New York City Storm Surges: Climatology and an Analysis of the Wind and Cyclone Evolution

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ABSTRACT

A climatological description (''climatology'') of storm surges and actual flooding (storm tide) events from 1959 to 2007 is presented for the New York City (NYC) harbor. The prevailing meteorological conditions associated with these surges are also highlighted. Two surge thresholds of 0.6–1.0 m and >1.0 m were used at the Battery, New York (south side of Manhattan in NYC), to identify minor and moderate events, respectively. The minor-surge threshold combined with a tide at or above mean high water (MHW) favors a coastal flood advisory for NYC, and the moderate surge above MHW leads to a coastal flood warning. The number of minor surges has decreased gradually during the last several decades at NYC while the number of minor (storm tide) flooding events has increased slightly given the gradual rise in sea level. There were no moderate flooding events at the Battery from 1997 to 2007, which is the quietest period during the last 50 yr. However, if sea level rises 12–50 cm during the next century, the number of moderate flooding events is likely to increase exponentially. Using cyclone tracking and compositing of the NCEP global reanalysis (before 1979) and regional reanalysis (after 1978) data, the mean synoptic evolution was obtained for the NYC surge events. There are a variety of storm tracks associated with minor surges, whereas moderate surges favor a cyclone tracking northward along the East Coast. The average surface winds at NYC veer from northwesterly at 48 h before the time of maximum surge to a persistent period of east-northeasterlies beginning about 24 h before the surge. There is a relatively large variance in wind directions and speeds around the time of maximum surge, thus suggesting the importance of other factors (fetch, storm duration and track, etc.).

1. Background and motivation

A large fraction of New York City (NYC) and coastal Long Island (LI), New York, is less than 5 m above mean sea level (MSL), making the region highly vulnerable to storm surge from both tropical storms and East Coast winter cyclones (northeasters). For example, during the December 1992 northeaster event, the water levels at the Battery on the southern tip of Manhattan in NYC (Fig. 1) peaked at ~2.5 m (8 ft) MSL (Colle et al. 2008; National Weather Service, Eastern Region 1994; U.S. Army Corps of Engineers 1995). The sea level overtopped the city's seawalls for only a few hours, but it was enough to flood the NYC subway and Port Authority Trans-Hudson (PATH) train systems at Hoboken, New Jersey, thus precipitating a shutdown of these transportation systems for several days.

The complex coastal geometry and bathymetry surrounding the NYC metropolitan region can enhance the water levels and create difficult coastal flood forecasts. Storm surge is enhanced in this region by the relatively shallow continental shelf and the southward bend in the coast from Long Island to New Jersey, which can funnel water toward the NYC harbor area when there are low-level easterly winds (Bowman et al. 2005). The coastal marsh and back-bay areas of the region, which are not represented in sophisticated storm-surge models (Westerink et al. 2008), can also lead to localized flooding.

As a result of these complexities determining storm surge, 85% of the coastal flood warnings issued by the National Weather Service (NWS) did not ''verify'' for

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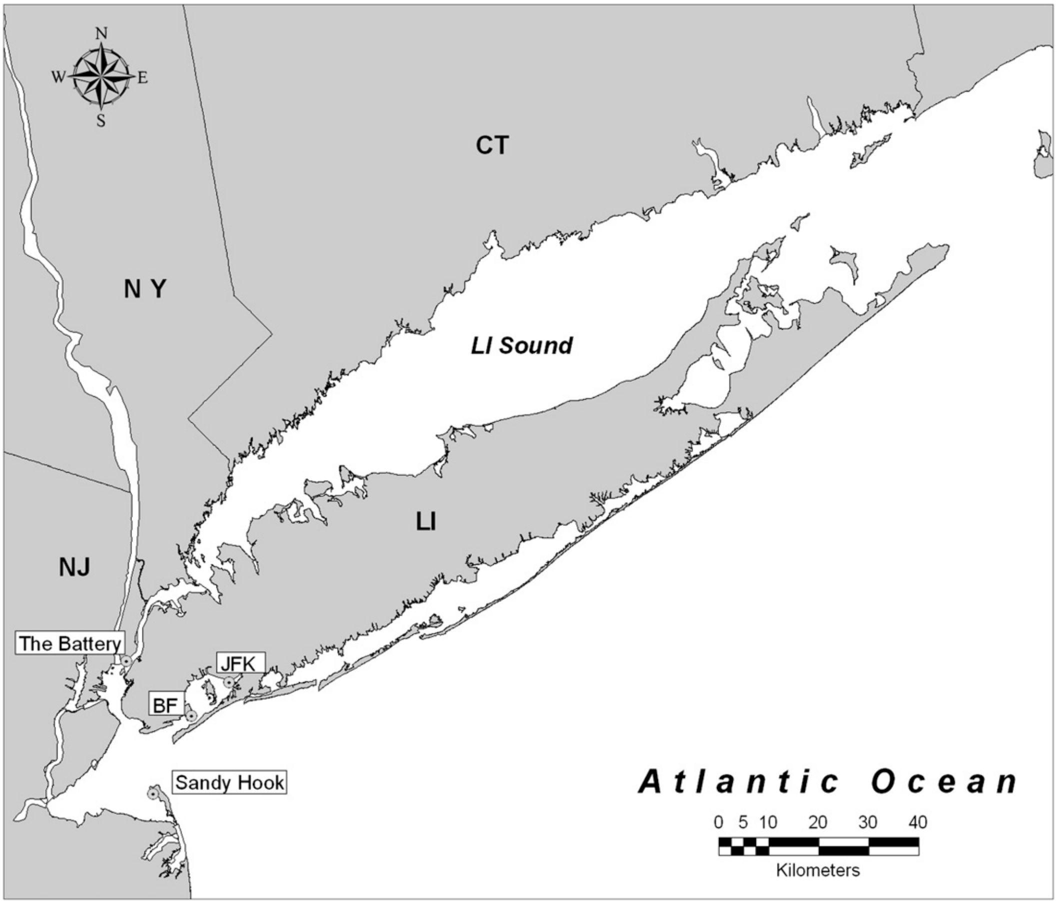

FIG. 1. The LI–NYC region of interest for this study. The Battery is the location of the storm-surge analysis, and the hourly surface winds were obtained at JFK and BF airports.

the NYC–LI area for 2001–06 (R. Watling, NWS Eastern Region Headquarters, 2007, personal communication). This is in comparison with ~50% of warnings that did not verify throughout the NWS Eastern Region (along East Coast and eastern Great Lakes) during this same period. The higher false-alarm rate for the NYC–LI area is attributed in part to the general lack of water-level observations and understanding about the movement of water and waves near the complex shoreline surrounding this area. As reviewed by Colle et al. (2008), there have been recent advances in ocean/surge modeling to help forecasters; however, there is still little understanding of the detailed meteorological evolution and climatological frequency of storm surges in the NYC–LI region, and it is a goal of this paper to improve that understanding.

Storm surge in the NYC–LI area can result from tropical storms and extratropical cycles. Hurricanes have directly hit NYC (Scileppi and Donnelly 2007), such as on 3 September 1821 (Ludlum 1963) and 25 August 1893 (National Hurricane Center 2008). The category-3 (~110 kt; 1 kt ≈ 0.5 m s^{-1}) winds during the 1821 event flooded a large portion of southern Manhattan (Ludlum 1963), but at that time the NYC population was only ~150 000. There have been no other direct hits by major hurricanes (greater than category 2) across NYC–LI since the 1938 "Long Island Express" (National Hurricane Center 2008). Hurricane Gloria (1985) was originally labeled as category 3 at landfall for Long Island but has since been reanalyzed as category 1 (C. Landsea 2008, personal communication). However, it is only a matter of time before another major hurricane will impact the NYC–LI area. The millions of people in this region and the billions of dollars at risk provide more motivation to understand the climatological behavior ("climatology") of storm surges in this area as well as the synoptic conditions that favor such events.

In contrast to tropical cyclones, in which storm-surge damage is generally confined to the coastal areas near landfall, East Coast winter storms (northeasters) can cause millions of dollars in damage over a larger region along the coast. For example, there was US$300 million in property damage and major coastal erosion along the mid-Atlantic coast during the March 1962 extratropical cyclone (Dolan 1987), and severe coastal erosion also occurred from Florida to New England during the 1993 March ''Superstorm'' (Kocin et al. 1995). As a result, intensity scales have been developed for the coastal impacts of East Coast winter storms (Dolan and Davis 1992; Zielinski 2002), in the same spirit as the 1–5 Saffir–Simpson scale used for hurricanes (Simpson 1974). For example, Dolan and Davis (1992) developed a 1–5 index based on storm ''power,'' which was defined as the storm's duration times the square of the maximum significant wave height.

The number of storm-surge events is likely related to track and frequency of cyclones near the coast. Numerous cool-season cyclone climatologies have been completed over the eastern United States and western Atlantic Ocean (Reitan 1974; Colucci 1976; Zishka and Smith 1980; Hayden 1981; Hirsch et al. 2001; Chan et al. 2003). For example, Hirsch et al. (2001) showed that there were ~12 East Coast winter storms annually from 1951 to 1997 on average, with a maximum during January. They also noted significant interannual variability, with periods ranging from 2.3 to 10.2 yr, and there are 44% more East Coast storms during El Niño years as compared with neutral or La Niña periods. Davis et al. (1993) highlighted that northeaster frequency decreased gradually from the 1950s to the late 1970s and then increased again through the mid-1980s. DeGaetano et al. (2002) showed that active East Coast winter-storm seasons tend to occur when there is above-normal temperature in the Gulf of Mexico during the previous storm season and during a positive phase of the North Atlantic Oscillation (and also El Niño). These studies have illustrated the climatological behavior of storm frequency, but there has been little work linking this variability to storm surges at particular locations. Zhang et al. (2000) used storm-surge data for several stations along the East Coast to highlight that there were no significant trends in the number and intensity of large surge events (greater than two standard deviations) over the last several decades, but the interdecadal variability was relatively large.

This paper focuses on the NYC area, given the large population and billions of dollars of infrastructure at risk. The first goal is to describe the frequency of minor-surge and moderate-surge events for NYC from 1959 to 2007. Second, since coastal flooding is also dependent on the phase of the tide, the frequency of coastal-flood events (surge plus tide) is also documented for NYC. Last, although it is fairly well known that many of these coastal-flooding events are likely attached to extratropical and tropical storms, the exact position, track, and strength of the cyclones as well as the associated wind direction and speeds favoring coastal flooding have not been quantified. Forecasters and emergency managers would benefit from a refined conceptual model of what local and regional atmospheric conditions favor flooding in the NYC area, and how the frequency of coastal flooding has changed over the past several decades. Overall, this study will address the following four motivational questions:

1) What is the interannual variability of minor- and moderate-storm-surge events for the NYC area during the last 50 yr? How does this compare with the actual number of flooding events given the storm tide (defined as the surge plus the tide)?
2) How is the number of flooding events affected by a slowly rising sea level over several decades?
3) How do the wind speed and direction evolve around NYC for weak-surge and moderate-surge events?
4) What are the cyclone positions and tracks that favor storm-surge events for the NYC area?

Section 2 describes the data and methods used in the analysis. Section 3 discusses the climatology as well as the wind and cyclone evolution associated with NYC storm-surge events. A summary and conclusions are presented in section 4.

2. Data and methods

According to the NWS, a coastal-flood advisory is often issued around the Battery when the water level reaches 2.04 m (6.7 feet) above mean lower-low water (MLLW) (J. Tongue, Upton/NYC NWS office, 2007, personal communication), and therefore we will refer to these as minor-surge events. The MLLW datum corresponds to the mean of all the lower of the low tides each cycle for the most recent epoch (the 19-yr period from 1983 to 2001; http://tidesonline.nos.noaa.gov/). Another reference is mean high water (MHW), which is the mean of all high tides during the same period. Because MHW is 1.44 m (4.73 ft) above MLLW at the Battery, a surge of 0.60 m (1.97 ft) above MHW is necessary to reach the coastal-flood-advisory criteria of the NWS at this location. A coastal-flood warning is issued by the NWS when the water level at the Battery exceeds 2.44 m (8.00 ft) above MLLW, which equates to a surge of ~1.0 m (~3.27 ft) above MHW. Because any particular storm-surge event can occur around a high tide, the surge thresholds for flooding are calculated relative to MHW in this paper. This provides an upper bound on the number of possible flooding events. Thus, thresholds of 0.6–1.0 m and >1.0 m are used to denote minor- and moderate-surge events, respectively.

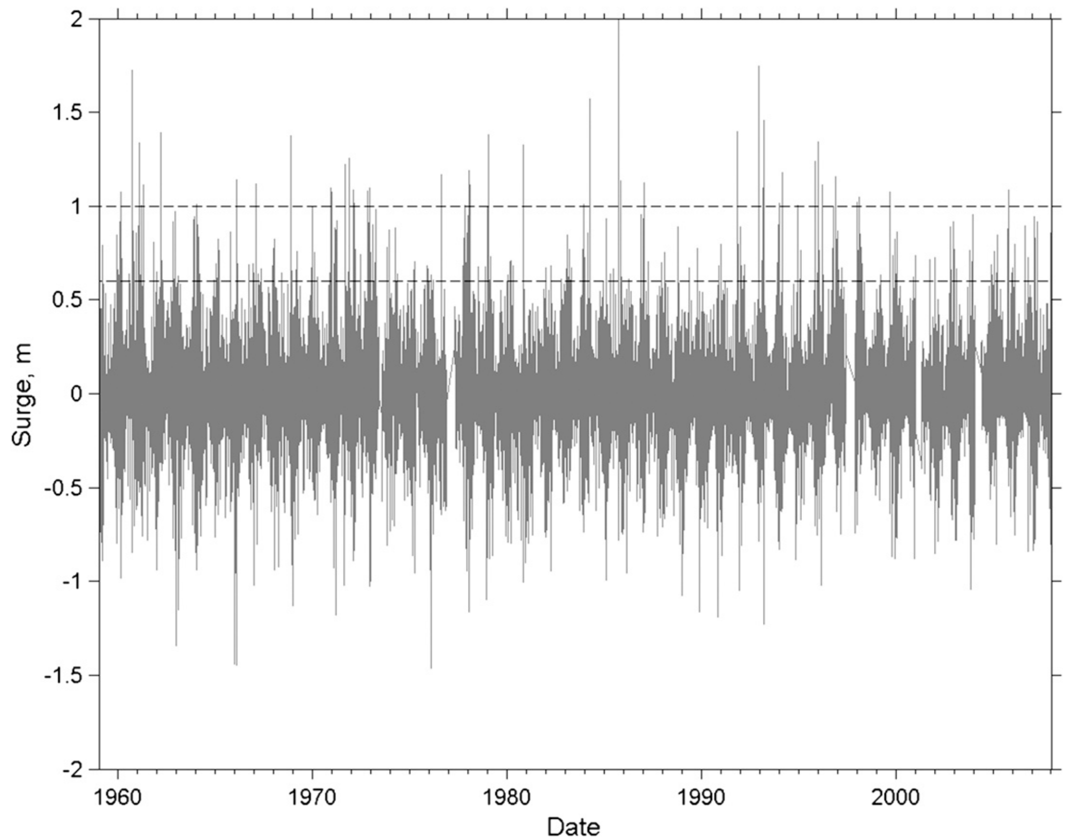

FIG. 2. Time series of the daily maximum positive surge (water level minus astronomical tide) at the Battery (see Fig. 1 for location) between 1959 and 2007. The two dashed lines represent the minor (0.6 m) and moderate (1.0 m) surge thresholds used in this study.

The difference between a minor- and moderate-surge event is only 0.4 m during MHW around NYC, and therefore forecasters also need to be aware of splash-over from wind waves that can locally enhance inundation flooding. For example, Cannon (2007) and Cannon et al. (2009) showed that 19% of storms did not meet the benchmark flooding threshold at Portland, Maine, yet flooding still occurred as a result of wave splash-over. It is fortunate that in the lower-Manhattan area the large ocean waves break before entering the NYC harbor. Thus, there is limited swell entering the harbor, and there is limited fetch for local wave generation at the Battery for easterly or northeasterly winds with an approaching coastal storm. Other areas around the NYC harbor (south and west side) as well as the open-ocean coastal areas of New York and New Jersey may have larger waves.

Verified hourly water-level observations at the Battery from 1959 to 2007 were obtained from the National Oceanic and Atmospheric Administration (NOAA; http://tidesandcurrents.noaa.gov/). To obtain the maximum daily surge, first the surge was calculated at each hour in the dataset by subtracting the NOAA-predicted astronomical tide. Second, because the NOAA tide data were based on the 1983–2001 epoch, the surge time series was detrended (subtract mean or best-fit line from the data) to extract the influence of local sea level rise on the tides. NOAA estimates a sea level rise at the Battery station of $\sim$2.77 mm yr^{-1}, which is close to our derived trend over nearly 50 yr ($\sim$2.85 mm yr^{-1}). Last, to remove the other long-period fluctuations, the average surge at each hour of the year from 1959 to 2007 was removed. For example, the average surge for all of the 0100 UTC 1 January times from 1959 to 2007 was obtained and was then subtracted from the surge for the same day and time of each individual year. To obtain the minor (0.6–1.0 m) and moderate (>1.0 m) events, first the daily maximum surge and its time of occurrence were obtained for each 0000–0000 UTC period for each day (Fig. 2). If a maximum daily surge exceeded the specified threshold (e.g., 0.6 m) for two straight days, only the largest of the two surge events was chosen if the two surges occurred within 24 h of each other. If a surge event was already counted as a moderate event during the 24-h period, it was not counted as a minor-surge event.

The minor and moderate surges do not represent the actual coastal-flood events at the Battery, because many surges occurred during a tide below MHW. As noted above, minor (coastal-flood advisory) or moderate (coastal-flood warning) flooding is favored around the Battery when the storm tide (surge plus tide) exceeds 2.04 and 2.44 m above MLLW (using the 1983–2001 epoch), respectively. Using these thresholds and the NOAA hourly water-level data at the Battery (based on the same epoch), the climatology of minor- and moderate-storm-tide-flooding events was also obtained for the Battery using the same 24-h procedure as for the storm-surge events above. The number of minor and moderate events was determined before and after adding a sea level rise correction obtained by detrending the Battery surge data.

The hourly surface observations from the National Climatic Data Center for John F. Kennedy airport (JFK) from 1973 to 2007 were used to investigate the 10-m-wind evolution associated with the Battery surge events, and additional observations from 1968 to 1970 were obtained from nearby (within ~5 km) Bennett Field airport (BF in Fig. 1). Before 1968, no observations were taken at night at BF; thus, the analysis is limited to the available data from 1968 to 2007. These two stations were used since they are relatively close to the Battery (Fig. 1) and they have a much longer record than offshore buoy data. A statistical wind direction and speed analysis at JFK/BF was constructed using the 226 minor-surge (0.6–1.0 m) and 46 moderate-surge (>1.0 m) events (Table 1). The storm surges at the Battery were also separated into tropical-storm events using the National Hurricane Center (NHC) best-track data (Jarvinen et al. 1984). This resulted in 17 tropical-storm events from 1959 to 2007 (Table 2).

To determine the cyclone positions and tracks associated with the surge events, the associated cyclones since 1979 were identified and tracked manually using sea level pressure data from the North American Regional Reanalysis (NARR), which is available every 3 h at 32-km grid spacing (Mesinger et al. 2006). Before 1979, the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research reanalysis at 2° resolution was used every 6 h (Kalnay et al. 1996). The closest 3- or 6-h reanalysis time to the time of maximum surge was used in the track analysis. The relevant cyclone at the time of maximum surge was identified as the closest cyclone that had at least one closed 2-hPa isobar of sea level pressure and a minimum pressure of 1012 hPa. The cyclone positions were saved on a 1.0° × 1.0° latitude–longitude grid. The pressure minimum associated with the cyclones was tracked manually every 6 h using the reanalysis sea level pressure data from 48 h before the time of maximum surge at the Battery to 24 h after the maximum surge. Because of the large number of minor-surge events (244), the minor threshold was increased from 0.6 to 0.8 m to focus on the more significant events (64) and to make it more feasible to manually track a fewer number of cases. The cyclone tracks for these relatively minor events will be

TABLE 1. List of the dates (time is UTC) and amount of surge for the 46 moderate-surge (>1.0 m above MHW) events or the NYC area from 1959 to 2007.

Date	Surge (m)
0600 19 Feb 1960	1.08
0600 26 Feb 1960	1.03
1800 12 Sep 1960	1.73
1000 4 Feb 1961	1.33
0600 9 Mar 1961	1.01
1400 13 Apr 1961	1.11
1900 6 Mar 1962	1.39
1600 13 Jan 1964	1.01
1600 23 Jan 1966	1.14
1400 30 Jan 1966	1.13
2100 27 Jan 1967	1.12
1500 12 Nov 1968	1.37
1000 17 Dec 1970	1.10
1000 28 Aug 1971	1.22
1100 25 Nov 1971	1.25
0500 4 Feb 1972	1.08
2100 19 Feb 1972	1.01
2200 8 Nov 1972	1.08
0100 16 Dec 1972	1.10
0400 10 Aug 1976	1.17
0300 8 Nov 1977	1.01
1700 20 Jan 1978	1.19
0000 7 Feb 1978	1.11
0200 25 Jan 1979	1.38
1800 25 Oct 1980	1.33
1800 4 Dec 1983	1.01
1400 29 Mar 1984	1.57
1700 27 Sep 1985	2.00
1000 5 Nov 1985	1.13
0100 23 Jan 1987	1.12
0900 31 Oct 1991	1.40
1700 11 Dec 1992	1.75
0100 5 Mar 1993	1.09
2200 13 Mar 1993	1.46
1500 4 Jan 1994	1.01
1000 3 Mar 1994	1.18
0900 24 Dec 1994	1.01
0000 15 Nov 1995	1.24
0600 8 Jan 1996	1.35
0300 20 Mar 1996	1.11
1900 19 Oct 1996	1.01
1200 6 Dec 1996	1.16
0400 30 Dec 1997	1.02
1500 5 Feb 1998	1.05
2300 16 Sep 1999	1.07
1300 25 Oct 2005	1.12

TABLE 2. List of the 17 tropical-storm dates (time is UTC) and surges for the NYC area from 1959 to 2007.

Date	Surge (m)
1400 30 Jul 1960	0.64
1800 12 Sep 1960	1.73
1700 22 Oct 1961	0.73
0600 23 Oct 1961	0.64
1000 29 Aug 1971	1.21
1600 22 Jun 1972	0.74
0400 10 Aug 1976	1.17
1900 14 Oct 1977	0.83
1700 27 Sep 1985	2.00
0900 31 Oct 1991	1.40
1600 13 Jul 1996	0.61
0200 9 Oct 1996	0.78
2300 16 Sep 1999	1.07
0900 19 Sep 2003	0.62
1300 25 Oct 2005	1.09
0200 26 Oct 2005	0.65
0000 3 Sep 2006	0.89

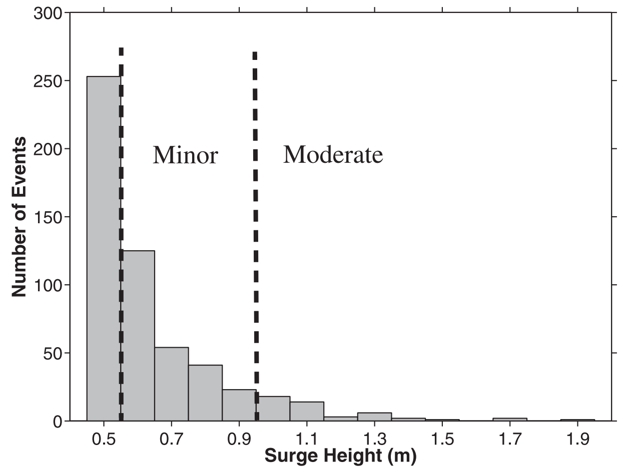

FIG. 3. The number of storm surges every 0.1 m, starting at 0.5 m, at the Battery from 1959 to 2007. The minor- and moderate-surge events are identified as those surge heights 0.6–1.0 m and >1.0 m, respectively.

compared with the >1.0-m-surge events. The 17 tropical-cyclone tracks since 1959 were obtained using the best-track data at NHC. A composite evolution of upper-level geopotential heights and sea level pressure for the moderate-surge events was also created using the Earth System Research Laboratory Internet site (http://www.cdc.noaa.gov/Composites/Hour).

3. Results

a. Climatology of NYC storm surges

Figure 2 shows a time series of the maximum daily storm surge at the Battery from 1959 to 2007.[1] The largest surge in the dataset is Hurricane Gloria (~2.0-m surge), which fortunately made landfall over central LI near a low tide on 28 September 1985. Hurricane Donna on 12 September 1960 also had a relatively high surge (1.73 m), as did the 11 December 1992 northeaster (1.75 m) highlighted in Colle et al. (2008). The number of events decreases exponentially from 253 cases for a 0.5–0.6-m daily surge to only 4 events for a >1.5-m surge (Fig. 3).

There is large interannual variability of negative and positive surges (Fig. 2), with several large-surge events (±1 m) occurring each decade on average. However, the most recent several years (2000–07) have been relatively quiet for storm surge, with only one surge event >1.0 m. To illustrate this interannual variability more clearly, the annual number of surge events from 0.6 to 1.0 m (minor events) and >1.0 m (moderate events) is shown for the years from 1959 to 2007 (Fig. 4). The number of minor-surge events ranges from 0 in 1981 to 14 in 1983 (Fig. 4a). During 1959–73, at least four minor-surge events occurred annually, but afterward these minor-surge events tended to become less frequent, with a noticeable reduction from 1984 to 1991. This trend is qualitatively similar to the relatively active period in East Coast winter storms during the 1960s as compared with the late 1970s and early 1980s (Davis et al. 1993). Overall, the 5-yr running mean of minor surges has decreased from around seven events per year in the early 1960s to around five events in the early 2000s.

There is also some qualitative relationship between the number of minor surges at the Battery and strong El Niño–Southern Oscillation (ENSO) events. Three of the four largest annual numbers of minor-surge events occurred during relatively strong El Niño periods. For example, during the large 1982/83 El Niño (see online at http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml), there were 14 surge events in 1983, especially early in the year (not shown). There were also relatively large numbers of minor surges during the 1972/73 and 1997/98 strong El Niño years. In contrast, there were relatively few minor-surge events during the strong La Niña periods of 1973/74, 1975/76, and 1988/89. There are too few years/events to develop a statistical correlation with moderate–strong ENSO (little or no correlation exists between surge and the more frequent minor-ENSO events). Storm surge at NYC may be more

[1] The Battery data were missing for four 1–3-month periods: from late 1976 to early 1977, late 1996, late 2000, and late 2003. These missing periods are relatively short and do not affect the results.

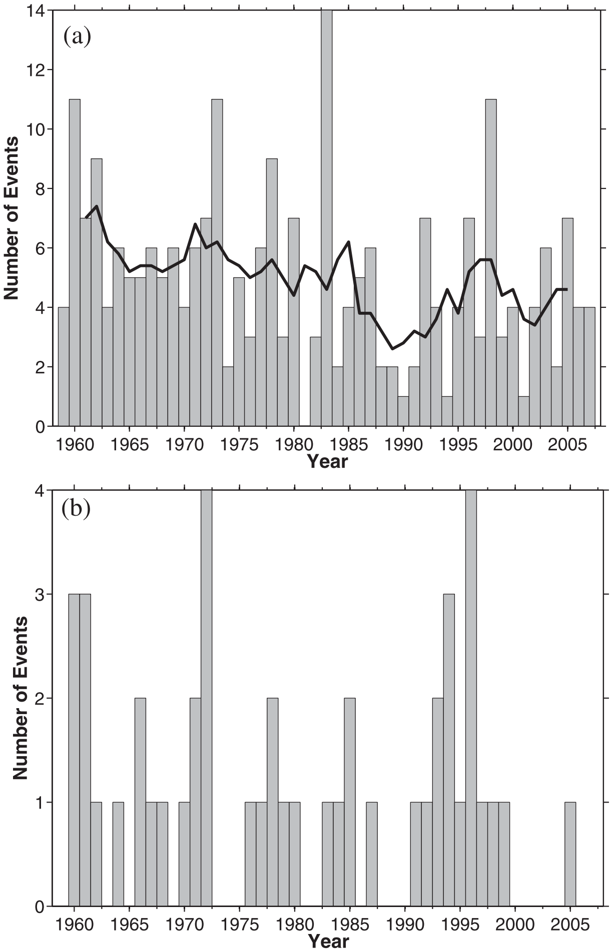

FIG. 4. The annual number of storm-surge events at the Battery (a) between 0.6 and 1.0 m above MHW and (b) greater than 1.0 m above MHW from 1959 to 2007. The solid line in (a) represents a 5-yr running mean of surge.

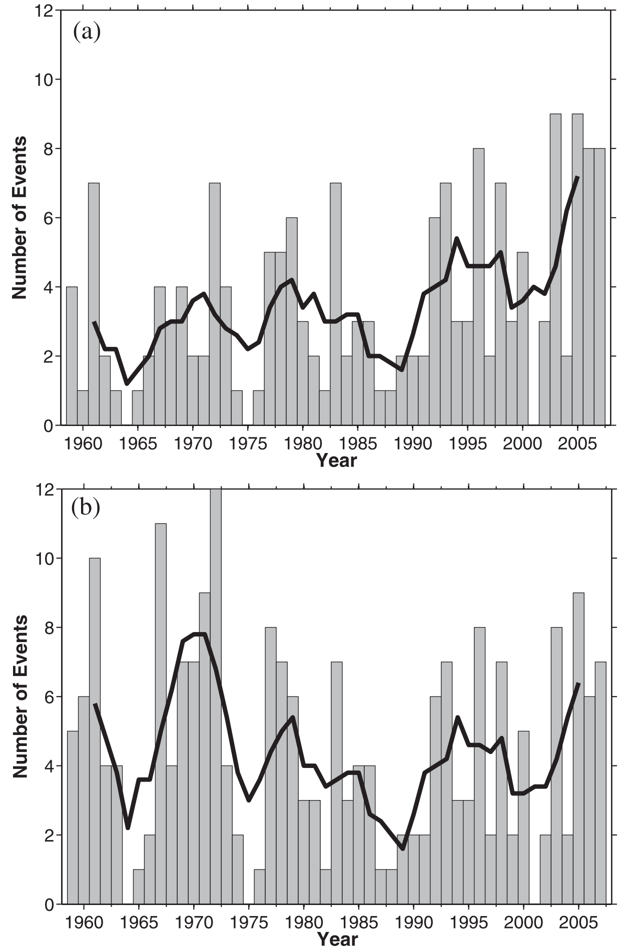

FIG. 5. The annual number of observed (storm tide) minor flooding events at the Battery (a) before and (b) after correcting for rising sea level from 1959 to 2007. The solid line is the 5-yr running mean. A minor flood (coastal flood advisory) occurs when the total water level exceeds 2.04 m above MLLW.

favored during El Niño, since northeasters occur slightly more often along the East Coast during El Niño events than during La Niña (Hirsch et al. 2001).

The moderate-surge events also have large interannual variability (Fig. 4b). There were a relatively large number of moderate surge events during the 1960s–early 1970s as well as during the early 1990s. Many of the relatively large El Niño events (e.g., 1982/83 and 1997/98) were not associated with anomalously large numbers of moderate surges. There were 15 moderate-surge events during the 1990s, but there was only 1 event during the period from 2000 to 2007. This recent decrease in surge activity from 2000 to 2007 at the Battery suggests a change in the number, intensity, or track of the East Coast cyclones as compared with the early–mid-1990s.

The storm tide (surge plus tide) was used to determine the annual number of actual minor-flood and moderate-flood events (days) at the Battery from 1959 to 2007 without removing sea level rise (Figs. 5a, 6). The number of minor-flood events increased later in the period (after the early 1990s). In contrast, it was shown above that the number of minor surges decreased in recent decades (Fig. 4a); thus, it was hypothesized that the increase in minor-flooding events is the result of a gradual increase in sea level. A sea level rise of ~2.8 mm yr^{-1} at the Battery results in a 0.10–0.15-m-higher water level in the early 2000s than in the early 1960s. Removing the sea level rise decreases the annual number of minor-flood events during the1990s–2000s by 1–2 and increases the minor events during the 1960s by 1–4 (Fig. 5b). As a result, removing sea level rise eliminates the increasing trend in minor-flood events. A relatively small change in water level (~0.1 m) can change the number of minor events noticeably, since there are many events each year near the threshold of a minor surge (Fig. 2).

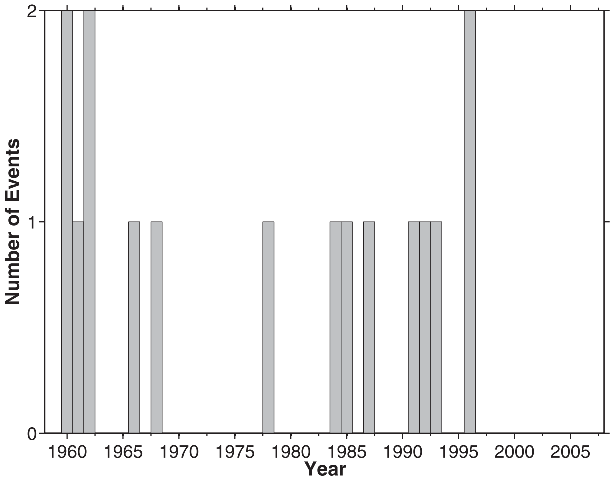

FIG. 6. As in Fig. 5a, but for the moderate flood events. A moderate flood (coastal flood warning) occurs when the water level exceeds 2.44 m above MLLW.

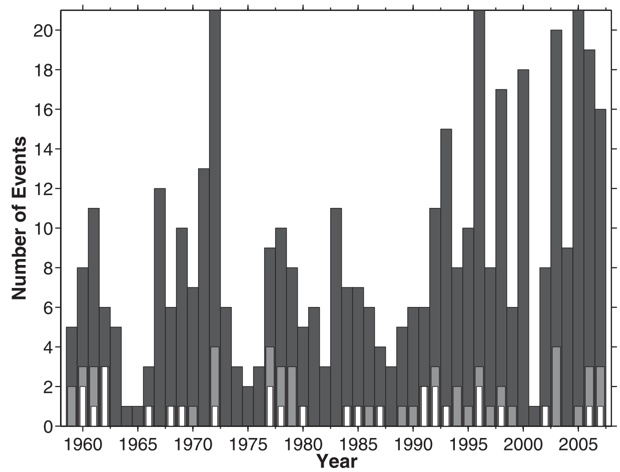

FIG. 7. The number of moderate flooding events each year at the Battery for the 1959–2007 period after adding a sea level rise of 12.5 cm (white bars), 25 cm (gray bars), and 50 cm (black bars).

There were a few clusters of moderate-flood events during the 1960s and mid-1980s–early 1990s (Fig. 6). Of interest is that there were no moderate-flood events from 1997 to 2007. This is the longest period in the nearly 50-yr record without a coastal-flood event. Future work will need to determine whether this is from some change in cyclone activity and intensity along the coast. The sea level rise correction had no impact on the distribution of moderate-flood events (not shown). This is consistent with the results of Zhang et al. (2000), who showed no increase in the number of major-surge events during the past several decades at several other sites along the East Coast. There is less impact by a ~0.1-m sea level rise for the moderate events, since a large surge (>1.0 m) is required for significant flooding to occur.

The Intergovernmental Panel on Climate Change (Parry et al. 2007) estimated that sea level will increase between 0.18 and 0.59 m during the next century. This will likely increase the number of moderate-flooding events for NYC. To illustrate this growing problem, sea level rises of 12.5, 25, and 50 cm were added to the observed water levels from 1959 to 2007 (Fig. 7). Looking at the 1997–2007 period as reference, during which there were no moderate-flood events in the current record (Fig. 6), this incremental rise in sea level increases the number of moderate-flooding events exponentially to 4, 16, and 136 events, respectively. This illustrates that NYC will become much more vulnerable to storm surge as sea level continues to rise.

Figure 8 shows the monthly frequency of minor- and major-surge events at the Battery from 1959 to 2007, with the tropical-cyclone events in dark gray. Storm surges occur primarily during the cool season (October–March) as a result of extratropical cyclones. For the minor events (Fig. 8a), the number of surge events increases rapidly from 3 in September to 19 in October as the extratropical storm track develops. The number of minor-surge events more than doubles from 21 in November to 52 in December and then decreases slightly to 47 in January. The relatively large number in December occurs a month before the climatological peak for northeasters along the East Coast that occurs in January (Hirsch et al. 2001). The lack of a well-defined January surge maximum may be the result of the storm track shifting slightly south (away) from NYC as the winter progresses. The number of minor-surge events rapidly decreases from 39 in March to 19 in April as the number of cyclones decreases.

For the moderate-surge events (Fig. 8b), there are several events from August (two) to September (three) associated with landfalling tropical storms (Table 2). As a result, there is a more steady increase in all moderate-surge numbers from August to October than for all of the minor surges. The number of moderate surges further increases from October (four) to December (seven) as the northeaster frequency increases. The peak number of moderate events occurs in January (nine), and then there is a rapid decrease from March (seven) to April (one). There are no moderate surges between May and July, since northeasters are relatively weak and there are few hurricanes this early in the warm season.

b. *Surface wind evolution associated with surge events*

Figure 9 shows the average hourly evolution (and 1 standard deviation) of the surface (10 m) wind direction and speed at JFK/BF for the minor and moderate surges

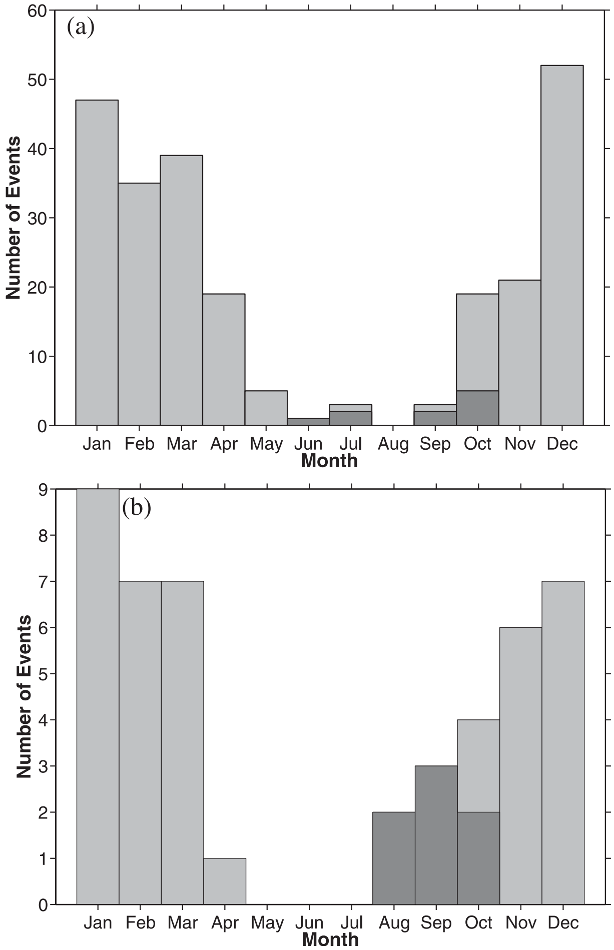

FIG. 8. The number of storm-surge events per month at the Battery from 1959 to 2007 for a surge of (a) 0.6–1.0 m and (b) greater than 1.0 m. The tropical-cyclone events are dark shaded.

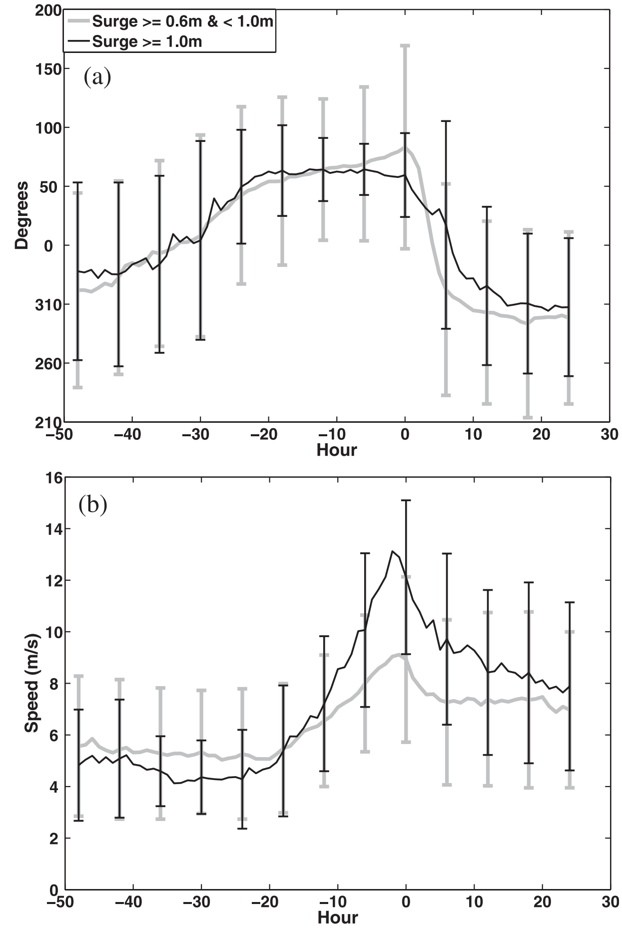

FIG. 9. Average (a) wind direction (°) and (b) wind speed (m s^{-1}) at 10 m for JFK and BF for the minor-surge (gray line) and moderate-surge (black line) events at the Battery. The line denoting ±one standard deviation is given by the vertical bar every few hours.

at the Battery. At 48 h before the time of maximum surge (−48 h), the average wind direction is northwesterly (Fig. 9a). From −36 to −24 h, the average wind veers from northerly to northeasterly (50°–70°). This wind direction persists until the time of maximum surge. The wind then rapidly backs to northwesterly 6 and 12 h after the time of maximum surge for the minor and moderate events, respectively. The relatively large standard deviation in the wind directions (20°–60° variation around mean) suggests that a NYC storm surge can occur for a fairly broad spectrum of wind directions around the mean. The wind direction variance is about one-half as large for the moderate events for the 12-h period before maximum surge, suggesting a more well-defined wind evolution for these events.

The average wind speeds are relatively weak (<6 m s^{-1}) 24–48 h before the time of maximum surge (Fig. 9b), with slightly (1–2 m s^{-1}) stronger mean wind evolution for the minor events (significant at the 95% level with Student's *t* test). The minor and moderate composite winds increase rapidly around 20 h before the time of maximum surge and reach their peak approximately 2 h before maximum surge. The average peak wind speed for the moderate events (13 m s^{-1}) is ~44% greater than the minor events (9 m s^{-1}), which is significant at the 99% level using a Student's *t* test. The standard deviation for the minor (±2 m s^{-1}) and moderate (±3 m s^{-1}) events around the time of maximum surge is relatively large, which suggests that there are a large number of events with greater and weaker winds around the mean. The average wind speed then rapidly decreases, such that it is similar to the minor events (~6.0 m s^{-1}) at ~20 h after maximum surge.

In summary, as expected, the moderate events have a larger wind speed on average than the minor events, but there is a large variance; thus, the local wind speed may not be a useful predictor for the magnitude of the surge event. A northeast wind favors a positive surge at the Battery, since the surface wind stress pulls water toward the New York Bight (near Sandy Hook, New Jersey, in Fig. 1). This elevated water setup over the bight forces the surge northward into the New York harbor (Colle et al. 2008). Furthermore, a northeast wind favors a setup of higher water to the right of the wind (northwest to the coast) through Ekman transport. Of interest is that the average peak wind speed occurs 2 h before the time of peak surge at the Battery. A further investigation of individual cases also revealed stronger winds a few hours before peak surge for several cases, which suggests that it can take 1–2 h for the high water to make it into the NYC harbor (Battery) area after the peak wind.

The surface wind distribution for the surge events at the Battery is shown more explicitly using wind rose plots for JFK at −24, −12, and 0 h relative to the time of maximum surge (Fig. 10). At 48 h before the time of maximum surge for the minor events (not shown), there is a large fraction ranging from northerly (13%), to northeasterly (12%), to west-southwesterly (8%). Nearly all winds are less than 12 m s^{-1} at this time. The wind direction and speed variability is similar at −48 h for the moderate events (not shown).

At 24 h before the minor-surge events (Fig. 10a), over 85% of the wind directions are from northerly to northeasterly, with a maximum in the northeasterly direction (~16%). Nearly one-half of the wind speeds are less than 6 m s^{-1} at this time. The moderate events also have relatively light winds at this time (Fig. 10b), but the winds are oriented more often in the east-northeasterly direction (~26%). By −12 h (Figs. 10c,d), nearly 60% of the winds are from north-northeasterly to east-northeasterly for the minor surges, and this percentage increases to ~80% for the moderate-surge events. Also, approximately 20% of the winds in moderate surges are greater than 9 m s^{-1}, and this decreases to ~15% for the minor surges.

At the time of maximum surge (Figs. 10e,f), ~90% of the wind directions for the moderate events range from northerly to easterly, with a clear peak from northeasterly to east-northeasterly. Nearly 70% of the wind speeds are greater than 12 m s^{-1} for the moderate surges. In contrast, nearly 40% of the winds associated with the minor surges are outside the northerly–easterly quadrant, with a large fraction (30%) in the east-southeasterly–southerly directions. Also, only a relatively small fraction (<10%) have wind speeds greater than 12 m s^{-1} for the minor surges in the northeasterly–easterly directions.

By +12 h (not shown), the winds rotate rapidly to more westerly for the minor and moderate surges, with most directions ranging from west-southwesterly to northerly. These offshore directions are less favorable for storm surge along the coast, thus explaining the rapid decrease in positive surge.

c. Cyclone tracks and composites

The developing northeasterly winds occurring with the onset of a surge event are suggestive of an approaching cyclone along the East Coast (northeaster). The cyclone positions were manually tracked backward 48 h and forward 24 h every 6 h from the time of maximum surge using the reanalysis sea level pressure data and methods described in section 2. The surges of 0.8–1.0 m (64 events) and >1.0 m (46 events) were used in the analysis from 1959 to 2007. A slightly higher threshold of 0.8 m was used instead of 0.6 m for the minor-surge tracks, because this made the effort of manual cyclone tracking more manageable. A separate analysis at the time of maximum surge was completed for the 0.6–1.0-m events, in which all cyclone positions at this time were marked for a region from 32°N, 86°W to 50°N, 62°W.

For the 64 minor surges (Fig. 11a), many cyclones originate over the southeastern United States at −48 h and then track northeastward both inland and offshore of the mid-Atlantic coast by the time of maximum surge. Afterward, they continue northeastward over the northeastern United States and Atlantic by 24 h after maximum surge. There is a large amount of scatter in these tracks, with a cluster of tracks along the coast and a few others originating near the Great Lakes region. Overall, a large number of these surge tracks do not represent the "classic" northeaster that tracks northeastward from the southeastern U.S. coast to the northeastern U.S. coast,[2] representing a "Miller type A" track (Miller 1946; Kocin and Uccellini 1990). Rather, there are a number of inland tracks that are more similar to a "Miller type B" track (Miller 1946).

For the stronger (>1.0 m) surge events (Fig. 11b), the cyclone tracks are clustered more along the coast than the minor-surge events. There are several exceptions, but the tracks for the stronger events suggest more cyclones developing along the Gulf of Mexico Coast or Southeast Coast and then moving north-northeast toward the southern tip of New Jersey. This is more representative of a Miller type-A northeaster storm track.

Figure 12 shows the number of surface cyclones at each point on a 1° latitude–longitude grid at the time of peak surge at the Battery for events with surges of 0.6–1.0 and >1.0 m. During the peak of a minor surge (Fig. 12a), the cluster of cyclones is located around New Jersey, where there is a peak of nine occurrences, and a surrounding region of at least three occurrences within 200–300 km of New Jersey. However, there are many NYC surge

[2] About 13 of these tracks are tropical-storm events. The tropical cases will be plotted separately in Fig. 15.

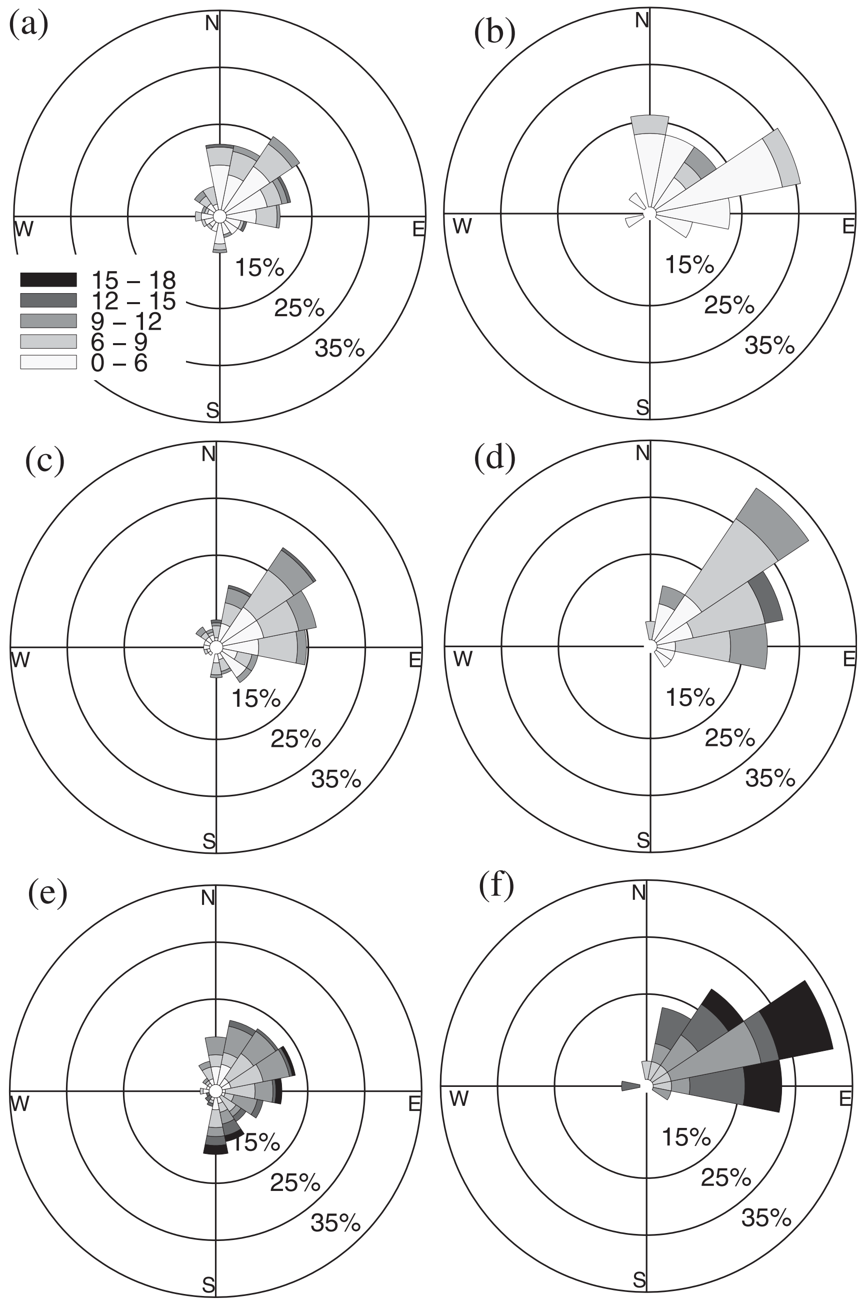

FIG. 10. Surface wind-rose plots at JFK/BF showing the frequency of wind direction and speed (shaded; m s^{-1}) at 24 h before the time of maximum surge at the Battery for the (a) minor- and (b) moderate-surge events. (c),(d) As in (a) and (b), but for 12 h before the time of maximum surge. (e),(f) As in (a) and (b), but for the time of maximum surge.

events with a cyclone position that is located either well offshore or over the Great Lakes, which suggests that a nearby developing cyclone is not a necessary prerequisite for a minor-surge event. In fact, 14 minor-surge events did not even have a cyclone in this plotted region and could not be included in this analysis. Of these noncyclone events, 10 events were associated with surface high pressure over New England and generally lower pressure to the south (not shown), which still favors easterlies across the NYC region (not shown).

All moderate surges were associated with a cyclone event within ~1000 km of NYC (Fig. 12b). The maximum frequency in cyclone position (nine occurrences) is situated just offshore (east) of Delaware. Overall, there

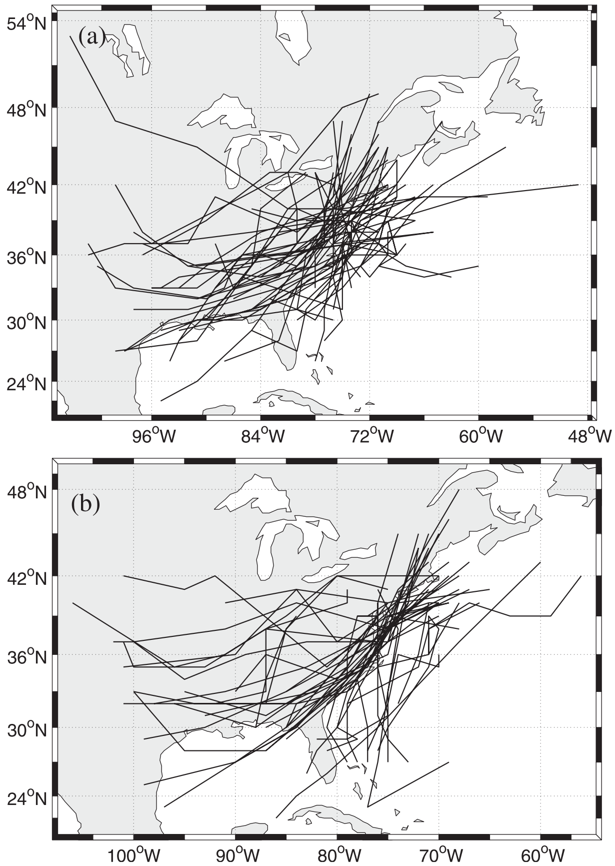

FIG. 11. (a) Cyclone tracks from 48 h before the time of maximum minor surge (0.8–1.0 m) at the Battery to 24 h after maximum surge, every 6 h. (b) As in (a), but for the moderate-surge (>1.0 m) events. The NYC area is denoted by the white box.

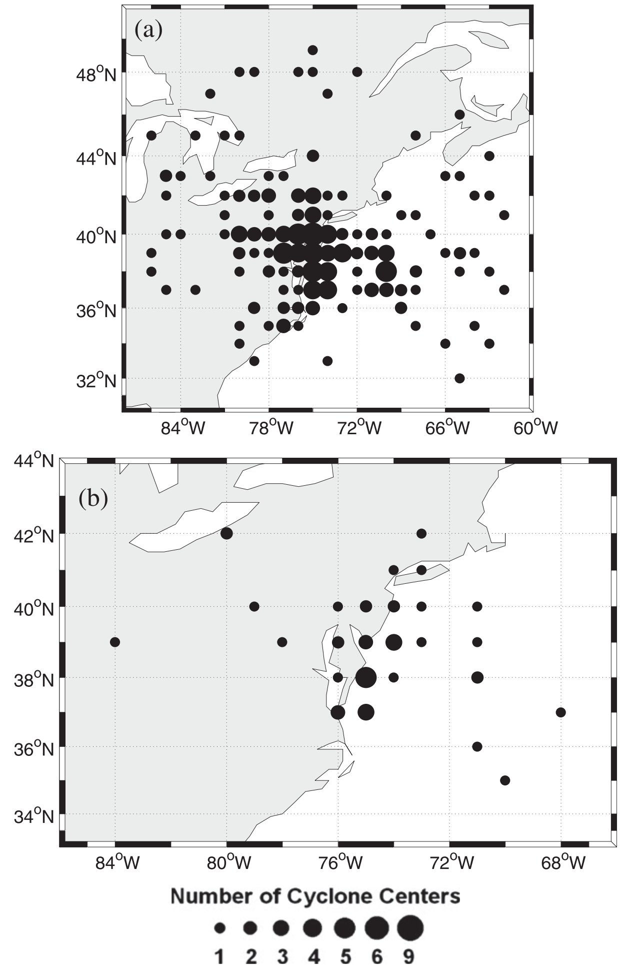

FIG. 12. (a) Surface cyclone position at the time of maximum surge for the surge events between 0.6 and 1.0 m. The number of cyclones every 1.0° of latitude and longitude is given by the filled-circle sizes in the bottom key. (b) As in (a), but for the moderate-surge (>1.0 m) events.

is a fairly large displacement between the location of most cyclones and the NYC surge, thus emphasizing that the surge impacts can occur relatively far from the cyclone center, especially in comparison with most hurricanes. The variance in storm positions indicates that other factors such as the duration and intensity of the storm and the radius of strong winds are likely important, rather than just the proximity of the low center.

A composite of the moderate-surge (>1.0 m) events at the Battery using the NCEP reanalysis and NARR (see section 2 for details) highlights the synoptic evolution at the surface and at 500 hPa. At 48 h before the time of maximum surge (−48 h), a short-wave trough at 500 hPa is located over the central United States (Fig. 13a). During the next day (−24 h), this trough amplifies and is situated near the Mississippi River Valley (Fig. 13b). The 500-hPa trough further amplifies and becomes negatively tilted by hour 0 (Fig. 13c), with the center of circulation over West Virginia. The trough weakens and lifts northeastward over northern New England by hour 24 (Fig. 13d).

At the surface at −36 h (Fig. 14a), an inverted trough extends northward from the Gulf Coast to the Midwest. Meanwhile, surface high pressure is located over southeastern Quebec, Canada. By −24 h (Fig. 14b), cyclogenesis over the Southeast results in a surface cyclone of 1012 hPa near Georgia and the Florida Panhandle while surface high pressure (1024 hPa) is entrenched over northern New England. As a result, the north–south surface pressure gradient increases along the mid-Atlantic Coast. The cyclone intensifies to 1004 hPa and moves northward to the coast of North Carolina by −12 h (Fig. 14c), and the pressure gradient continues to increase over the NYC area. The orientation of the isobars would seem to favor strong easterly surface winds; however, the winds are slightly more east-northeasterly in the JFK time series (cf. Fig. 10d), since there is likely some cold-air

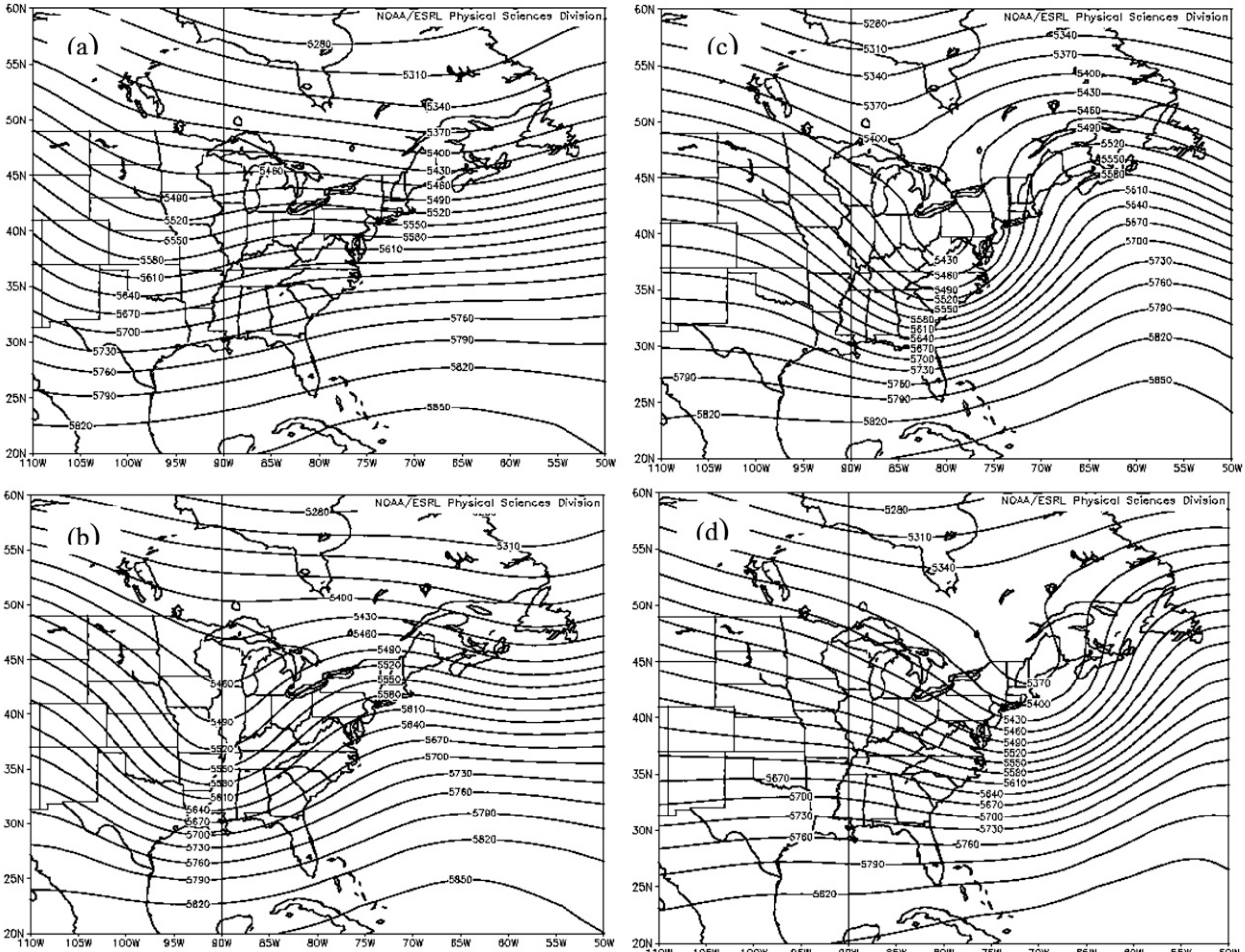

FIG. 13. Composite of 500-hPa geopotential heights (solid every 60 m) for the moderate-storm-surge events (>1.0 m) at (a) −48, (b) −24, (c) 0, and (d) +24 h relative to the time of maximum surge.

channeling (damming) along the east side of the New England terrain (Bell and Bosart 1988). At the time of maximum surge (Fig. 14d), the cyclone deepens to 996 hPa and is located just south of the coast of New Jersey. The cyclone weakens slowly to 998 hPa over Cape Cod, Massachusetts, by 12 h (Fig. 14e) and then to 999 hPa over southern Nova Scotia, Canada, by 24 h (Fig. 14f).

The above composite simply denotes an average of all cyclone events, but, as the storm tracks illustrate, there is a fairly large variance in the tracks approaching the NYC area (Fig. 11). Furthermore, there are only five hurricanes in the above composite, and if this sample were larger the composite would likely show a composite track just offshore the coast. For example, there were 17 tropical events from 1959 to 2007 that yielded minor-to-moderate surges (Table 2). Figure 15 shows the tracks of tropical minor- and moderate-surge events. Most of these events originate over the northern Caribbean Sea or Gulf of Mexico at 48 h before the time of maximum surge at the Battery. Nearly 60% of these cyclones move northward along the East Coast and pass within ~200 km of NYC. However, there are a relatively large number of other cases that have tracks farther away from NYC, thus again illustrating the diverse set of cyclone tracks that yield a potentially problematic storm surge around NYC.

4. Summary and conclusions

The goal of this paper is to understand the climatological frequency of storm-surge and coastal-flooding events at NYC from 1959 to 2007 as well as the local surface winds and cyclone tracks during these events. Two surge thresholds of 0.6–1.0 and 1.0 m were used to denote minor- and moderate-flooding events (maximum surge over 24 h) at the Battery (south side of Manhattan in NYC), respectively. The minor- and moderate-surge thresholds combined with a tide above mean high water are associated with a coastal-flood advisory and warning,

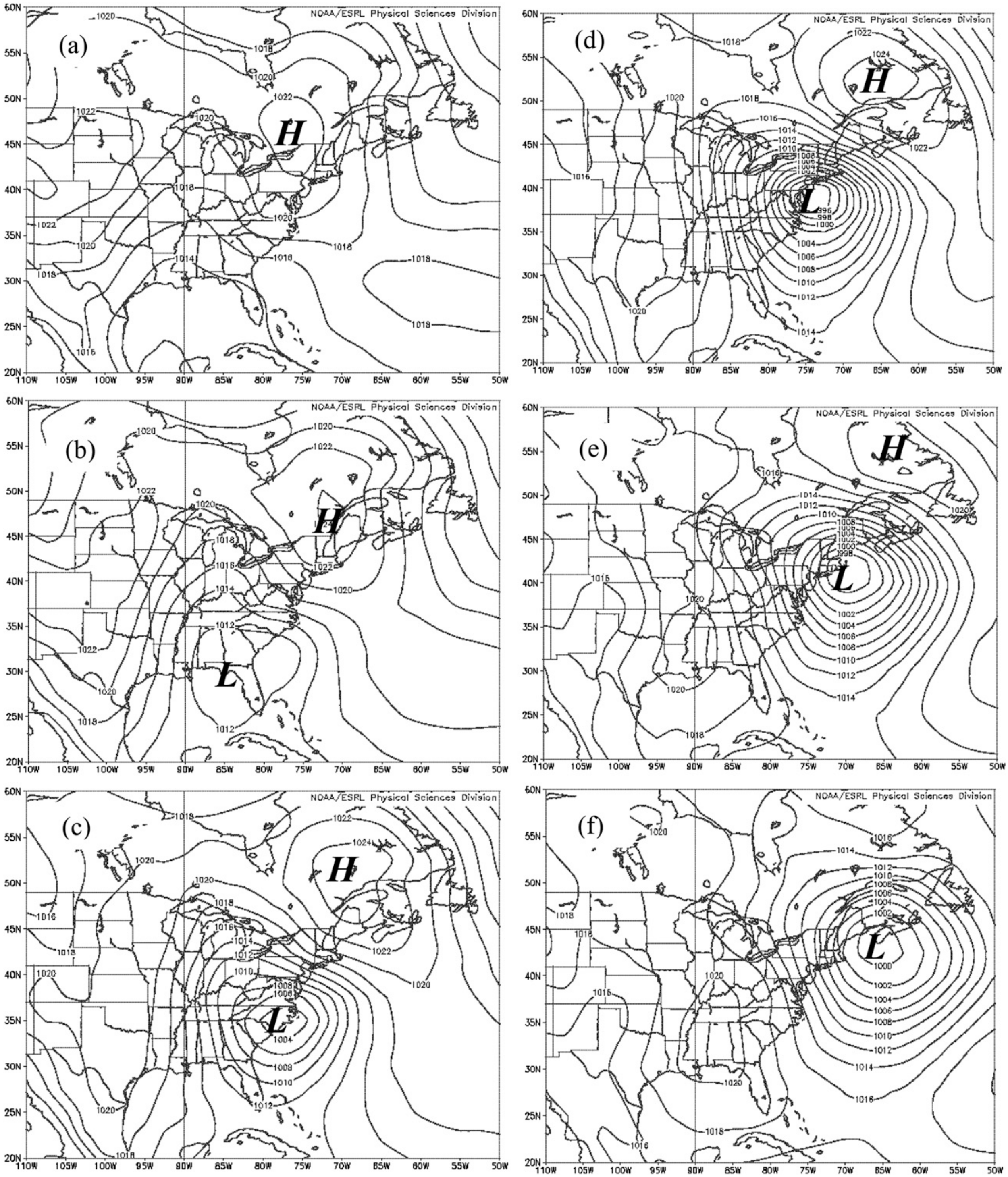

FIG. 14. Composite of sea level pressure (solid contours; every 2 hPa) for the moderate-storm-surge events (>1.0 m) at (a) −36, (b) −24, (c) −12, (d) 0, (e) +12, and (f) +24 h relative to the time of maximum surge.

respectively. There were 244 minor and 46 moderate daily surges from 1959 to 2007, which, combined with the observed tide (storm tide), yielded 174 minor- and 16 moderate-flooding events.

The number of minor- and moderate-surge events varies dramatically each year, ranging from 14 to 0 minor events. The number of minor-surge events has decreased gradually from a relatively active period during the 1960s

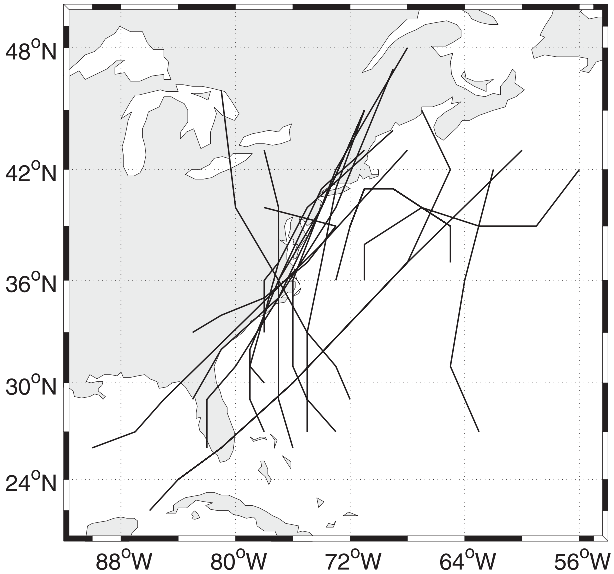

FIG. 15. Tropical-cyclone tracks for 1959–2007 from 48 h before the time of maximum minor surge (0.6–1.0 m) at the Battery to 12 h after maximum surge, every 6 h.

to noticeably fewer events in the late 1980s and 2000–07. Some of this variation matches qualitatively the variation in cyclone frequency determined by previous studies, and three of the top four minor-surge years were associated with years with strong El Niño, whereas the years with strongest La Niña tended to have fewer surges than did other years. There has been only one moderate-surge event during the period from 2000 to 2007, but since this event occurred during a relatively low tide there were no actual moderate-flooding (storm tide) events during this period. The 1997–2007 period is the quietest moderate-surge period in the ~50-yr dataset, which suggests that the cyclone intensities and/or tracks may be different than they were 10–20 yr ago.

The number of minor-flood (storm tide) events has been steadily increasing since 1990 even though the number of minor-surge events has been decreasing. This apparent paradox can be explained by the fact that sea level has been rising by about 2.8 mm yr^{-1} on average at the Battery during the past 50 yr. After removing this sea level rise from the Battery water levels, the number of minor-flood events no longer increases over the decades. Thus, sea level rise over the last few decades may already be enhancing the number of nuisance flooding (coastal-flood advisory) events around NYC. The sea level rise has not increased the number of moderate-flooding (coastal-flood warning) events in the last several decades. Parry et al. (2007) estimates that the global average sea level will likely rise by 0.18–0.59 m during the next century. If one increases sea level at the Battery by 13, 25, and 50 cm, the number of moderate-flooding events during the 1997–2007 period increases to 4, 16, and 136 events, respectively. This illustrates that NYC will be increasingly more vulnerable to storm surge as sea level continues to rise, thus suggesting the need to take more immediate action to protect the city from more frequent and larger flooding events.

The tracking of many individual cyclone events suggests that minor flooding occurs for a diverse set of storm tracks around the East Coast, whereas moderate coastal floods are more associated with a cyclone track northward along the coast. This variability was highlighted in the surface wind evolution at John F. Kennedy and Bennett Field airports, located relatively close to the Battery. The average winds veer from an average northwesterly direction −48 h before the surge event to east-northeasterly ~24 h before the time of maximum surge, which persists until the time of maximum surge. The average wind direction is similar for the minor- and moderate-surge events, but the winds are more concentrated around the east-northeast direction for the moderate events at the time of maximum surge. The average wind speeds for the moderate surges (13 m s^{-1}) are ~4 m s^{-1} larger than for the minor events, but there is a large standard deviation and some overlap between minor and moderate. As a result, using winds alone to distinguish the magnitude of the surge event may not be useful. Other factors may need to be considered, such as the onshore fetch from the Atlantic, duration of the event, wave amplitude, and local water movements within the harbors.

It is interesting that the average peak wind speed occurs 2 h before the time of peak surge at the Battery. Further investigation of individual cases also revealed stronger winds a few hours before peak surge for several cases, which suggests that it may take 1–2 h after the peak wind for the high water associated with the surge to impact fully the NYC harbor area. Future work will need to investigate more carefully the movement and source of surge water around the NYC area using a coupled high-resolution ocean–atmospheric model. Also, additional research is needed to investigate the global teleconnections that may be associated with the decadal variability in East Coast cyclone frequency and associated storm surge.

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