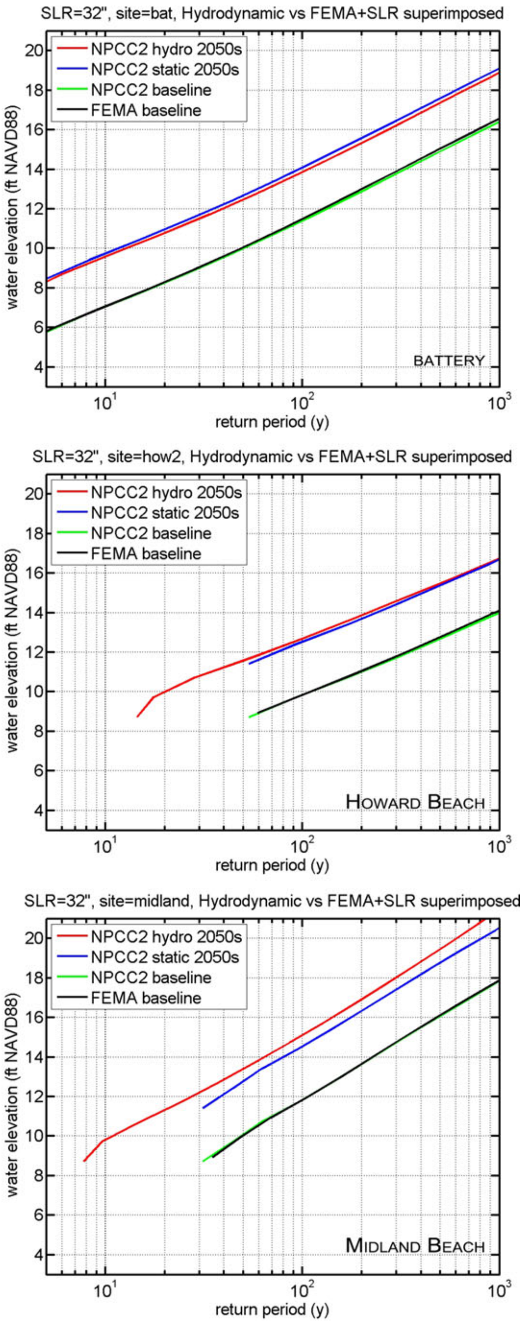

Figure 4.3. Comparison of NPCC2 (green) with FEMA (black) baseline flood exceedance curves as well as NPCC2 static (blue) and dynamic (red) flood exceedance curves for the NPCC2 2050s 90th-percentile sea level rise. Each curve shows the average return period for a flood that exceeds a given flood elevation. Source: Stevens Institute of Technology.

the greatest change in the 100-year flood zone are in the broad flat land area (a floodplain in geographic terms) of southern Queens and eastern Brooklyn around Jamaica Bay. There are other increases in the flooding area across the entire region, including the southern Bronx (the Bronx and Hutchinson River floodplains), and northern Brooklyn (Newtown and Gowanus Creek floodplains).

Contrasting dynamic and static flood assessment approaches

A comparison of the dynamic and static assessments of flood zone boundary contours in the 2050s is shown in Figures 4.5 and 4.6. The results are similar, especially when considering the entire region.

Many New York City floodplain regions in Figure 4.6 show dynamic mapping results that are similar to static mapping results—in many cases the two are only inches higher or lower. Variations in these results arise due to factors such as wind direction (which can blow up higher sea levels in downwind areas) and friction (which initially reduces flood height for a shallow flow, then eventually has little effect as the flow becomes deeper). (For full details, see Appendix IID, NPCC, 2015.)

Results of stillwater elevations for the three specific study locations are compared in Figure 4.3 and Table 4.1. At the Battery, the site of the New York City financial district and a historical tide gauge station off lower Manhattan, the results show dynamic stillwater elevations that are just below those calculated with the static method. At Howard Beach, a neighborhood in southern Queens with a slightly sloping floodplain on the north shore of Jamaica Bay, the dynamic results are equal to or a few inches higher than the static results. At Midland Beach, a neighborhood on the eastern shore of Staten Island that is only a few feet above normal high tides, the dynamic results for the 2050s are substantially higher (>0.5 ft) than the static results, but for the 2080s they are substantially lower (>1.0 ft; Table 4.1). Reasons for these results are discussed below.

A spatial view of the difference between dynamic and static 100-year flood calculations is presented in Figure 4.6. Like the Battery, most other deep-water, estuarine, or open coastal locations show dynamic flood elevations equal to or a few inches lower than the static results.

One exception is the Meadowlands in New Jersey, where dynamic modeling results are close to 1 foot

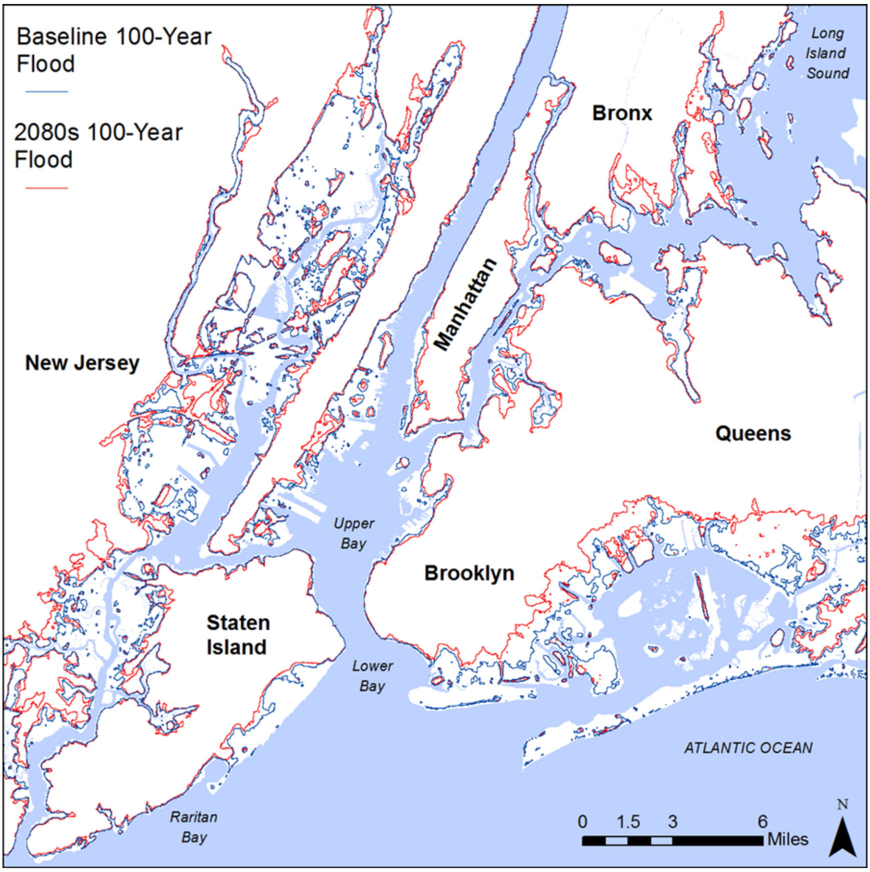

Figure 4.4. The 100-year flood zone for baseline sea level (mean sea level, 1983–2001, as used by FEMA) and for the NPCC2 2080s 90th-percentile sea level rise scenario using the dynamic model.

lower than those of the static mapping approach. These differences are likely related to several factors. First, as flood levels rise with sea level rise, the floodplain cross-section across which the flood travels is expanding. Thus, some volume of water is spreading outward and inland instead of just rising upward as noted in a prior study of the area (Moore *et al.*, 1981). Second, the result could be related to interactions between the tide and the storm surge or to changes to the resonance of the tides (e.g., Zhong *et al.*, 2008). Third, the differences could also be related to the frictional effects of wetlands (e.g., Resio and Westerink, 2008). These and other mechanisms need to be evaluated further.

There are also a small number of locations where the static methods underestimate future flood heights by more than 0.5 feet. For example, Midland Beach dynamic results for the 2050s are greater than the static results by more than 0.5 feet, yet for the 2020s and 2080s they are equal or in one case lower than the static results (the 2080s 500-year water elevation) (Table 4.1). These dynamic modeling results for Midland Beach are also found in FEMA's results for 100-year flood elevations, where the lowest-lying area of Midland Beach has ~0.5 feet lower stillwater elevations than the surrounding more elevated regions.

The results at Midland Beach stem from two combined factors: (1) the dominance of only one extratropical cyclone in the FEMA assessment; and (2) the placement of the low-lying neighborhood behind an elevated waterfront land berm, which makes the statistical analysis of flood zones complex. In the FEMA study, areas that are not flooded for a given storm are referred to as "upland points" (FEMA, 2014b), and the dynamic model-based statistics are supplemented for nonflooding storms with water elevations from nearby flooded areas (effectively

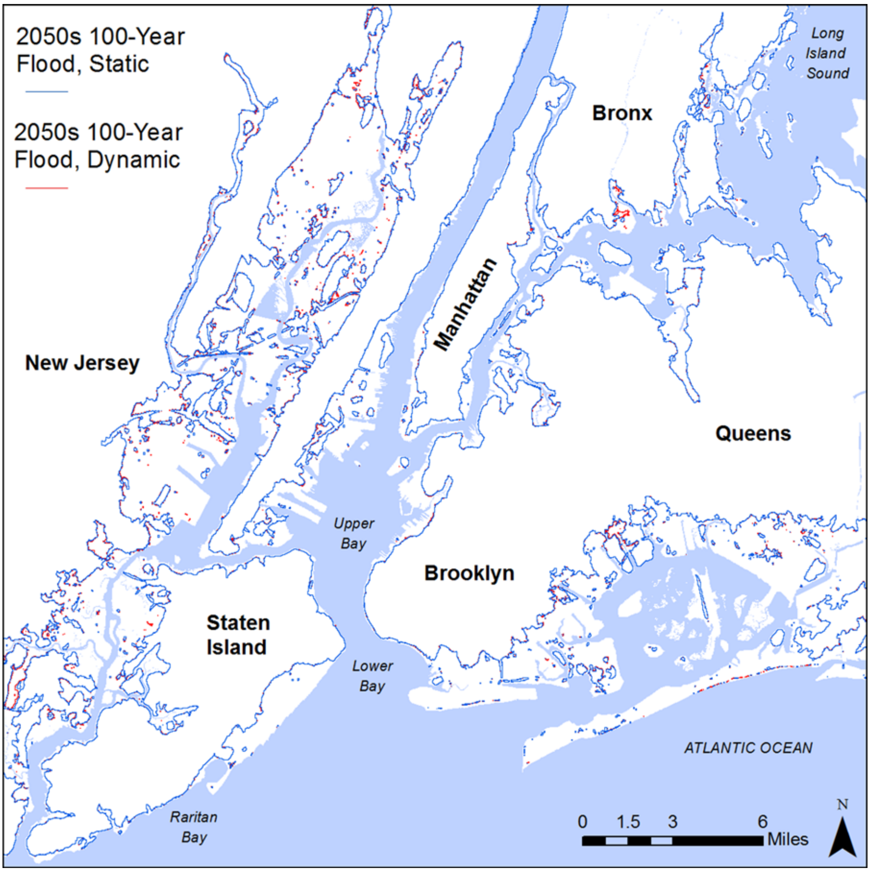

Figure 4.5. Comparison of dynamic model and static flood area contours for the 100-year flood area of the NPCC2 2050s 90th-percentile sea level rise scenario.

a static flood-mapping method). The combination of these two factors leads to erratic results in the assessment of the impact of sea level rise for Midland Beach; however, berm-protected sites are relatively rare in the broader New York metropolitan region.

Cases where the dynamic and static results differ by more than 0.5 feet are more widespread in the case of flooding from tropical cyclones only (Fig. 4.6, bottom). The difference between these results for the combined flood assessment (Fig. 4.6, top; note different color scales) occurs because the extratropical cyclone 100-year flood height is higher than the tropical cyclone 100-year flood height in the FEMA study, and thus, the extratropical cyclones more strongly influence the combined assessment. The larger differences (dynamic versus static) for tropical cyclones are likely driven by the very strong winds during tropical cyclones that can drive up large sea level gradients, particularly in shallow areas of flooding. Friction and water velocity, which combine to reduce inland penetration of a fast-moving storm surge (e.g., a hurricane surge) and have less effect on a slow-moving storm surge (e.g., a nor'easter), also play a role.

These results indicate that the static flood-mapping approach is not always the "conservative" method (i.e., erring on the side of a high risk bias and therefore leading to a more risk-averse response) of estimating the effect of sea level rise on flood heights. Future studies should use both dynamic and static methods in the absence of funding constraints. Continuing use of static mapping methods allows for comparisons to previous assessments.

An ancillary benefit of dynamic modeling of flood hazards is the availability of the model for adaptation experiments. During the development of the City's comprehensive climate resiliency plan,

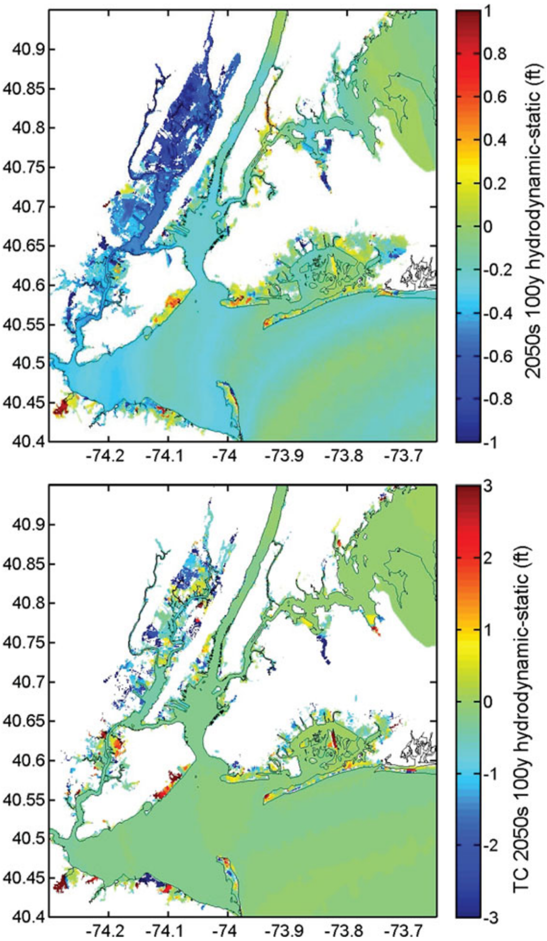

Figure 4.6. **Difference between dynamic and static mapping results for 100-year flood elevations (NPCC2 2050s 90th-percentile sea level rise). Top panel shows results for the combined assessment of extratropical cyclones and tropical cyclones; bottom panel shows results for tropical cyclones only. Note difference in color scales.**

A Stronger, More Resilient New York, dynamic modeling was used to test the effects of coastal adaptation options such as storm-surge barriers, breakwaters, and wetlands (City of New York, 2013b). The dynamic modeling provided quantitative information on the efficacy of these flood adaptations and on how they could be iteratively adjusted to address problems such as "backdoor flooding" (flood waters that do not go over high ground at the front of a barrier island but instead go around the low-lying area behind the island, as occurs with Coney Island).

Sensitivity analysis of storm climatology change

Storm climatology changes are changes to the frequencies or intensities of storms for a given area. Like sea level changes, storm climatology changes can alter return periods for a given flood level (Lin *et al.*, 2012). Recent evidence suggests this may already be occurring due to both regional reductions in aerosol emissions (Villarini and Vecchi, 2012) and atmospheric warming (Grinsted *et al.*, 2013; see Chapter 2). Grinsted *et al.* (2012) found a doubling of "Katrina-level" tropical cyclones in years with warm global air temperatures, based on analysis of historical tide gauge data in the U.S. East and Gulf Coasts.

A sensitivity test was conducted based on this finding, where the annual rates of tropical cyclones were doubled in the statistical analysis. For the same test no change was imposed for extratropical cyclones, as there is no consensus on how climate change will affect their storm surges in the New York metropolitan region (Chapter 2, NPCC, 2013). The results were that the 100-year and 500-year flood for the Battery increased by 0.7 and 0.6 feet, respectively, under doubled annual rates of tropical cyclones. These are relatively small increases compared to the increases driven by sea level rise because extratropical cyclones dominate the impact of storm surge in the FEMA and NPCC2 assessments. For a discussion of this dominance, see the last three paragraphs of the next section.

Study limitations

The use of NPCC2 90th-percentile, high-end projections of sea level rise is useful for conservative, risk-averse planning, but the lack of a similar assessment using median estimates of sea level rise is a limitation of this study. The sea level rise projections are near-worst-case scenarios for the specific future decades that the projections are targeting.

Besides uncertainty in the amount of projected sea level rise, there is also uncertainty about the time it will take to arrive at a given amount. Sea level rise is expected to occur and to be unavoidable due to greenhouse gases already added to the atmosphere, but the exact amount and timing are difficult to project (see Chapter 2 of Levermann *et al.*, 2013). However, the conclusions of this chapter on the differences between dynamic and static coastal flooding calculation methods are independent of

Table 4.1. 100-year and 500-year still water elevations (NAVD88) for baseline 1983–2001 sea level[a] and future decades with NPCC2 sea level rise projections, comparing dynamic (D) and static (S) modeling results

	The Battery, Manhattan				Howard Beach, Queens				Midland Beach, Staten Island			
	100-year return (ft)		500-year return (ft)		100-year return (ft)		500-year return (ft)		100-year return (ft)		500-year return (ft)	
Sea level	D	S	D	S	D	S	D	S	D	S	D	S
Baseline (1983–2001)	11.3	–	14.8	–	9.7	–	12.5	–	11.7	–	16.0	–
2020s	12.3	12.3	15.7	15.8	10.8	10.7	13.5	13.6	12.7	12.7	16.8	17.0
2050s	13.8	14.0	17.3	17.5	12.6	12.4	15.4	15.2	15.0	14.4	19.3	18.7
2080s	15.9	16.2	19.4	19.7	15.0	14.7	17.6	17.5	16.6	16.6	19.6	20.9

[a]The 1983–2001 values are from the current NPCC2 statistical analysis and are nearly identical (within 0.1 ft) to FEMA's results. However, the earlier NPCC Climate Risk Information 2013 report cites baseline (1983–2001) values for the Battery that are 0.4–0.5 ft lower (10.8, 14.4 ft). This difference arose because the earlier NPCC report utilized a location from the FEMA FIRMs in Battery Park, whereas the work for this chapter utilizes the location of the in-water tide gauge in the FIRMs for the purposes of historical comparison and cross-comparisons with other studies.

the uncertainty in the rate at which the sea level rise occurs.

This NPCC2 study relied on the FEMA hazard assessment approach, which is an extremely detailed study of the region's storms and flooding; yet the FEMA approach has limitations. One limitation is that Hurricane Sandy is not included in the storm set because the storm climatology assessment was completed before Sandy hit the New York metropolitan region. This raises the question of how Sandy's storm track and record-setting storm surge would have affected results. Future studies will need to utilize data for Hurricane Sandy as well as more recent storms to build a more complete storm climatology in what are currently data-poor conditions.

A further limitation is that tropical cyclones in the New York metropolitan region often take on extratropical characteristics (Colle *et al.*, 2008), as was the case with Sandy (Blake *et al.*, 2013). The FEMA study utilized representations of idealized tropical cyclones (e.g., Fig. 4.1) that lack the more complex characteristics of extratropical cyclones. Further study of hybrid storms, transitions between tropical and extratropical storms, and methods for representing synthetic tropical cyclone wind and pressure fields will be useful for improving the accuracy of future hazard assessment studies.

The FEMA study found that the hazard assessment results for New York Harbor at the Battery for the flood elevations of 100- and 500-year storm tides are influenced predominantly by the extratropical cyclones. However, a recent study has recovered storm tide data from the 1800s and has shown that the three highest storm tides from 1821 to the present were either tropical cyclones (the major storm of 1821 and Hurricane Donna in 1960) or tropical-extratropical hybrid storms (Sandy) (Talke *et al.*, 2014). Yet, the largest *storm surge* within the time period used by FEMA (1927–2009) was an extratropical cyclone on November 25, 1950, at 7.6 feet. That storm surge peaked at the time of low tide, and the *storm tide* was only the sixth highest from 1821 to present (Talke *et al.*, 2014). Thus, the relative importance of extratropical cyclones, tropical cyclones, and hybrid storms for defining the region's flood hazards is an important topic for further research.

Uncertainties in flood hazard assessment for the New York metropolitan region (e.g., defining the 100-year flood elevation) are large, and more research should be done on historical events and on hazard assessment methods to reduce these uncertainties. The recent FEMA hazard assessment found substantially higher estimates of 100-year and 500-year storm tides for New York City (except for the upper East River and Long Island Sound) than those of other studies or data analyses.

For example, the FEMA (2014a) estimate of the 100-year flood elevation at the Battery tide gauge is 11.3 feet (NAVD88), whereas a statistical analysis by NOAA of observed storm tides from 1893 to 2013 results in a 100-year flood elevation of 7.86 feet (NAVD88) (http://tidesandcurrents.noaa.gov/est), a difference of 3.4 feet. Putting this into perspective, Hurricane Sandy produced an 11.3-foot storm tide at the Battery. Prior to the new FEMA study, FEMA's old estimate for the 100-year flood elevation was estimated to be 8.6 feet (NAVD88) based on USACE Waterways Experiment Station Implicit Flood Model results in the 1980s (Horton *et al.*, 2010). A recent study of tropical cyclone storm tides concluded that the 100-year tropical cyclone storm tide is 6.45 feet (NAVD88) (Lin *et al.*, 2012), compared with the FEMA 100-year tropical cyclone storm tide of 8.83 feet (FEMA, 2014a). Discrepancies for 500-year storm tides are similarly large. Again, further research is needed to understand and reduce these large discrepancies and uncertainties.

4.4 Conclusions and recommendations

The static and dynamic flood-mapping methods for projecting the effects of sea level rise on coastal flood elevations in the New York metropolitan region give similar results for most locations, usually within ±0.5 feet. Therefore, the flood zone boundaries produced from these two methods are very similar.

In a small number of areas, the methods differ by more than 0.5 feet. These exceptions are geographically more widespread in regard to flooding from tropical cyclones (hurricanes) than from extratropical cyclones (nor'easters).

Uncertainties in flood hazard assessment for the New York metropolitan region (e.g., defining the 100-year flood elevation) and in the rate of future sea level rise are much larger than differences between the dynamic and static flood-mapping methods. Recent studies assessing the present-day 100-year flood elevation for the Battery have differed substantially (a range of 3.4 feet), while the 80% uncertainty range (90th percentile minus the 10th percentile) in NPCC2 sea level rise predictions for the 2080s is 3.75 feet.

Research recommendations

More research should be done on historical storm events and on hazard assessment methods to reduce the uncertainty in defining New York City flood hazards. The 100-year and 500-year flood heights from FEMA's (2014a) present-day hazard assessment are influenced predominantly by the extratropical cyclones, but new storm tide data from the 1800s demonstrate that the three highest storm tides from 1821 to the present came from tropical cyclones.

Future dynamic modeling efforts should study a broader set of sea level scenarios. However, computational dynamic modeling of storm surges for hazard assessment is time intensive, and this limits the potential for simulating many different scenarios. Therefore, either faster models, different statistical techniques, or a much larger allocation of computational resources will be required.

Research is needed to understand the geography and storm conditions that cause some locations to have higher (or lower) dynamic modeling flood heights than static flood-mapping heights.

Resiliency recommendations

Dynamic modeling identified some locations in the New York metropolitan region where results differed from static flood-mapping methods. Therefore, it is recommended that dynamic modeling continue to be used alongside static flooding assessments as resources allow. An ancillary benefit of dynamic modeling of flood hazards is the ability to conduct adaptation experiments such as testing locations for storm surge barriers.

For more complete probabilistic risk analyses and cost-benefit studies in the context of sea level rise and adaptation strategies for important infrastructure and coastal land-use planning, it would be highly advisable to consider the storm tide elevations for much longer recurrence periods (e.g., 1000 to 5000 years), together with a thorough quantification of their uncertainties.

Acknowledgments

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References

Blake, E.S., T.B. Kimberlain, R.J. Berg, *et al.* 2013. *Tropical Cyclone Report: Hurricane Sandy (AL182012)*. Miami, FL: National Hurricane Center.

Booij, N., L. Holthuijsen, and R. Ris. 1996. The "SWAN" wave model for shallow water. *Coastal Engineering Proceedings.* **1:** 668–676.

City of New York. 2013a. Chapter 2: Climate Analysis. In *A Stronger, More Resilient New York.* New York: New York City Economic Development Corporation.

City of New York. 2013b. Chapter 3: Coastal Adaptation. In *A Stronger, More Resilient New York.* New York: New York City Economic Development Corporation.

Colle, B.A., F. Buonaiuto, M.J. Bowman, *et al.* 2008. New York City's vulnerability to coastal flooding. *Bull. Am. Meteorol. Soc.* **89:** 829–841.

Colle, B.A., K. Rojowsky, and F. Buonaito. 2010. New York City storm surges: climatology and an analysis of the wind and cyclone evolution. *J. Appl. Meteorol. Climatol.* **49:** 85–100.

FEMA. 2014a. *Region II Coastal Storm Surge Study: Overview.* Washington, DC: Federal Emergency Management Agency.

FEMA. 2014b. *Final Draft Report: Joint Probability Analysis of Hurricane Flood Hazards for New York–New Jersey*. Washington, DC: Federal Emergency Management Agency.

Georgas, N., P. Orton, A. Blumberg, *et al.* 2014. The impact of tidal phase on Hurricane Sandy's flooding around New York City and Long Island Sound. *J. Extreme Events* **01:** 1450006–16.

Grinsted, A., J.C. Moore, and S. Jevrejeva. 2012. Homogeneous record of Atlantic hurricane surge threat since 1923. *Proc. Natl. Acad. Sci. USA* **109:** 19601–19605.

Grinsted, A., J.C. Moore, and S. Jevrejeva. 2013. Projected Atlantic hurricane surge threat from rising temperatures. *Proc. Natl. Acad. Sci. USA* **110:** 5369–5373.

Horton, R., V. Gornitz, M. Bowman, and R. Blake. 2010. Climate observations and projections. In Climate Change Adaptation in New York City: Building a Risk Management Response. C. Rosenzweig and W. Solecki, Eds. *Ann. N.Y. Acad. Sci.* **1196**: 41–62.

Levermann, A., P.U. Clark, B. Marzeion, *et al.* 2013. The multimillennial sea-level commitment of global warming. *Proc. Natl. Acad. Sci. USA* **110:** 13745–13750.

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke. 2012. Physically based assessment of hurricane surge threat under climate change. *Nature Climate Change* **2:** 462–467.

Luettich, R., J. Westerink, and N.W. Scheffner 1992. *ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries. Report 1. Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL.* Vicksburg, MS.

Moore, C., S. Dendrou, and R. Taylor 1981. *New York City Flood Insurance Study Report no. 7.* Prepared for the New York Department of Environmental Conservation.

NPCC. 2010. Climate Change Adaptation in New York City: Building a Risk Management Response. C. Rosenzweig and W. Solecki, Eds. *Ann. N.Y. Acad. Sci.* **1196:** 1–354.

NPCC. 2013. *Climate Risk Information 2013: Climate Change Scenarios and Maps.* New York: New York City Panel on Climate Change.

NPCC. 2015. Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report. C. Rosenzweig and W. Solecki, Eds. *Ann. N.Y. Acad. Sci.* **1336:** 1–149.

Orton, P., N. Georgas, A. Blumberg, and J. Pullen. 2012. Detailed modeling of recent severe storm tides in estuaries of the New York City region. *J. Geophys. Res.* **117:** C09030.

Resio, D.T., and J.J. Westerink. 2008. Modeling the physics of storm surges. *Physics Today* **61:** 33–38.

Sweet, W., C. Zervas, S. Gill, and J. Park. 2013. Section 6: Hurricane Sandy inundation probabilities today and tomorrow. *Bull. Am. Meteorol. Soc.* **94:** S17–S20.

Talke, S., P. Orton, and D. Jay. 2014. Increasing storm tides at New York City, 1844–2013. *Geophys. Res. Lett.* **41:** 3149–3155.

Villarini, G., and G.A. Vecchi. 2012. Twenty-first-century projections of North Atlantic tropical storms from CMIP5 models. *Nature Climate Change* **2:** 604–607.

Zhang, K., Y. Li, H. Liu, *et al.* 2013. Comparison of three methods for estimating the sea level rise effect on storm surge flooding. *Climatic Change* **118:** 487–500.

Zhong, L., M. Li, and M. Foreman. 2008. Resonance and sea level variability in Chesapeake Bay. *Cont. Shelf Res.* **28:** 2565–2573.