New York City's evolving flood risk from hurricanes and sea level rise

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On the evening of October 29th, 2012, Hurricane Sandy made landfall along the mid-Atlantic coast, bringing with it strong winds, destructive waves, and a catastrophic storm surge in New York Harbor. Hurricane Sandy generated a storm surge height of 2.87 m above mean tidal level (MTL) at The Battery in New York City (NYC) (Blake et al. 2013). The storm destroyed more than 650,000 buildings, 8 million customers lost power, and roads, bridges, and subways were closed, mainly as a result of the enormous storm surge and large waves (Blake et al. 2013). Hurricane Sandy highlighted the need to better understand NYC's changing flood hazard and emphasized the necessity of adaptation measures and resiliency planning to help protect against future flood events.

Five years after Sandy, coastal flooding remains a major concern for NYC, with nearly 50 million built square meters and 400,000 residents living within the current 100-year floodplain (PlaNYC 2013), and rates of local relative sea level rise (SLR) that exceed the global average (Miller et al. 2013; Engelhart et al. 2009; Kemp and Horton 2013). In a changing climate, the evolution of the coastal flood hazard for NYC will depend upon not only rising sea levels but also upon storm-surge events associated with hurricanes (where storm surge is defined as the atypical rise of water during a storm), which in turn will depend on changing storm characteristics (Garner et al. 2017; Reed et al. 2015; Lin et al. 2012, 2016; Little et al. 2015).

It is important to understand the ways in which storm surge events i) have already changed for NYC over the past millennium and ii) are likely to change in the future for a range of possible climates and physical assumptions (Reed et al. 2015; Garner et al. 2017). However, the brevity of the observational record of hurricanes in the Atlantic basin (extending from 1851 to the present), as well as potential biases in the record, presents a challenge to the accurate analysis of long-term trends in storm activity and severely limits the scope of potential investigations of coastal flood hazard associated with hurricanes (Kozar et al. 2013). Similarly, the instrumental record of sea level for NYC, recorded by the NOAA tide gauge network, goes back to only 1920.

We have worked to overcome the limitations of the relatively short observational record of Atlantic hurricanes by producing libraries of hundreds of years of synthetic storms under downscaled past and future climate simulations (Reed et al. 2015; Garner et al. 2017). For each of these storms, we generated storm surge heights at The Battery in NYC using the Advanced Circulation (ADCIRC) model, which predicts storm surge and flooding by solving the equations of motion for moving ocean waters on a rotating Earth (Luettich et al. 1992). We combined peak storm surge heights with proxy relative sea level records from New Jersey (850–2005 CE; Kemp and Horton 2013; Kemp et al. 2013) and with localized probabilistic SLR projections for NYC (2000-2300; Kopp et al. 2014, 2017) to estimate overall flood heights at The Battery from 850–2300 CE.

Generating synthetic storms

We generated synthetic hurricanes by downscaling a range of Coupled Model Intercomparison Project version 5 (CMIP5) models, focusing on the Last Millennium and representative concentration pathway (RCP) 8.5 simulations from three models: the Max-Planck-Institute (MPI) Earth System Model, the Coupled Climate System Model 4.0 (CCSM4), and the Institut Pierre Simon Laplace (IPSL) Earth System Model.

By essentially inserting a high-resolution hurricane model within the broader context of the relatively coarse-resolution global climate models, we generated a large number of hurricanes consistent with Last Millennium and future RCP 8.5 simulated climates (Emanuel et al. 2006, 2008; Kozar et al. 2013; Reed et al. 2015; Garner et al. 2017; Emanuel 2017).

We filtered the hurricanes to focus on those that travel within 250 km of The Battery for the pre-industrial era (850–1800 CE; ~5000 storms from each model), modern era (1970–2005; ~5000 storms for each model), and the future (2010–2100 or 2300; ~12,000 storms per century for each model; Reed et al. 2015; Garner et al. 2017).

Driven by the trajectories, wind fields, and pressure fields of each of the synthetic hurricanes, we employed the ADCIRC model to project storm surges at The Battery (Lin et al. 2012; Reed et al. 2015; Garner et al. 2017; Lin et al. 2016). Storm surge was modeled on a 100 m resolution grid at The Battery (Lin et al. 2012; Reed et al. 2015; Garner et al. 2017). The ADCIRC model has previously been used to model and forecast storm surge events for coastal regions (e.g., Westerink et al. 2008; Colle et al. 2008; Lin et al. 2003; Dietrich et al. 2010).

Changing storm characteristics

Although modeled mean storm surge heights were not statistically different between the pre-industrial and modern eras, the largest and most extreme storm surge

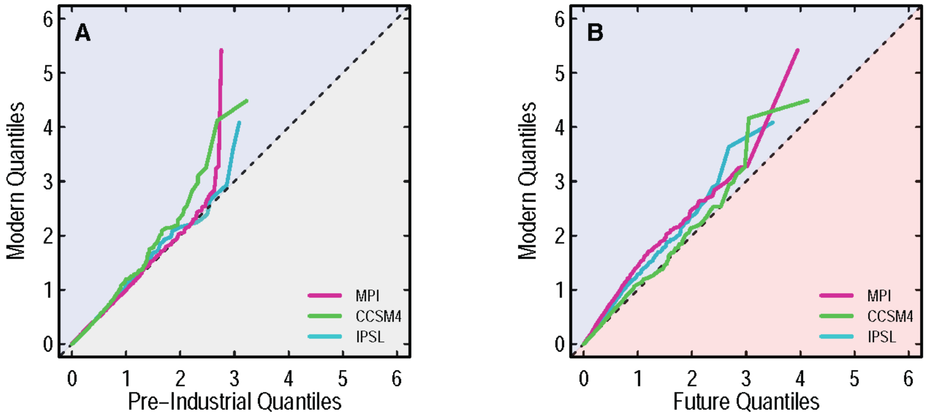

Figure 1. Quantile-Quantile plots of storm surge for a) the pre-industrial (gray) and modern (blue) eras, and b) the modern (blue) and future (red) eras for the MPI model (magenta), the CCSM4 model (green), and the IPSL model (cyan). The 1:1 line is shown by the black dashed line; points that deviate from this line indicate that the two distributions being compared differ from one another (e.g., points that fall into the blue portion of the figure indicate that modern storm surges for that portion of the distribution are greater than storm surges for that portion of the distribution from the other time period included on the plot).

events tended to be larger in the modern era than in the pre-industrial era (Figure 1; Reed et al. 2015). This result is not trivial, since such extreme events are likely to produce the most severe impacts for NYC (Aerts et al. 2013). A principal component analysis of the characteristics of storms impacting NYC for the pre-industrial and modern eras revealed that the largest storm surges at The Battery were generally caused by two different types of storms (Reed et al. 2015).

The first type of storm was characterized by large radius of maximum wind (RMW) (Reed et al. 2015). Although not necessarily intense, these hurricanes can be larger than average and, thus, can produce long-lived surges at The Battery, much as Sandy did in 2012 (Jones et al. 2003; Brandon et al. 2015). In this kind of event, the possibility of the storm surge overlapping with a high astronomical tide is heightened (Kemp and Horton 2013), meaning that overall flood heights may be exacerbated beyond those modeled in these studies (Reed et al. 2015).

The second type of storm was characterized by intensity. Although not necessarily large, these hurricanes have high maximum wind speeds and low minimum pressures (Reed et al. 2015). Storm surges from such events tend not to be as long-lived as surges from larger, less intense storms, but the winds and pressures associated with such hurricanes are capable of producing very large storm surge heights in NYC (Weisberg and Zheng 2015), similar to the surge that was observed during the Hurricane of 1938 (Landsea et al. 2014).

In future projections, hurricanes continued to become both more intense (increased maximum wind speeds and decreased minimum pressures) and potentially larger (increased RMW). Surprisingly, our analysis did not identify a corresponding increase in storm surge heights (Figure 1; Garner et al. 2017). This is because for future simulations hurricanes at the latitude of NYC tended to track farther eastward, staying farther out to sea than during the modern era (1980–2000; Figure 2). This shift in storm tracks compensated for the increase in hurricane size and intensity, resulting in little change or even slight decreases to storm surge heights at The Battery in the future (Garner et al. 2017). Such a shift in storm tracks is consistent with previous studies (Hall and Yonekura 2013; Baldini et al. 2016; Kossin et al. 2014; van Hengstum et al. 2016; Roberts et al. 2016). One possible explanation for this track shift may be changing sea level pressure fields, with projected future sea level pressures during August and September slightly higher over the US Atlantic coast and slightly lower over the North Atlantic than during the modern era (Garner et al. 2017).

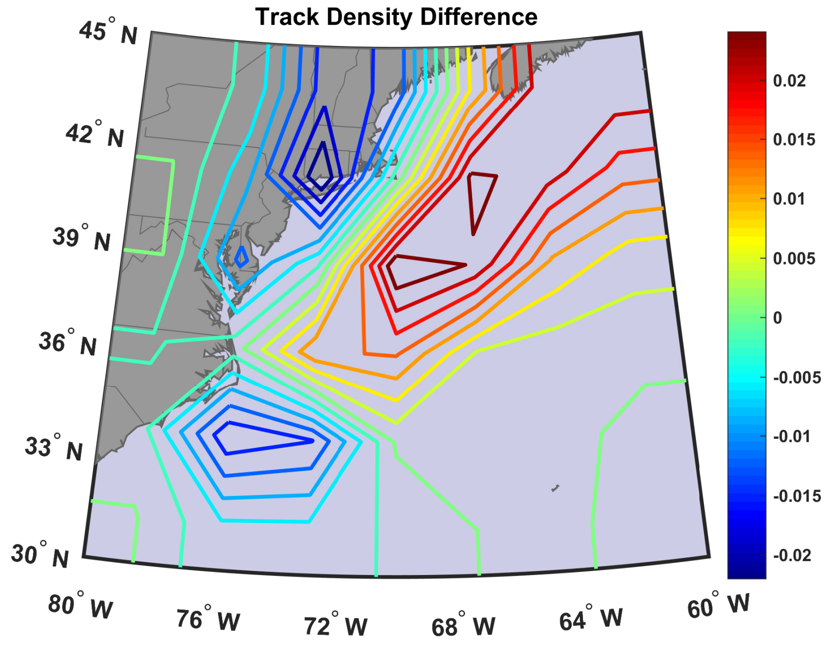

Figure 2. Multi-model mean difference between future and modern synthetic hurricane track densities from the MPI, CCSM4, and IPSL models. Track densities are determined by the sum total of tracks crossing through each grid box over 20-year periods from 2080–2100 and 1980–2000, divided by the area of that grid box and the number of years (21). Here the grid box latitude–longitude scales are determined by the output resolution of the model in question. Warmer colors (reds) indicate an increase in the number of future tracks relative to modern tracks, while cooler colors (blues) indicate a decrease in the number of future tracks relative to modern tracks. Figure from Garner et al. 2017.

The importance of rising sea levels

Flood heights are not determined by storm surge alone; they also include contributions from mean sea level, tidal variability, and wave action. In our analyses, we focused on the effects of storm surge and local relative sea level change.

We estimated overall flood height by linearly combining modeled peak storm surge heights with changes in mean sea level, as determined from proxy records (for the past) and localized probabilistic SLR projections (for the future) relative to a pre-industrial baseline. Non-linear effects of SLR on storm surge heights are expected to be small at The Battery (Lin et al. 2012; Orton et al. 2015), though it is possible that for very large amounts of SLR such a linear combination could result in an underestimate of the overall flood height (McKee Smith Ã et al. 2009; Zhang et al. 2013).

Relative SLR at The Battery for the pre-industrial era was estimated from proxy records taken from salt-marsh sediment cores from Cape May Courthouse and Leeds Point, New Jersey. These two reconstructions were combined to produce a single relative sea level record that accurately conveys multi-decadal to centennial-scale trends in relative sea level during the past two millennia (Kemp et al. 2013).

Future sea level at The Battery was based on localized, probabilistic projections from Kopp et al. (2014) for RCP 4.5 and 8.5, which included thermal expansion and ocean dynamics, glacier melt, ice sheet contributions, land water storage, non-climatic local sea level change, and gravitational effects on sea level. Under RCP 8.5, SLR by 2100 was 0.55-1.4 m and by 2300 was 1.5-5.7 m. Kopp's et al. (2014) central projections of Antarctic ice sheet contributions were based on those of IPCC AR5, with information about tail risk derived from a structured expert elicitation study. New research regarding ice-shelf hydrofracturing and ice-cliff collapse mechanisms suggest that these mechanisms have the potential to significantly increase the likelihood of extreme outcomes in the second half of this century and beyond (DeConto and Pollard, 2016). Thus, we also used two additional SLR projections for the RCP 4.5 and 8.5 scenarios with enhanced contributions from the Antarctic ice sheet (Kopp et al. 2017). The enhanced Antarctic ice sheet projections produced a SLR of 0.88-2.5 m and 10.7-15.7 m by 2100 and 2300, respectively, under RCP 8.5.

Despite the minimal change in storm surge, SLR (nearly 2 m in the region from the beginning of the pre-industrial era to the end of the modern era; see Figure 1 in Reed et al., 2015) caused a large increase in the flood hazard for NYC from the pre-industrial to the modern era (Figure 3). For example, a flood height with a return period of 500 years was 2.25 m during the pre-industrial era; this increased to 3.3-3.7 m during the modern era. In addition, the return period of the 2.25 m flood decreased from 500

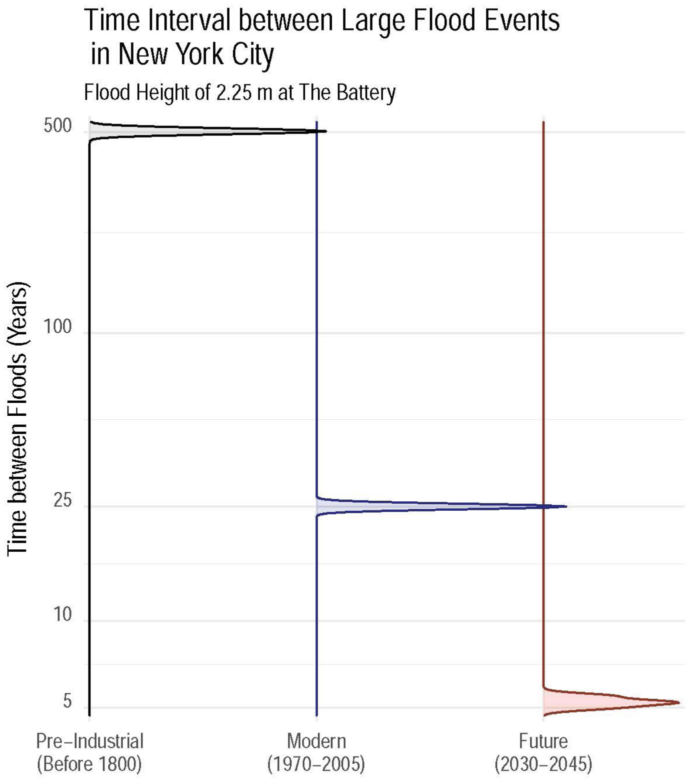

Figure 3. Return periods of the 2.25 m flood height at The Battery for the pre-industrial era (gray), modern era (blue), and future era (red).

years to ~25 years during the transition from the pre-industrial to modern era (Reed et al., 2015).

The late 21st and 23rd centuries show dramatic increases in flood hazard especially under the RCP 8.5 scenario with rapid collapse of the Antarctic ice sheet. The 500-year flood height increased to 4.0-5.1 m by the end of the 21st century and 5.0-15.4 m by the end of the 23rd century. The 2.25 m flood decreased to approximately five years by 2030-2045 in our simulations (Figure 3; Garner et al. 2017).

Evolving flood risk

From the pre-industrial era to the modern era, the increased coastal flood hazard in NYC was driven by local relative SLR and increases in the extremes of the types of storms — large and intense — that cause the most destructive storm surge flooding for the region (Reed et al. 2015). In the future, though storm size and intensity are projected to increase, overall storm surge heights will remain unchanged in NYC because of an eastward shift in storm tracks (Garner et al. 2017). We note that the possibility remains for a very rare event in which a damaging storm breaks this pattern by traveling directly over NYC. Ultimately, flood hazard will continue to increase in the future, with SLR playing a significant role in determining the magnitude.

Because sea level responds relative to a changing climate on long timescales, NYC is already committed to future SLR. Therefore, the findings from this study suggest that it is imperative to invest in adaptation strategies to help make NYC's infrastructure more resilient to future flooding, in order to protect the property and residents living within the current 100-year flood plain (PlaNYC 2013). The results presented here also provide hope for NYC. Given the dominant role of SLR in increased future flood risk, our results suggest that by taking appropriate steps both now and in the coming decades to mitigate climate change we may be able to avoid the worst-case scenarios.

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