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 have either used localized water level or beach erosion data to identify and characterize the storms, or 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 may affect the localized assessment of storm impact on the coastal communities.

A method that uses data from National Data Buoy Center (NDBC) stations in the New York metropolitan area to identify East Coast Cool-weather Storms (ECCSs) and characterize their climatology 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. Our 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. 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 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 storms 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 to The Battery. 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 (NY) and New Jersey (NJ). The eustatic sea level rise expected in the future climate (Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4) 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 U.S. East Coast cool-weather storms in a changing climate.

Studies that classify East Coast cool weather storms 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 years. 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 East Coast cool-weather storm counts in the period from 1885 to 1978 based on weather maps and ship logs. The analysis of East Coast cool-weather storms based on surface weather maps is advantageous because of the length of the available record. However, their construction can be highly subjective, 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-year 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 meteorology 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 characterize their frequency and duration. A more desirable methodology is one that identifies the storm independently of its impacts, as this would allow a prediction of the impact of a forecasted storm.

More recently, NCEP/NCAR reanalysis data (Kalnay et al. 1996) for the period 1948-97 were used by Hirsh et al. (2001) to identify East Coast cool-weather storms 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 reanalysis data is 2.5 by 2.5 degrees of 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 to that of Hirsh et al. (2001) to identify East Coast cool-weather storms and examined the relationship between those storms and the storm surge activity near Long Island, New York. 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 East Coast Cool-weather Storms (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, wind damage) using a focused regional approach. The present work 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 forecasted 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 [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 Figure 1. The buoys chosen are the 6-meter Navy Oceanographic Meteorological Automated Devices (NOMAD) buoy of NDBC Station 44004 located at 38.48N and 70.43W, in 3182 m deep water and with a data record from 1977-present, the 3-meter discus (circular hulled) buoy of NDBC Station 44025 located at 40.25N, 73.17W, in 36.3 m deep water and with a data record from 1991-present, and the 3-meter discus buoy of NDBC Station 44017 located at 40.69N, 72.05W in 46 m deep water with a data record from 2002-present. The focus of the presentation here will be on data from the first two buoys (NDBC Stations 44004 and 44025) due to 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 website provided above for detailed information). Measurements include wave height, period and direction, air, water and dew point temperatures, atmospheric pressure, wind speed, gusts and wind direction.

Multi-year 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 where the surface pressure was less than two standard deviations below the mean was considered a single event as long as the continuous string lasted longer than four hours and was separated from all other continuous groups of measurements by at least twenty four hours. A search algorithm for local minima and maxima in the surface pressure time series for each storm was applied to further refine 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 United States Daily Weather Maps Project website [Available online at 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 tropical cyclones that maintain their tropical character throughout their evolution, data from the National Hurricane Center [Available on line at http://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 Figure 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 less than one standard deviation below the mean pressure tendency, Level 2 storms have pressure tendencies between one standard deviation below the mean and one standard deviation above the mean, and Level 3 storms have pressure tendencies 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 5m winds, precipitation and significant wave heights (top third of wave heights). Precipitation data were obtained from the National Climate Data Center Global Surface Summary of Day Data [Available online at http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html] at stations in Shirley (725016), MacArthur Airport (725035) and Montauk (720068). See Figure 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 Sandy Hook (see Figure 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 for three beaches along eastern Long Island from the Stony Brook University, Coastal Ocean Action Strategies (COAST) Institute (see Figure 1).

Differences between consecutive profile measurements, which have an approximate four to six-week temporal resolution, 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 NDBC Station 44004, is only seventeen years 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 spanning 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 seventeen-year record at NDBC Station 44025 are adequate.

Due to 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 near-shore 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 East Coast cool-weather storms based on reanalysis data of Hirsch et al. (2001) (Hereafter HDC01). The local impacts of ECCSs on the region are discussed at the end of this section.

a. Storm Classification

To determine the thresholds for ECCS identification, the time series of the surface pressure shown in Figure 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 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 compared to our ECCS storm count. As discussed by HDC01, because Davis et al. (1993) include "anticyclonic storm types" (high-pressure systems) in their annual storm totals, comparison of storm count totals between their study and ours are difficult to assess.

The classification of ECCSs into Level 1, 2, and 3 storms based on the pressure tendency is summarized in Tables 1a, b. Columns 2 and 3 of Table 1a and 1b show the pressure tendency thresholds and storm counts for NDBC Stations 44025 and 44004, respectively. For reference, the mean ECCS pressure tendency for NDBC Station 44004 was 0.81 hPa/hour with a standard deviation of 0.49 hPa/hour and the mean pressure tendency for NDBC Station 44025 was 0.74 hPa/hour with a standard deviation of 0.43 hPa/hour. The table shows some differences in storm counts for each ECCS level between NDBC Station 44025 and NDBC Station 44004 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, compared to 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. Figure 3, panels a, b, d, e, g and h, shows analyzed sea-level pressure maps from Modern Era Retrospective analysis for Research and Applications (MERRA, Rienecker et al. 2008) of the NASA Goddard Global Modeling and Assimilation Office and panels c, f and i show surface pressure and temperature time series for individual storms representative of each storm level at NDBC Station 44025. Panels a, b and c correspond to the Level 1 storm of February 5 – 6, 1998, panels d, e and f correspond to the Level 2 storm of April 9 – 11, 1998 and panels g, h and i correspond to the Level 3 storm of March 13 – 15, 1993. For each case, the two sea-level pressure maps depict the location of the storm before arriving to 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 U.S. East coast.

The typical Level 1 storm exhibits the behavior shown in the analyzed sea-level pressure maps of figures 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 figures 3d and 3e have similar surface pressure values 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 figure 3d to its position shown in figure 3e. In contrast, the typical Level 3 storm (shown in figures 3g and 3h) has a track which originates in the Gulf or along the Southeast Coast 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 Figure 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 non-zero) 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 towards storms in late fall (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 further 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 is not enough data to determine this statistically.

The interannual distributions of storms occurring during October through April (cool-weather season) at both NDBC Stations are shown in Figures 4b and 4d and are relatively similar throughout the record. The exceptions to this are in the three year span 1997-2000, towards the middle of the record. Both NDBC Stations show an alternating year see-saw 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 Tables 2 a and b. 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 winds, 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 meters) recorded at this station is 14.14 m/s, with a maximum value of 22.5 m/s and a minimum value of 4.9 m/s. 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, with a maximum value of 27.7 m/s and a minimum value of 6.2 m/s. 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) reported by the study of HDC01. The precipitation at both stations (Islip and Shirley) shows an increase in precipitation intensity with storm level, and larger Level 1 and 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 the two NDBC Stations. Significant wave height is the average height of the highest 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 ‘non-storm’ composite of 1.26 meters, and at 44004 the ‘all storm’ composite is 4.02 m in contrast to a ‘non-storm’ composite of 2.04 m. The dominant wave period is longer at 44004 than at 44025, but shows little difference at either NDBC Station due to 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) to the correspondence between the surge and measurements from the more distant NDBC Station’s buoy (44004 - see Figure 1 for location of The Battery relative to the NDBC Stations). Storm surge composites for Level 1, 2, and 3 storms as diagnosed at NDBC Station 44025 are 0.27 m, 0.39 m, and 0.68 m. For storms at NDBC Station 44004, the Level 1 composite is 0.25 m, Level 2 is 0.41 m, and Level 3 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 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 which, according to Colle et al. (2008), 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, for example, 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 the predictors. The regression equations for the data from the buoys at NDBC Stations 44025 and 44004 are:

$ESS_{44025} = 0.2055 H_{44025} - 0.0851$ with an RMS error of 0.167 m

$$ESS_{44004} = 0.0872 H_{44004} + 0.0533 \qquad \text{with an RMS error of 0.22 m}$$

where ESS_{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 to 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, 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 Station 44017 and NDBC Station 44025 than when they were assessed using data from NDBC Station 44004. For example, during the beach profile measurement performed between 8/23/2006 and 11/27/2006 at Tiana Beach (see Figure 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 9/2/2004 and 11/11/2004 there were 2 Level 2 storms as assessed at all 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 1/21/2005 to 2/24/2006 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 which are independent of the impacts themselves.

4. Summary

A method for identifying and categorizing East Coast Cool-Weather Storms (ECCSs) 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 Hirsch et al. (2001) 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 near-shore, in relatively shallow waters, and the other located several hundred kilometers off-shore, 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, 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 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 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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References

Carter, D. J. T., and L. Draper, 1988: Has the north-east Atlantic become rougher? *Nature*, **332**, 494.

Colucci, S. J., 1976: Winter cyclone frequencies over the eastern United States and adjacent western Atlantic, 1964-1973. *Bull. Amer. Meteor. Soc.*, **57**, 548–553.

Colle, B. A., X. Rojowsky, and F. S. Buonaiuto, 2008: A composite analysis of the storm evolution and tracks associated with storm surge events for New York City. *Submitted*.

Colle, B. A., F. S. Buonaiuto, M. J. Bowman, R. E. Wilson, R. Hunter, A. Mintz, and D. Hill, 2007: New York City's vulnerability to coastal flooding. *Bull. Amer. Meteor. Soc.*, **89**(6), 829–841.

Davis, R. E., R. Dolan, and G. Demme, 1993: Synoptic climatology of Atlantic coast northeasters. *Int. J. Climatol.*, **13**, 171–189.

DeGaetano, A. T., 2008: Predictability of seasonal East Coast winter storm surge impacts with application to New York's Long Island. *Meteor. Appl.*, **2**, 231–242.

DeGaetano, A. T., M. E. Hirsch, and S. J. Colucci, 2002: Statistical prediction of seasonal East Coast winter storm frequency. *J. Climate*, **15**, 1101–1117.

Hayden, B. P., 1981: Secular variation in Atlantic Coast extratropical cyclones. *Mon. Wea. Rev.*, **109**, 159–167.

Hirsh, M. E., A. T. DeGaetano, and S. J. Colucci, 2001: An East Coast winter storm climatology. *J. Climate*, **14**, 882–899.

Intergovernmental Panel on Climate Change (IPCC), 2007: *Climate Change 2007. Fourth Assessment Report: The AR4 Synthesis Report*, Cambridge University Press.

Kalnay E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-Year reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Mather, J. R., H. Adams III, and G. A. Yoshioka, 1964: Coastal storms of the eastern United States. *J. Appl. Meteor.*, **3**, 693–706.

Miller, J.E., 1946: Cyclogenesis in the Atlantic Coastal region of the United States. *J. of Meteorology* **3**: 31–44.

Rienecker, M. M., M. J. Suarez, R. Todling, J. Bacmeister, L. Takacs, H.-C. Liu, W. Gu, M. S. Sienkiewicz, R. D. Koster, R. Gelaro, I. Stajner, and J. E. Nielsen, 2008: The

GEOS-5 Data Assimilation System – Documentation of Versions 5.0.1, 5.1.0, and 5.2.0. NASA Tech. Memo., 118 pp. [GEOS5–104606, Vol. 27]

Zhang, K., B. C. Douglas, and S. P. Leatherman, 2000: Twentieth-century storm activity along U.S. east coast. *J. Climate*, **13**, 1748–1761.

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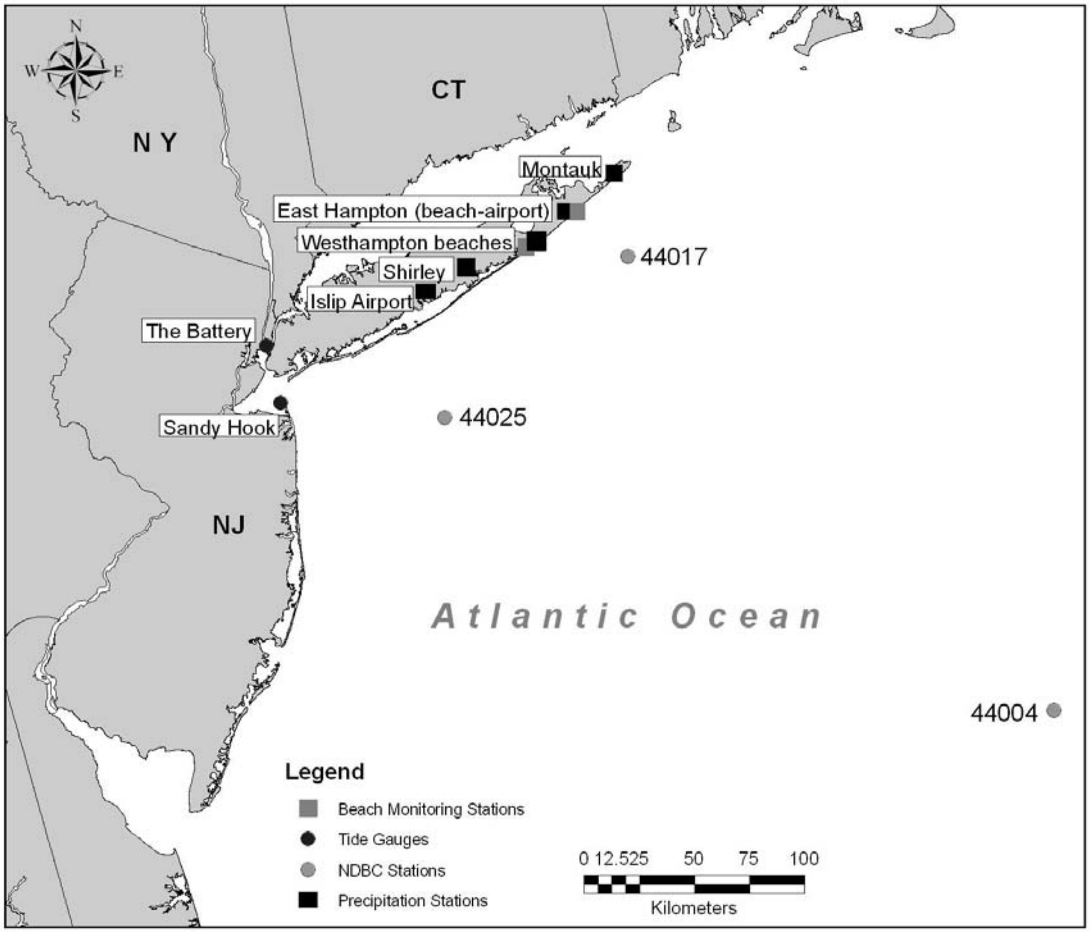
FIG. 1. Map of the study region. Markers indicate the locations of National Data Buoy Center Stations 44025, 44004 and 44017, the locations of precipitation measurements, beach profile measurements and NOAA water level gauges in New York Harbor. Westhampton beaches include Tiana Beach and Shinnecock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

FIG. 2. Time series of surface pressure anomaly in hPa at a) NDBC Station 44004, and b) NDBC Station 44025. The red portions of the curves identify the time periods when the surface pressure was more than two standards deviation from the mean.

FIG. 3. Left Panels: analyzed sea-level pressure from MERRA for typical storms of each level as identified at NDBC Station 44025, marked with an "X". Right Panels: surface pressure and temperature time series measured at the station. a, b and c) correspond to typical Level 1 storms; d, e, and f) to Level 2 storms; g, h, and i) to Level 3 storms.

FIG. 4. a, b) Monthly and cool-weather season storm counts for NDBC Station 44025 and c, d) same as a, b) for NDBC Station 44004.



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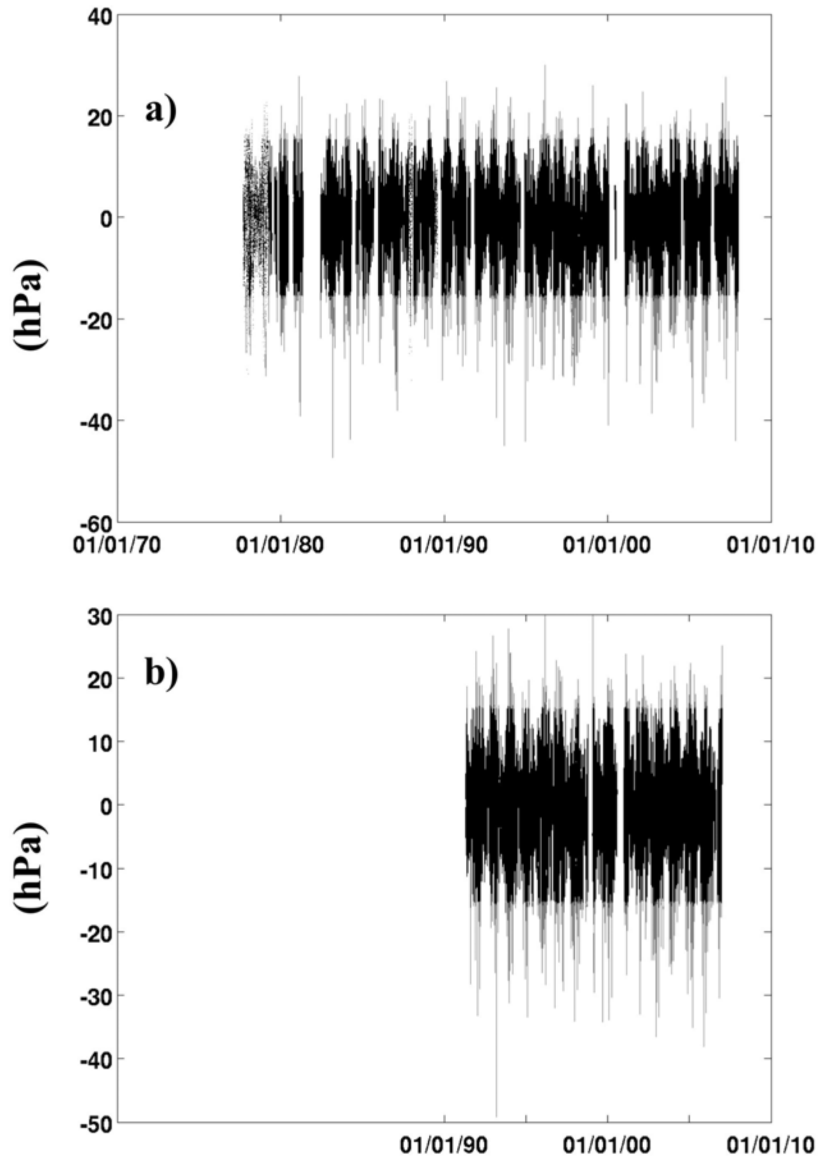

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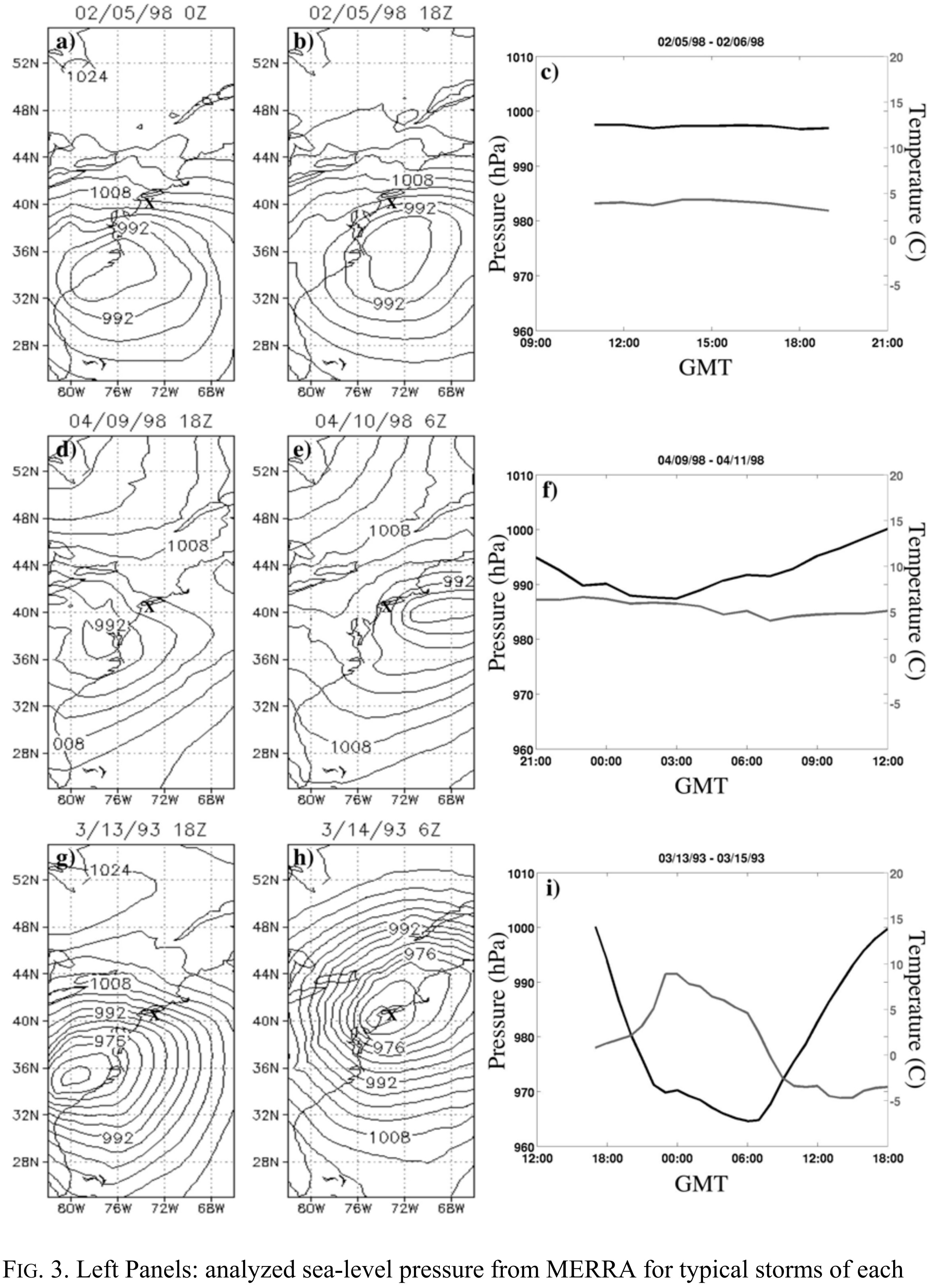

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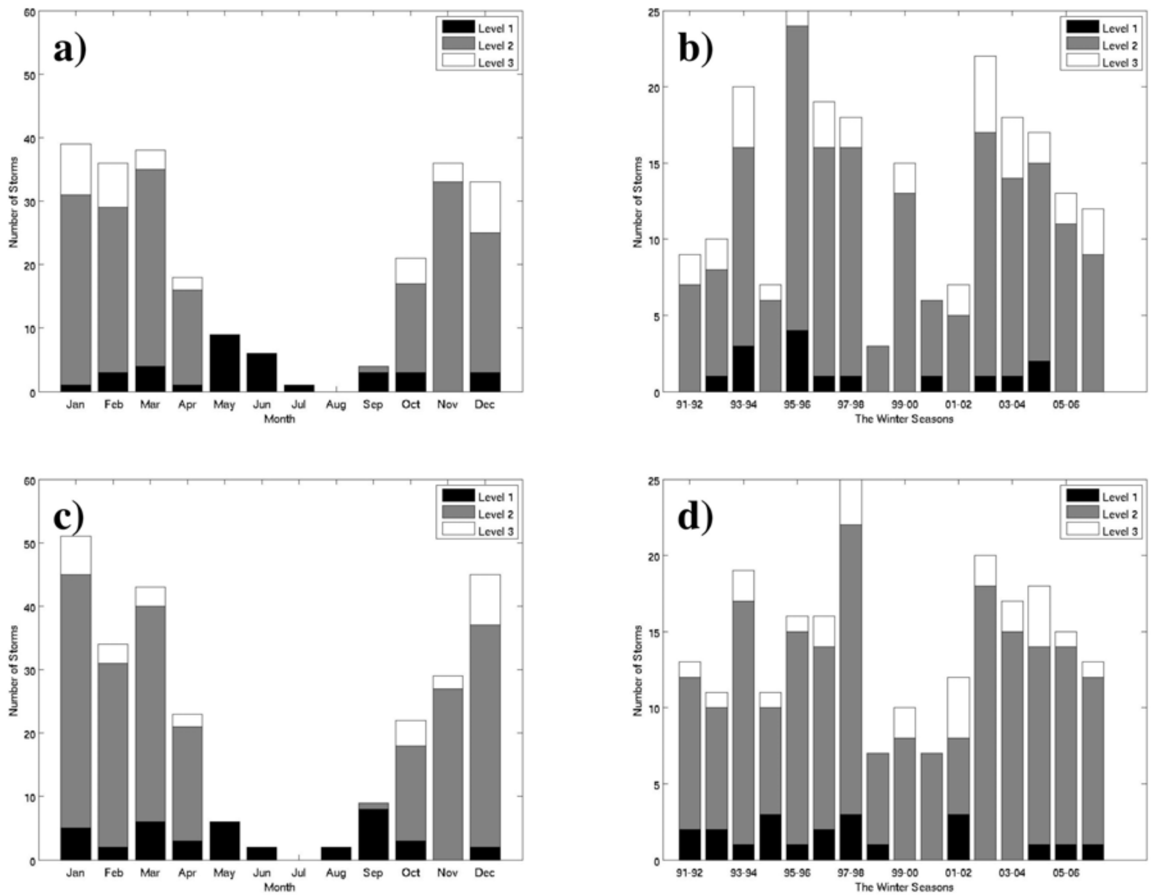

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TABLE 1. Intensity thresholds for each storm level. a) NDBC Station 44025; b) NDBC Station 44004

a)	**NDBC Station 44004**		
Storm Class	Pressure Tendency (PT) Criterion	Storm Count Period 1991-2007	Storm Count Period 1977-2007
Level 1	PT < 0.32 hPa/hr	20	31
Level 2	0.32 ≤ PT <1.30 hPa/hr	196	310
Level 3	PT ≥ 1.30 hPa/hr	27	48

b)	**NDBC Station 44025**	
Storm Class	Pressure Tendency (PT) Criterion	Storm Count Period 1991-2007
Level 1	PT < 0.30 hPa/hr	15
Level 2	0.30 ≤ PT < 1.17 hPa/hr	172
Level 3	PT ≥ 1.17 hPa/hr	35

TABLE 2. Storm Class Characteristics. * indicates that data are for the period 2001-2007

a)	**Mean ECCS Characteristics for NDBC Station 44004 – Period 1977-2007**						
Storm Class	Minimum Pressure (hPa)	Duration (hours)	Significant Wave Height; H_s (m)	Dominant wave period (sec)	Maximum Wind at 5 m (m/sec)	Precipitation (mm) IS	SH*
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
Clim.	993.85 ± 5.86	17	4.02 ± 1.44	9.35 ± 1.54	15.77 ± 3.62	6	7

b)	**Mean ECCS Characteristics for NDBC Station 44025 – Period 1991-2007**						
Storm Class	Minimum Pressure (hPa)	Duration (hours)	Significant Wave Height; H_s (m)	Dominant wave period (sec)	Maximum Wind at 5 m (m/sec)	Precipitation (mm) IS	SH*
Level 1	998.61 ± 2.57	13	2.05 ± 0.58	7.54 ±1.70	10.84 ± 3.38	no data	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
Clim.	994.30 ± 6.20	17	2.53 ± 1.01	7.97 ± 1.62	14.14 ± 3.49	9	10.75