East Coast Cool-Weather Storms in the New York Metropolitan Region

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ABSTRACT

New York coastal regions are frequently exposed to winter extratropical storm systems that exhibit a wide range of local impacts. Studies of these systems either have used localized water-level or beach erosion data to identify and characterize the storms or have used meteorological conditions from reanalysis data to provide a general regional ''climatology'' of storms. The use of meteorological conditions to identify these storms allows an independent assessment of impacts on the coastal environment and therefore can be used to predict the impacts. However, the intensity of these storms can exhibit substantial spatial variability that may not be captured by the relatively large scales of the studies using reanalysis data, and this fact may affect the localized assessment of storm impact on the coastal communities. A method that uses data from National Data Buoy Center stations in the New York metropolitan area to identify East Coast cool-weather storms (ECCSs) and to describe their climatological characteristics is presented. An assessment of the presence of storm conditions and a three-level intensity scale was developed using surface pressure data as measured at the buoys. This study identified ECCSs during the period from 1977 through 2007 and developed storm climatologies for each level of storm intensity. General agreement with established climatologies demonstrated the robustness of the method. The impact of the storms on the coastal environment was assessed by computing ''storm average'' values of storm-surge data and by examining beach erosion along the south shore of Long Island, New York. A regression analysis demonstrated that the best storm-surge predictor is based on measurements of significant wave height at a nearby buoy.

1. Introduction

East Coast cool-weather storm (ECCS) systems, locally referred to as nor'easters, are a dominant storm type experienced by communities in the New York coastal regions. These systems bring high winds, heavy rain, flooding, ice storms, blizzards, heavy snow, and extreme wind chills. These storm systems are primarily responsible for the erosion of the barrier beaches and for the general westward transport of sediment throughout the littoral system that extends from Montauk at the eastern tip of Long Island to The Battery at the southern end of Manhattan Island, both in New York. The heavy surf during such events has destroyed numerous piers, seawalls, marinas, roads, boats, and shorefront homes. Coastal flooding associated with these storm systems has compromised transportation infrastructure. For example, the December 1992 storm resulted in over $230 million in disaster assistance (DeGaetano et al. 2002) and temporarily flooded subway routes between New York and New Jersey. The eustatic sea level rise expected in the future climate (Bernstein et al. 2007), which enhances the storms' ability to erode the beaches, along with the continued development on the shorefront, is expected to increase the negative impacts of these extratropical storms on these densely populated regions. These considerations make it critical to assess the potential behavior of ECCSs in a changing climate.

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Studies that classify ECCSs have been conducted using coastal damage reports, surface weather maps, wave heights, water levels, and reanalysis data. Mather et al. (1964) used coastal damage reports in New York and New Jersey and determined that coastal storms affect the region on average once every 1.4 yr. One important limitation to this approach is that coastal development over time increases the apparent number of damaging storms (Zhang et al. 2000). Colucci (1976) used surface weather maps to compute an annual storm frequency in the region from Cape Hatteras, North Carolina, to the easternmost point of Maine. Hayden (1981) identified an increasing trend in ECCS counts in the period from 1885 to 1978 based on weather maps and ship logs. The analysis of ECCSs based on surface weather maps is advantageous because of the length of the available record. However, construction of such maps can be highly subjective, and even more so over the ocean. In addition, this type of analysis is useful in terms of describing storm behavior but is limited in terms of predictive capability.

Coastal storms produce large waves and storm surge, and these data have been used to study coastal storm activity. A 25-yr-long observational record of local wave-height measurements was used in a study by Carter and Draper (1988) to investigate long-term trends. Davis et al. (1993) extended the record by using climatological data to hindcast wave heights that were used to define a five–storm class classification system of nor'easters based on the potential for coastal damage. The advantage of this approach is that the localized nature of the wave-height data can be used to assess the storm impact on a specific beach. The disadvantage of this approach is the error introduced by the hindcast as well as the a priori assumptions used to relate local meteorological conditions to wave height. Hourly water-level data from tide gauges were used by Zhang et al. (2000) to infer storm surge, which in turn was used to identify individual storms and to characterize their frequency and duration. A more desirable method is one that identifies the storm independent of its impacts, because this would allow a prediction of the impact of a forecast storm.

In a more-recent study, National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) for the period 1948–97 were used by Hirsch et al. (2001, hereinafter HDC01) to identify ECCSs based on surface pressure, tracks, location, and near-surface winds. They developed a "climatology" of these storms and identified a clear influence of the phase of the El Niño–Southern Oscillation on the frequency of storms, finding that more storms occur during El Niño events. The spatial resolution of the NCEP–NCAR reanalysis data is $2.5° \times 2.5°$ in latitude and longitude, corresponding roughly to an area of 25 600 km^2. At this spatial resolution, a disadvantage of this approach for use in assessing storm impacts is that the localized impact of any particular storm event on a specific beach is difficult to assess. Another similar disadvantage of this approach was pointed out in the study of DeGaetano (2008). He used a slightly modified method relative to that of HDC01 to identify ECCSs and examined the relationship between those storms and the storm-surge activity near Long Island. He found that the seasonal predictability of storm surge based on those storms was limited in part by the large geographic scope needed to identify storms with this method. He makes the point that individual surge events at a particular location are affected by the storms that impact only a small part of the region of study.

All of these studies have provided a general characterization of ECCSs along the East Coast of the United States as a whole. Given the focused regional extent of these coastal storm systems, however, it is crucial to investigate the storm properties (winds, precipitation, and waves) and the resulting impacts (erosion, storm surge, flooding, and wind damage) using a focused regional approach. The work presented here has advantages over the existing methods to characterize ECCSs for use in studying local storm impacts. We assess the behavior of ECCS systems in the New York metropolitan area using meteorological data from ocean buoys to define and classify the storms and describe their climatology. In addition, we compute climatological means of the impact of the storms on water levels and beaches. Our method has a local focus, uses meteorological conditions to assess the storms, and provides a highly localized independent assessment of storm impacts. This method therefore has the potential to be used to predict the impact of forecast ECCSs. The method is described in detail in the next section, and the resulting climatology is presented and discussed in section 3.

2. Technique for identification and characterization of ECCSs

Time series from three buoys in the New York metropolitan region were obtained from the National Data Buoy Center (NDBC; available online at http://www.ndbc.noaa.gov/maps/Northeast.shtml). A map of the region showing the locations of the buoys is shown in Fig. 1. The buoys chosen are the 6-m Navy Oceanographic Meteorological Automated Devices buoy of NDBC station 44004 located at 38.48°N, 70.43°W in 3182-m-deep water and with a data record from 1977 to present, the 3-m discus (circular hulled) buoy of NDBC

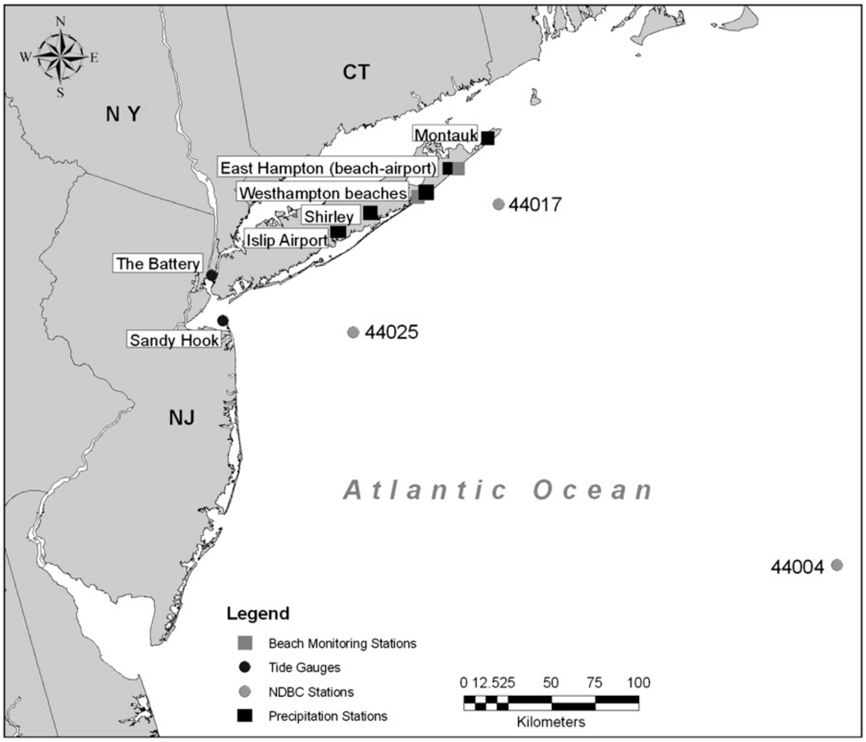

FIG. 1. Map of the study region. Markers indicate the locations of NDBC stations 44025, 44004, and 44017 and the locations of precipitation measurements, beach-profile measurements, and NOAA water-level gauges in New York Harbor. Westhampton beaches include Tiana Beach and Shinnecock Beach.

station 44025 located at 40.25°N, 73.17°W in 36.3-m-deep water and with a data record from 1991 to present, and the 3-m discus buoy of NDBC station 44017 located at 40.69°N, 72.05°W in 46-m-deep water and with a data record from 2002 to present. The focus of the presentation here will be on data from the first two buoys (NDBC stations 44004 and 44025) because of the short time span of the data record from the third buoy (NDBC station 44017). The NDBC stations record oceanographic and meteorological data each hour using different averaging periods for the different variables being measured, as well as different sampling methods (see the Web site provided above for detailed information). Measurements include wave height, period, and direction; air, water, and dewpoint temperatures; atmospheric pressure; and wind speed, gusts, and direction.

Multiyear averages were computed for each hour from the surface pressure time series, and a threshold of two standard deviations below this average was set to determine a potential ECCS. A continuous block of measurements for which the surface pressure was less than two standard deviations below the mean was considered to be a single event as long as the continuous string lasted longer than 4 h and was separated from all other continuous groups of measurements by at least 24 h. A search algorithm for local minima and maxima in the surface pressure time series for each storm was applied to refine further the identification of individual storms. Storms for which the surface pressure time series showed a local maximum but no local minimum were removed from consideration, and storms whose surface pressure time series showed more than a single local minimum were split into the appropriate number of storms. The choice of the thresholds and other parameters used to identify ECCSs was verified by using daily weather maps for each storm from the U.S. Daily Weather Maps Project Web site (http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html) to examine the tracks and temporal evolution of the storms incident at the buoys.

To eliminate from our ECCS analysis those tropical cyclones that maintained their tropical character throughout their evolution, data from the National Hurricane Center (available on line at http://www.nhc.noaa.gov/pastall.shtml) listing all tropical systems during our study period were used in conjunction with daily weather maps. A particular storm was deemed tropical in nature based on a determination by the Hurricane Data Center that a tropical system was present in the area of our study where the NDBC stations are located (see Fig. 1). The absence of frontal structure was used to confirm the tropical nature of the storms eliminated from our list of ECCSs.

The ECCSs were then classified into three levels of storm intensity based on the pressure tendency, which is the rate of change of surface pressure with time. Pressure tendencies were computed from hourly surface pressure data for each storm using data from each buoy, and mean and standard deviation values were computed for all ECCSs as identified at a particular buoy. Means and standard deviations were computed based on the absolute value of the pressure tendency at any given time. Level-1 storms have pressure tendencies that are less than one standard deviation below the mean pressure tendency, level-2 storms have pressure tendencies that are between one standard deviation below the mean and one standard deviation above the mean, and level-3 storms have pressure tendencies that are greater than one standard deviation above the mean.

Storm composites were computed to characterize a level-by-level storm climatology of minimum pressure, storm duration, maximum 5-m winds, precipitation, and significant wave heights H_s (top one-third of wave heights). Precipitation data were obtained from the National Climatic Data Center Global Surface Summary of the Day Data (available online at http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html) at New York stations in Shirley (725016), MacArthur Airport (725035), and Montauk (720068) (see Fig. 1 for station locations). All other data for the storm composites are from the buoy data records.

To assess the local impact of the ECCSs on the New York metropolitan region, storm composites of storm surge were computed. Hourly storm surge was computed using water-level and astronomical tide data at The Battery and at Sandy Hook, New Jersey, (see Fig. 1) for the period 1958–2007 obtained from the National Oceanographic and Atmospheric Administration (NOAA; available online at http://tidesandcurrents.noaa.gov/). To compute the storm surge, astronomical tide levels were subtracted from the observed water levels at the gauges. The record was then detrended to remove both the long-term sea level change and the average annual cycle.

Beach profiles were also examined to assess storm impacts. Beach-profile data were obtained from the Stony Brook University Coastal Ocean Action Strategies (COAST) Institute for three beaches along eastern Long Island (see Fig. 1). Differences between consecutive profile measurements, which have a temporal resolution of approximately 4–6-weeks, were used to compute average shoreline recession or accretion rates and changes in beach volume. To establish connections between erosion at a specific beach and the storm activity as assessed at the different buoys, storm counts for each buoy's storm determinations were computed during each beach-profile survey period.

The potential limitations of the methods presented here to determine and characterize ECCSs are related mainly to the length of the data records and to the Eulerian nature of the buoy measurements. The record of the data from NDBC station 44025, in closer proximity to the coast than is NDBC station 44004, is only 17 yr in duration, which may limit the statistical robustness of the climatology. NDBC station 44004, however, has a longer data record and was used to support the robustness of the analysis based on NDBC station 44025. Calculations of the threshold values to determine storms and storm intensity at NDBC station 44004 were performed with the entire record and with a subset of the data record that spans the period 1991–2007, which corresponds to the record at NDBC station 44025. Storm counts based on these two sets of thresholds were statistically indistinguishable, supporting the assumption that our statistics based on the 17-yr record at NDBC station 44025 are adequate.

Because of the Eulerian nature of the measurements used in our analysis, we cannot determine the spatial relationship between the location of a storm's minimum surface pressure and the buoy at any given time. From our classification, therefore, a level-1 storm may result either from an intense storm affecting the East Coast region but tracking at a distance or from a weak storm overhead. Based on an extensive examination of surface weather maps and storm-track locations for our level-1 storms, we concluded that the majority of level-1 storms identified at the nearshore buoy tracked at a distance and only ''grazed'' the buoy location. These storms do have a reduced impact on the coastal environment, however, and are correctly identified as ''weak'' storms for our analysis.

3. Results and discussion

Results of the analysis described in section 2 are presented here. The focus of this presentation is on the data from NDBC stations 44025 and 44004 because of their longer data records. Thresholds for storm classifications are presented and discussed, followed by a discussion of composite climatologies of storm characteristics. Comparisons are made along the way with the study of ECCSs based on reanalysis data of HDC01. The local impacts of ECCSs on the region are discussed at the end of this section.

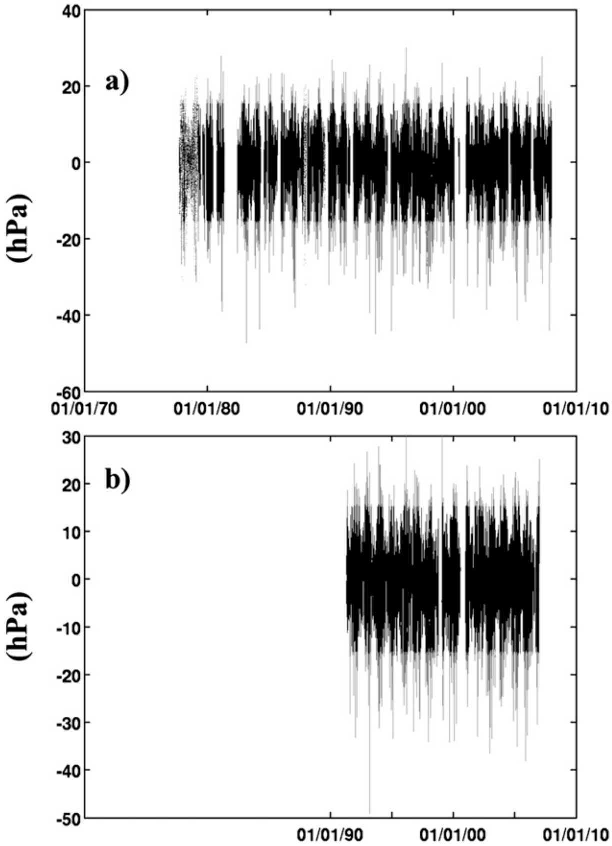

FIG. 2. Time series of surface pressure anomaly (hPa) at NDBC stations (a) 44004 and (b) 44025. The gray portions of the curves identify the time periods during which the surface pressure was more than 2 std dev from the mean.

a. Storm classification

To determine the thresholds for ECCS identification, the time series of the surface pressure shown in Figs. 2a and 2b were analyzed as described in the previous section. The mean surface pressure for NDBC station 44004 was 1016.7 hPa, with a standard deviation of 7.7 hPa. For NDBC station 44025, the mean surface pressure was 1016.2 hPa, with a standard deviation of 7.6 hPa. The similarity in mean surface pressure suggests that any differences in storm counts are not related to the small differences in the choice of thresholds. After the elimination process, 389 ECCSs were identified at NDBC station 44004 and 222 were identified at NDBC station 44025. During the period of record of NDBC station 44025, 243 ECCSs were identified at NDBC station 44004. This translates into an average storm count per year of 12 and 13 at NDBC stations 44004 and 44025, respectively. These counts are in close agreement with the 11 storm per year average reported by HDC01. For the purpose of comparison with a study based on wave height, the equivalent

TABLE 1. Intensity thresholds for each storm level at NDBC stations 44004 and 44025.

Storm class	Pressure tendency (PT) criterion	Storm count for 1991–2007	Storm count for 1977–2007
NDBC station 44004			
Level 1	PT < 0.32 hPa h^{-1}	20	31
Level 2	$0.32 \leq$ PT < 1.30 hPa h^{-1}	196	310
Level 3	PT ≥ 1.30 hPa h^{-1}	27	48
NDBC station 44025			
Level 1	PT < 0.30 hPa h^{-1}	15	—
Level 2	$0.30 \leq$ PT < 1.17 hPa h^{-1}	172	—
Level 3	PT ≥ 1.17 hPa h^{-1}	35	—

Davis et al. (1993) intensity-scale level was computed using the calculated significant wave height and observed storm duration for both NDBC stations' buoys. The total number of storms (1189) is large relative to our ECCS count. As discussed by HDC01, because Davis et al. (1993) include ''anticyclonic storm types'' (high pressure systems) in their annual storm totals, a comparison of storm-count totals between their study and ours is difficult to assess.

The classification of ECCSs into level-1, level-2, and level-3 storms based on the pressure tendency is summarized in Table 1. Shown are the pressure tendency thresholds and storm counts for NDBC stations 44004 and 44025. For reference, the mean ECCS pressure tendency for NDBC station 44004 was 0.81 hPa h^{-1} with a standard deviation of 0.49 hPa h^{-1} and the mean pressure tendency for NDBC station 44025 was 0.74 hPa h^{-1} with a standard deviation of 0.43 hPa h^{-1}. The table shows some differences in storm counts between NDBC station 44025 and 44004 for each ECCS level for the same time period, and these differences may be related to the difference in threshold values. ECCSs at the strongest and most destructive storm level appear on average 2 times per year, as compared with the 3 times per year reported in the study of HDC01, who set a threshold for strong storms at the top quartile of surface wind speed measurements.

Our storm classification is based solely on the standard deviation of the pressure tendency record but resulted in three types of storms with distinctly different characteristics. Figures 3a,b,d,e,g,h show analyzed sea level pressure maps from Modern Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2008) of the National Aeronautics and Space Administration Goddard Global Modeling and Assimilation Office and Figs. 3c,f,i show surface pressure and temperature time series for individual storms representative of each storm level at NDBC station 44025. Figures 3a–c correspond to the level-1 storm of

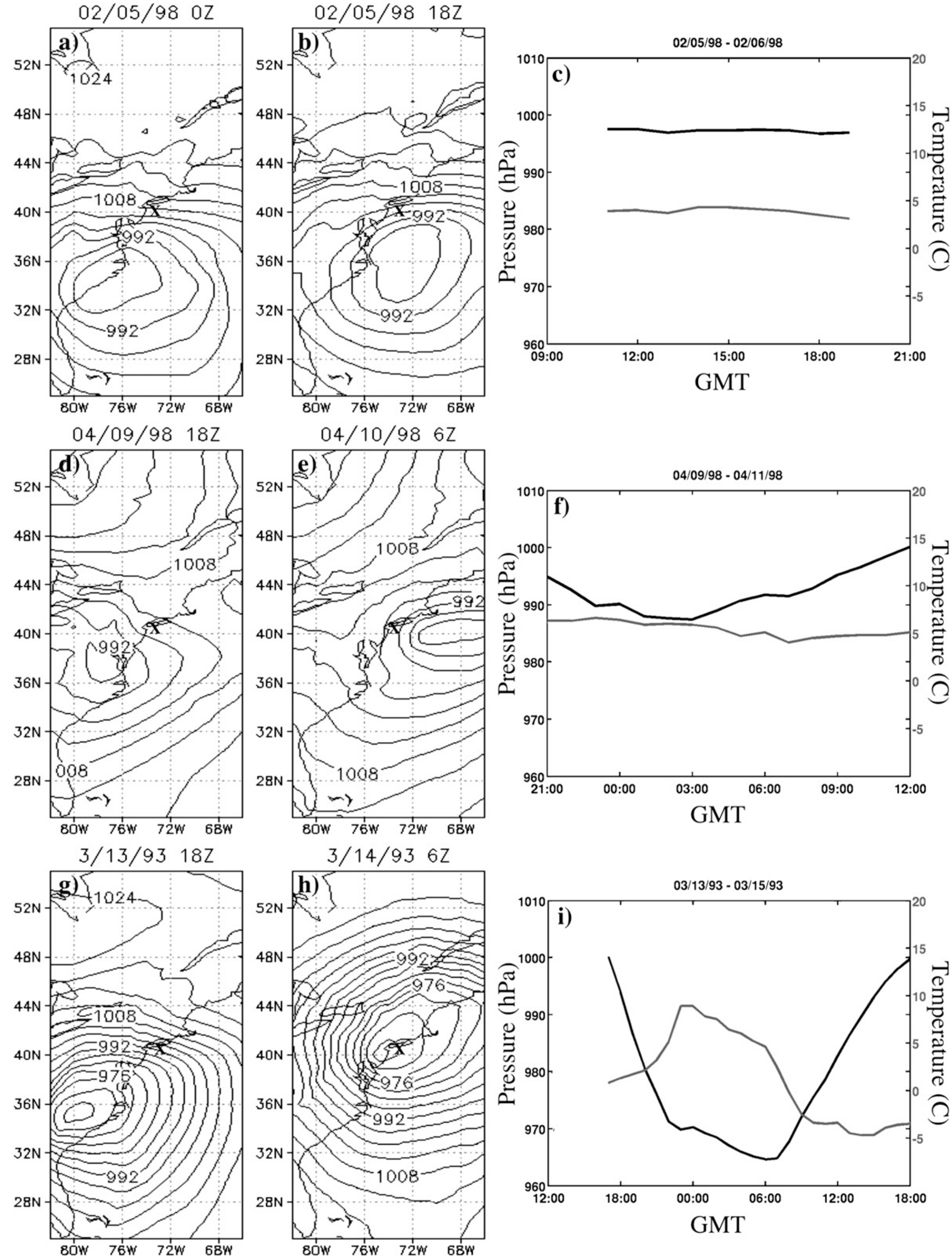

FIG. 3. (a),(b) Analyzed sea level pressure from MERRA as identified at NDBC station 44025, marked with an "x," along with (c) surface pressure (black line) and temperature (gray line) time series measured at the station, for typical level-1 storms. (d)–(f) As in (a)–(c), but for level-2 storms. (g)–(i) As in (a)–(c), but for level-3 storms.

5–6 February 1998, Figs. 3d–f correspond to the level-2 storm of 9–11 April 1998, and Figs. 3g–i correspond to the level-3 storm of 13–15 March 1993. For each case, the two sea level pressure maps depict the location of the storm before arriving at the buoy and while the storm was overhead. The surface pressure and temperature curves exhibit behavior consistent with the storm classification. That is, level-1 storms exhibit the smallest surface pressure and temperature drop, the surface pressure and temperature change increases for level-2 storms, and these changes reach their largest value for level-3 storms. The temperature trace of level-3 storms has the typical structure associated with the passage of a warm front followed by a cold front, which characterizes the most intense storms that affect the East Coast.

The typical level-1 storm exhibits the behavior shown in the analyzed sea level pressure maps of Figs. 3a and 3b. The surface pressure is of moderate intensity, but the storm's center passes far enough away from the location of the NDBC station's buoy, marked with an ''x'' on the maps, so as to be classified as a weak event. This particular date shows a storm passing to the east of the NDBC station's buoy, but there were also a significant number of events in this category for which the storm center tracked to the west of the buoy. The typical level-2 storm shown in the analyzed sea level pressure maps of Figs. 3d and 3e has surface pressure values that are similar to those of the typical level-1 storm, but it tracks closer to NDBC station 44025. The large majority of the level-2 storms exhibit inland tracks like the one that can be seen in the movement of the storm from its position shown in Fig. 3d to its position shown in Fig. 3e. In contrast, the typical level-3 storm (shown in Figs. 3g,h) has a track that originates in the Gulf of Mexico or along the coast of the U.S. Southeast and moves northward. This is the canonical Miller-A storm (Miller 1946).

The annual and interannual distributions of ECCS counts at both NDBC stations for the time period 1991–2007 are shown in the histograms of Figs. 4a–d. Figures 4a and 4c show that the annual distribution at both NDBC stations is similar, with a maximum storm count in January and a minimum during the summer months. The January maximum is also found in the study of HDC01 using a much longer time record. The histograms show small (but nonzero) numbers of ECCSs in June detected by our method at both NDBC stations that are confirmed extratropical storms based on examination of the daily weather maps. The primary difference between the ECCS annual distributions at the two NDBC stations is in the contrast between winter and spring storm counts. The distribution at NDBC station 44025 is more skewed toward storms in late autumn (November) and in late winter months (February), whereas the distribution at NDBC station 44004 shows higher storm counts in the remaining months. This difference in distribution is consistent with the geographical location of the two buoys. NDBC station 44025 is located farther to the north and is more likely to record winter storms arriving from the northwest sector. There is some indication that the fewer spring storms at NDBC station 44025 are more likely to be classified as level 2 or level 3 than the storms at NDBC station 44004, but there are not enough data to determine this statistically.

The interannual distributions of storms occurring during October–April (cool-weather season) at both NDBC stations are shown in Figs. 4b and 4d and are relatively similar throughout the record. The exceptions to this are in the 3-yr span 1997–2000, toward the middle of the record. Both NDBC stations show an alternating-year seesaw pattern in storm counts, also reported in the study of HDC01.

b. *ECCS climatology*

Composite storm characteristics for each storm at each NDBC station were computed, and the level-by-level climatologies are summarized in Table 2. The minimum surface pressure and storm-duration values are similar for both stations. We note that the values of the storm duration were highly variable. Some of the differences between the climatologies at the two NDBC stations are consistent with the differences expected between conditions at a location 50 km offshore in relatively shallow water and at a location 400 km offshore in deep water. This pattern of differences is seen in the maximum-wind, wave-height, and dominant-wave-period fields, all of which are higher for all storm levels at NDBC station 44004, which is the deep-water buoy.

The average of the minimum storm surface pressure values for all ECCSs at NDBC station 44025 ranges between a minimum of 964.6 hPa and a maximum of 1005.7 hPa, with an average value of 994.30 hPa. The average maximum near-surface winds (at 5 m) recorded at this station are 14.14 m s^{-1}, with a maximum value of 22.5 m s^{-1} and a minimum value of 4.9 m s^{-1}. These values are similar to those computed for all the ECCSs recorded by NDBC station 44004 over the entire data record (1977–2007). At this station the average minimum surface pressure is 993.85 hPa, with a maximum of 1006.0 hPa and a minimum of 968.4 hPa. The average value of the maximum near-surface winds recorded at NDBC station 44004 is 15.77 m s^{-1}, with a maximum value of 27.7 m s^{-1} and a minimum value of 6.2 m s^{-1}. These values are in good agreement with the values for average minimum surface pressure (1004.0 hPa) and average maximum winds (16.35 m s^{-1}) reported by the study of HDC01. The precipitation at both New York

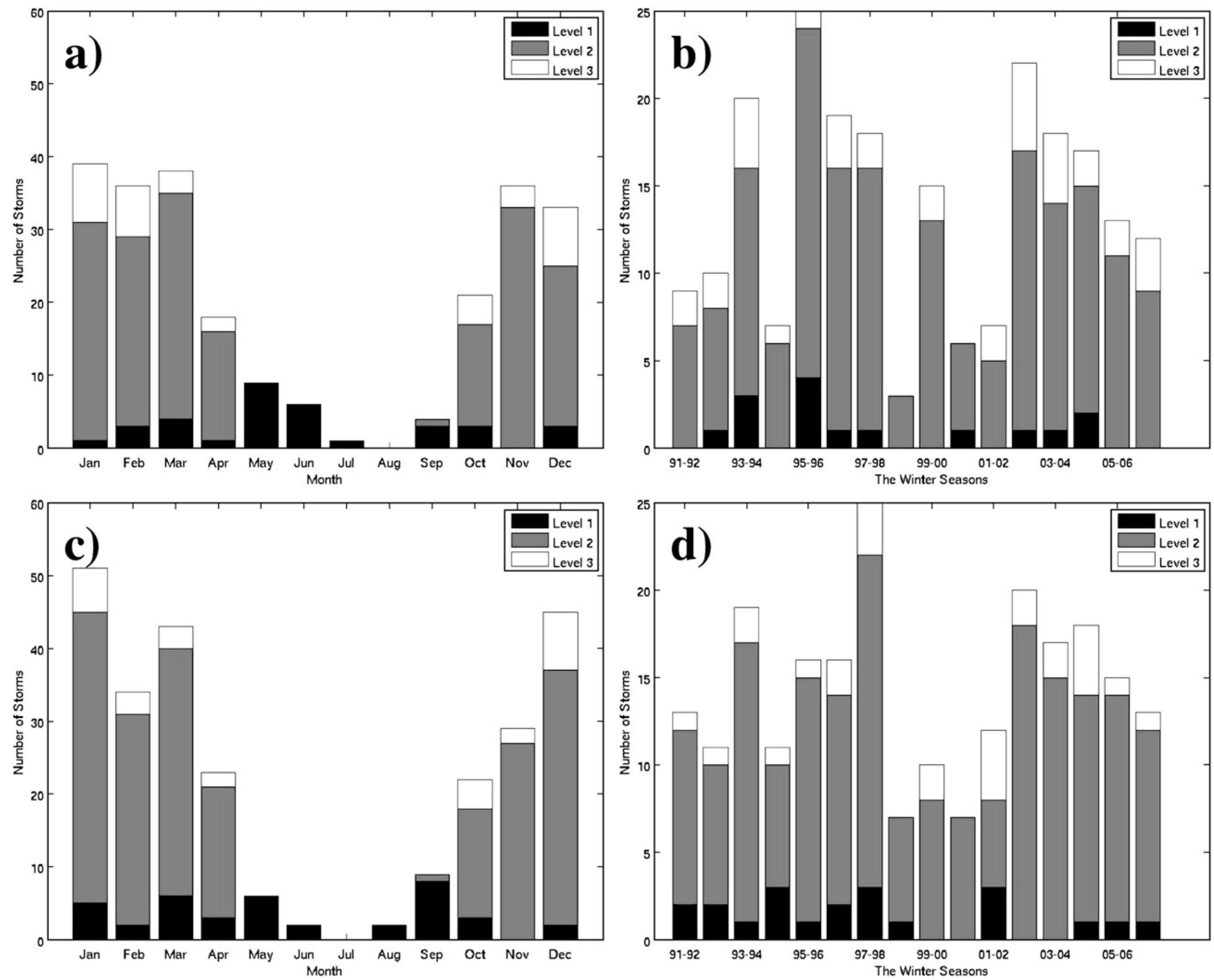

FIG. 4. (a) Monthly and (b) cool-weather-season storm counts for NDBC station 44025. (c),(d) As in (a) and (b), but for NDBC station 44004.

stations (Islip and Shirley) shows an increase in precipitation intensity with storm level and larger level-1 and level-2 composites for storms identified at NDBC station 44025 than for storms identified at NDBC station 44004. The strongest storm category, level 3, shows little difference between composites at the two NDBC stations.

The significant wave height and the dominant wave period are used to describe the wave field as measured at

TABLE 2. Mean ECCS storm-class characteristics. The Shirley precipitation data are for the period 2001–07.

Storm class	Min pressure (hPa)	Duration (h)	H_s (m)	Dominant wave period (s)	Max wind at 5 m (m s^{-1})	Precipitation (mm) Islip	Shirley
NDBC station 44004 (period 1977–2007)							
Level 1	999.20 ± 3.42	15	3.40 ± 1.20	9.14 ± 1.79	12.27 ± 2.89	2.25	0.75
Level 2	994.22 ± 5.07	18	3.95 ± 1.37	9.34 ± 1.46	15.67 ± 3.36	5.5	6.5
Level 3	987.97 ± 7.24	13	4.84 ± 1.68	9.49 ± 1.85	18.48 ± 6.63	12	12.5
Climatology	993.85 ± 5.86	17	4.02 ± 1.44	9.35 ± 1.54	15.77 ± 3.62	6	7
NDBC station 44025 (period 1991–2007)							
Level 1	998.61 ± 2.57	13	2.05 ± 0.58	7.54 ± 1.70	10.84 ± 3.38	—	1.25
Level 2	995.54 ± 4.53	17	2.43 ± 1.00	7.96 ± 1.64	13.80 ± 3.25	8.5	9.5
Level 3	986.37 ± 7.96	18	3.24 ± 1.01	8.24 ± 1.48	17.31 ± 2.42	12.75	17.75
Climatology	994.30 ± 6.20	17	2.53 ± 1.01	7.97 ± 1.62	14.14 ± 3.49	9	10.75

the two NDBC stations. Significant wave height is the average height of the highest one-third of the waves, and dominant wave period is the period with maximum energy, which is the peak period in seconds of the waves. The wave heights increase with storm strength at each buoy, ranging from a level-1 composite of 2.05 m to a level-3 composite of 3.24 m at NDBC station 44025 and ranging from a level-1 composite of 3.40 m to a level-3 composite of 4.84 m at NDBC station 44004. The ''all storm'' composite value at 44025 is 2.53 m, in contrast to a ''nonstorm'' composite of 1.26 m, and at 44004 the all-storm composite is 4.02 m in contrast to a nonstorm composite of 2.04 m. The dominant wave period is longer at 44004 than at 44025 but shows little difference at either NDBC station because of the storm strength.

c. *Local impacts of ECCSs*

To assess the local impact of the ECCSs we primarily use the time series of storm surge at The Battery and compare the correspondence between the surge and measurements from the local NDBC station's buoy (44025) with the correspondence between the surge and measurements from the more distant NDBC station's buoy (44004; see Fig. 1 for location of The Battery relative to the NDBC stations). Storm-surge composites for level-1, level-2, and level-3 storms as diagnosed at NDBC station 44025 are 0.27, 0.39, and 0.68 m. For storms at NDBC station 44004, the level-1 composite is 0.25 m, the level-2 composite is 0.41 m, and the level-3 composite is 0.47 m. The clear increase of maximum storm surge with storm level as measured at NDBC station 44025 for all three levels is in contrast to the small increase of maximum storm surge with the step from level-2 storms to level-3 storms as measured at NDBC station 44004. The level-3 surge composite at NDBC station 44025 exceeds the value of 0.6 m that, according to Colle et al. (2010), can result in minor flooding at The Battery for mean high-water (mean of all high tides) conditions.

A statistical assessment of the relative correspondence between the storm surge at The Battery and the storms as evaluated at NDBC stations 44025 and 44004 was performed. As part of this assessment we obtain a predictor of a metric of the storm surge: namely, its maximum value for a given storm. For a given cool-weather storm, this statistical approach may or may not provide a better prediction of storm maximum surge than that of a physically based model [see, e.g., Colle et al. (2007) and references cited therein], but its simplicity warrants its use for the purpose of our analysis. Using multiple-regression analysis, estimates for the maximum storm surge during a given storm were constructed based on combinations of the individual storm composites of various fields measured at the NDBC stations. The fields used as part of the regression were the minimum pressure, pressure tendency, wind speed, wind gustiness, wave height, and storm duration. The regression analysis at both NDBC stations demonstrated that the most significant predictor of the maximum storm surge for each storm is the storm-composite significant wave height. An F test on the sum of the squares of the error revealed that the surge estimated with wave height alone is statistically the same as the surge estimated using all of the predictors. The regression equations for the data from the buoys at NDBC stations 44025 and 44004 are $\mathrm{ESS}_{44025} = 0.2055H_{44025} - 0.0851$ with an RMS error of 0.167 m and $\mathrm{ESS}_{44004} = 0.0872H_{44004} + 0.0533$ with an RMS error of 0.22 m, where $\mathrm{ESS}_{\mathrm{xxxxx}}$ and H_{xxxxx} are the estimated maximum storm surge and the individual storm-composite significant wave height at the appropriate buoy, respectively. A polynomial relation between the significant wave height field and the surge did not improve this estimate. The estimate for the surge using wave heights at NDBC station 44004 as the predictor was compared with the estimate using wave heights measured at NDBC station 44025 using an F test, and the estimate using NDBC station 44025 data produces a smaller error with 95% confidence.

The assessment of the impact of ECCSs on coastal erosion was conducted using the quasi-monthly COAST institute measurements of volume loss/gain and movement of the shoreline. The intuitive expectation of a general correspondence between storm counts as determined at any of the buoys and beach erosion between beach-profile measurement times was difficult to establish from the available data. The relatively regular spacing between profile measurements (usually approximately 4 weeks and sometimes 3 months) makes it difficult to assess exactly when in the beach erosion/rebuilding cycle the storm took place and therefore difficult to assess how much erosion took place as a consequence of the storm. There were some beach erosion measurements that showed the expected correspondence between erosion and storm counts and showed a better correspondence when the storms were assessed using data from NDBC stations 44017 and 44025 than when they were assessed using data from NDBC station 44004. For example, during the beach-profile measurement performed between 23 August and 27 November 2006 at Tiana Beach (see Fig. 1 for location), there were 6 storms in total as assessed at NDBC station 44025, 5 storms in total as assessed at NDBC station 44017, and 2 storms assessed at NDBC station 44004. During this time, the beach lost approximately 28 m^3 of sand per meter of shoreline. At Shinnecock Beach during the same time period, the measurements showed erosion of 88 m^3 of sand per meter of shoreline.

There were some beach-profile measurements, however, that showed large erosion amounts during periods with very few storms. For example, for the time period between 2 September and 11 November 2004 there were 2 level-2 storms as assessed at all of the NDBC stations' buoys and a loss of 66 m^3 of material per meter of shoreline. There were also some time periods with higher storm counts and either little erosion or net beach rebuilding. An example of this is the 21 January 2005–24 February 2006 beach measurement period at Tiana, during which there were 9 storms as assessed at NDBC stations 44025 and 44004 and 5 storms as assessed at NDBC station 44017, and a loss of only 12 m^3 of sand per meter of shoreline. The difficulty in establishing clear trends in the available erosion data makes it impossible to use the data to assess the relative correspondence between NDBC station location and storm impact. Beach profiles measured before and after specific storm events are needed to establish the connections and potential predictive capacity for beach erosion due to ECCSs.

The discussion of the local impacts of ECCSs on storm surge at The Battery has demonstrated that the use of highly localized measurements (from NDBC station 44025) provides a better estimate of the highly localized surge. This result suggests that the wave-height field at NDBC station 44025 may serve as a predictor for the storm surge at The Battery. An assessment of the use of our regression relation in predicting storm surge would make use of a combination of fine-resolution meteorological forecasts (to identify storms using our technique), wave-height forecasts at NDBC station 44025, and our regression equation. This potential for prediction of the local impact of ECCSs on the surge based on our technique emphasizes the advantage of identifying storms and evaluating intensity with meteorological data that are independent of the impacts themselves.

4. Summary

A method for identifying and categorizing East Coast cool-weather storms based on measurements from National Data Buoy Center stations' buoys was developed in this study and used to assess storms at several buoys in the New York metropolitan region. The storm identification was based on the hourly surface pressure at the NDBC station, and the storms were characterized into three levels of intensity based on the pressure tendency, or the rate of deepening of the storm. Tropical storms were identified and removed from consideration in this study based on records from the National Hurricane Center.

Storm climatologies for each storm level were computed and are in general agreement with the established climatology of HDC01 for winter storms in this region. The study focused on a comparison among the composites for each storm intensity level at each of two buoys—one located nearshore, in relatively shallow waters, and the other located several hundred kilometers offshore, in relatively deep waters. The robustness of the method was established based on agreement with the existing climatologies, the physically consistent differences found between the climatologies at the two buoys, and the determination that the record length is statistically adequate.

The advantage of the local scope of the method presented here was demonstrated with an analysis of the impact of the storms on storm surge at The Battery on Manhattan Island in New York. A regression analysis determined that the storm-composite significant wave height is the best predictor of storm-composite surge. Furthermore, the significant wave height measured at the local NDBC station's buoy (44025) is a better predictor of surge at The Battery than is the significant wave height measured at the more distant NDBC station's buoy (44004). The advantage of using meteorological data to identify the storms and to independently assess a climatology of impacts lies in the potential for using the method presented in this study for storm-surge prediction based on meteorological forecasts.

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