Statistical Prediction of the Storm Surge Associated with Cool Weather Storms at The Battery, New York

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ABSTRACT

The winter and early spring weather in the New York Metropolitan Region is highly influenced by extratropical storm systems, and the storm surge associated with these systems is one of the main factors contributing to inundation of coastal areas. The present study demonstrates the predictive capability of an established statistical relationship between the "storm maximum" storm surge associated with an extratropical storm system and the storm composite significant wave height. Data from publicly available retrospective forecasts of sea level pressure and of wave heights, along with a regression equation for storm surge, were used to predict the "storm maximum" storm surge for 41 storms in the New York Metropolitan region during the period from February 2005 to December 2008. The statistical storm surge estimates were compared to the surge values predicted by NOAA's extratropical storm surge model, NOAA's operational surge forecast which includes an error correction and to water gauge observations taken at The Battery, N.Y. The mean difference between the statistical surge prediction and the observed values is shown to be smaller than the difference between NOAA's deterministic surge prediction and the observed surge at the 95% significance level and to be statistically indistinguishable from the difference between NOAA's operational surge forecast and the observed values of surge. These statistical estimates can be used as part of a system for predicting coastal flooding.

1. Introduction

The New York Metropolitan Region is particularly vulnerable to the damage caused by the frequent extratropical low-pressure systems that occur during fall, winter and spring months. In association with the storms, severe conditions such as high winds, heavy rain, blizzards, very low temperatures and storm surge can prevail for several hours and up to a few days. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4 2007) estimates that over the next century global sea level is likely to rise from between 18 to 59 cm, and this will extend the zone of impact from storms, storm surge, and storm waves farther inland. The potential for property damage and loss of life due to storm surge and flooding and necessitate accurate predictions of high water levels associated with storm conditions.

Storm surge is commonly defined as the difference between the predicted astronomical tide and the observed water level associated with a particular phenomenon such as a storm. The predicted astronomical tide is the daily change in water level produced by the gravitational interactions of the earth, moon and sun and it is calculated by performing complex harmonic analysis of observations of water level at a given location. The characteristics of storm surge depend on, for example, tides, wind stress, atmospheric pressure, wave height, transport of water by waves and swell and effects of coastline configuration and bathymetry. Predictions of storm surge have been made using both dynamical and statistical methods. The earliest efforts at dynamical modeling were hampered by the lack of meteorological observations over the water and by the need to make oversimplifications to make the dynamics computationally tractable. This led researchers to develop empirical and statistical relationships between wind and pressure fields and water level changes based on relationships derived from simplified theory and equations of motion. An early method for forecasting the maximum storm surge based on connections between significant wave height and storm surge in the Boston region was presented by Tancredo (1958). He used the Bretschneider-revised Svedrup-Munk method (Bretschneider, 1951) to compute significant wave heights from equations that relate wave heights to wind data and a regression equation to forecast storm surge from these computed significant wave heights. Another statistical method, this one based on linearized two-dimensional hydrodynamic equations, was developed by Harris (1962) and consisted of a regression equation that related the surge at a specific location and time to a "meteorological factor" selected according to the type of observation and the location of the observation station. Harris and Angelo (1963) tested the model using past data from Buffalo, New York and Toledo, Ohio. The authors concluded that the prediction obtained with this approach was equivalent or superior to a prediction based on the direct integration of the hydrodynamic equations and using the same data.

A method using statistical relationships derived purely from observations was developed by Pore et al. (1974), who related meteorological data to the observed storm surge. The technique is based on data for 13 winter seasons, from 1956 to 1969, and data from eight east coast water gauge stations for the storms that caused surge equal to or greater than two feet. Atmospheric surface pressure values, with appropriate time lags, were considered as possible predictors of the storm surge. The surge equation for New

York involved predictors at eight grid points with time lags ranging from 0 to 6 hours. A test of this method using data from a series of past storms revealed that the time of the peak surge values was determined correctly, but the forecasts were generally too low. This low bias was adjusted by multiplying the forecasted surge by the reciprocal of the correlation coefficient between the storm surge and the predictors. This statistical method to forecast storm surge became operational shortly after its development and it continues to be used today to guide the official National Oceanic and Atmospheric Administration (NOAA) surge forecasts.

More recently, DeGaetano (2008) investigated another statistical approach and used a published series of strong East Coast winter storms, storms during the October-April storm season, to correlate the occurrence of storms to extreme surge events at three water gauge stations in the New York Metropolitan region. Extreme surge events were defined based on hourly values that exceeded either the 99^{th} or the 99.9^{th} percentiles from October through April over the period of record. Analysis revealed that less than 7% (24%) of the extreme surge events defined using the 99^{th} (99.9^{th}) percentile threshold occurred in association with these storms. The author concludes that even though the occurrence of strong storms and extreme surge is correlated, the predictive capability of this correlation is limited. He suggested a possible explanation for this limitation associated with the fact that the storms used in the analysis represent coast-wide conditions, whereas the extreme surge events at the water gauge stations used to detect surge were caused only by those storms that directly affect the Metropolitan Region.

Present dynamical models include the NOAA ET-SURGE model developed by Kim et al. (1996), the Advance Circulation Model for Coastal Ocean Hydrodynamics (ADCIRC) model of Luettich et al. (1992), and the Estuarine Coastal and Ocean Model (ECOM) of Blumberg and Mellor (1987). ET-SURGE is NOAA's deterministic, real-time, forecast model for extratropical storm surge information (Ji et al., 2010). It is the extratropical version of the Sea, Lake and Overland Surge from Hurricanes (SLOSH) model (Jelesnianski et al., 1992). The ADCIRC model solves a set of steady state, barotropic equations, and was developed to simulate wind driven and tidal circulation in coastal waters. The specifics of the ADCIRC grid enable the simulation of flooding of coastal areas above sea level during storm events (Colle et al., 2008). ECOM is the model currently run by the New York Harbor Observing and Prediction System, and uses a technique that solves separate equations for the fast, barotropic, external waves and slow, baroclinic, internal waves. Despite the considerable improvement of models and availability of observations, modeling of storm surge and prediction of coastal flooding remains a problematic issue. For example, the National Weather Service (NWS)'s extratropical storm related flood warnings that were issued to coastal residents during the period from 2002-2006 had a false-alarm rate of 85% (Colle et al., 2008), indicating the necessity of a better understanding of the complexities determining storm surge.

In addition to the surge forecasts at lead-time of a few days, the availability of accurate weather forecasts out to 5-10 days or longer raises the issue of longer term surge forecasts as well. Owing to larger computers and more sophisticated models, Numerical Weather Prediction (NWP) skill has improved markedly over time (Simmons and

Hollingsworth, 2002) and NWP centers are generally issuing forecasts out to ten days or longer. The National Centers for Environmental Prediction, for example, now issues forecasts out to 16 days. The advent of more reliable seasonal and climate forecasts offers the opportunity for storm surge forecasts on those longer time scales as well. The IPCC AR4 report contains an entire section devoted to regional downscaling of coarse resolution simulations of future climate (IPCC AR4 2007; Working Group 1, Chapter 11) making it possible to drive storm surge models on regional scales. In addition to characterizations of regional storm strength and frequency in a future climate, characterizing storm surge and inundations would of interests to regional planners, as it would guide mitigation measures, such as the construction of storm walls.

A new statistical method for storm surge developed using observations is presented here. It is based on a regression relation between storm surge and significant wave heights established in a study by Salmun et al. (2009), who used a focused regional approach to investigate properties of coastal storm systems (winds, precipitation and waves), and the resulting regional impacts (erosion, storm surge, flooding, wind damage). The method presented here chooses a set of storms for evaluation purposes from observed sea level pressure, and uses time series of forecasted significant wave heights along with the regression equation to compute a forecasted storm surge. The statistical forecast is then evaluated against dynamically predicted storm surge and is compared to the storm surge calculated from water level observations at The Battery. The present study seeks to establish the predictive value of the regression equation of Salmun et al. (2009). Following this introduction, the statistical method as well as the forecast products used is presented. A discussion of the results and of the comparisons of these results to the observed storm surge values and to the storm surge forecast by NOAA are presented in Section 3, followed by the summary and conclusions.

2. Data and Methods

The method used in the present paper follows the work of Salmun et al. (2009), hereafter referred to as S09. To aid the description of the present method, we begin with a summary of the relevant details of S09. The flow diagram of Figure 1 outlines both methodologies, that used by S09 and the present one. The section of the flow diagram above the dotted line corresponds to the early work and the section below the dotted line corresponds to the present work. S09 used sea level pressure data from National Data Buoy Center (NDBC) stations in the New York metropolitan area to identify East Coast Cool-weather Storms (ECCSs) based on the times at which the pressure is below a statistically determined threshold. This is depicted in the progression from left to right across the top of the flow diagram.

The list of storms compiled in this manner, along with wind and wave data collected at the NDBC station and the observationally based storm surge at The Battery, were used to compute storm composite values of wind and wave fields and observed storm surge. This step of the method is depicted in the center of the upper half of the diagram. In most instances the storm composite is a simple average of field values over the duration of the storm. The exceptions are the storm composites of significant wave height and storm surge. Significant wave height is defined as the average of the top third largest wave heights during the observing period (hourly in the case of the data from the NDBC stations). The storm composite significant wave height is computed here as the average of the 'top third' largest significant wave heights during the storm event. The storm composite storm surge is defined here as the maximum value of the surge attained during the storm period, hereafter referred to as "storm maximum" storm surge (SSMAX). The storm composite values were used to perform a regression analysis to determine the best storm composite predictors of SSMAX at The Battery. This step of the methodology is depicted in the bottom sequence of the upper half of the flow diagram.

The observed storm surge data were calculated using water level data at The Battery for the period 1959 - 2007 obtained from NOAA [http://tidesandcurrents.noaa.gov/]. The values of storm surge were computed as the difference between the observed water levels at the water gauge and the NOAA-predicted astronomical tide levels. The average seasonal cycle in mean sea level caused by changes in ocean variables was removed and the resulting time series was corrected for sea level rise during the period of observation. Details of the computation of storm surge from observations at The Battery can be found in Colle et al., 2009.

The regression equation constructed to calculate SSMAX at The Battery using the storm composite significant wave height measured at NDBC station 44025, denoted by $SSMAX_{44025}$ and H_{44025}, respectively, was:

$$SSMAX_{44025} = 0.2055H_{44025} - 0.0851 \quad \text{with RMS error of 0.167m.}$$

The fields used as part of the regression analysis reported in S09 were the storm composites of minimum pressure, pressure tendency, wind speed, wind direction, wind gustiness, significant wave height, wave direction, dominant wave period and storm duration. The regression analysis revealed that SSMAX estimated using the significant wave height as the sole predictor is statistically equivalent to SSMAX estimated using any other combination of predictors. In addition, S09 reported that the regression analysis performed using observations taken at other NDBC stations in the region showed that the best estimate of observed SSMAX at The Battery was obtained when using predictors based on data from NDBC station 44025. A map of the study area, indicating the locations of NDBC station 44025 and The Battery, is provided in Figure 2.

To establish the predictive value of the regression equation obtained by S09, a series of retrospective forecasts of SSMAX were performed using forecasted sea level pressure fields, forecasts of significant wave heights, and the regression equation to compute SSMAX. The NOAA ET-SURGE standard forecast of surge was used for comparison, and both the NOAA and the statistical forecasts were compared against storm surge data computed from observations of water level at The Battery. This procedure is depicted in the bottom half of the flow diagram in Figure 1.

The present study, intended to evaluate the part of our methodology to estimate the storm surge, puts aside the evaluation of the accuracy of the underlying storm forecasts themselves. We therefore choose a list of test cases from the list of storm events that were accurately forecast. The list of storms identified at NDBC station 44025 corresponding to the period February 2005 – December 2008 was the starting list of candidate events for the testing process. This is indicated by the arrow (broken line) from the upper to the lower half of the flow diagram of Figure 1. Retrospective forecasts of sea level pressure were used to verify the existence of candidate events in the forecast record. Forecasts produced by the North American Mesoscale-Weather Research and Forecasting system (NAM-WRF, for storm dates prior to June 2006) weather forecast model and by the WRF-Nonhydrostatic Mesoscale Model (running in the NAM time slot for storm occurring after June 2006) were obtained from NOAA's National Operational Model Archive and Distribution System (NOMADS) [http://nomads.ncdc.noaa.gov/]. The choice of NAM forecasts (instead of the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) used as driving data for the wave model referred to below) for the purpose of eliminating storms not in the forecast record was motivated by the report of Charles and Colle (2009) that the GFS forecasts outperform the NAM forecasts in terms of predicting the minimum pressure during storm events. The more conservative criterion resulted in the elimination of one extra storm event from the list of test cases. NAM sea level pressure values are available at three-hour time intervals and point values at the location of interest (40.25N 73.17W) were calculated using a bilinear interpolation. Any storm not forecasted was eliminated from the final list of test storms. In addition, storm starting times and ending times were adjusted based on forecasted sea level pressure. Results of SSMAX forecasts of 41 storm events selected using the method described here during the period February 2005 – December 2008 are presented in this study. This is depicted by the sequence at the top of the bottom half of the flow diagram.

In direct analogy to the procedure used in S09 and depicted in the center of the lower half of the diagram, storm composite significant wave heights were computed based on retrospective forecasts from NOAA's WAVEWATCH III™ (WWIII) operational wave model for each storm event (retrospective forecast data were obtained from the Marine Modeling and Analysis Branch server [ftp://polar.ncep.noaa.gov/pub/history/waves]), and used as the predictor for SSMAX at The Battery. The model output includes point data at locations of the NDBC data buoys.

For comparison against the statistical SSMAX prediction, "storm maximum" storm surge was computed from NOAA ET-SURGE predictions. ET-SURGE is forced by basin scale surface winds and sea level pressure from the GFS, and the predicted surge is added to the predicted astronomical tide and to a model error correction term to produce a prediction of water level at The Battery. Details of NOAA's ET-SURGE model are available from www.nws.noaa.gov/mdl/etsurge. Archived surge predictions at The Battery produced by the ET-SURGE model were obtained from NOAA (Arthur A. Taylor, personal communication). The NOAA operational storm surge forecast consists of the ET-SURGE output and an error correction, computed as the 5-day running mean of the previous 5 days' error of ET-SURGE output. The analysis presented here will include ET-SURGE estimates with and without the error correction, which was computed using the archive data.

The regression equation used to produce the statistical SSMAX forecasts was slightly modified from the regression equation derived in S09. The study reported in S09 derived the regression equation using observations at hourly intervals for the period 1991-2007. WWIII retrospective forecasts are available at 3-hourly intervals and include data for 2008. Therefore, retrospective predictions of SSMAX at The Battery were computed according to a slightly modified regression equation derived from observations at NDBC station 44025 for the period 1991-2008, using three-hourly data. The equation used in the present analysis is

$$SSMAX_{44025} = 0.1961 H_{44025} - 0.0412 \quad \text{with RMS error 0.145 m.}$$

The values of "storm maximum" storm surge (SSMAX) computed as described above from the statistical forecasts, the NOAA ET-SURGE model output, the NOAA operational forecasts and the observations at The Battery are compared and the results are presented in the next section.

3. Discussion of Results

Each of the 41 ECCS test events was assigned a storm ID number. The dates, beginning and end, and duration in hours corresponding to each ID number can be found in Table 1 – Storm List. The focus of the discussion presented here is the analysis of 12-hour lead time forecasts and results for 24- and 48-hour lead time forecasts will be briefly summarized for comparison. Figure 3, panels a and b, show the SSMAX for each predicted ECCS event. The black bars in Figure 3a represent the SSMAX statistical estimates using our method (STAT FCST) and the dark gray bars in both panels represent the observed SSMAX at The Battery (OBS). The error bars in Figure 3a, represented by the white portion of the dark gray bars, correspond to the RMS error of the regression, that is, the RMS error associated with the regression estimate of SSMAX when the observed significant wave height is the predictor. The white bars in Figure 3b represent the SSMAX computed from ET-SURGE model output, and the light gray bars represent SSMAX computed from the anomaly-corrected NOAA operational surge forecast.

The error in the SSMAX estimate using the regression equation based on the predicted significant wave heights can be thought of as having a contribution due to the significant wave height forecast error and a contribution due to the regression equation estimate itself. Assessment of the SSMAX prediction error relative to the error in an SSMAX estimate using observed significant wave heights leaves us with a measure of the error due to the predictive nature of the significant wave heights. An SSMAX forecast inside the error bars is one for which the predicted significant wave heights are statistically indistinguishable from the observed significant wave heights as an SSMAX predictor.

Figure 3 shows that the observed SSMAX at The Battery (the dark gray bars common to both panels in the figure) is always positive and ranges from 0.1 to about 0.92 m, while the black bars in Figure 3a range from 0.17 to 0.83 m. Examination of the statistical forecast series in relation to the error bars around the observed series shows 66% of the points lie inside the error bars when significant wave height is the predictor. Based on the discussion above this indicates that in two third or more of the cases using predicted significant wave heights does not have a negative impact on the statistical estimates of SSMAX. Figure 3b shows that the values of SSMAX from the ET-SURGE model output are negative for four of the test cases, and range from -0.28 to 0.72 m, while the NOAA operational forecast of SSMAX is negative in only one case, and ranges from -0.19 to 0.84 m. The anomaly correction itself (not shown) ranges from -0.13 to 0.28, indicating the variability in the error of the ET-SURGE model output.

The differences between the statistical and observed SSMAX are shown alongside the differences between the ET-SURGE model output and observed SSMAX and the differences between NOAA's operational forecast and the observed SSMAX in Figure 4. The black bars represent the error of the statistical estimates of SSMAX using significant wave height, the white bars represent the error of the ET-SURGE model output of SSMAX, and the light gray bars represent the error of NOAA's operational forecast of SSMAX. The mean and standard deviation of the difference between estimates of SSMAX using our statistical method and observations are 0.0534 and 0.1591, respectively, those of the error in the ET-SURGE model output of SSMAX are -0.2477 and 0.1186, respectively, and those of the error in NOAA's operational forecast are -

0.1459 and 0.1151, respectively. These metrics are summarized in Table 2 along with those for the 24- and 48-hour lead time forecasts.

Typical sea level pressure fields from NASA's Modern Era Retrospective-Reanalysis for Research and Applications (Bosilovich, 2008) are shown in Figures 5a and 5b for storms for which the statistical SSMAX errors are small, and storms for which the statistical SSMAX errors are large, respectively. Those events for which the errors in SSMAX were smaller (Figure 5a) were stronger and their centers passed over or close to NDBC buoy 44025. The storms for which the errors in SSMAX forecast were larger (Figure 5b) were weaker and passed farther away. This suggests that the regression relation more easily captures the behavior of the surge during stronger and closer storms, possibly due to a more robust physical relationship between wave heights and surge during stronger events and possibly due to reduced sampling error inherent in the Eulerian nature of our technique.

The statistics of Table 2 indicate that in general the statistical SSMAX estimates tend to slightly underpredict or overpredict the observed SSMAX on average and that the NOAA SSMAX forecasts, with and without the anomaly correction, tend to underpredict the observed SSMAX. A series of statistical tests revealed that the error in NOAA's ET-SURGE SSMAX is greater than the error of the statistical SSMAX estimates at greater than the 95% significance level, while the error in the NOAA operational forecast of SSMAX is statistically indistinguishable from the error in the statistical SSMAX forecasts. The statistical comparisons for the 24- and 48-hour lead time forecasts show the same pattern. Comparison among the statistical SSMAX forecast at the 12-, 24- and 48-hour lead time shows that the 12- and 24-hour lead time forecast errors are statistically indistinguishable and that both are statistically smaller that the 48-hour lead time forecast errors at the 95% significance level.

A qualitative analysis of those ECCS events for which the error in the statistical SSMAX prediction was large resulted in a distinction between those events for which the SSMAX error was due mainly to errors in forecasted significant wave heights and those events for which the SSMAX error was mainly due to the failure of the regression relation. In general, underpredictions of SSMAX (storm ID numbers 3, 5, 14, 38 and 40) are attributable to errors in forecasted significant wave heights while overpredictions of SSMAX (storm ID numbers 10, 20, 21, 29 and 30) are attributable to failure of the regression relation.

4. Summary and Conclusions

A new statistical method for predicting “storm-maximum” storm surge related to East Coast Cool-Weather Storms was presented here, demonstrating the predictive capability of an established regression relation between storm-averaged significant wave height and storm-maximum surge. The statistical method was tested by performing a series of retrospective forecasts during the period from February 2005 to December 2008, using existing operational forecasts of surface pressure from NOAA’s North American Mesoscale (NAM-WRF) weather forecast model, operational forecasts of wave height from NOAA’s WAVEWATCH III model, and the regression relation established based on observations of sea level pressure and significant wave heights from the NDBC station closest to New York Harbor. The statistical storm-maximum surge prediction was compared to NOAA ET-SURGE model output, to the operational surge forecast from NOAA and to the water level observations taken at The Battery, NY. A distinction was made between events for which the error in the statistical prediction was due to errors in the predicted wave heights and events for which the error was due to a failure in the regression relation.

The results of the evaluation of our method for 12-, 24- and 48-hour lead time forecasts showed that the mean error is smaller than the mean error of the ET-SURGE model forecasts with 95% confidence and statistically indistinguishable from the NOAA operational forecast which is the ET-SURGE output with an anomaly correction. An advantage that the statistical method offers relates to the limitations of the error correction technique used by NOAA. The led time of NOAA's operational storm surge forecast is limited to the time span over which the anomaly correction can be assumed constant. In the context of weather predictions that go out for 10 days or more, operational seasonal predictions and longer term climate forecasts, it would be highly desirable to explore corrections to the dynamical storm surge forecast that do not require constancy of these corrections throughout the forecast.

The method presented here establishes a robust prediction of the storm maximum storm surge associated with a particular forecasted storm, which could provide valuable information as an element of operationally issued storm warnings. The present results lend confidence to the usefulness of our statistical technique as an element of an improved error correction methodology for use in operational surge forecasts. This application of our method would require a quantitative characterization of the error of the statistical prediction in terms of the nature, location and strength of the storms.

Acknowledgments.

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List of Figures

FIG. 5. Typical sea level pressure maps corresponding to a) storms for which the statistical estimate of “storm maximum” storm surge has small errors, and b) storms for which the “storm maximum” storm surge has larger errors.

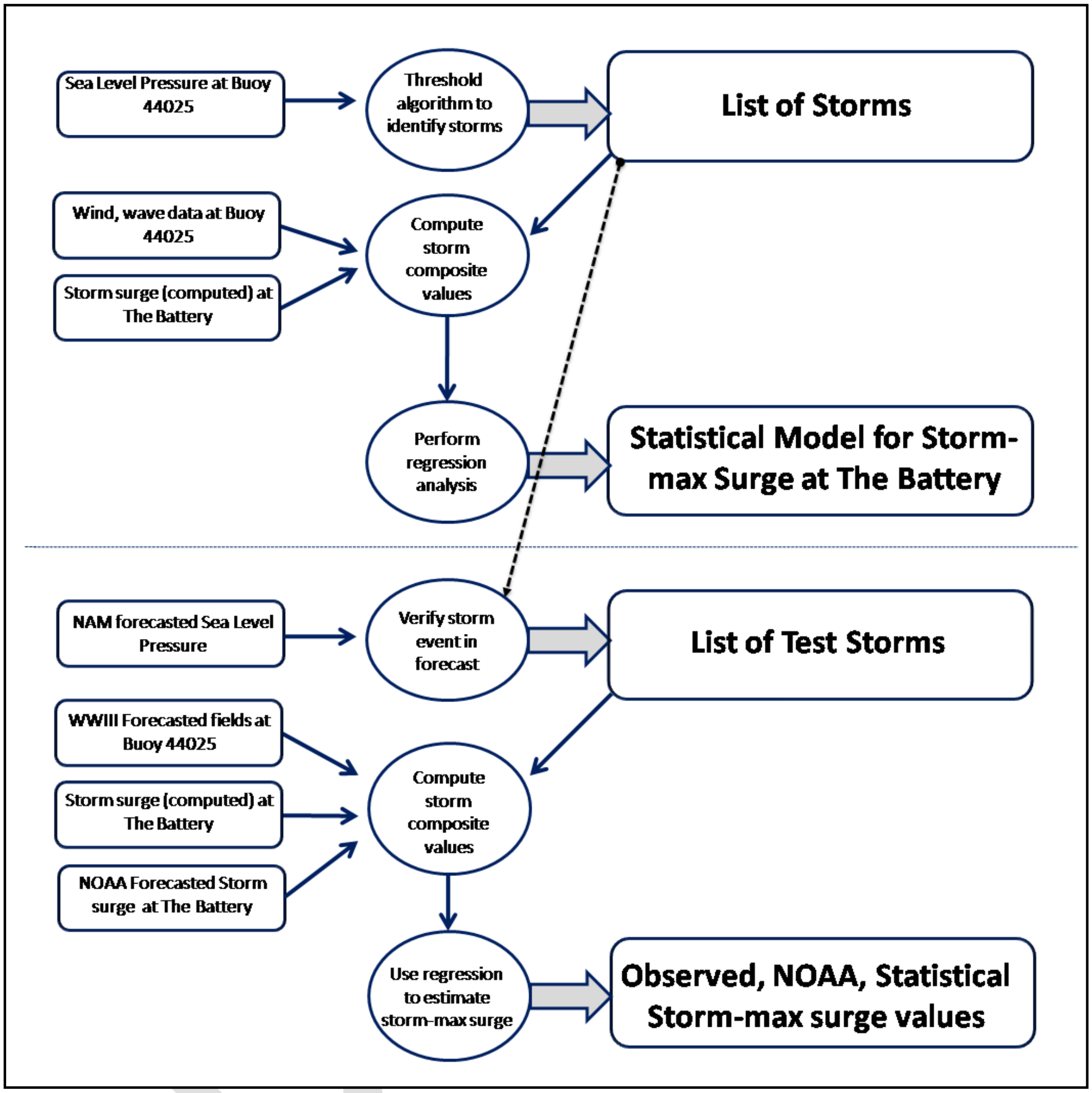


FIG. 1. Flow diagram outlining the methodologies used by Salmun et al., 2009, and the one used in the present work. The top panel of the flow diagram, above the dotted line, corresponds to the early work and the bottom section, below the dotted line, corresponds to the present work

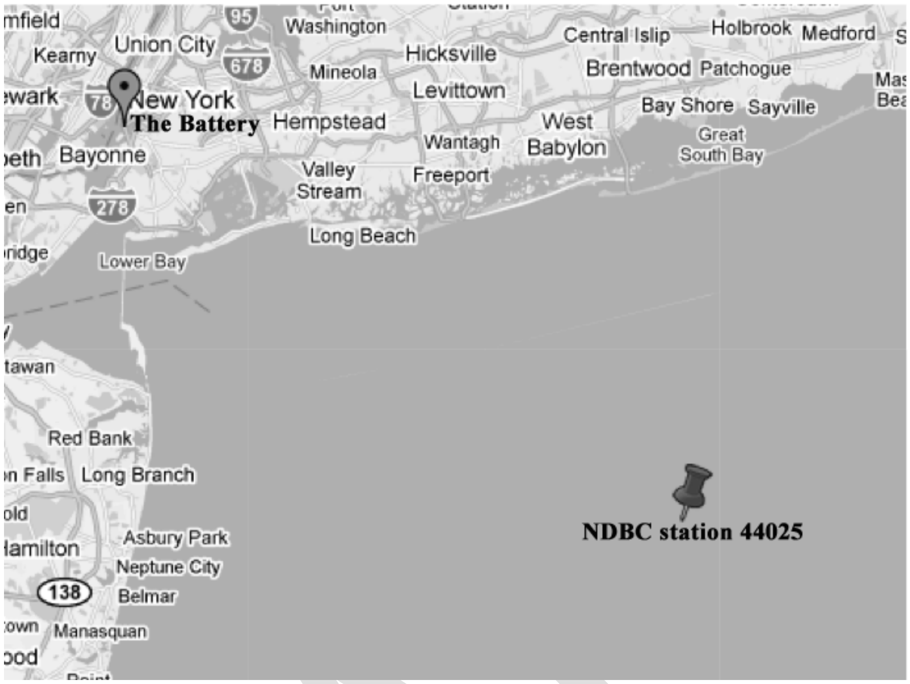
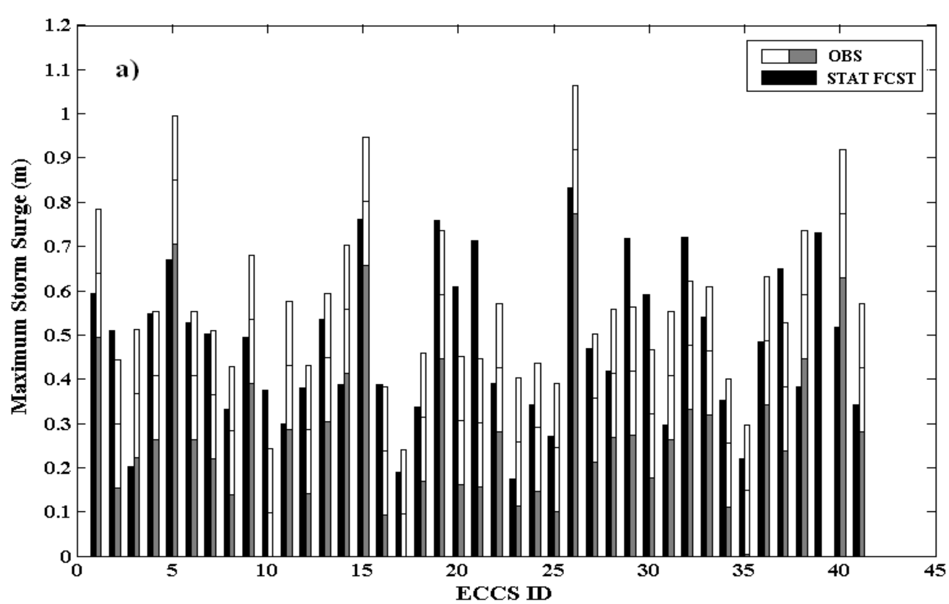


FIG. 2. A reference map of the study area showing the locations of The Battery and NDBC station 44025.



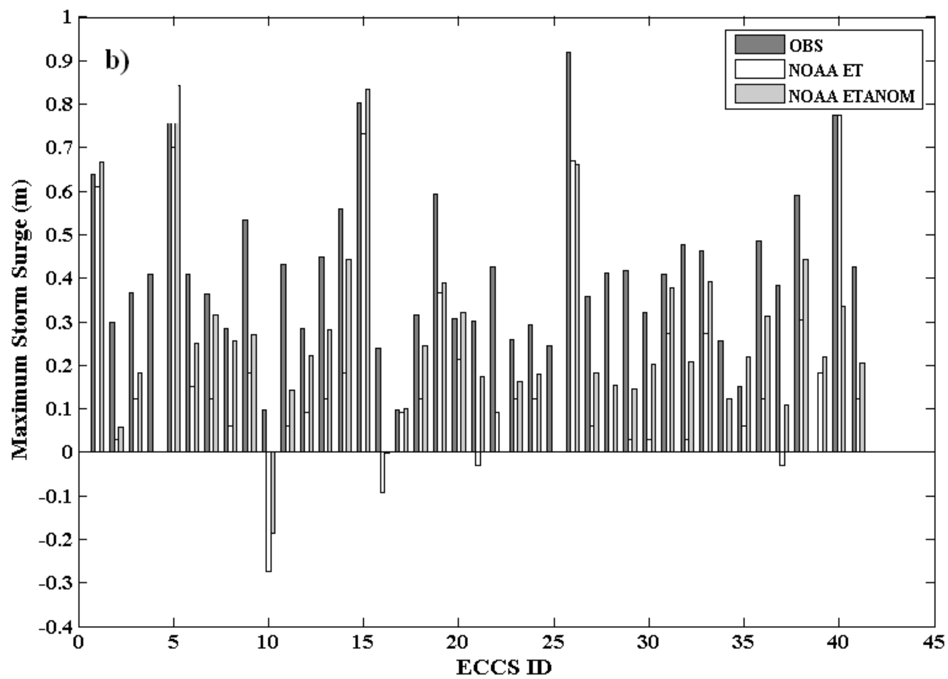


FIG. 3. “Storm maximum” storm surge for each predicted ECCS event. a) Estimates of “storm maximum” storm surge using the statistical methodology presented here, and b) using NOAA’s ET-SURGE model output and using the operational forecasts provided by NOAA. Data are for 12-hour lead time forecasts and the observed “storm maximum” storm surge correspond to data at The Battery, N. Y. The error bars in panel a) are the root mean square error of the regression.

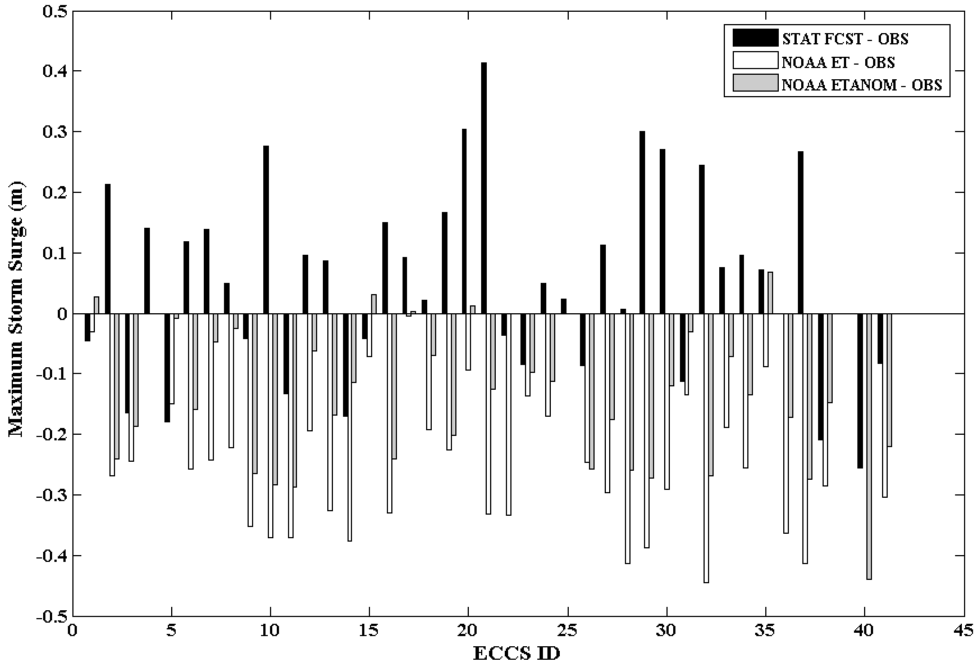


FIG. 4. The (forecasted – observed) difference of the "storm maximum" storm surge using the statistical model, (STAT FCST – OBS), using NOAA ET-SURGE model output, (NOAA ET – OBS), and using NOAA operational storm surge forecasts (NOAA ETANOM – OBS).

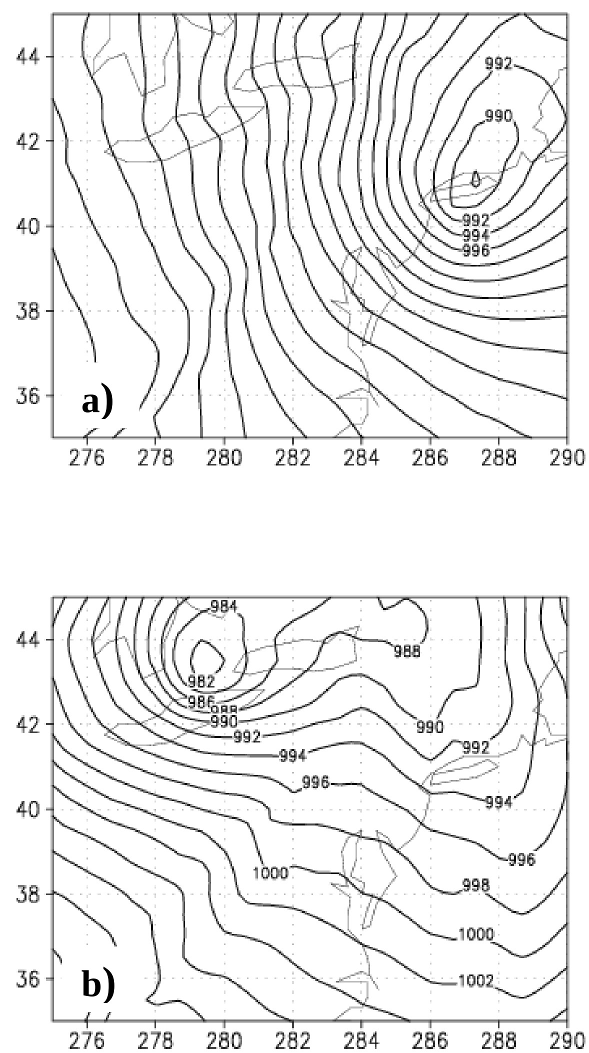


FIG. 5. Typical sea level pressure maps corresponding to a) storms for which the statistical estimate of "storm maximum" storm surge has small errors, and b) storms for which the "storm maximum" storm surge has larger errors.

TABLE 1. Storm List: ECCS events used as part of this study. Columns 2 through 6 refer to the beginning and ending of storms as recorded at NDBC station 44025 and columns 7 through 11 as recorded in the 12-hr NAM forecast.

	Storm recorded at NDBC station 44025					Storm as per 12 h forecast				
ID	Storm Starts	H	Storm Ends	H	Dur	Storm Starts	H	Storm Ends	H	Dur
1	3/1/05	0.00	3/2/05	9.00	33	03/1/05	3:00	3/2/05	15:00	36
2	3/7/05	21.00	3/9/05	6.00	33	3/8/05	0:00	3/9/05	0:00	24
3	3/11/05	15.00	3/13/05	3.00	36	3/11/05	21:00	3/13/05	12:00	39
4	3/28/05	21.00	3/29/05	15.00	18	3/28/05	21:00	3/29/05	12:00	15
5	4/3/05	0.00	4/3/05	21.00	21	4/2/05	12:00	4/4/05	9:00	45
6	4/24/05	6.00	4/25/05	12.00	30	4/24/05	3:00	4/24/05	15:00	12
7	10/15/05	15.00	10/15/05	21.00	6	10/15/05	18:00	10/16/05	9:00	15
8	11/10/05	6.00	11/10/05	15.00	9	11/9/05	18:00	11/10/05	18:00	24
9	11/22/05	3.00	11/24/05	3.00	48	11/22/05	3:00	11/23/05	9:00	30
10	11/24/05	6.00	11/25/05	0.00	18	11/24/05	18:00	11/25/05	0:00	6
11	12/26/05	3.00	12/27/05	9.00	30	12/26/05	12:00	12/27/05	9:00	21
12	12/29/05	9.00	12/30/05	9.00	24	12/29/05	12:00	12/30/05	15:00	27
13	1/14/06	9.00	1/15/06	21.00	36	1/14/06	9:00	1/15/06	12:00	27
14	2/5/06	3.00	2/5/06	21.00	18	2/5/06	3:00	2/6/06	6:00	27
15	2/12/06	9.00	2/12/06	21.00	12	2/12/06	9:00	2/13/06	0:00	15
16	3/14/06	9.00	3/14/06	18.00	9	3/14/06	9:00	3/14/06	18:00	9
17	4/15/06	12.00	4/16/06	0.00	12	4/15/06	12:00	4/16/06	6:00	18
18	10/20/06	12.00	10/20/06	21.00	9	10/20/06	12:00	10/21/06	0:00	12
19	10/28/06	12.00	10/29/06	12.00	24	10/28/06	15:00	10/30/06	0:00	33
20	11/8/06	21.00	11/10/06	3.00	30	11/9/06	0:00	11/10/06	3:00	27
21	11/17/06	3.00	11/17/06	12.00	9	11/17/06	6:00	11/17/06	18:00	12
22	12/26/06	9.00	12/27/06	6.00	21	12/26/06	12:00	12/27/06	6:00	18
23	1/29/07	0.00	1/29/07	9.00	9	1/28/07	15:00	1/29/07	9:00	18
24	2/3/07	0.00	2/3/07	6.00	6	2/2/07	12:00	2/3/07	15:00	27
25	2/23/07	0.00	2/23/07	6.00	6	2/22/07	15:00	2/23/07	18:00	27
26	4/15/07	18.00	4/17/07	18.00	48	4/15/07	12:00	4/17/07	21:00	57
27	1/30/08	9.00	1/30/08	15.00	6	1/29/08	21:00	1/31/08	3:00	30
28	2/6/08	12.00	2/7/08	9.00	21	2/6/08	0:00	2/7/08	21:00	45
29	2/13/08	18.00	2/14/08	0.00	6	2/13/08	9:00	2/14/08	9:00	24
30	2/18/08	12.00	2/19/08	0.00	12	2/18/08	0:00	2/19/08	12:00	36
31	2/26/08	21.00	2/27/08	18.00	21	2/26/08	9:00	2/28/08	6:00	45
32	3/8/08	18.00	3/9/08	0.00	6	3/8/08	6:00	3/9/08	12:00	30
33	3/20/08	0.00	3/20/08	18.00	18	3/19/08	21:00	3/21/08	3:00	30
34	4/12/08	15.00	4/13/08	0.00	9	4/12/08	12:00	4/13/08	3:00	15
35	10/2/08	0.00	10/2/08	12.00	12	10/2/08	0:00	10/2/08	12:00	12
36	10/28/08	9.00	10/29/08	0.00	15	10/28/08	12:00	10/29/08	6:00	18
37	11/15/08	18.00	11/16/08	18.00	24	11/15/08	21:00	11/16/08	21:00	24

38	12/1/08	0.00	12/1/08	12.00	12	12/1/08	3:00	12/1/08	12:00	9
39	12/12/08	9.00	12/12/08	15.00	6	12/12/08	9:00	12/12/08	15:00	6
40	12/21/08	15.00	12/22/08	6.00	15	12/21/08	15:00	12/22/08	3:00	12
41	12/31/08	9.00	12/31/08	18.00	9	12/31/08	12:00	12/31/08	21:00	9

TABLE 2. Metrics for the error associated with the statistical estimate of SSMAX, the NOAA ET-Surge model output estimate of SSMAX and the NOAA operational forecast of SSMAX at The Battery, N. Y., for the 12-, 24- and 48-hour lead time forecasts.

Lead Time	Statistic	STAT - OBS	NOAA ET - OBS	NOAA ETANOM - OBS
12-hour	Mean (m)	0.0534	-0.2477	-0.1459
	STD	0.1591	0.1186	0.1151
24-hour	Mean (m)	0.0927	-0.2346	-0.121
	STD	0.1597	0.1266	0.126
48-hour	Mean (m)	0.0418	-0.2713	-0.137
	STD	0.1341	0.1346	0.1474