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Risk assessment of hurricane storm surge for New York City

N. Lin,¹ K. A. Emanuel,² J. A. Smith,¹ and E. Vanmarcke¹

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[1] Hurricane storm surge presents a major hazard for the United States. We apply a model-based risk assessment methodology to investigate hurricane storm surge risk for New York City (NYC). We couple a statistical/deterministic hurricane model with the hydrodynamic model SLOSH (sea, lake, and overland surges from hurricanes) to generate a large number of synthetic surge events; the SLOSH model simulations are compared to advanced circulation model simulations. Statistical analysis is carried out on the empirical data. It is observed that the probability distribution of hurricane surge heights at the Battery, NYC, exhibited a heavy tail, which essentially determines the risk of New York City being struck by a catastrophic coastal flood event. The peaks-over-threshold method with the generalized Pareto distribution is applied to estimate the upper tail of the surge heights. The resulting return periods of surge heights are consistent with those of other studies for the New York area. This storm surge risk assessment methodology may be applied to other coastal areas and can be extended to consider the effect of future climate change.

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1. Introduction

[2] Hurricanes present major hazards for the United States. Associated with extreme winds, heavy rainfall, and storm surge, land-falling hurricanes often cause enormous damage and losses to coastal regions. In particular, much of the damage and loss of life results from hurricane storm surge (the rise of near-shore water associated with the storm). The Galveston Hurricane of 1900 struck Galveston, Texas, and drove a devastating surge ashore; between 6,000 and 12,000 lives were lost, making it the deadliest natural disaster in U.S. history. The costliest hurricane in U.S. history, Hurricane Katrina of 2005, produced one of the greatest recorded storm surges in the U.S., on the order of 7.6 m (25 ft) around Bay St. Louis, Mississippi, causing more than \$125 billion in losses and resulting in more than 1,836 fatalities.

[3] A rapidly increasing percentage of the U.S. population is located on or near the coast. Risk assessment of hurricane storm surge provides the basis for risk mitigation and related decision making. Traditional data-based risk assessment methods may not be applicable, as historical records of hurricane storm surge at a particular location often do not suffice to make meaningful estimates of surge risks. This is especially the case for places like New York and Boston, which may be threatened by high-intensity, low-frequency hurricanes. Some advanced statistical methods have been developed to infer the probability distribution of surge

heights from the storm statistics; these include the Joint Probability Method (JPM) and the Empirical Simulation Technique (EST) [Scheffner *et al.*, 1996], both of which have been used in FEMA coastal surge studies [Divoky *et al.*, 2005]. However, these methods still rely heavily on historical observations of storms and surges. Also, the complex, but to some extent predictable, physical processes of hurricane storm surge may not be adequately captured in the statistical relationships between storm characteristics and surge heights, again, due to limited historical observations.

[4] We develop a model-based hurricane storm surge risk assessment methodology by coupling a statistical/deterministic hurricane model [Emanuel *et al.*, 2006] with the hydrodynamic models SLOSH (sea, lake, and overland surges from hurricanes) [Jelesnianski *et al.*, 1992] and ADCIRC (advanced circulation model) [Luettich *et al.*, 1992; Westerink *et al.*, 1992], respectively. These three model components have all been evaluated and applied in various studies. The hurricane and SLOSH models are highly computationally efficient, enabling one to simulate a large number of synthetic surge events and carry out extensive statistical analyses. ADCIRC model simulations are applied to evaluate the SLOSH model simulations. This risk assessment methodology does not rely on historical data on storm tracks or surges, and explicitly involves the physics of the hurricane and storm surge. It is particularly useful for data-scarce regions like New York City, where scientific estimates of the return periods of extreme coastal flood events may have important engineering, social, and political applications.

[5] Located at the vertex of the right angle made by Long Island and New Jersey, New York City is highly vulnerable to hurricane storm surge. It has been struck by extreme storms in recorded history and, based on the local sedi-

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mentary evidence, prehistory [see *Scileppi and Donnelly*, 2007]. The 1921 hurricane struck NYC directly, producing a 4.0 m (13 ft) “wall of water,” which flooded lower Manhattan as far north as Canal Street. The “Long Island Express” of 1938 produced flood heights of 3.0–3.5 m (10–12 ft) in Long Island and up to 5.2 m (17 ft) in southern New England, killing as many as 700 people. Hurricane Donna of 1960 produced the 2.55 m (8.36 ft) highest recorded water level at the Battery and flooded lower Manhattan to West and Cortland Streets. In addition to hurricane storm surge, New York City is also highly vulnerable to extratropical storm surge and sea level rise, especially considering that much of the seawall that protects lower Manhattan is only about 1.5 m above mean sea level [*Colle et al.*, 2008]. Risk assessment of each of these hazards and their combination is urgently needed.

[6] In the current study, we apply the model-based risk assessment methodology to investigate the hurricane storm surge risk of New York City. We generate a large number of synthetic storms over the entire Atlantic ocean basin; the storms that pass within 200 km of the Battery, NYC, are applied with the SLOSH model to simulate surge events around the New York area. The “most dangerous storms” are identified and further investigated with the ADCIRC model; intercomparison between the ADCIRC and SLOSH model simulations are carried out. These models and methods are introduced in section 2, while the simulation results are presented in section 3. Statistical modeling is conducted in section 4 to derive the empirical probability density function of extreme storm surges at the Battery, and the mean return periods of surge heights are obtained. Section 5 concludes the paper with a summary and comments on further work.

2. Analysis Methodology

[7] This hurricane storm surge risk assessment methodology is based on a statistical/deterministic hurricane model and the hydrodynamic models SLOSH and ADCIRC. Highly computationally efficient, the hurricane model and the SLOSH model (with a relatively coarse grid) are coupled to generate a large number of synthetic surge events around a site of interest. Statistical analysis can then be carried out to estimate the probability density function (PDF) of storm surge heights for the site. Combining the PDF of storm surge heights and the annual storm frequency, which may be estimated from the hurricane model, mean return periods of surge heights can be predicted. However, the SLOSH simulation may not be able to capture some unusual water responses to storms at locations with complex geophysical features. Other hydrodynamic models may be used to evaluate SLOSH model simulated surge fields. In the current study, we use the ADCIRC model (with a high-resolution grid) to evaluate the SLOSH simulations for the “most dangerous storms,” the synthetic storms that may cause the highest surges at the site of interest. These three model components of the hurricane storm surge risk assessment methodology are introduced in this section.

2.1. Hurricane Model and Simulations

[8] Historical data on hurricanes making landfall in a local area are very limited. Hurricane return levels may be esti-

mated from geological information and/or the historical data about hurricanes landfalling in neighboring regions [*Elsner et al.*, 2008]. Hurricane risk assessment, which involves the statistical quantification of hurricane effects at particular locations, often relies on Monte Carlo simulations of synthetic storms, using site-specific or track simulation approaches. Early site-specific approaches [e.g., *Georgiou et al.*, 1983] were developed to estimate the probability distribution of hurricane wind speed at a site of interest, based on fitted probability distributions of frequency and intensity parameters for the historical storms that came close to the site. In hurricane storm surge risk assessment, a track simulation approach that involves simulating storm tracks from genesis to lysis may be used, as the coastal storm surge is also greatly affected by offshore storm characteristics. A common method of Monte Carlo simulation of storm tracks is based on the statistical properties of all historical tracks in an ocean basin [*Vickery et al.*, 2000; *Powell et al.*, 2005; *Emanuel et al.*, 2006; *Rumpf et al.*, 2007; *Hall and Jewson*, 2007]. A limitation of this method is that its robustness depends on (the sufficiency of) the historical track data set and, for this reason, its application may be problematic for locations like New York City. For the purposes of the current study of storm surge risk for NYC, we apply the second of the two track simulation methods of *Emanuel et al.* [2006], which enables one to generate synthetic tracks according to the statistics of environmental winds, rather than that of the historical tracks, and estimate storm intensity along the simulated tracks with a deterministic, ocean-atmosphere-coupled tropical cyclone model. Without relying directly on the hurricane database, this model generates synthetic tracks that are in statistical agreement with the database [see *Emanuel et al.*, 2006; *Emanuel*, 2006], and it has been used in various applications [e.g., *Hallegatte*, 2007; *Emanuel et al.*, 2008].

[9] In this synthetic track simulation method [*Emanuel et al.*, 2006], track origin points are generated by randomly drawing from a smoothed space-time probability distribution estimated from the post-1970 best track Atlantic hurricane data (updated from *Jarvinen et al.* [1984]). Once generated, a storm is then moved according to a vertical average of the deep tropospheric environmental winds, corrected for “beta drift” [*Holland*, 1983]. Along each track so generated, the Coupled Hurricane Intensity Prediction System (CHIPS) [*Emanuel et al.*, 2004] is run to predict the storm intensity, according to environmental factors, including potential intensity, depth of the ocean mixing layer, and thermal stratification of the ocean below the ocean mixing layer. For the current study, we generate a large number of synthetic tracks over the Atlantic Basin, among which 7555 tracks pass within 200 km of the site of Battery, NYC (74.02 W, 40.9 N). We apply these, and the hydrodynamic models, to evaluate hurricane storm surge risk for NYC.

2.2. SLOSH Model and Simulations

[10] The selected synthetic tracks are applied in the SLOSH [*Jelesnianski et al.*, 1992] model to simulate storm surges for New York City. SLOSH is a two-dimensional tropical storm surge model, developed by the Techniques Development Laboratory of the National Weather Service, for real-time forecasting of hurricane storm surge. It is

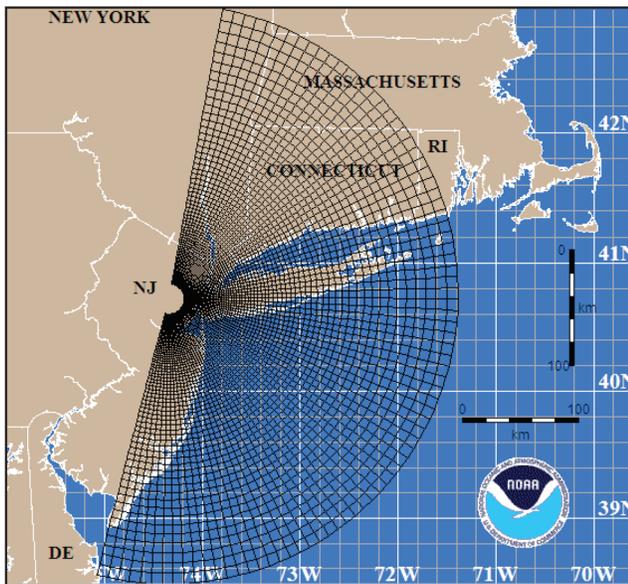


Figure 1. SLOSH mesh for the New York area [Jelesnianski et al., 1992].

currently the only model used by the National Hurricane Center to provide real-time hurricane storm surge guidance [Massey et al., 2007]. The performance of the SLOSH model has been evaluated using observations of storm surge heights from past hurricanes [Jarvinen and Lawrence, 1985; Jarvinen and Gebert, 1986]; the accuracy of the surge heights predicted by the model is $\pm 20\%$ when the hurricane is adequately described [Jelesnianski et al., 1992].

[11] The SLOSH model uses polar grid, which allows for a fine mesh in primary coastal regions of interest and a coarse mesh in the open ocean. The SLOSH grid used in the current study is the New York basin grid of a polar coordinate system with 75 arcs and 82 radials (Figure 1). The resolution of the grid near New York City is about 1.3 km. The SLOSH model is run to simulate the storm surge and flooding caused by individual hurricanes. The model's input for describing the hurricane include parameters such as the hurricane's observed position, intensity, size, and translational velocity, in every hour for about 100 h (about 70 h before and 30 h after landfall). The vector field of driving forces on a water surface is determined within the SLOSH model by a parametric hurricane model [see Jelesnianski et al., 1992]. The wind field computed by the SLOSH parametric model was compared with the surface wind observations analyzed by the Hurricane Research Division (HRD) by Houston et al. [1999]; in most cases, the differences between the SLOSH and HRD surface peak wind speeds were 6% or less.

[12] With some simplification in the physics represented [Jelesnianski et al., 1992] and with relatively coarse grids, the SLOSH simulation runs very fast. A typical simulation takes less than 20 seconds on a regular PC, and the simulations for all 7555 synthetic tracks for New York City take only about 2 days. The highly efficient implementation, with adequate accuracy, makes SLOSH a good candidate for model-based risk assessment of hurricane storm surge.

2.3. ADCIRC Model and Simulations

[13] In order to evaluate the SLOSH simulations of hurricane storm surge for the New York area, hydrodynamic simulations are also carried out with the two-dimensional, depth-integrated implementation of ADCIRC. ADCIRC is a finite element model developed by Luetlich et al. [1992] and Westerink et al. [1992] for the purpose of simulating hydrodynamic circulations along shelves and coasts, and within estuaries. The 2-D, depth-averaged module of ADCIRC is used in this study. ADCIRC has been used by Colle et al. [2008] to simulate storm surge induced by Hurricane Floyd (1999) in the New York Harbor region. Recent applications of the ADCIRC model to study storm surge for other coastal areas include [Westerink et al., 2008] for New Orleans, Louisiana; Shen et al. [2005, 2006] and Lin et al. [2010] for Chesapeake Bay; and Chen et al. [2008] for northeastern Gulf of Mexico. These studies have demonstrated the high accuracy of the ADCIRC model in simulating coastal storm surge.

[14] The ADCIRC model allows the use of an unstructured grid with very fine resolution near the coast and much coarser resolution in the deep ocean. The grid used in this study, follows closely meshes developed by Colle et al. [2008]. The resolution of the mesh ranges from 70 km to several hundred kilometers offshore to as high as 10 m around New York City. The bathymetric data for grid cells were obtained from the NOS database of the coastal hydrographic surveys, the U.S. army corps of engineers nautical charts, and multibeam data collected by Stony Brook University ship surveys [Colle et al., 2008].

[15] The ADCIRC model fully describes the complex physical process associated with storm surge and often uses grids of very high resolution over a relatively large domain. In such cases, the model is computationally expensive to be applied to large numbers of simulations. In the current analysis, ADCIRC simulations are carried out for 9 synthetic storms which generate the highest storm surges in SLOSH simulations. For each of the synthetic storms, the ADCIRC simulation is forced by storm wind speed and surface pressure at each grid point. In order to make a consistent comparison between the SLOSH and ADCIRC surge simulations, the SLOSH wind field model [Jelesnianski et al., 1992] is used to generate the wind fields in the ADCIRC simulations. For simplicity, the pressure field is generated using the Holland pressure distribution model [Holland, 1980], with a B parameter taken from Vickery and Wadhera [2008]. ADCIRC model parameters are similar to those in the work of Colle et al. [2008]. In setting the parameterization of subgrid-scale processes in the ADCIRC simulations, the bottom stress is determined by a hybrid friction relationship [see Westerink et al., 2008] and the wetting-and-drying algorithm is utilized.

3. Simulation Results

[16] We generate a large number of synthetic tracks over the Atlantic Basin, of which 7555 tracks pass within 200 km of the Battery; the model-estimated annual frequency of tropical storms that pass within 200 km of the Battery is about 0.26. Storm surge analysis for each of the 7555 simulated synthetic tracks for New York City is carried out with the SLOSH model. The characteristics of NYC storm

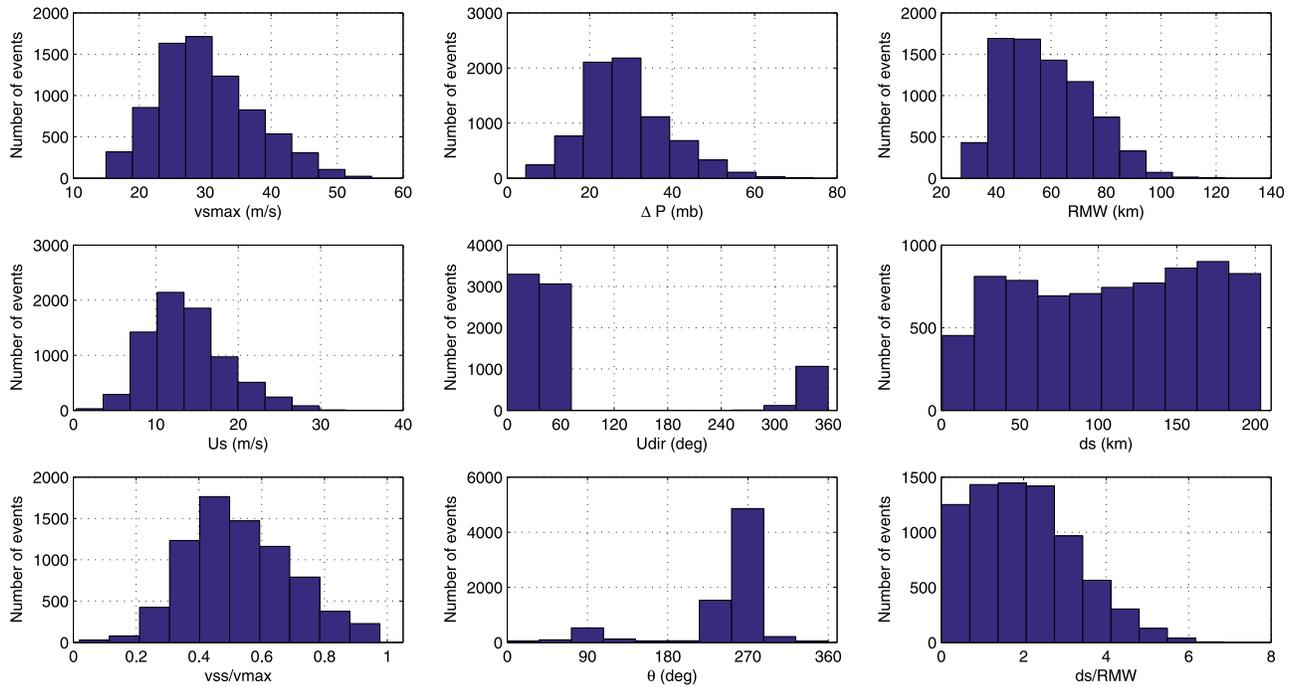


Figure 2. Characteristic parameters of the 7555 synthetic storms that pass within 200 km of the Battery when they are at their closest distances to the Battery. Notations: v_{smax} , maximum symmetrical wind speed; ΔP , pressure deficit (the difference between the central pressure of the storm and the pressure at the outer-most closed isobar); RMW , radius of maximum wind speed; U_s , translational speed; U_{dir} , translational direction; ds , distance between storm center and the Battery; v_{ss}/v_{max} , ratio of the wind speed at the Battery site to the storm maximum wind speed (including the translational effect); θ , anti-clockwise angle from the storm translational direction to site-to-storm direction (storm moving to the left of the site if $0 < \theta < 180$ degree; right if $180 < \theta < 360$ degree); ds/RMW , ratio of the site-storm distance to the radius of maximum wind speed of the storm.

surges are investigated, based on the extensive empirical data set. The 9 storms generating the highest surges in the SLOSH simulations are further investigated with the AD-CIRC model.

3.1. Synthetic Storms for New York City

[17] The characteristic parameters associated with each simulated storm track include the storm’s position, intensity (maximum wind speed and pressure deficit), size (radius of maximum wind), and translational velocity. The storm surge at a coastal site is highly correlated with these characteristics of the storm, especially when it passes close to the site. The histograms of the characteristic parameters of the 7555 storm tracks generated for the NYC case, when they are at their closest distances to the Battery site, are shown in Figure 2. This track data set includes storms with characteristics within relatively broad ranges that are consistent with the hurricane climatology in the area. Most tracks pass by the Battery toward the northwest or northeast. Also, most storms travel to the right of NYC. However, a small number of storms travel to the left of the Battery and, if associated with high intensity, tend to induce extreme storm surge.

3.2. SLOSH Model Simulated Storm Surges

[18] The histogram of the SLOSH simulated storm surge (more precisely, the amplitudes of the primary surge in the storm surge time series) at the Battery site is shown in

Figure 3. The histogram peaks at about 0.4 m of storm surge and rapidly decreases as the value of storm surge increases, but the tail extends to over 5 m. Further discussion about this long tail is included in section 4.

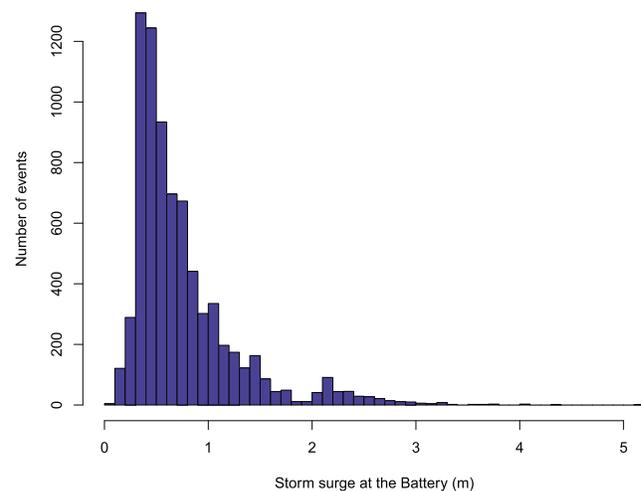


Figure 3. Histogram of the SLOSH model simulated (primary) storm surge at the Battery for 7555 synthetic tracks that pass within 200 km of the Battery site.

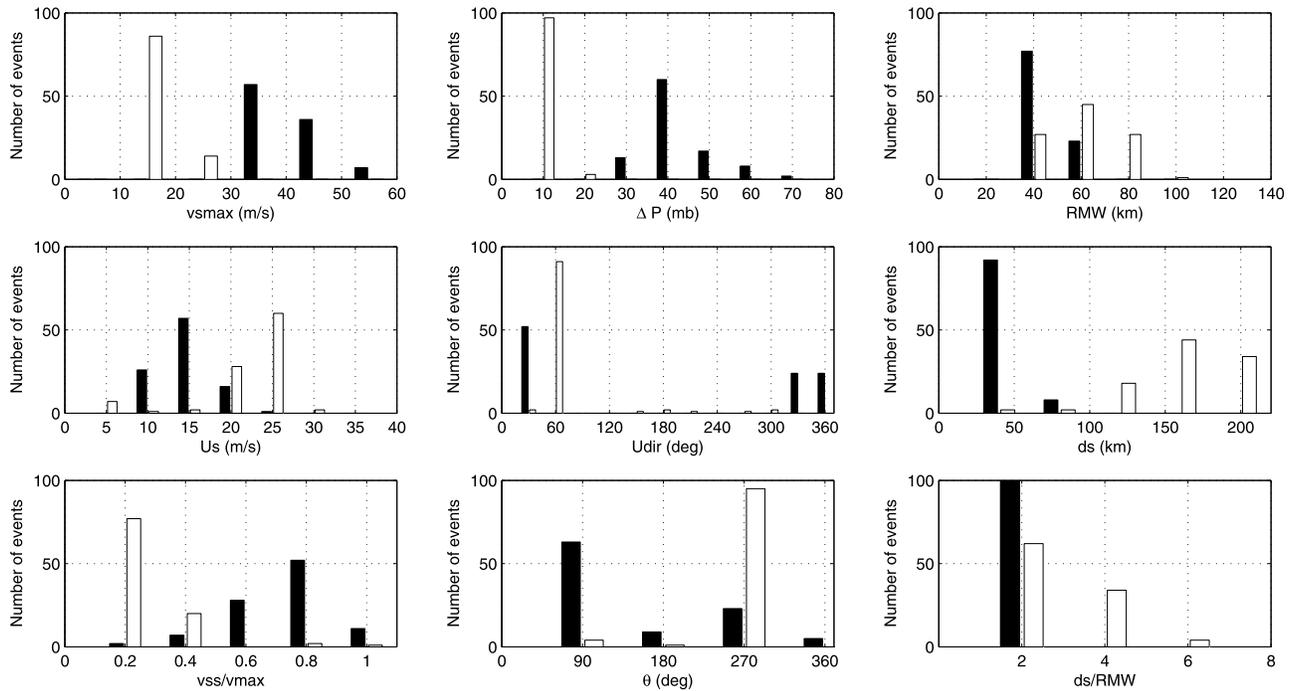


Figure 4. Comparison between the characteristic parameters of the 100 highest surge generating storms (solid bar) and those of the 100 lowest surge generating storms (hollow bar), when they are at their closest distances to the Battery. Notation same as in Figure 2.

[19] This extensive empirical data set enables one to investigate the characteristics of extreme storm surges for New York City. Characteristic parameters of the 100 highest and the 100 lowest surge-generating storms (according to the SLOSH simulations) are compared in Figure 4, when they are at their closest distances to the Battery. It is obvious that the highest storm surges are caused by storms that are intense when they pass by the site; they have high maximum wind speeds, large pressure deficits, and relatively compact structures. Slowly moving storms induce higher surges at the Battery than fast moving storms, especially as the Battery is located in a sheltered harbor rather than on the open coast. Almost all storms that cause high surges travel within ± 45 degrees of due North, while most of those causing low surges travel northeast (about 45–75 degrees). Many high surge generating storms travel to the west of the Battery; however, a number of storms travelling to the east of the Battery also induce high surges, due to their relatively high intensities when passing over the water. It is interesting to note that almost 80% of the 100 high surge generating storms pass most closely by the Battery at a distance of around 40 km; also, most of these storms have a radius of maximum wind (RMW) of about 40–60 km. Therefore, most large surges are incurred in the cases when the closest distance between the storm center and the Battery site is about the RMW so that the site experiences high winds, close to the maximum wind speed in the storm if the site is also on the right side of the track. (For detailed discussion about the dynamic sensitivity of the storm surge to hurricane characteristics, see *Weisberg and Zheng [2006]*.)

[20] Storm characteristic parameters in Figure 4 represent, to some extent, the surge environment of a site. Simpler and

better indicators may also exist; for a coastal site with relatively simple geophysical features, the storm surge may be well correlated with the wind speed parameters at the site, such as (1) the maximum wind speed and (2) the wind speed at the time when the wind speed component in a critical direction reaches its maximum, during storm's passage. This is because both of these two wind-related parameters are in turn highly correlated with the storm characteristics. The second parameter is also relevant to the geophysical features of the site that affect the storm surge. For New York City, we found that the critical wind direction is about 130 degrees (from southeast; see Figure 5); this may be related to the existence and orientation of Long Island, NY. The correlation between storm surge and the wind speed when the wind component in the critical direction reaches its maximum is relatively high, and it is much higher than that between the storm surge and the maximum wind speed, especially for large surges (Figure 5).

3.3. Evaluation With ADCIRC Simulations

[21] We carry out ADCIRC simulations for the 9 highest surge generating storms (Figure 6), according to the SLOSH simulations for the 7555 synthetic tracks. The time series of simulated storm surge at the Battery from the ADCIRC and SLOSH models are compared in Figure 7. Estimates of primary surges from the SLOSH and ADCIRC model simulations are consistent, except that the SLOSH analysis significantly underestimates the surge amplitude for one storm (Storm 1892) and overestimates it for two other storms (Storms 15518 and 16719). Storm 1892 is only the 433rd most intense storm (in the set of 7555 storms) when it

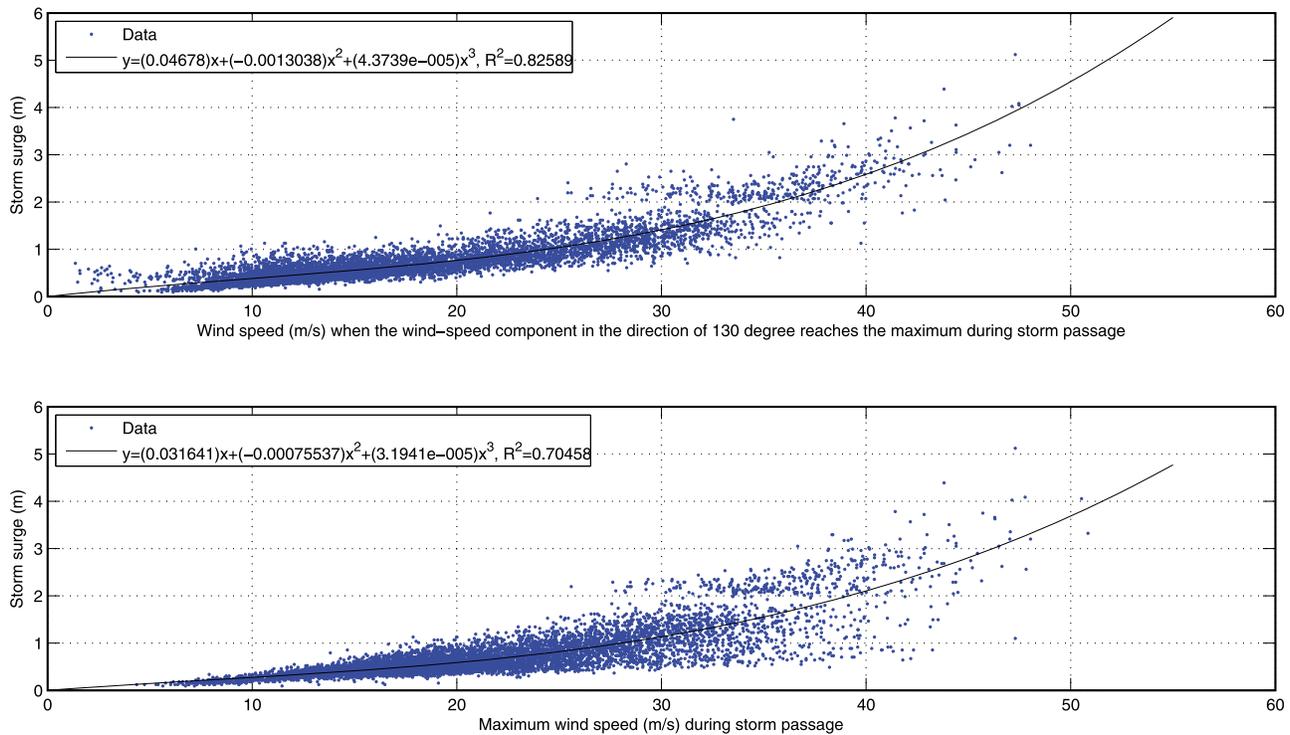


Figure 5. (top) Correlation between the storm surge and the wind speed at the time when the wind speed component in the direction of 130 degree reaches its maximum. (bottom) Correlation between the storm surge and the maximum wind speed at the Battery.

passes by the Battery, but it heads northwest and travels to the left of the Battery with a relatively slow translational speed. It generates the highest surge in the ADCIRC simulation of 5.21 m, but it only causes a surge of 4 m in the SLOSH simulation. This indicates that the ADCIRC simulations are more sensitive to those storm characteristics, in addition to the storm intensity, than are the SLOSH simulations, likely due to their very different grid resolutions. Nevertheless, the SLOSH simulations of surge amplitudes at the Battery for the “most dangerous storms” do not appear biased relative to the results of the ADCIRC simulations, and compare reasonably well to the ADCIRC simulations (see Figure 8), with about a 12% difference on average.

[22] It is also noted that SLOSH simulations exhibit excessive negative surges after the primary peaks in most cases, which may be due to the relatively small size of the SLOSH simulation domain. In their study of the ADCIRC simulations of storm surge along the Florida shelf using three domains of different sizes, *Blain et al.* [1994] also observed excessive negative surges in the simulations when using their smallest domain, which was confined to the continental shelf. They suggested that the excessive negative surges are induced by the drying of coastal elements of a small simulation domain when the hurricane winds come off the land. Their simulations also showed that the simulation with their smallest domain significantly underestimated the amplitude of the primary surge, as the behavior of resonant modes within the Gulf of Mexico was not well captured. This phenomenon, however, is not observed in the current study for the New York area. Therefore, as long as the quantity of interest is the surge peak amplitude, the SLOSH

model is suitable for risk assessment of hurricane storm surge for New York City.

[23] The spatial distributions of simulated storm surges over New York and New Jersey coast are also investigated.

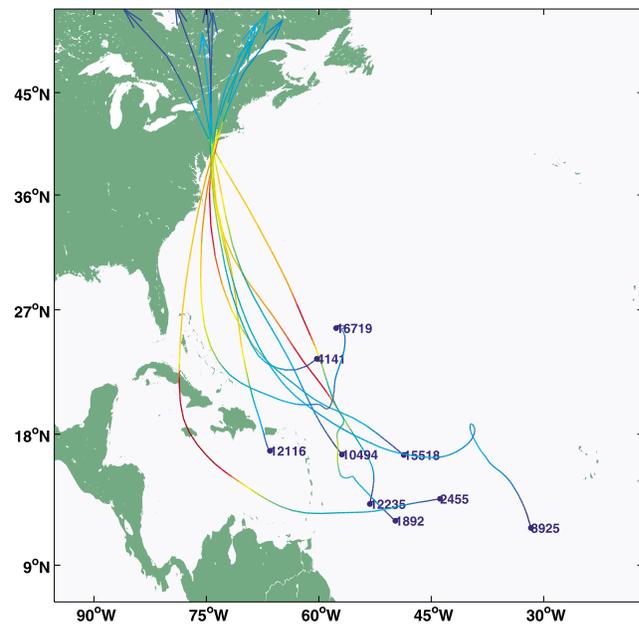


Figure 6. The nine (of the 7555) synthetic storms that generate highest surges at the Battery in the SLOSH model simulations.

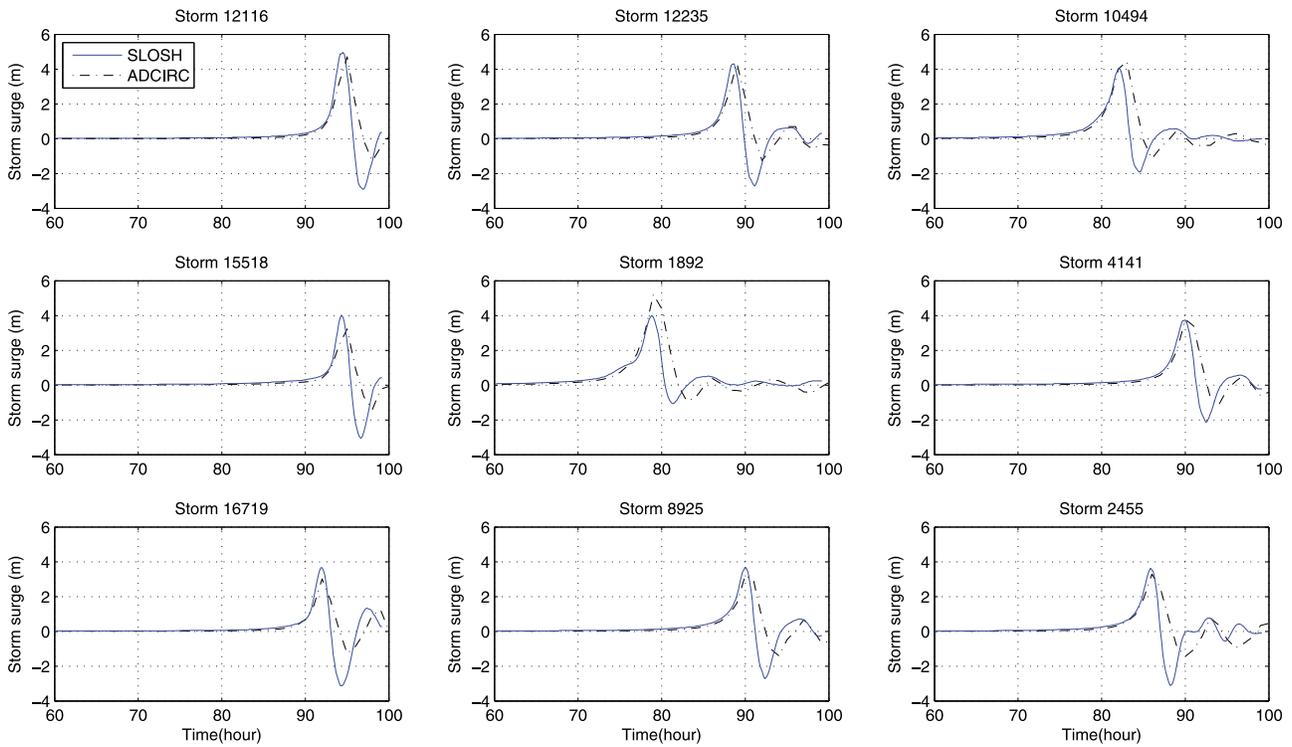


Figure 7. Comparison of storm surge time series at the Battery estimated from the SLOSH and ADCIRC models for the nine highest surge generating storms (Figure 6).

The general pattern of the surge spatial distributions agrees well between the two models in most simulations. The comparison between simulated surge spatial distributions for

the highest surge incurring storm (Storm 12116) in the SLOSH simulations is shown in Figure 9. Since the ADCIRC mesh used in this study is confined over the open

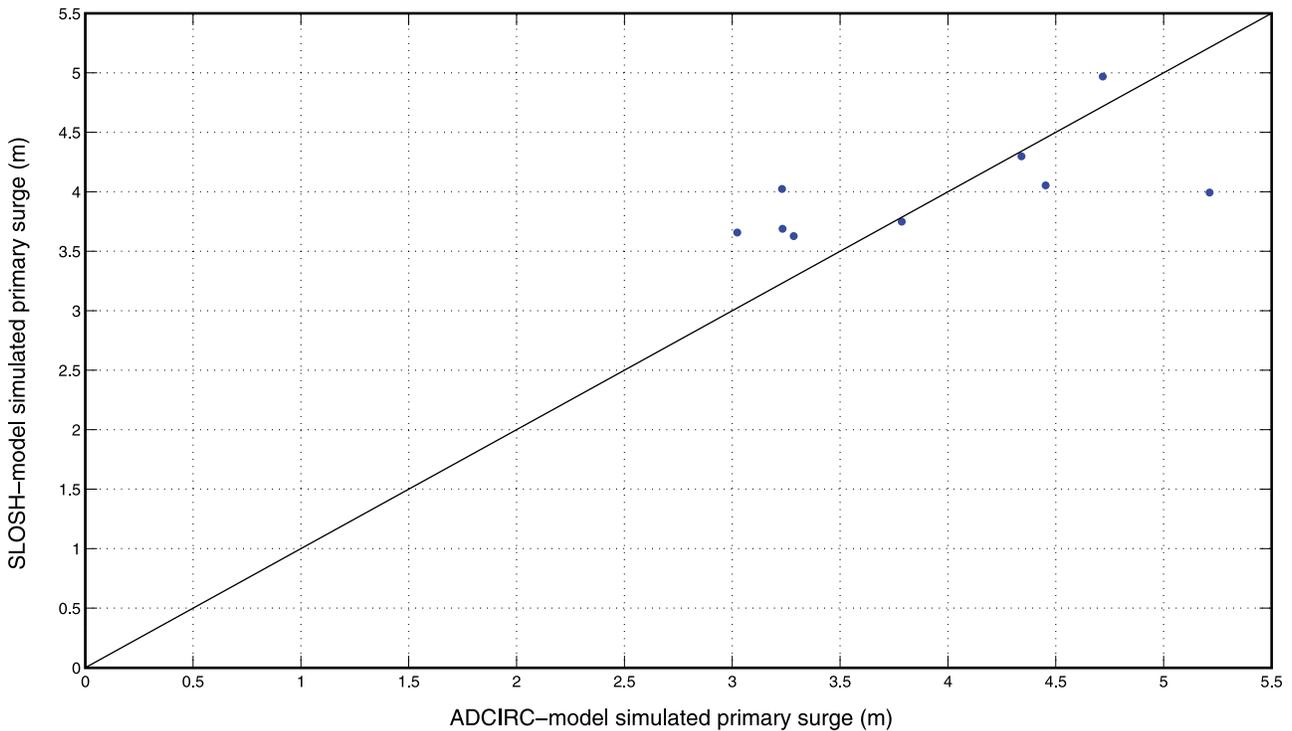


Figure 8. Comparison of the primary surge at the Battery estimated from the SLOSH and ADCIRC models for the nine highest surge generating storms (Figure 6).

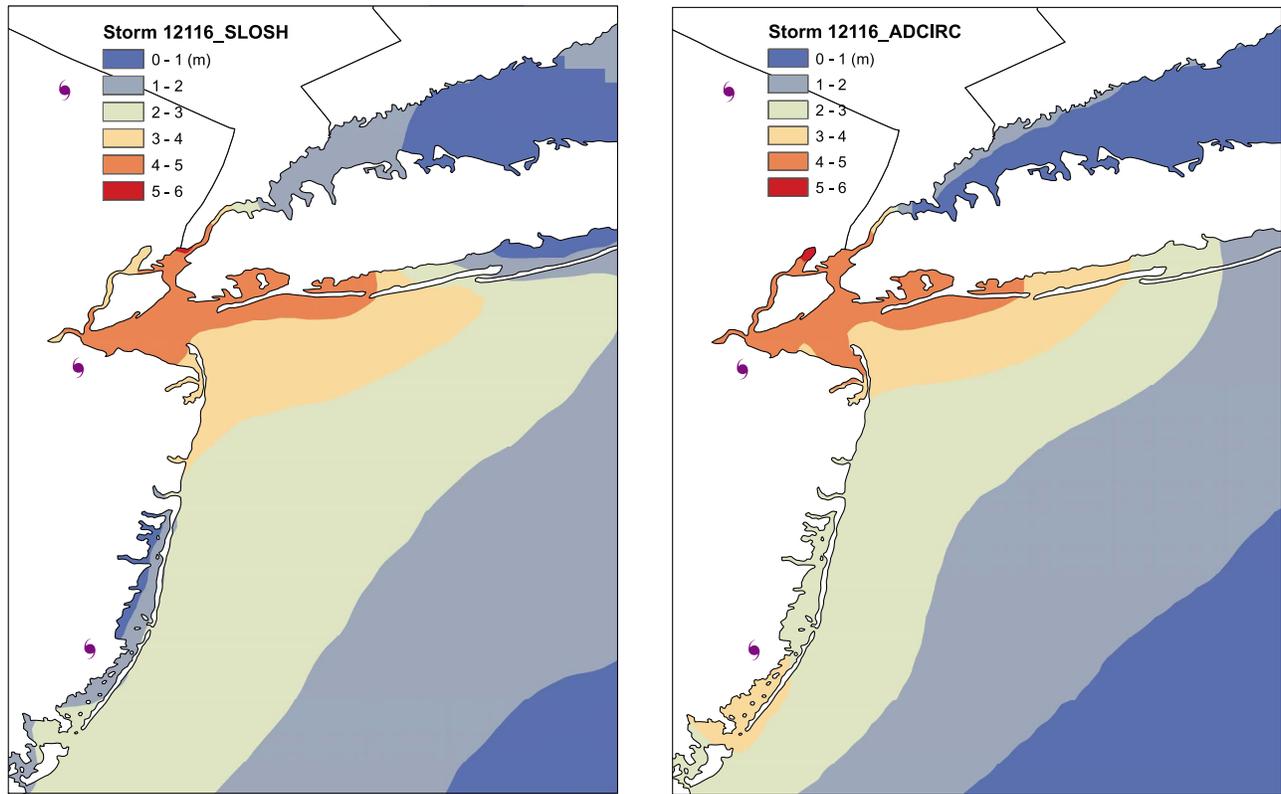


Figure 9. Comparison of spatial distributions of the storm surge estimated from the SLOSH and ADCIRC models, for Storm 12116.

ocean, the surge estimations within the bay area of the New Jersey and Long Island coasts are obtained from statistical extrapolation from the mesh outside the bay. Nevertheless, the ADCIRC simulation shows high surges around an inlet on the south New Jersey coast (Figure 9), which also exists in the ADCIRC simulations for some of the other storms. SLOSH simulations cannot capture this feature and always predict low surge heights within the bay areas (Figure 9). This indicates again that, using relatively coarse grids which cannot resolve detailed topography, the SLOSH model may not be able to capture some local features in the storm surge fields.

4. Storm Surge Risk Assessment

[24] The SLOSH model simulated surges compare relatively well with the ADCIRC-model simulated surges (Figures 7 and 8), assuring us of its reasonable accuracy for surge risk assessment for New York City. We carry out statistical modeling with the SLOSH model generated surge data to obtain an empirical probability density function of the surge heights at the Battery site, which, together with the estimated annual storm frequency, is used to determine the mean return periods of surge heights for New York City.

[25] The statistics of SLOSH simulated surges (Figure 3) show that, among the 7555 synthetic storm surges, only 115 are higher than 2.5 m, 32 higher than 3 m, 5 higher than 4 m, and 1 higher than 5 m. Also, the largest value of the storm surge (5.12 m) is about 8.5 standard deviations (0.51 m) away from the mean (0.75 m). The quantile-quantile (Q-Q)

plot (Figure 10) shows that the tail of the surge distribution is heavier than exponential. It is this tail that determines the risk of New York City experiencing a catastrophic coastal flood event.

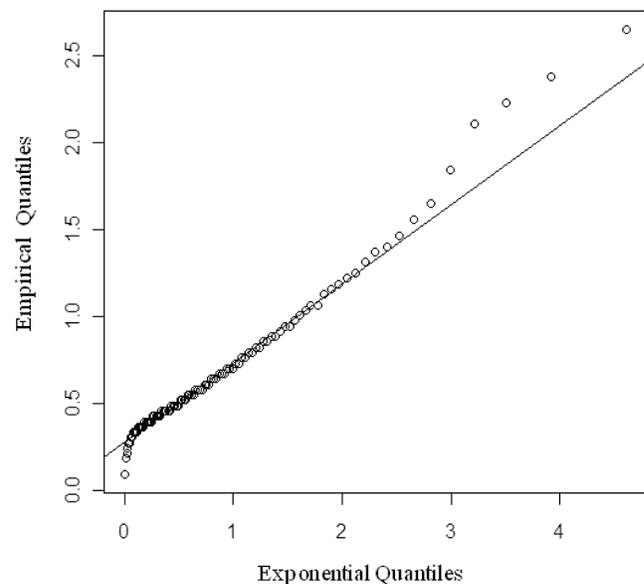


Figure 10. Exponential Q-Q plot of SLOSH model simulated storm surge heights. (The points of the Q-Q plot should be on the straight line if the sample distribution was indeed from the exponential distribution family.)

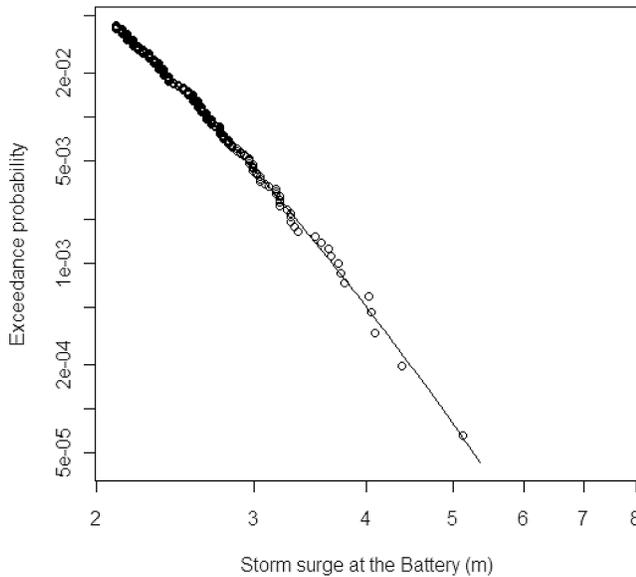


Figure 11. GPD fit for the upper tail of the storm surge distribution in log scale.

[26] To estimate the upper tail of storm surge heights we use the peaks-over-threshold (POT) method with the generalized Pareto distribution (GPD) [Pickands, 1975; Davison and Smith, 1990; Walton, 2000]. The GPD arises as the limiting distribution for exceedances of large thresholds, i.e.,

$$F(x) = P\{X \leq u + x \mid X > u\}, \quad (1)$$

for large u . The GPD function takes the form

$$F(x) = 1 - \left(1 + \xi \frac{x}{\sigma}\right)^{-\frac{1}{\xi}}; \quad x \geq 0, \quad (2)$$

where ξ is the shape parameter and σ is the scale parameter.

[27] A threshold of 2.10 m is selected for GPD analyses, reflecting levels at which major storm surge damage occurs in the region. This threshold is also selected by fitting the GPD at a range of thresholds and looking for stability of parameter estimates [see, e.g., Coles, 2001]. The estimated shape parameter of the GPD is 0.076 (maximum likelihood estimate), supporting the inference that storm surge heights are “heavy tailed.” The upper tail of the surge height distribution is illustrated in Figure 11. The Q-Q plot (Figure 12) shows good agreement between the data and the GPD model. Also, random samples from the fitted GPD are consistent with the empirical data (see Figure 13).

[28] The annual exceedance frequency of storm surge is the product of the surge height exceedance probability and the annual storm frequency. The exceedance probability describes the likelihood of storm surge exceeding a given level,

$$P\{X > l\} = [1 - F(l - u)]P\{X > u\}; \quad l \geq u, \quad (3)$$

where $P\{X > u\}$ is the probability of storm surge exceeding a threshold, about 0.043 for the threshold of 2.10 m. The annual storm frequency, in this case, is the annual frequency of storms (with any possible intensity) ever passing within 200 km of the Battery site (estimated as 0.26). The recip-

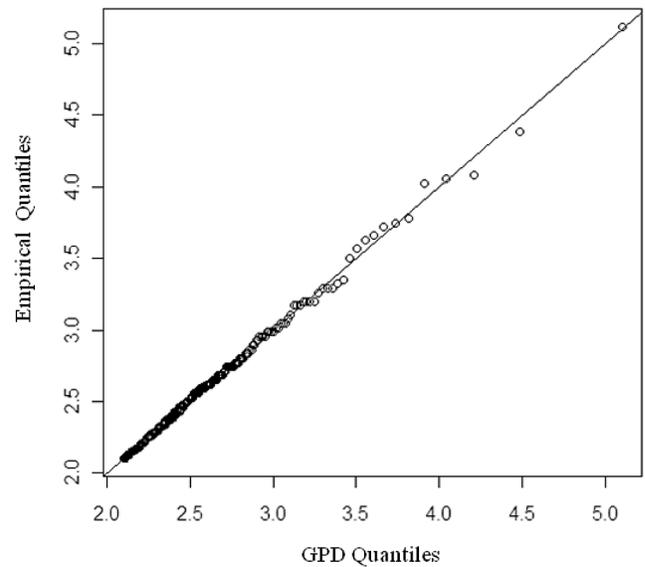


Figure 12. GPD Q-Q plot of SLOSH-model simulated storm surge heights. (The points of the Q-Q plot should be on the straight line if the sample distribution was indeed the fitted GPD.)

rocal of the annual exceedance frequency is the mean return period of the storm surge heights. The obtained mean return period for the Battery site is shown in Figure 14, as well as the 95% confidence limits (estimated by the Delta method [see, e.g., Coles, 2001]). The curve of mean return period corresponds to an unbounded distribution, because the estimated GPD shape parameter is positive.

[29] It should be noted that, for a given return period, the height of hurricane storm surge estimated in the current study may be expected to be lower than the estimated height of coastal flood, as discussed in other studies for New York

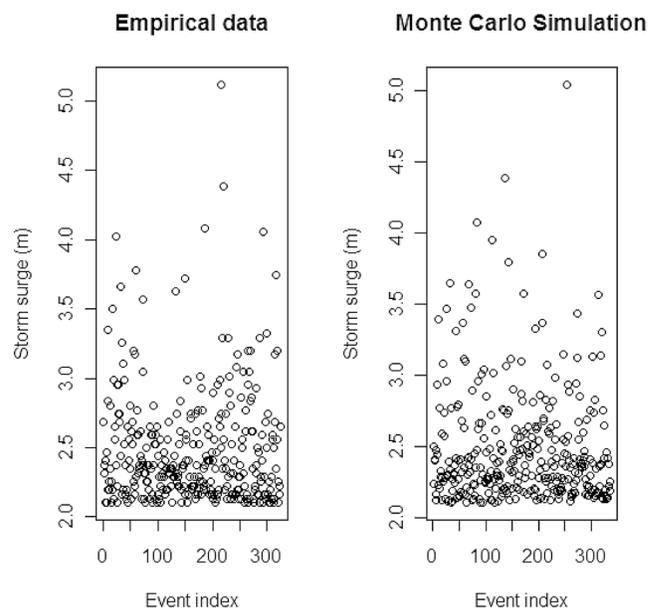


Figure 13. Monte Carlo simulations of storm surge using the fitted GPD compared with the empirical data.

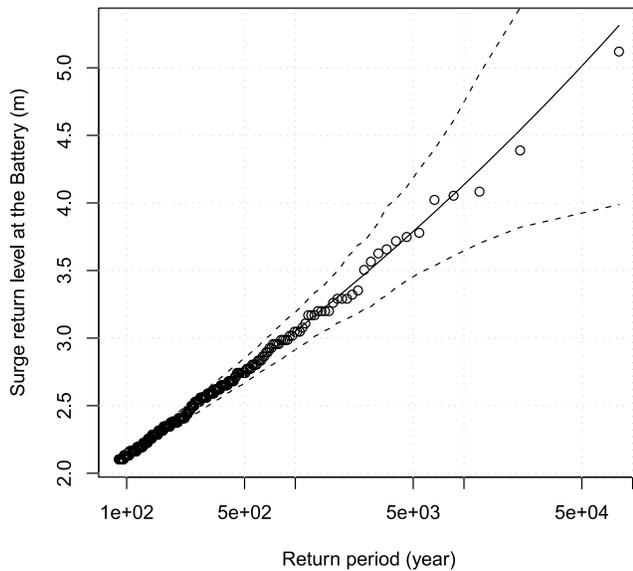


Figure 14. Return level plot for extreme storm surge heights for New York City. The solid curve is the mean return level. The dashed curves are the 95% confidence limits. The open circles are the empirically estimated return levels.

City [e.g., *Rosenzweig and Solecki, 2001; Gornitz et al., 2001; Rosenzweig and Solecki, 2009*]. In risk assessment, the latter includes hurricane and extratropical storm surge, astronomical tide, wave runup, and, possibly, sea level rise. The estimated 100 year storm surge of about 2.14 m and 500 year storm surge of about 2.76 m (Figure 14) are consistent with the 100 year flood level of 2.62 m and 500 year flood level of 3.26 m reported by *Rosenzweig and Solecki [2009]* for the current climate condition, considering the effect of astronomical tide (about 0.5 m at high tide for NYC) and wave runup. The 10 year flood level in the work of *Rosenzweig and Solecki [2009]* is much higher than the hurricane storm surge estimated in current study (not shown). This is because the extratropical cyclones (Nor'easters), which are more frequent than hurricanes, are the main source of the 1-in-10 year coastal floods for NYC [*Rosenzweig and Solecki, 2009*]. How to meaningfully combine the estimated storm surge caused by hurricanes with other components of coastal flood level in risk assessment is another topic and will be further studied.

5. Summary and Future Work

[30] Risk assessment of hurricane storm surge for New York City is carried out by generating a large number of synthetic surge events and performing statistical modeling on the empirical data. This is done by coupling a statistical/deterministic hurricane model with the hydrodynamic model SLOSH. The characteristics of NYC storm surges are discussed, based on the empirical data set. The SLOSH model simulations are compared with ADCIRC model simulations; the two hydrodynamic models agree reasonably well with each other in the simulations for the storms that generated the highest surges in the SLOSH simulations. The heavy-tail feature of the probability distribution of New York hurri-

cane storm surge heights is modeled with a generalized Pareto distribution (GPD). The estimated return periods of surge heights are consistent with previous studies.

[31] Since the hurricane model used in this study does not rely on the historical data of storm tracks, it can be used to generate synthetic storms under projected climate change scenarios [see *Emanuel et al., 2008*]. Further work will be carried out to predict NY hurricane storm surge risk in alternate future climate environments. The New York area is also vulnerable to sea level rise, which may lead to a marked increase in extreme flood levels in the long term [*Gornitz et al., 2001*]. The projected sea level rise, astronomical tide, and wave effects will be (stochastically) combined with the storm surge to predict the return periods of future coastal floods. This risk assessment methodology may be applied to other coastal regions. For locations where SLOSH model simulations are not accurate enough, a statistical downscaling method may be developed to adjust SLOSH model simulated surge fields, for greater consistency with ADCIRC model simulated surge fields. In addition, both SLOSH model and ADCIRC model with a 2-D mode may overestimate the bottom stress and thus underestimate the surge [*Weisberg and Zheng, 2008*], the impact of which to the surge risk estimation needs to be investigated.

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