Twentieth-Century Storm Activity along the U.S. East Coast

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ABSTRACT

It has been speculated that future global warming will change the frequency and severity of tropical and extratropical storms. The U.S. east coast is heavily impacted by such storms, so it is important to determine their natural temporal variability for the last century during which global warming has been relatively small. Storm surge data obtained from hourly tide gauge records provide a unique quantitative measure of storm duration and intensity, unlike qualitative estimates based on eyewitness reports or meteorological hindcasts. To demonstrate the potential of storm surge data for climate analysis, the authors have evaluated 10 very long records of water level anomalies. An analysis of the hourly tide gauge records along the U.S. east coast shows a considerable interdecadal variation but no discernible long-term trend in the number and intensity of moderate and severe coastal storms during this century. However, sea level rise over the last century has exacerbated the damage to fixed structures from modern storms that would have been relatively minor a century ago.

1. Introduction

Long-term (interdecadal and longer) storm activity is an enduring concern of coastal scientists. Coastal storms are major agents that can cause drastic changes of coastal landforms such as beach and dune erosion, overwash processes, and opening of tidal inlets on barrier islands (Leatherman 1982). Although the impact of individual storms on coastal landforms is significant and well documented (Carter 1988), there are few studies of the role of storms on long-term changes of coastal landforms. Part of the reason is a lack of quantitative information on historical storm activity. A number of researchers (El-Ashry 1971; Hayden 1975; Gorman and Reed 1989; Fenster and Dolan 1994) believe that an alleged relatively recent increase of storminess is one reason for the extensive beach erosion along the East Coast. However, this idea has not been adequately validated based on quantitative analyses of long-term storm activity and beach erosion data.

Damage to property along the U.S. coasts caused by severe tropical and extratropical storms has increased tremendously in recent decades. Hurricane Andrew alone in 1992 resulted in about $25 billion in damage (National Weather Service 1992). The increased number of vulnerable structures that have been built in coastal regions is certainly one reason for the increased damage to property. Another factor could be a change of coastal storm severity or frequency.

Global warming due to increasing concentration of greenhouse gases in the atmosphere may cause tropical and extratropical storm activity to change (Emanuel 1987; Idso et al. 1990; Knuston et al. 1998). Mather et al. (1964) showed an increased trend of damaging storms along the East Coast from 1921 to 1962. Hayden (1975) stated that there was an increase in extratropical storm severity along the mid-Atlantic coast based on hindcast wave data from 1942 to 1974. Carter and Draper (1988) reported that the North Atlantic has become rougher in recent years in terms of recorded wave data during 1962–86. Is it possible that the small twentieth-century global warming (0.5°C) has already resulted in an increase in the severity of coastal storms, or is the

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apparent increase just part of the fluctuation of the natural climate system? Industries such as offshore oil exploration companies, and coastal residents, have serious concerns about whether global warming results in an increase in extreme waves and high water levels. These concerns require accurate and quantitative documentation of long-term historical storm activity to examine whether the global warming that has occurred in this century has resulted in significant change in storminess and, in addition, to establish a baseline storm climatology against which any future changes resulting from global change can be compared.

2. Indexes of storm activity

Historical weather records provide valuable sources for meteorologists to document decadal and long-term storm activity for construction of a meteorological storm index. Resio and Hayden (1975) investigated the secular variations in mid-Atlantic extratropical storm activity from 1899 to 1938 and from 1947 to 1970 by examining the changes in frequencies of surface pressure patterns over the area from 20° to 90°N and from 0° to 180°E. An 8.9% increase in storm frequency from the 1940s to the 1960s was found. Hayden (1981) also studied the secular variation of storms along the Atlantic coast from 1885 to 1975 by analyzing cyclone frequencies in 74 grid cells (2.5° lat × 5.0° long). His results show that the cyclone frequency over the marine area increased, while decreasing over the continent since the early part of this century. The increase in number reached a maximum in the 1960s. Landsea (1993) investigated seasonal and long-term trends of intense hurricanes (Saffir–Simpson categories 3, 4, and 5) in the Atlantic basin in terms of historical tropical storm track data. He demonstrated that there was a declining trend in incidence of intense hurricanes in the last 30 years, but prior to the hurricane swarm of 1995.

Since coastal storms produce large waves and storm surges, wave and surge records can be used to document historical coastal storm activity. Carter and Draper (1988) and Bacon and Carter (1991) used wave records measured by a shipboard wave recorder attached to the *Seven Stones Light Vessel* in the North Atlantic Ocean from 1962 to 1986 to study the long-term trend of wave climate. They found an annual rate of increase of 2.2 cm yr^{-1} in significant wave height, for a total increase of 28% during the 25-yr period. Bouws et al. (1996) analyzed more than 20 000 hand-drawn wave charts of the North Atlantic Ocean from 1960 to 1988. They reported that the 50th percentile of annual significant wave height increased at the rate of 2.3–2.7 cm yr^{-1}.

Unfortunately, there are no very long instrumental wave records available along the U.S. east coast. Most wave data recorded by National Oceanic and Atmospheric Administration's (NOAA's) National Data Buoy Center instruments are less than 20 yr old. The data from the *Seven Stones Light Vessel,* believed to be the longest instrumental wave record in the world (Carter and Draper 1988), has a length of only 25 yr. The use of such a short series to detect a long-term trend is doubtful because of low-frequency climate variations. An alternate and indirect way to obtain historical wave information is to hindcast past wave conditions based on historical weather charts. Dolan and Davis (1992, 1994) and Davis et al. (1993) used the Severdrup, Munk, and Bretschneider method (U.S. Army Corps of Engineers 1984) to hindcast significant wave heights; they proposed an index of storm strength (storm wave height × storm wave duration) for extratropical events (northeasters) along the East Coast. They concluded that there was a decline in the count of storms from the early 1960s to the mid-1970s followed by an increase to 1983, establishing that there are interdecadal variations of storm strength.

Historical records of storm impacts on the beach can also be used to characterize storm activity. Coastal storms have caused a great deal of property damage and beach erosion during the twentieth century, and such events are always of concern to scientists and the public. There are numerous newspaper reports and historical documents on beach erosion and damage caused by great storms (e.g., Savadove and Buchholz 1993; Friedlander et al. 1977). Using historical records from periodicals, newspapers, and weather summaries, Mather et al. (1964) investigated storms producing significant damage on the East Coast from 1921 to 1962. They found that the number of damaging storms increased from 2 yr^{-1} in the early 1940s to over 7 yr^{-1} in the late 1950s and early 1960s. Mason et al. (1996) used historical newspaper reports on storm damage to study storm activity in the Bering Sea from 1898 to 1993. They concluded that more storms than average occurred during 1900–13, 1936–46, 1974–76, and in 1992, while fewer occurred from 1916 to 1928 and from 1947 to 1959. The problem with this approach is that coastal development over time increases the apparent number of damaging storms.

Although all of the above methods can be used to document historical storm activity, these studies suffer various problems such as lack of long-term data (Mather et al. 1964), reliance on hindcast data whose quality is difficult to determine (Dolan and Davis 1992), and examining storm activity based on only a simple index of occurrence or frequency (Hayden 1981). For climate investigations, a quantitative, comprehensive, and objective measure is preferable. Hourly values of water level data provide a unique measurement record of tropical and extratropical storms affecting the East Coast. Coastal storms are accompanied by storm surges. These are defined as water level fluctuations beyond the astronomical tide, induced by meteorological factors such as wind and atmospheric pressure in a coastal or inland water body with a duration of a few minutes to a few days (Murty 1984). The duration of the surge is related to the duration of the storm and its amplitude to storm

TABLE 1. Tide gauges with hourly records longer than 50 yr along the East Coast.

Station name	Lat	Long	Start–end
Portland, ME	43°,39.4′N	70°,14.8′W	1912–97
Boston, MA	42°,21.5′N	71°,03.0′W	1921–97
Newport, RI	41°,30.3′N	71°,19.6′W	1930–96
New York, NY	40°,42.0′N	74°,00.9′W	1920–97
Sandy Hook, NJ	40°,28.0′N	74°,00.6′W	1910–97
Atlantic City, NJ	39°,21.5′N	74°,25.1′W	1911–97
Hampton Roads, VA	36°,56.8′N	76°,19.8′W	1927–97
Wilmington, NC	34°,13.6′N	77°,57.2′W	1935–97
Charleston, SC	32°,46.9′N	79°,55.5′W	1922–96
Mayport, FL	30°23.6′N	81°,25.9W	1928–97

severity (Harris 1958; Pore 1961), enabling storm surges to be used as accurate indexes of storm frequency and severity. The recent availability of very long hourly tide gauge records from the National Ocean Service (NOS) of the NOAA makes it possible to do an accurate census of storms during the twentieth century along the East Coast. This research is designed to investigate the historical change of storm activity along the East Coast in this century by

- establishing quantitative and objective indexes of storm severity,
- determining the long-term trend and interdecadal variations in the number and severity of coastal storms over this century, and
- examining the geographical variation in changes of storm activity along the U.S. east coast.

3. Data

Hourly water level records from tide gauges and historical tropical storm track data were used in this study. There are a large number of tide gauges with long records along the U.S. coasts; a dozen gauges along the East Coast have been operated by the NOS since the early part of this century. An archive of chart and punched-paper tape recordings of historical data, recorded before modern digital techniques were established, has been maintained. Average hourly water level values have been computed from this source by the NOS and are now being made available to the scientific community for the first time (http://www.opsd.nos.noaa.gov/). U.S. tide gauge hourly water levels have an accuracy of 1–2 cm (S. Gill 1999, personal communication), far more than adequate for this investigation. Table 1 lists the tide gauges used in this study. The length of hourly water level records ranges from 60 to 90 yr. Figure 1 displays the geographical locations of these gauges. The East Coast is well covered.

The tropical storm track data used in this study were compiled by Landsea (1993). The track data consist of 6-h positions with longitude and latitude, estimated maximum sustained surface winds, and measured central pressures if available. These data span from 1886 to 1995. Central pressure and wind speed data of storms may be less accurate before 1944, when the U.S. Air Force and Navy began routine reconnaissance flights into storms. Also, some short-lived tropical storms were

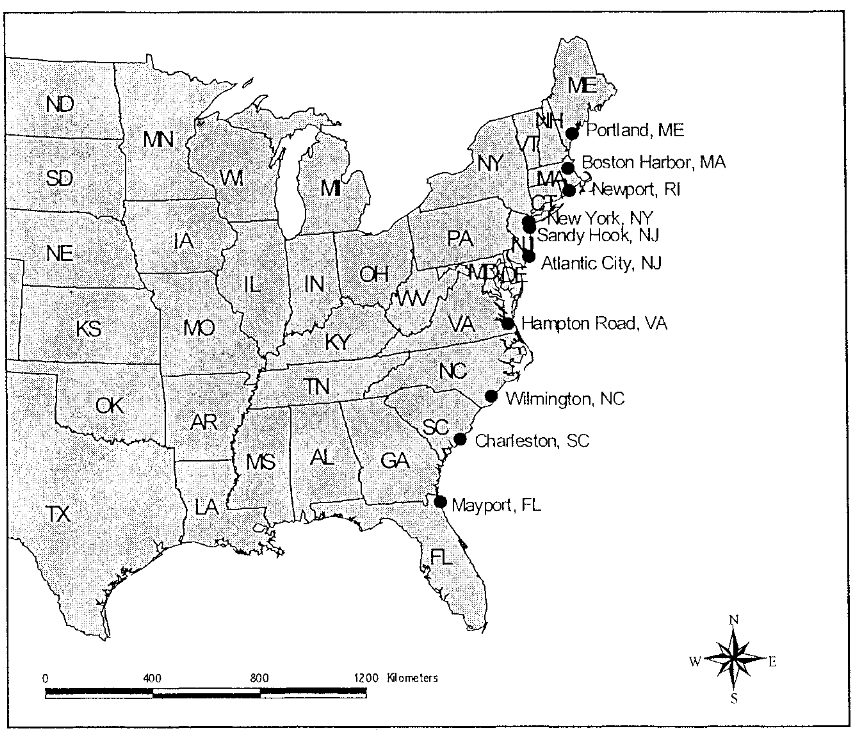

FIG. 1. Location of tide gauges recording long-term hourly water level.

likely unobserved (Landsea 1993). However, lack of accurate central pressure and wind speed data has no significant influence on this research. Only track position data are used in this study, and short-lived tropical cyclones have little effect on surges occurring at a specific location.

4. Tides and storm surges

There are two fundamental components of elevated water level associated with coastal storms: surge and astronomical tide. The former is the increase of water level due to the storm; the latter is the result of astronomical forces. Since it is the storm surge amplitude and duration that reflect the inherent strength of a storm, it is necessary to remove the contribution of the astronomical tide from the elevated water level in order to detect and analyze historical changes in the number and severity of storms.

Harmonic analysis was used in this investigation to separate tide and storm surge components. The water level at any specific location can be described by the following equation (Pugh 1987):

$$h_t = z_0 + x_t + s_t, \tag{1}$$

where h_t is the observed water level, z_0 a mean level, x_t tidal component, and s_t a storm surge at time t. The tide is the response of water level to astronomical forces. It can be expanded as a group of harmonic constituents:

$$x_t = \sum_{i=1}^{M} H_i \cos(\sigma_i t + \varphi_i), \tag{2}$$

where H_i is the amplitude of, σ_i the frequency of, and φ_i the phase of a constituent; and M is the number of constituents. The H_i and φ_i are determined by a least squares fit (Pugh 1987).

The sea level records along the east coast show a rising trend and interdecadal fluctuations for the past 100 yr (Douglas 1991). For example, the long-term linear trend at Atlantic City, New Jersey, is about 3.9 mm yr^{-1}, and sea level rose 0.35 m from 1911 to 1993. This trend can obscure the detection of storm surges and should be separated from the record because the rms value of all storm surges at Atlantic City is only about 0.16 m (the value is small because storms are relatively infrequent). Since there is no significant trend of water level change in a year, individual harmonic analyses were performed for each year in this analysis. The influence of the long-term trend and interdecadal fluctuations of water level on storm surges is eliminated by using this yearly analysis procedure because the long-term trend and interdecadal changes are absorbed into the z_0 term in Eq. (1).

There are several hundred components in the development of the tidal potential (Cartwright and Taylor 1973). Fortunately, only several dozen are important. The NOS tide prediction program contains 37 constituents. Harris (1991) indicated that another seven harmonic constituents are also important along the East Coast. Thus, the 44 harmonic constituents identified by Harris are used in this study.

a. *Correcting water level data*

In the process of recording hourly water levels, errors may occasionally occur due to mechanical and human factors. There are two basic types of errors in the data: one is an outlier value abnormally higher than adjacent values; the other is a phase shift which results in large tidelike fluctuating residuals (Pugh and Vassie 1978; Zhang 1998). These incorrect data produce false water level values and, consequently, could influence the statistics of storm events. Fortunately, these errors can be detected easily from the data residuals after tidal components are removed from the water level record. Outliers show up as spikes, which do not in any way resemble storm surges. Erroneous phase shifts in contrast cause tidelike fluctuations in the residual which are obvious and easily corrected. Since these data errors influenced the initial harmonic analysis, the harmonic analysis was repeated on the corrected water level data to produce the final storm surge dataset.

b. *Interaction between surges and tides*

The method [Eq. (1)] that separates storm surges from recorded water levels implies that there is no significant nonlinear interaction between surge and tide; that is, the storm tide is a linear combination of storm surge and astronomical tide. However, at certain locations such as in an estuary, interaction between tides and surges due to local topographic and runoff effects can result in considerable changes of surge amplitude and phase. One good example is the river Thames. Rossiter (1961) found that the interaction there between tides and surges causes larger positive surges occurring at the rising tide.

In order to check whether there is a significant interaction between tides and surges along the East Coast, the tidal cycle was divided into four stages following Rossiter (1961). These four stages are low water, rising tide, high water, and falling tide. This division into four stages is used in coastal science to characterize the tidal cycle (Murty 1984). In our investigation low and high water are defined as 1.5 h before and after low tide and high tide time, respectively; the rising tide is the period between low and high water stages, and the falling tide is the period between high and low water stages. The distributions of tide-corrected (i.e., tidal components removed) water levels for these four different stages were compared to detect any interaction between surges and tides. If there is no significant interaction between tides and surges, the tide-corrected water level distributions at the four stages should be the same. This result can be displayed in so-called quantile–quantile (Q–Q) plots. These are very useful tools to examine whether two

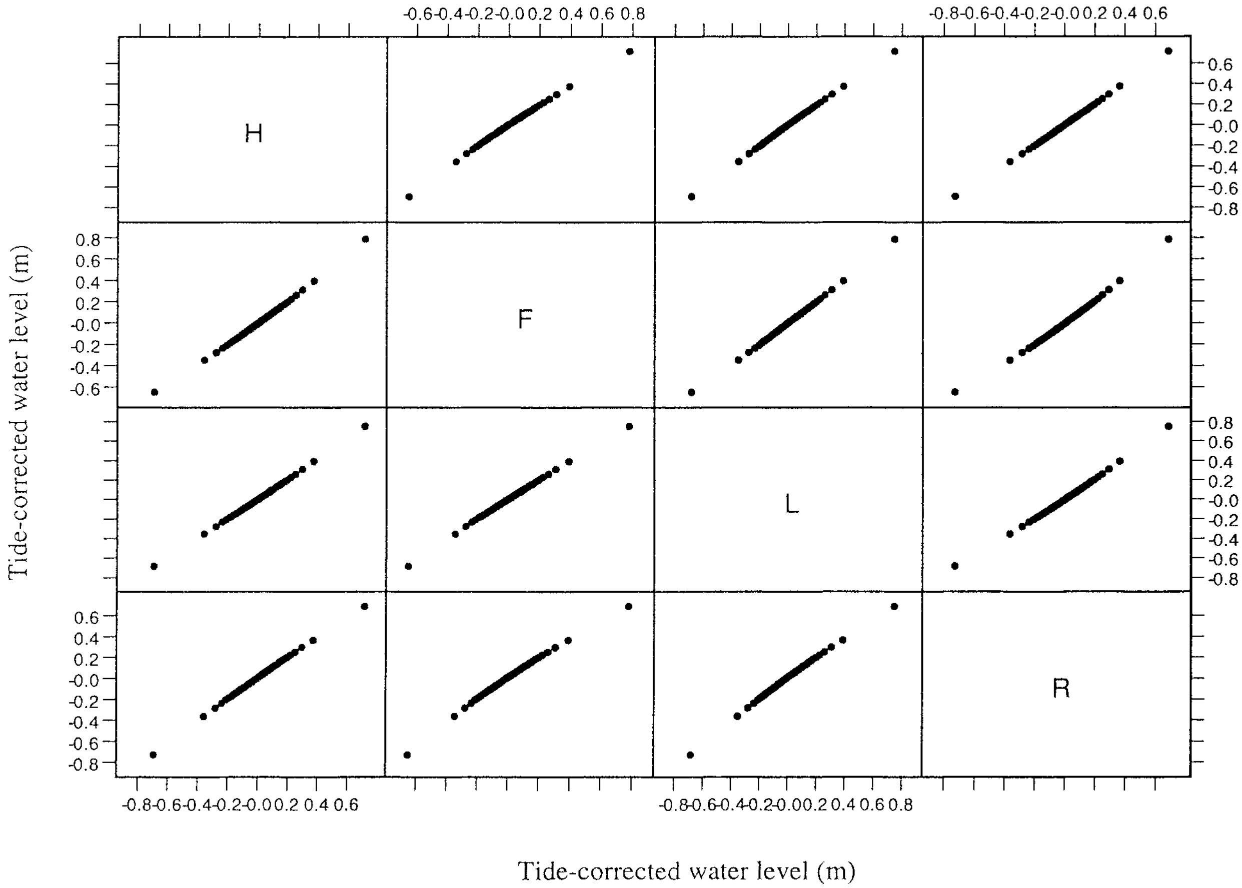

FIG. 2. Quantile–quantile plots for tide-corrected water level (i.e., tidal components removed) distributions during high (H), falling (F), low (L), and rising (R) tide at Atlantic City.

datasets have the same distribution (Rice 1988). If two distributions are the same, the Q–Q plot will be a straight line with a slope of 45°.

Two typical gauge records, Atlantic City (open coast) and Charleston, South Carolina (harbor), were selected to examine the interaction between tides and surges. Figure 2 shows that Q–Q plots of tide-corrected water levels between any two tidal groups at Atlantic City approximate a straight line, indicating that there is no significant interaction between tides and surges at this open coast gauge. The very flat ''U'' shapes of Q–Q plots of surge distributions at Charleston (Fig. 3) denote that there is only a slight interaction at this harbor gauge site. The Q–Q plots of the other tide gauges we used are similar to either of these two gauges, indicating that there is no significant interaction between surges and tides along the East Coast. Therefore, it is appropriate to compute storm surges for this study by subtracting the astronomical tides from water levels.

c. Identifying storm events

In order to identify storm events, it is necessary to define a criterion. For example, Dolan and Davis (1992, 1994) used 1.5-m maximum significant wave height as a criterion to delineate storms but did not present clear physical reasons why this value was chosen. There is another problem with using wave data. Distant storms can produce large swell waves unaccompanied by damaging winds or storm surge, resulting in an exaggeration of the number of coastal storms. An alternative is to use a more direct measure of coastal storms, the storm surge itself. The apparent storm surge signal (i.e., the residual water level after the long-term sea level and tidal components have been removed) consists of water level fluctuations caused by meteorological processes along with weak tidal signals produced by nonlinear shallow-water effects. It is very difficult to separate the latter minor signals from storm surges completely, but they have small magnitude compared with water level fluctuations caused by large storms on the open coast as shown above and in Figs. 4 and 5. Figure 4 shows the storm surge for the December 1992 severe northeaster at Atlantic City. Note that the storm surge signal is very large compared to the minor variations and the few-centimeter noise level of the data. The distribution of all anomalous water levels (residuals) about their mean over a complete record closely approximates a normal distribution

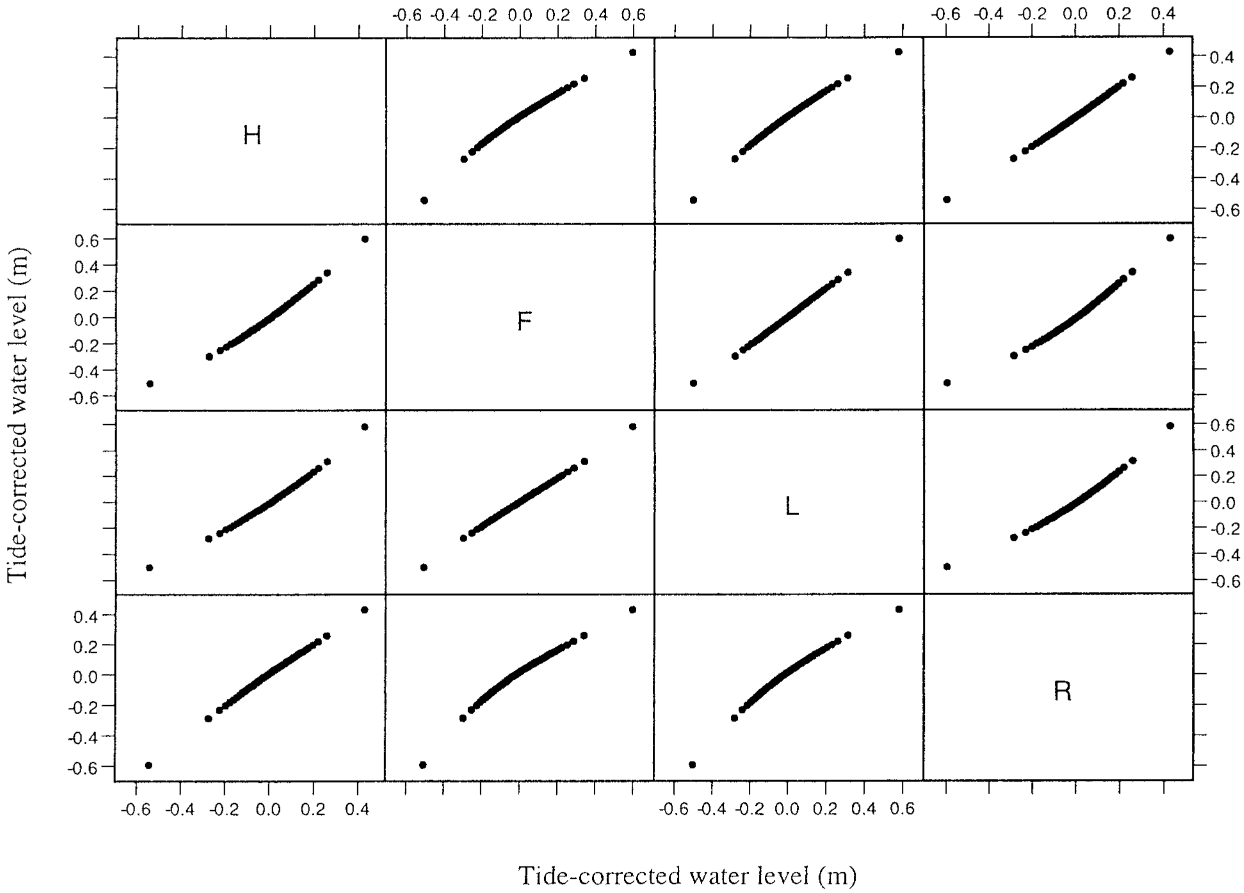

FIG. 3. Quantile–quantile plots for tide-corrected water level distributions during high (H), falling (F), low (L), and rising (R) tide at Charleston.

(Zhang 1998). Since our interest is in severe storms, we chose surges greater than 2 standard deviations as a criterion to determine a major storm event. This choice is arbitrary but serves to focus our analysis on the largest, most damaging storms.

At a harbor gauge, strong shallow-water effects can influence detection of moderate storms (Fig. 5). The shallow-water effects can be removed by filtering the residuals using a low-pass (Gaussian) filter. Numerical tests (Fig. 5) showed that a 19-h filter with a width of 2 standard deviations reduces shallow-water effects with a distortion of low-frequency components that is tolerable for detecting important storms. However, this low-pass filter also damps the amplitude of storm surges with a duration of less than 19 h. To diminish shallow-water effects and maintain original storm surge information, three steps were taken to identify a storm event. First, possible storm events were identified from residuals using 2 standard deviations as a criterion; then storm events were also identified from the low-pass-filtered residuals; finally only those storms detected in both unfiltered residuals and low-pass-filtered residuals were retained.

There are situations when lesser storms occur close together, creating a difficulty in counting individual events. In addition, sometimes water level can continue to oscillate after the passage of the hurricane center because of the free motion of the water in returning to its normal level and the change of wind direction (Redfield and Miller 1957). These oscillations can cause a negative surge, but they are generally less than one tidal cycle in period. Thus, one tidal cycle (12 h for the semidiurnal tide along the East Coast) was chosen as a criterion to discern storm events. If the interval between two storm events is more than 12 h, they were taken to belong to different storm events; otherwise, they were regarded as continuation of a single storm event.

d. Separating tropical and extratropical storms

Hurricanes and northeasters have different effects on coastal erosion. Although hurricanes produce higher surges, they have shorter duration and influence a relatively small length of coastline. Normally, the influence of a hurricane on a specific coastal position spans less than one day and stretches no more than 200 km. In contrast, northeasters generally have lower windspeeds, last for several days, impact a coastline length of more

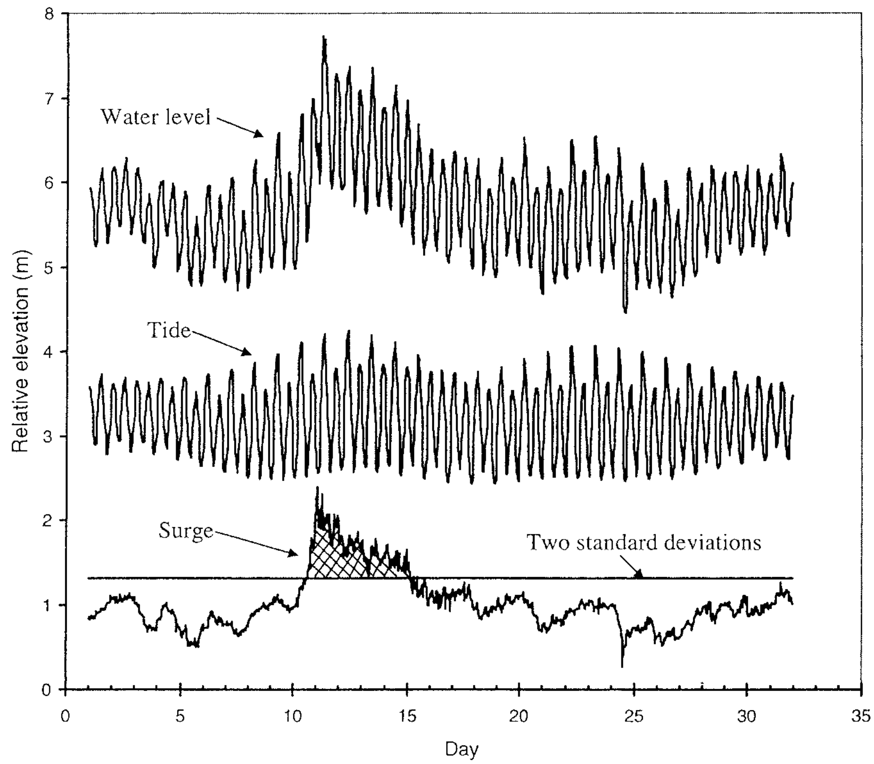

FIG. 4. Water level, tide, and storm surge at Atlantic City during Dec 1992. Note this storm resulted in elevated water levels over 4 days. Such a long duration storm is very damaging. The crosshatched area is the integrated intensity of the storm, a measure of storm force.

than 1500 km, and are accompanied by relatively lower surges. But northeasters can be more destructive to the beach, dunes, and nearby buildings than hurricanes because their storm waves can bash the shore for several high tides. To compare the effects of hurricanes and northeasters on coastal erosion, it is necessary to separate hurricane and northeaster events. Generally, most hurricanes occur from June to September, and northeasters prevail from October to May in the midlatitudes. However, a considerable number of tropical storms occur in October. There have been tropical storms even in November based on historical track records of tropical storms (Neumann et al. 1993). So a feasible way to separate hurricanes and northeasters is to use historical hurricane track data. A search scheme based on a circular area can be employed to identify tropical storms that influence particular coasts based on tropical storm track data. First, all tropical storms for a year that fall within a circle with a tide gauge as the center are selected. Then start and end dates of a storm surge event are compared with start and end dates of selected tropical storms. If the two periods overlap, the storm event is selected as a tropical storm.

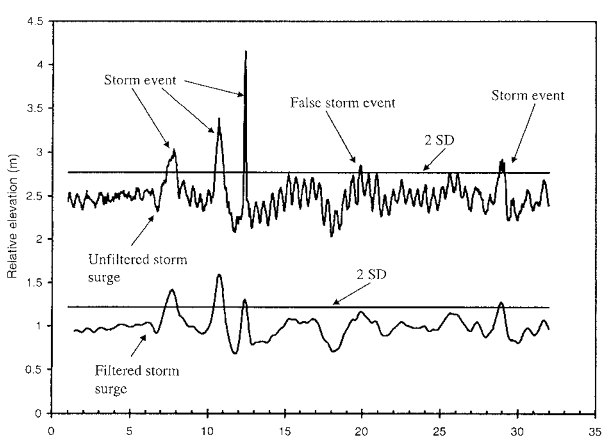

FIG. 5. Storm surge and filtered storm surge at Portland, ME, during Jan 1977. Note that the shallow-water effects are removed by the 19-h Gaussian filter, but the surge amplitude of the storm event with duration less than 19 h is only damped by the low-pass filter.

Clearly, the radius of the circle should be determined in terms of the spatial distribution of storm surge amplitude. Redfield and Miller (1957) studied the distribution of storm surge amplitude from a storm center to an edge perpendicular to the storm path based on tide gauge records and field observations. Their work demonstrated that maximum water level occurred 90–130 km to the right of storm paths. A surge elevation of a few feet can extend for several hundred miles; radii of 600, 800, 1000, and 1200 km were selected for circle searches. The circle searches were performed in ascending order of radius until there was no significant difference between the number of tropical events from an adjacent small circle (radius of 600 km) and those from a larger circle (with radius of 800 km). The tropical storms within the small circle were used to identify tropical events.

e. Indexes for measuring storm activity

To detect and classify changes of historical storm activity, three indexes have been used in this research:

- count: number of storm events during a certain period,
- duration: number of hours of storm surges over 2 standard deviations during a certain period, and
- integrated intensity: total area (m-h) under storm surge curves and above 2 standard deviations during a certain period.

The first two indices reflect counts and duration of storms. The third index reflects the storm severity. Figure 4 shows the integrated intensity (the crosshatched area) of the December 1992 northeaster at Atlantic City. All these indexes for tropical and extratropical storms can be calculated for identified storm events. The whole procedure to analyze historical storm activity from hourly tide gauge records has been implemented in C++ code and the commercial software package SPLUS.

5. Results

a. Seasonal changes

The selected indexes show a clear seasonal pattern in coastal storm activity along the East Coast. Monthly mean integrated intensity of storm surges over 2 standard deviations is high from November to April and low from May to October (Fig. 6), indicating more storms occur from November to April every year and less storm activity from May to October. The other two indices, monthly mean number of storms and monthly mean duration, display a similar pattern (Zhang 1998).

As noted above, most hurricanes occur from June to September, while northeasters prevail from October to March. The large value of the three indexes during November to April suggests that most of the storm activity in a year is the result of northeasters. These northeasters are the dominating storm forces causing episodic erosion along the East Coast.

The influence of extratropical storms versus tropical storms is not uniform along the East Coast. The impact of tropical storms increases from north to south along the East Coast. Monthly mean integrated intensity from May to September for storm activity from the Portland, Maine, to Atlantic City gauge displays low values (Fig. 6), indicating that the influence of tropical storms is small north of the Sandy Hook, New Jersey, gauge. This trend is consistent with the spatial distribution of tropical storms along the east coast. The statistics of tropical storms affecting the U.S. east and gulf coasts show that the frequency of landfalling tropical storms and hurricanes decreases dramatically from Virginia northward (Neumann et al. 1993). The influence of tropical storms becomes more and more significant from the gauge at Hampton Roads, Virginia, toward the south. The monthly mean integrated intensity shows fairly large values in June and September at the Charleston gauge. The values at the Mayport, Florida, gauge in June, September, and October are approximately equal to, or more than, those in January and February, implying that the influence of tropical storms is as important as that of extratropical storms at Mayport.

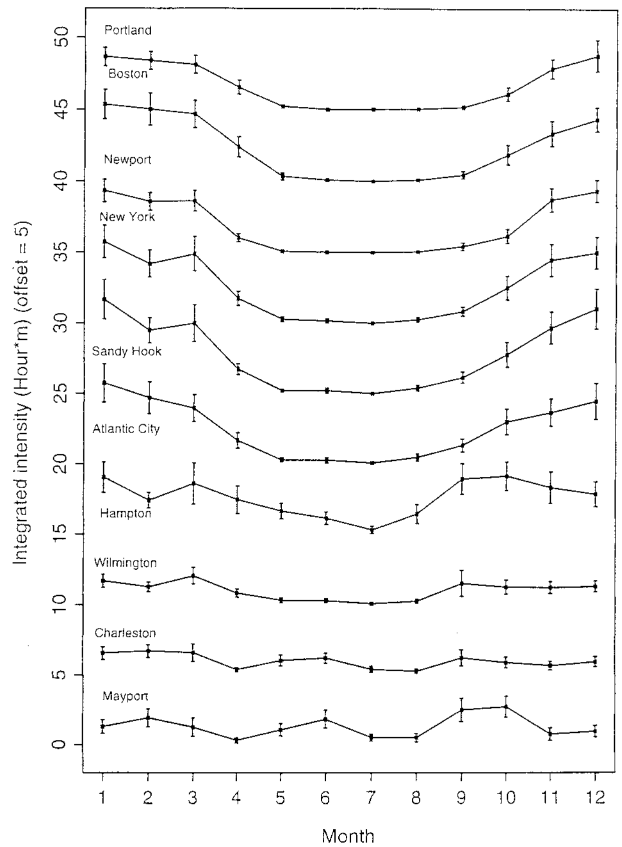

FIG. 6. Monthly mean integrated intensities of storm surges over 2 std dev along the East Coast. The series are offset (i.e., separated) by five units and the range of an error bar set to 0.2 std dev for the sake of clarity.

b. Interdecadal changes

There are significant interdecadal variations of storm activity along the East Coast (Figs. 7–9). These quasiperiodic interdecadal fluctuations are not surprising. Such fluctuations are commonplace in climate records, sea level being a typical example (Douglas 1991). It is hard to quantify exactly the decadal changes in Figs. 7–9 due to discontinuous index curves caused by data

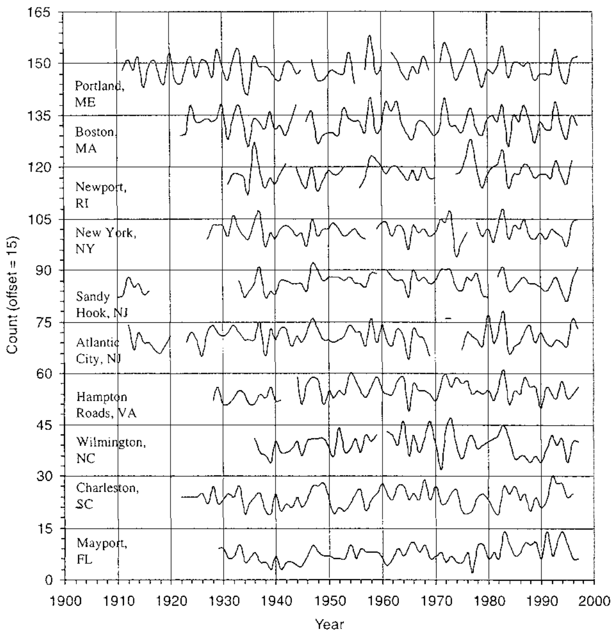

FIG. 7. Annual number of storms with surges over 2 std dev along the East Coast. Series are offset by 15 units.

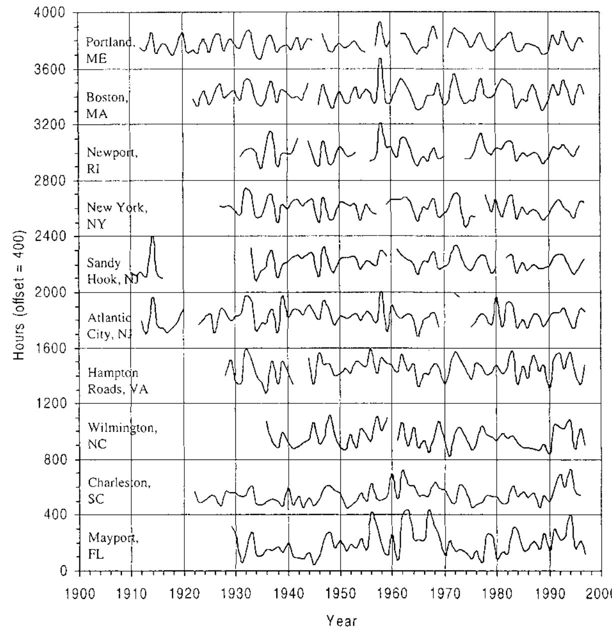

FIG. 8. Annual number of hours of storms with surges over 2 std dev along the East Coast. Series are offset by 400 units.

gaps. Empirical orthogonal function (EOF) analysis is a powerful tool for compressing interrelated data and extracting comprehensive information (Kutzbatch 1967; Aubrey and Emery 1986). To detect the dominant spatial and temporal modes of historical storm activity, EOF analysis was applied to 67 yr of index series during 1930–96. The 10 tide gauges listed in Table 1 and Fig. 1 were utilized because storm surge records at most gauges are complete during this period.

Storm surges recorded at a particular tide gauge are influenced by storm size, path, and local topography. Since the east coast covers about a 3100-km length of coastline, there are considerable spatial changes in the storm indexes, especially duration and integrated intensity. To prevent the gauges with large storm surge indexes from dominating the variance when EOFs are computed, the storm indexes were normalized by subtracting their mean value and dividing by their standard deviations.

Equal temporal observations are required to compute eigenfunctions (Emery and Aubrey 1991). However, small gaps exist in the storm index series (Figs. 7–9). There are two ways to deal with the gapped data. One is to interpolate the missing data in terms of adjacent gauges since decadal variations of storm indexes are correlated spatially. The other is to estimate the correlation coefficients by removing data from the complete series corresponding to the gaps in the incomplete ones. Only those points existing in both series are used to compute correlation coefficients (Aubrey and Emery 1986). The gapped records have little effects on EOF results in our analysis since the missing points only vary from 2 to 6 (Figs. 7–9), relatively small compared with the length of series (normally 67). Numerical testing shows that there is no significant difference in EOF analysis results based on the two methods. The first method was used for this paper.

The EOF analysis shows that the first and second eigenfunctions for annual integrated intensity account for 54% and 15% of the variance, respectively. This

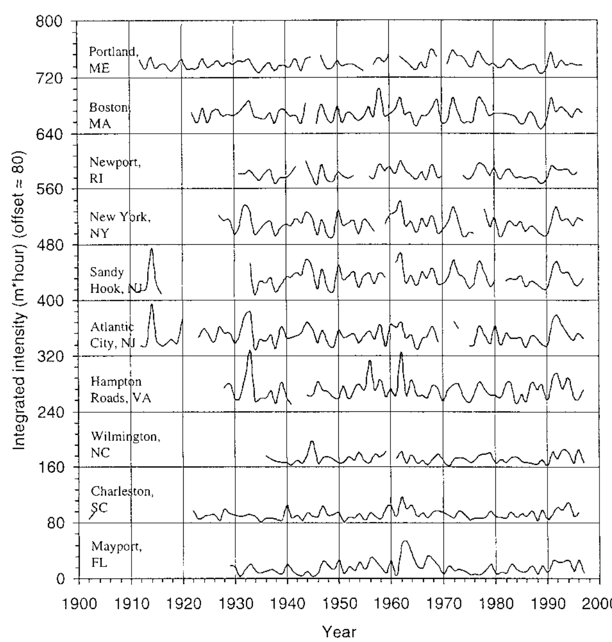

FIG. 9. Annual integrated intensity of surges over 2 std dev along the East Coast. Series are offset by 80 units.

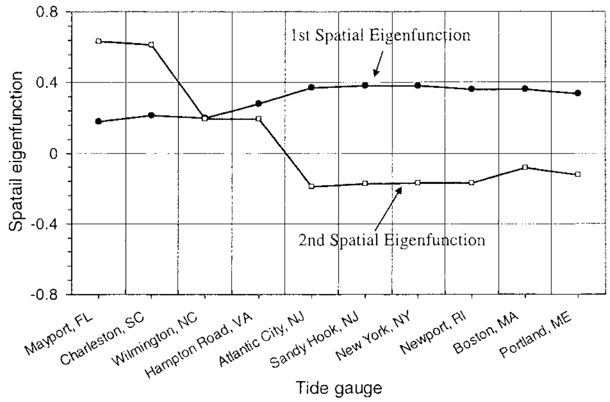

FIG. 10. Spatial eigenfunctions for annual integrated intensity.

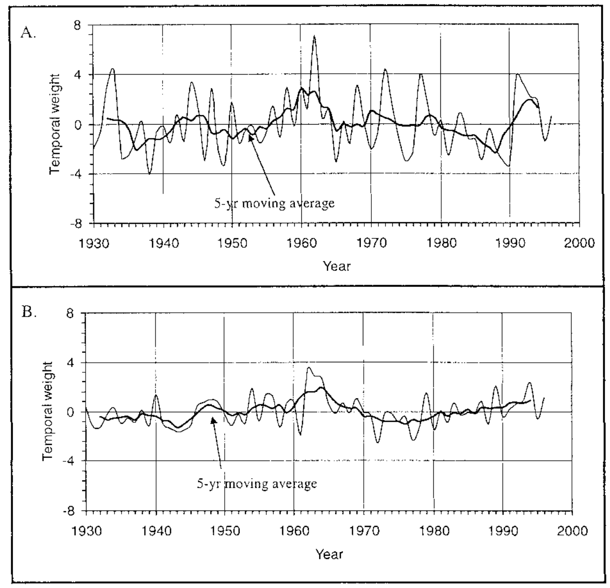

FIG. 11. Annual weights of the (a) first and (b) second temporal eigenfunctions for annual integrated intensity.

indicates that most of the variation in decadal changes is described by the first two eigenfunctions. The first spatial eigenfunction values for annual integrated intensity are small at the Mayport and Charleston gauges, and large from Atlantic City to Portland. The second spatial eigenfunction shows a reverse pattern (Fig. 10). These findings suggest that there are two different types of decadal changes in storm activity along the East Coast. The first eigenfunction mainly represents the fluctuation pattern of storm activity north of the Hampton Roads gauge (north pattern: northeaster-dominated), while the second eigenfunction mainly represents the fluctuation pattern of storm activity south of the Wilmington, North Carolina, gauge (south pattern: influenced by both northeasters and hurricanes). Results from EOF analysis of the other two storm indices, annual number of storms and annual duration of storms, display a similar spatial pattern (Zhang 1998). It is interesting to note that the Atlantic City and Charleston gauges, respectively, can represent the storm activity for the entire north and south parts of the East Coast in terms of the results from the EOF analysis. This finding validates the results of Zhang et al. (1997).

The third eigenfunction is not entirely insignificant. It accounts for 10% of the variance of the annual integrated intensity. The third spatial eigenfunction shows a large value at Hampton Roads and Wilmington, indicating that it mainly represents a hybrid fluctuation pattern at the Hampton Roads and Wilmington gauges. This region represents the transition between the northern and southern patterns.

Figure 11 shows temporal eigenfunctions for annual integrated intensity. There are peaks around the mid-1940s and early 1960s; troughs in the late-1930s, around 1950s, and late 1980s in the first temporal eigenfunction. The second temporal eigenfunction displays less variation than the first temporal eigenfunction. The yearly integrated intensity increased since 1930 and reached its maximum values in early 1960s. The yearly integrated intensity declined from the mid-1960s to the mid-1970s, then rose again slowly since the mid-1970s. Note that both temporal eigenfunctions display large values in the early 1960s, indicating severe storm activity along the entire East Coast during this period.

To examine the relative role of tropical and extratropical storm activity on a decadal scale, the circle search was used to separate the different series based on historical storm track data. The results show that northeasters dominate hurricanes along the East Coast; hurricane activity increases from north to south. The mean values of the three indexes show that tropical storm indexes are less than 30% of those of extratropical storms (Table 2), indicating that extratropical storm activity dominates the entire East Coast. There is a distinct pattern in the spatial changes of the three storm indexes. The ratios of mean tropical values to extratropical ones from the gauges north of Hampton Roads are less than 10%. These ratios increase to 10%–27%, with a maximum at Mayport. This means that the northern part of the East Coast is mainly influenced by extratropical

TABLE 2. Ratio (%) of annual count, duration, and integrated intensity of tropical to extratropical storms.

Tide gauge	Count	Duration	Integrated intensity
Portland	2	2	3
Boston	3	3	4
Newport	3	2	4
New York	5	5	6
Sandy Hook	5	6	6
Atlantic City	7	8	9
Hampton Roads	13	18	24
Wilmington	9	12	20
Charleston	13	15	25
Mayport	20	24	27

TABLE 3. Results of linear regression to annual count of tropical, extratropical, and both types of storm.

Tide gauge	Tropical storms	Extratropical storms	All storms
Portland	0.001 ± 0.003	0.014 ± 0.016	0.015 ± 0.016
Boston	−0.003 ± 0.004	0.008 ± 0.019	0.005 ± 0.020
Newport	−0.002 ± 0.005	0.033 ± 0.021	0.031 ± 0.022
New York	−0.005 ± 0.004	0.014 ± 0.018	0.009 ± 0.019
Sandy Hook	−0.002 ± 0.004	0.028 ± 0.013	0.026 ± 0.013
Atlantic City	0.001 ± 0.004	0.008 ± 0.014	0.009 ± 0.014
Hampton Roads	0.003 ± 0.005	0.026 ± 0.018	0.028 ± 0.017
Wilmington	−0.001 ± 0.009	0.002 ± 0.025	0.002 ± 0.027
Charleston	0.001 ± 0.006	0.016 ± 0.014	0.017 ± 0.014
Mayport	−0.012 ± 0.007	0.059 ± 0.015	0.047 ± 0.015

storm activity. However, the southern part shows some influence of extratropical storms, but as expected, a greater tropical storm activity, as can be seen in Fig. 6.

c. Long-term changes

Tables 3–5 list the linear regression rates and uncertainties of the three indexes for all tropical and extratropical storms. The uncertainties shown are too optimistic by a considerable factor because of the decadal and longer fluctuations in the data. Note that the linear regression rates are very small, and there is no significant long-term trend either in annual count, duration, or integrated intensity, indicating that there is no significant trend in storm activity during this century along the East Coast. In contrast, Landsea (1993) found a declining trend in incidence of intense hurricanes in the last 30 yr. This trend is not evident in the hurricane surges at Atlantic City and Charleston. However, Landsea derived his results based on the statistics of all intense hurricanes at the scale of the Atlantic basin. The decrease in incidence of intense hurricanes at the basin scale does not translate into a decrease in number of hurricanes affecting a specific tide gauge because of the limited spatial extent of hurricane influence.

6. Discussion

Mather et al. (1964, 1967) documented temporal changes of damaging storms along the East Coast from 1912 to 1962, based on historical records from periodicals, newspapers, and weather summaries. They found that the annual number of damaging storms increased from two in early 1940s to over seven in late 1950s and early 1960s. This change is much larger than found in this study. But the damage from a storm is not only determined by its severity, but also, to a much larger extent, by the development status of the coast. Populations and development have increased along most sections of the U.S. Atlantic coast since the beginning of this century (Hebert and Taylor 1975). Therefore, relying on the number of damaging storms biases the estimate of storm activity to more recent times. The number of damaging storms cannot be used as an objective index to reflect the change of storm activity.

Resio and Hayden (1975) and Hayden (1981) investigated the secular variations in mid-Atlantic extratropical storm activity by analyzing changes in frequencies of surface pressure patterns and number of cyclones over North America. An increase in storm frequency from the 1940s and 1960s along the Atlantic coast was found. Their findings are similar to the results reported here. However, storm severity during a year is not only determined by count, but also, to a much greater extent, by duration and magnitude of each storm. Thus, a comprehensive index such as integrated intensity is required to define storm impact.

Analysis of annual storm indexes shows that there are significant decadal variations in storm activity. These decadal changes have an aliasing effect on the computed long-term trend when the storm surge record is short and will lead to erroneous estimates of the long-term trend of storminess. In order to demonstrate this effect, successive linear trends of annual count and in-

TABLE 4. Results of linear regression to annual duration of tropical, extratropical, and both types of storm.

Tide gauge	Tropical storms	Extratropical storms	All storms
Portland	0.029 ± 0.041	0.318 ± 0.263	0.347 ± 0.270
Boston	0.037 ± 0.078	0.118 ± 0.381	0.155 ± 0.403
Newport	0.038 ± 0.072	0.028 ± 0.451	0.066 ± 0.463
New York	−0.099 ± 0.103	−0.233 ± 0.390	−0.331 ± 0.407
Sandy Hook	0.010 ± 0.106	0.427 ± 0.344	0.437 ± 0.357
Atlantic City	0.073 ± 0.113	0.218 ± 0.358	0.291 ± 0.358
Hampton Roads	0.191 ± 0.235	0.395 ± 0.482	0.586 ± 0.466
Wilmington	0.157 ± 0.206	−0.738 ± 0.521	−0.580 ± 0.572
Charleston	0.035 ± 0.113	0.492 ± 0.284	0.527 ± 0.301
Mayport	−0.240 ± 0.247	0.928 ± 0.594	0.688 ± 0.613

TABLE 5. Results of linear regression to annual integrated intensity of tropical, extratropical, and both types of storm.

Tide gauge	Tropical storms	Extratropical storms	All storms
Portland	0.014 ± 0.010	0.025 ± 0.035	0.039 ± 0.037
Boston	0.023 ± 0.020	−0.030 ± 0.061	−0.007 ± 0.066
Newport	0.018 ± 0.020	0.010 ± 0.056	0.028 ± 0.059
New York	0.004 ± 0.020	−0.073 ± 0.077	−0.069 ± 0.081
Sandy Hook	0.018 ± 0.020	0.062 ± 0.074	0.080 ± 0.078
Atlantic City	0.017 ± 0.021	−0.020 ± 0.062	−0.003 ± 0.067
Hampton Roads	−0.024 ± 0.047	0.044 ± 0.086	0.020 ± 0.098
Wilmington	0.020 ± 0.025	−0.048 ± 0.044	−0.029 ± 0.052
Charleston	−0.004 ± 0.019	0.048 ± 0.031	0.044 ± 0.034
Mayport	−0.021 ± 0.028	0.080 ± 0.063	0.060 ± 0.066

tegrated intensity at Atlantic City were computed based on intervals ranging from 10 to 60 yr (Figs. 12 and 13).

The Atlantic City record presents some problems. Figures 7–9 show that Atlantic City suffered several years of data losses after 1970. To complete the record, we compared data from nearby Sandy Hook (about 130 km from Atlantic City) with those from Atlantic City over their common, complete interval (1933–93). It was found that there is good correlation between storm indices at Atlantic City and Sandy Hook (Zhang et al. 1997), so the Atlantic City record was made complete by using interpolated values from Sandy Hook.

Figure 12 shows storm count trends at Atlantic City for all continuous intervals of 10, 20, 30, and 40 yr in length. The raw data were used to compute the trends by linear regression. Each point corresponds to the trend over the preceding and following n (2 yr)$^{-1}$, where n is the interval in question. The 10-yr linear regression rate varies from −0.5 to +0.7 events per year. There-

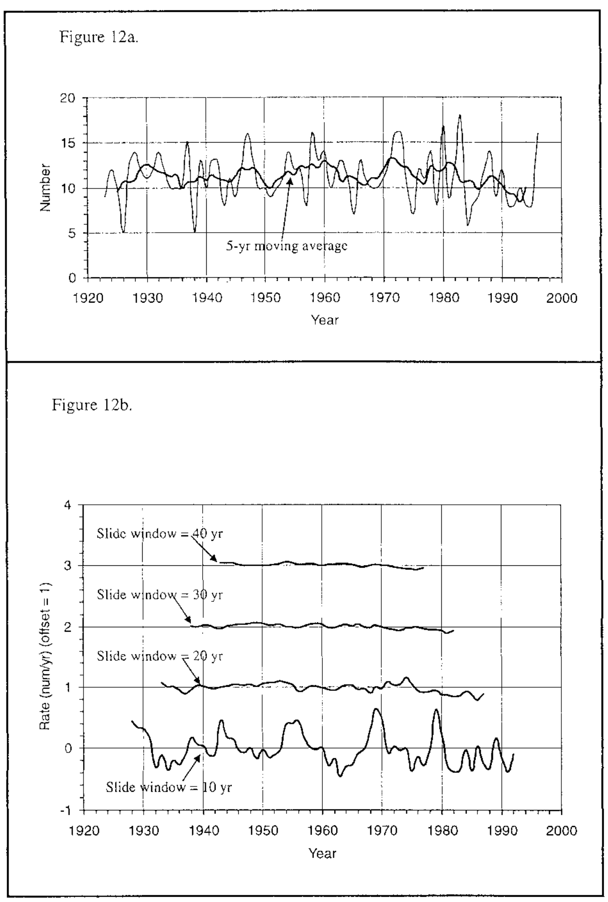

FIG. 12. (a) Annual count of storms with surge more than 2 std dev at Atlantic City. (b) Trends of annual count at Atlantic City for all continuous intervals of 10, 20, 30, and 40 yr in length.

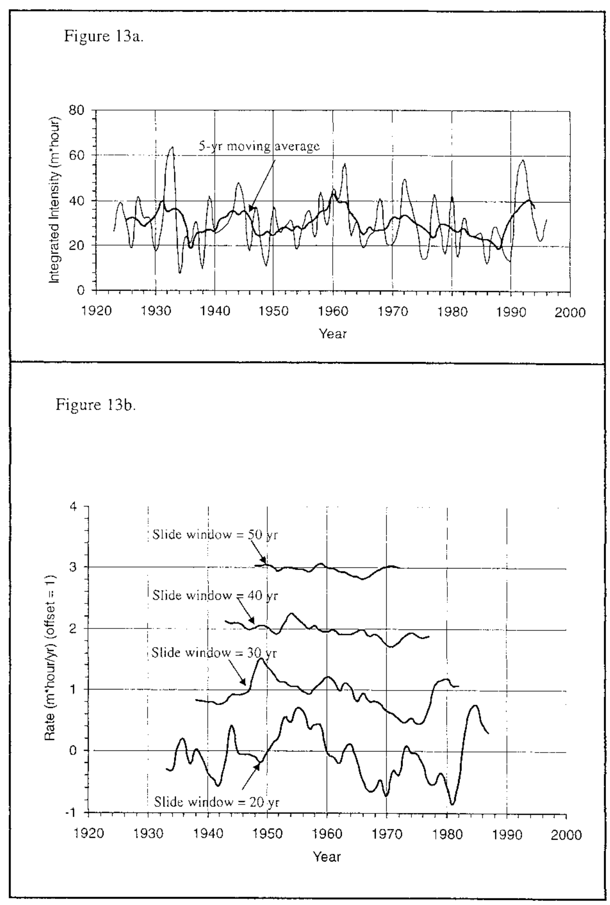

FIG. 13. (a) Annual integrated intensity of storm surges more than 2 std dev deviations at Atlantic City. (b) Trends of annual integrated intensity at Atlantic City for all continuous intervals of 10, 20, 30, and 40 yr in length.

fore, it is incorrect to use 10 yr of data to estimate the long-term trend of annual storm counts. The 20-yr window lowers drastically the fluctuations of linear regression rates for count, but there are still considerable changes (Fig. 12). Linear regression rates from a 40-yr window shows little variations from zero. The linear regression rates for the integrated intensity index from 20-, 30-, 40-, and 50-yr windows show that at least 50-yr records are required to obtain a reliable estimate of the underlying long-term trend in this century for that parameter (Figs. 13a and 13b).

Carter and Draper (1988) and Bacon and Carter (1991) reported that the North Atlantic has become rougher in recent years in terms of 25 yr (1962–86) of instrumental recorded wave data. Although wave height and storm surge are different climate indexes they are related closely because they are normally induced by the same meteorological events. Tancreto (1958) demonstrated a high correlation between maximum storm surge and significant wave height. Thus wave height will display similar decadal fluctuations, and using short-term wave data to estimate the long-term trend in coastal storm activity will produce biased results.

Although there is no significant long-term trend in storminess based on the storm indexes along the East Coast, sea level rise has resulted in the increase of storm impact on the shore. The long-term trends at Atlantic City and Charleston are 3.9 and 3.4 mm yr^{-1}, respectively (Douglas 1991). This sea level rise, amounting to nearly 40 cm century^{-1}, is large compared to the rms value (about 16 cm) of the nontidal water level variations (the rms value of anomalous water level including storm surge events over the record is so small because storms are infrequent). This makes the apparent number and severity of storms appear to increase with time because of sea level rise (Zhang et al. 1997). While removal of the trend of sea level is needed to reveal the true number of storms as well as their intensity, it is also true that sea level rise inexorably exacerbates the damage done by a storm of a given magnitude at any particular coastal area through time.

7. Conclusions

Storm surge records can be used to document quantitatively the number of storm events and their severity. The three indexes proposed here (count, duration, and integrated intensity) computed from storm surge records provide an objective, quantitative, and comprehensive measure of historical storm activity.

The count, duration, and integrated intensity of storms along the East Coast display considerable interdecadal variation. There was more storm activity (number) and intensity (duration and magnitude) during the mid- to late 1950s and early 1960s over the period of record for 10 locations along the East Coast. Also, there are clear seasonal patterns in storm activity. North of Hampton Roads, Virginia, northeasters dominate, and the storm activity is concentrated from November to April. For southeast coast, storm activity during June, September, and October is also significant; the influence of hurricanes increases southward.

Analysis of the hourly tide gauge records from 10 tide gauges along the East Coast does not show any discernible long-term secular trend in storm activity during the twentieth century. This suggests a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 yr. However, climate can change abruptly. Relatively large global warming is predicted in the next century, which may cause a major change in coastal storm activity. If future hourly tide gauge records are evaluated using methods employed in this paper, it will be possible to detect the response of tropical and extratropical storms to global warming.

Finally, although there is no significant long-term trend of storm activity along the East Coast during this century, the effect of sea level rise over the last century has exacerbated the flooding from modern storms that would have been less damaging a century ago. Thus the intensive coastal development that has taken place over the last half century becomes more subject to flood damage from coastal storms even though the trend in the number and severity of storms has remained unchanged.

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