Spatial Variations in Major U.S. Hurricane Activity: Statistics and a Physical Mechanism

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ABSTRACT

The authors provide a statistical and physical basis for understanding regional variations in major hurricane activity along the U.S. coastline on long timescales. Current statistical models of hurricane activity are focused on the frequency of events over the entire North Atlantic basin. The exception is the lead author's previous work, which models the occurrence of hurricanes over the Caribbean Sea, Gulf of Mexico, and the southeast U.S. coast separately. Here the authors use statistics to analyze data from historical and paleoclimatic records to expand this work. In particular, an inverse correlation in major hurricane activity across latitudes at various timescales is articulated. When activity is above normal at high latitudes it tends to be below normal at low latitudes and vice versa. Past research, paleoclimatic records, and historical data hint at the potential of using the North Atlantic oscillation (NAO) as an indicator of where storms will likely track over long timescales. An excited (relaxed) NAO is associated with higher (lower) latitude recurving (nonrecurving) storms. The Gulf (East) Coast is more susceptible to a major hurricane strike during a relaxed (excited) NAO.

1. Introduction

Regional and global climate patterns determine the frequency of North Atlantic hurricanes (Elsner et al. 1999; Shapiro 1989; Gray 1984). A cold phase of the Southern Oscillation, weak vertical shear of the upper-level horizontal winds, and above-normal African rainfall are conditions that favor the abundance of tropical storms and hurricanes. These atmospheric conditions are statistically linked to the vitality of the hurricane season and are used in empirical models to forecast activity several months in advance (Elsner and Schmertmann 1993; Gray et al. 1992).

Much less work and very little understanding have been achieved in solving the climate puzzle with regard to the question of where storms are likely to go based on climate conditions a month or two in advance. Lehmiller et al. (1997) outline the problem and show the potential for specific forecast models based on regional and large-scale climate factors. The present work expands on this by providing a physical framework for understanding the problem, and by suggesting statistical linkages that may lead to more detailed hurricane climate forecast models.

The present approach is largely empirical. The work is based on the hypothesis that regional variations in major hurricane activity along the U.S. coastline can be explained in terms of the position of the polar jet stream over North America and the location of the subtropical high over the North Atlantic Ocean. Shifts in the position of the subtropical high are related to the intensity of the North Atlantic oscillation (NAO). Regional fluctuations in hurricane activity are manifest across seasonal, interannual, decadal, and millennial timescales. Space–time stochastic models that incorporate these oscillations could prove useful in forecasting changes in major hurricane probabilities.

The paper is laid out as follows. Section 2 describes the data and data sources used in the analysis. Information about hurricanes are gathered from several sources. Data from both historical records and paleo-

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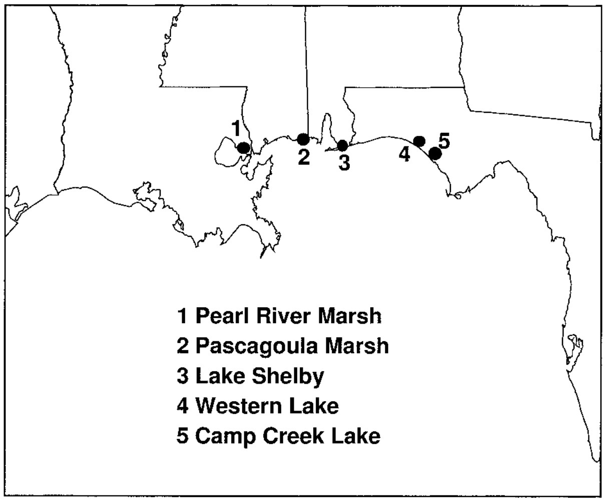

FIG. 1. Location of the five stratigraphic sites shown in Fig. 2. The sites are coastal lakes and marshes along the north-central Gulf Coast.

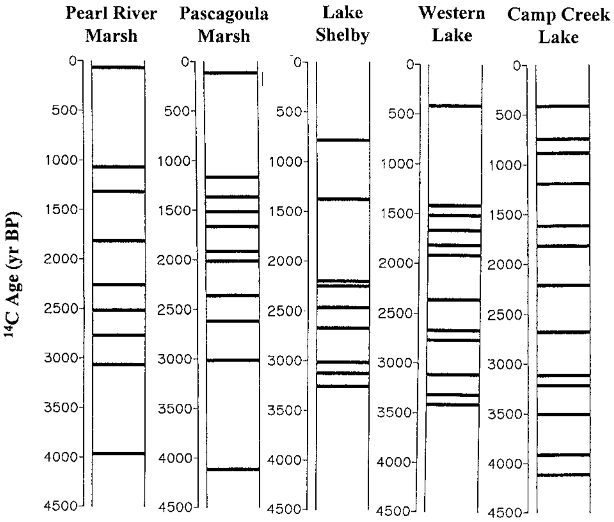

FIG. 2. Stratigraphic records of sand layers in marshes and lakes along the northern Gulf Coast. Sand layers are indicated by a black horizontal bar. Radiocarbon dates are uncalibrated ^{14}C ages in years before present (yr BP). The top sand layer in the Pearl River and Pascagoula marshes was caused by Hurricane Camille in 1969. The Camp Creek Lake record from northwestern Florida may contain hurricanes of strength less than category 3. From Liu (1999).

climate proxies are employed. Section 3 describes the variations in major hurricane activity along portions of the U.S. coastline on the millennial timescale. A physical mechanism related to the position of the subtropical high is used to explain these variations. We are motivated to understand the available historical hurricane record from this perspective. Section 4 first asks whether the millennial-scale variations can be detected in the historical hurricane record. Section 5 then explores the relationship of the NAO to observed changes in major U.S. hurricane activity on the interannual and decadal timescales. We make use of statistical tests and paleoclimatic data to suggest that an intensified NAO will increase the likelihood of a major East Coast hurricane conditioned on the favorability of storm development. Section 6 provides a summary and section 7 lists the primary findings.

2. Data

We make use of several different datasets on various timescales. Data are used in two ways. Hurricane data are employed to quantify the regional fluctuations in major U.S. hurricane activity on the seasonal, interannual, decadal, and millennial timescales. Data on the first three timescales are obtained from historical hurricane records. In particular we rely on the best-track data for the period 1901–98. Description and limitations of these records are provided in Neumann et al. (1993). From these data the interest is in hurricanes that made landfall along the coastline at category 3 or higher on the Saffir–Simpson scale of hurricane destruction potential.

For the period 1851–1900 we use the records of Fernández-Partagás and Diaz (1995a,b, 1996a,b). These records provide an important extension to the best-track data especially with respect to U.S. hurricanes. The authors of these data include their opinion on whether they felt the archived information is sufficient to claim a particular storm as a major hurricane at landfall. Historical hurricane data over the period 1801–50 are provided by Ludlum (1963). Here the author's acknowledgment of extensive damage and/or the use of the adjective ''great'' is used to identify major hurricanes. The historical records are not uniformly comprehensive. There is greater uncertainty about individual weak and open-ocean storms during the nineteenth century. However, the focus of our work is major U.S. hurricanes so it is unlikely that this known data bias will seriously affect the analysis.

On the millennial timescale we make use of paleotempest reconstructions from proxy records derived from coastal lake and marsh sediments (Liu and Fearn 1993, 1997). Overwash deposits preserved in the sediments of lakes and marshes along the Gulf Coast enable records of prehistoric catastrophic hurricane landfalls from Louisiana to Florida. These records extend back more than 4500 yr before present (BP).

Also, data are used in this study to isolate covariability with hurricane variations. For example, can specific factors be isolated that explain the shift in major hurricane activity? Values of the NAO considered here are obtained from the Climate Research Unit at the University of East Anglia, United Kingdom. Strength of the present work rests with the diversity of data employed. We begin the analysis with a look at variations in major U.S. hurricane activity across the spectrum of timescales.

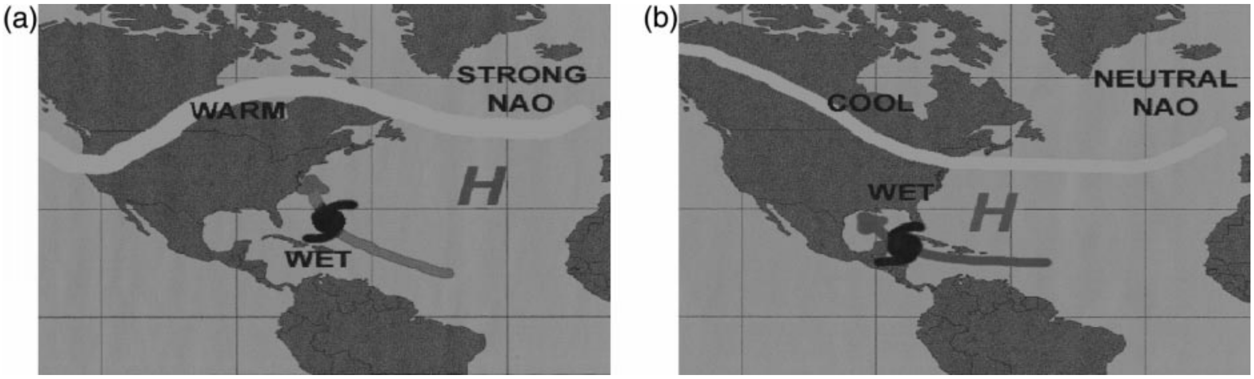

FIG. 3. A sketch of the inferred mean Jul midlatitude jet stream and subtropical high for conditions of (a) strong and (b) neutral NAO. A southwestward shift of the Bermuda high by 3000 yr BP likely brought less precipitation to the northeast Caribbean and more catastrophic hurricanes to the Gulf Coast. Adapted from Liu (1999).

3. Regional variation in major hurricanes: Paleoclimate records

Developments in this field of paleotempestology have allowed the reconstruction of millennial-scale histories of major hurricane landfalls along the Gulf Coast. Five sites of interest along the northern Gulf Coast (Fig. 1) have been cored and examined for sand deposits spanning the last 4500 yr. The sites include Pearl River Marsh, Louisiana, Pascagoula Marsh, Mississippi, Lake Shelby, Alabama, Western Lake, Florida, and Camp Creek Lake, Florida. Figure 2 shows the sand layer stratigraphies of the sites plotted on a time axis given in radiocarbon years BP (Liu 1999). The first layer corresponds to the category-5 Hurricane Camille of 1969. Camille left her mark on the Pearl River and Pascagoula Marshes. Overwash deposits are likely recorded only for category-4 and -5 intensity storms. Large secular variations in major hurricane landfalls are noted over the period. Fewer strikes are inferred during the period 4500–3400 yr BP and during the recent 1000 yr. In contrast, catastrophic hurricane frequencies were high during the period 3400–1000 yr BP. The corresponding landfall probabilities are three to five times higher during this period than during the preceding or ensuing millennia (Liu and Fearn 1999).

The stratigraphic records indicate the possibility of significant low-frequency shifts in major hurricane occurrences along the Gulf Coast. An abundance of proxy data (pollen, tree rings, ice cores) allows inferences concerning Holocene climate variations. It is speculated that this millennial-scale variability is related to changes in the mean position of the Bermuda high as part of hemispheric-scale changes in the climate (Liu 1999; Forman et al. 1995). The mid-Holocene warm period featured a more northerly jet stream across North America allowing a poleward shift of the subtropical ridges. Low-

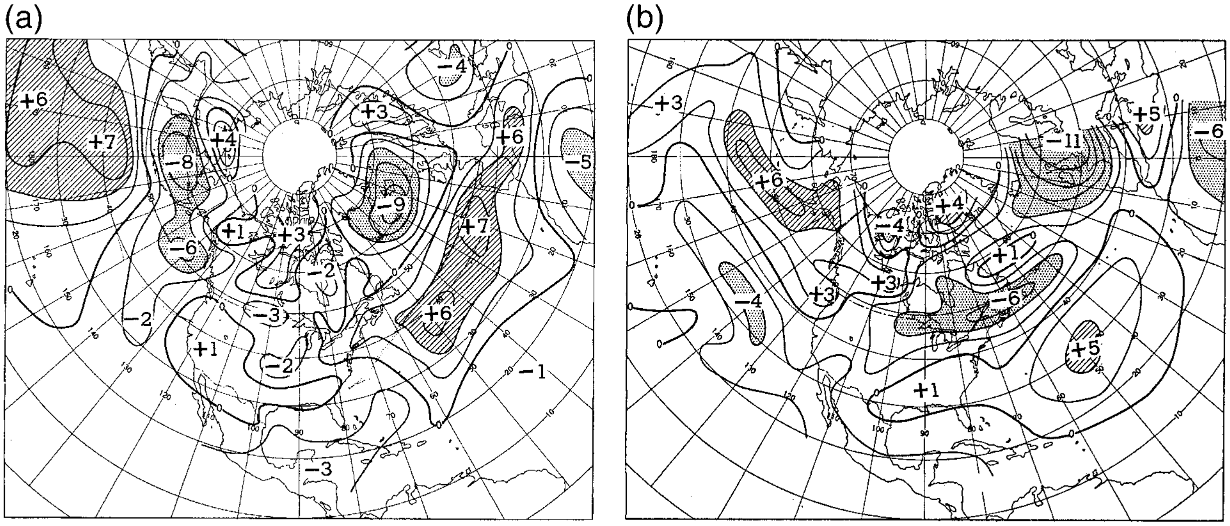

FIG. 4. Height field at 700 mb. Values are average departures from normal in tens of feet for the 5 yr (Aug–Oct) of (a) maximum and (b) minimum tropical cyclone incidence. Values are based on data over the period 1933–55. Reproduced from Ballenzweig (1959).

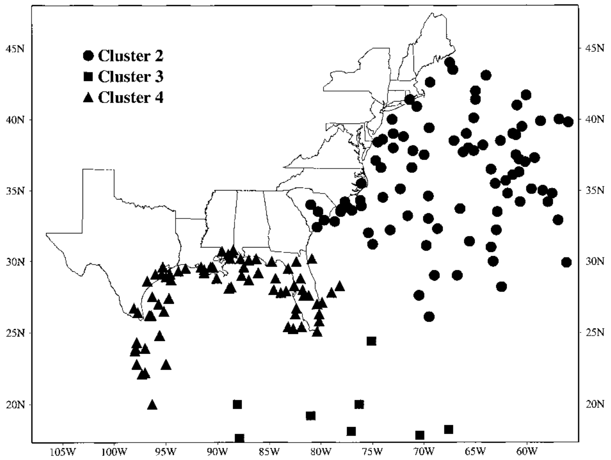

FIG. 5. Cluster analysis of major hurricane dissipation points. The location shows where the hurricane was last at an intensity of 85 kt. Points indicate distinct cluster membership. Note that the Gulf Coast cluster 4 is separated from the East Coast cluster 2. Clusters 1, 5, and 6 occur over the central North Atlantic and are not shown on this map.

TABLE 1. Major hurricanes along the western Gulf Coast, 1801–1920. [L63] refers to the Ludlum 1963 dataset, [F-P/D95] to the Fernández-Partagás and Diaz dataset, and [BT] to the best-track dataset. Here ''H'' is used as an abbreviation for ''hurricane,'' and ''S'' as an abbreviation for ''storm.''

Year	Month	Day	Name/data source
1812	8	19	Great Louisiana H 1812 [L63]
1819	7	27	Bay St. Louis H 1819 [L63]
1821	9	15	September H 1821 [L63]
1831	8	18	Barbados to LA H 1831 [L63]
1837	10	4	Racer's H 1837 [L63]
1852	8	25	Great Mobile H 1852 [L63], S1 (1852) [F-P/D95a]
1854	9	17	Matagorda H 1854 [L63], S3 (1854) [F-P/D95a]
1855	9	15	Mid–Gulf shore H 1855 [L63], S6 (1855) [F-P/D95a]
1860	8	11	1860-H I [L63], S1 (1860) [F-P/D95a]
1860	9	14	1860-H II [L63], S4 (1860) [F-P/D95a]
1860	10	2	1860-H III [L63], S6 (1860) [F-P/D95a]
1875	9	16	S3 (1875) [F-P/D95b]
1879	9	1	S4 (1879) [F-P/D95b]
1880	8	12	S2 (1880) [F-P/D95b]
1886	8	20	S5 (1886) [F-P/D96a]
1893	10	1	S10 (1893) [F-P/D96b]
1900	9	8	[BT], S1 (1900) [F-P/D96b]
1906	9	27	[BT]
1909	7	21	[BT]
1909	9	20	[BT]
1915	8	17	[BT]
1915	9	29	[BT]
1916	7	5	[BT]
1916	8	18	[BT]
1918	8	6	[BT]
1919	9	14	[BT]

TABLE 2. Major hurricanes along the western Gulf Coast, 1921–98. Here [BT] refers to the best-track dataset.

Year	Month	Day	Name/data source
1926	8	26	[BT]
1926	9	21	[BT]
1932	8	13	[BT]
1933	9	4	[BT]
1934	6	16	[BT]
1941	9	23	[BT]
1942	8	30	[BT]
1947	9	19	[BT]
1957	6	27	Audrey [BT]
1961	9	11	Carla [BT]
1964	10	3	Hilda [BT]
1965	9	10	Betsy [BT]
1967	9	20	Beulah [BT]
1969	8	17	Camille [BT]
1970	8	3	Celia [BT]
1974	9	7	Carmen [BT]
1979	9	12	Frederic [BT]
1980	8	9	Allen [BT]
1983	8	18	Alicia [BT]
1985	9	2	Elena [BT]
1992	8	26	Andrew [BT]

and midatmospheric flow around the ridges funneled the hurricanes toward higher latitudes. With a neoglacial cooling of the climate beginning around 3000 yr BP, the jet stream shifted southward with the Bermuda high located closer to the eastern Greater Antilles. This kept the low-latitude hurricanes from recurving, increasing

TABLE 3. Major hurricanes along a portion of the East Coast, 1801–1998. Here [L63] refers to the Ludlum 1963 dataset, [F-P/D95] to the Fernández-Partagás and Diaz dataset, and [BT] to the best-track dataset. Here ''H'' is used as an abbreviation for ''hurricane,'' and ''S'' as an abbreviation for ''storm.''

Year	Month	Day	Name/data source
1806	8	23	Great Coastal H 1806 [L63]
1815	9	23	Great September Gale 1815 [L63]
1821	9	3	Norfolk and Long Island H 1821 [L63]
1827	8	25	Great North Carolina H 1827 [L63]
1842	7	12	Destructive North Carolina H 1842 [L63]
1869	9	8	Sep Gale 1869, East NE [L63], S6 [F-P/D95a]
1879	8	18	S2 (1879) [F-P/D95b]
1899	8	17	No name [BT], S3 (1899) [F-P/D96b]
1906	9	17	No name [BT]
1933	9	16	No name [BT]
1938	9	21	No name [BT]
1944	9	14	No name [BT]
1954	8	31	Carol [BT]
1954	9	11	Edna [BT]
1954	10	15	Hazel [BT]
1955	8	12	Connie [BT]
1955	9	19	Ione [BT]
1960	9	12	Donna [BT]
1985	9	27	Gloria [BT]
1993	8	31	Emily [BT]
1996	9	5	Fran [BT]

TABLE 4. Seasonal distribution of major hurricanes. Values are the percentage of all major hurricanes that occurred by numbered month of the hurricane season from 1801 to 1998.

Location	6	7	8	9	10
NC–ME	0.0	4.5	36.4	54.5	4.5
TX–AL	4.3	6.4	36.2	44.7	8.5

TABLE 5. Hurricane occurrences. Values are the frequency of hurricanes in 50-yr intervals for Puerto Rico, Jamaica, and Bermuda. Bermuda's record begins in 1609. Adapted from Elsner and Kara (1999).

Years	Puerto Rico	Jamaica	Bermuda
1501–50	7	0	—
1551–1600	2	1	—
1601–50	3	0	8
1651–1700	2	4	2
1701–50	9	8	6
1751–1800	10	12	5
1801–50	13	11	9
1851–1900	6	5	10
1901–50	6	5	11
1951–98	2	2	6

the likelihood of landfall along the Gulf Coast. Figure 3 shows a schematic of the situation as illustrated in Liu and Fearn (1999) based on the work of Forman et al. (1995). The contention that geomorphological or sea level changes are responsible for the stratigraphic signatures is largely discounted based on the similarity in records across the region and by the lack of limnological changes in the sedimentary rocks (Liu and Fearn 1999).

4. Regional variation in major hurricanes: Historical records

The inferred inverse correlation in major hurricane activity across the centuries between the Gulf Coast and East Coast is explained by large-scale changes in sea level pressure (SLP) patterns over the North Atlantic. When the position of the subtropical high is favorable for storms to remain south over the Gulf Coast it is less favorable for them to track northwestward and vice versa. Table 5 shows the frequency of hurricanes affecting Jamaica, Puerto Rico, and Bermuda in 50-yr intervals. Data are based on historical records as described in Elsner and Kara (1999). Jamaica and Puerto Rico share the 17°N latitude, while Bermuda is located on the same longitude as Puerto Rico but at 32°N latitude. A likelihood ratio test using a maximum likelihood equivalent of the chi-square statistic for the occurrence of hurricanes over Jamaica and Bermuda is 20.36 with a p value <0.01, indicating a significant (inverse) relationship. In particular, the period from the mid-eighteenth to the mid-nineteenth century featured hurricanes over Jamaica and Puerto Rico, but relatively few storms over Bermuda. The next century experienced a reversal in this pattern with more high latitude storms coincident with relatively fewer storms across the Caribbean.

To examine whether these variations exist on shorter timescales we turn to the historical records. The observation of significant regional variations in major U.S. hurricanes is not new. Namias (1955) noted differences in coastal vulnerability to hurricanes over time. He suggested that vulnerability is related to changes in large-scale midlatitude wave patterns. Using data over the period 1933–55, Ballenzweig (1959) confirmed this notion by noting a large departure in 700-mb height patterns over the North Atlantic between years of high and low hurricane activity. Figure 4 shows the original analysis of Ballenzweig. Years of high hurricane activity featured below-normal August–October heights over Iceland and above-average heights over the Azores. In contrast, years of little hurricane activity featured above-average heights farther to the south and west.

Two interesting points about this early work are made in light of the present study. First, the period of record used by Ballenzweig featured many high latitude major hurricanes. Second, the 700-mb height–hurricane association has yet to be exploited in modeling seasonal hurricane activity. Both these facts point to the possibility that the link between the extratropical circulation and hurricane activity is related to where storms are likely to track rather than to how many occur. That is, North Atlantic pressure patterns influence the general steering flow, but not hurricane development mechanisms. This perspective on hurricane climate that considers the abundance of storms as separate from where they go is a central tenet of the present analysis.

We examine this idea by first considering regional variations in landfalling major hurricanes along portions of the U.S. coastline. Elsner and Kara (1999) suggest an inverse relationship between hurricane activity at low and high latitudes. The relationship holds across a spectrum of timescales. Because of this spatial covariability in hurricane activity across latitudes, we consider major hurricanes along two separate sections of the coastline. Hurricane activity at low latitudes is represented by storms making landfall from Texas to Alabama. Here, we consider the entire northwestern Gulf Coast from Brownsville, Texas, to the Florida border. At high latitudes we consider storms making landfall from North Carolina northward to Maine.

A cluster analysis using distances in spherical coordinates of the locations where major hurricanes decay divides the storms that affect the Gulf Coast and Florida from those that menace the East Coast from South Carolina to Maine (Fig. 5). The method is compact clustering based on Euclidean distance of the positions where major hurricanes weaken to 85 kt or less using the 6-hr best-track intensity and location values. Although this clustering is not used again in the present analysis, and some storms are actually intensifying at landfall, it provides additional justi-

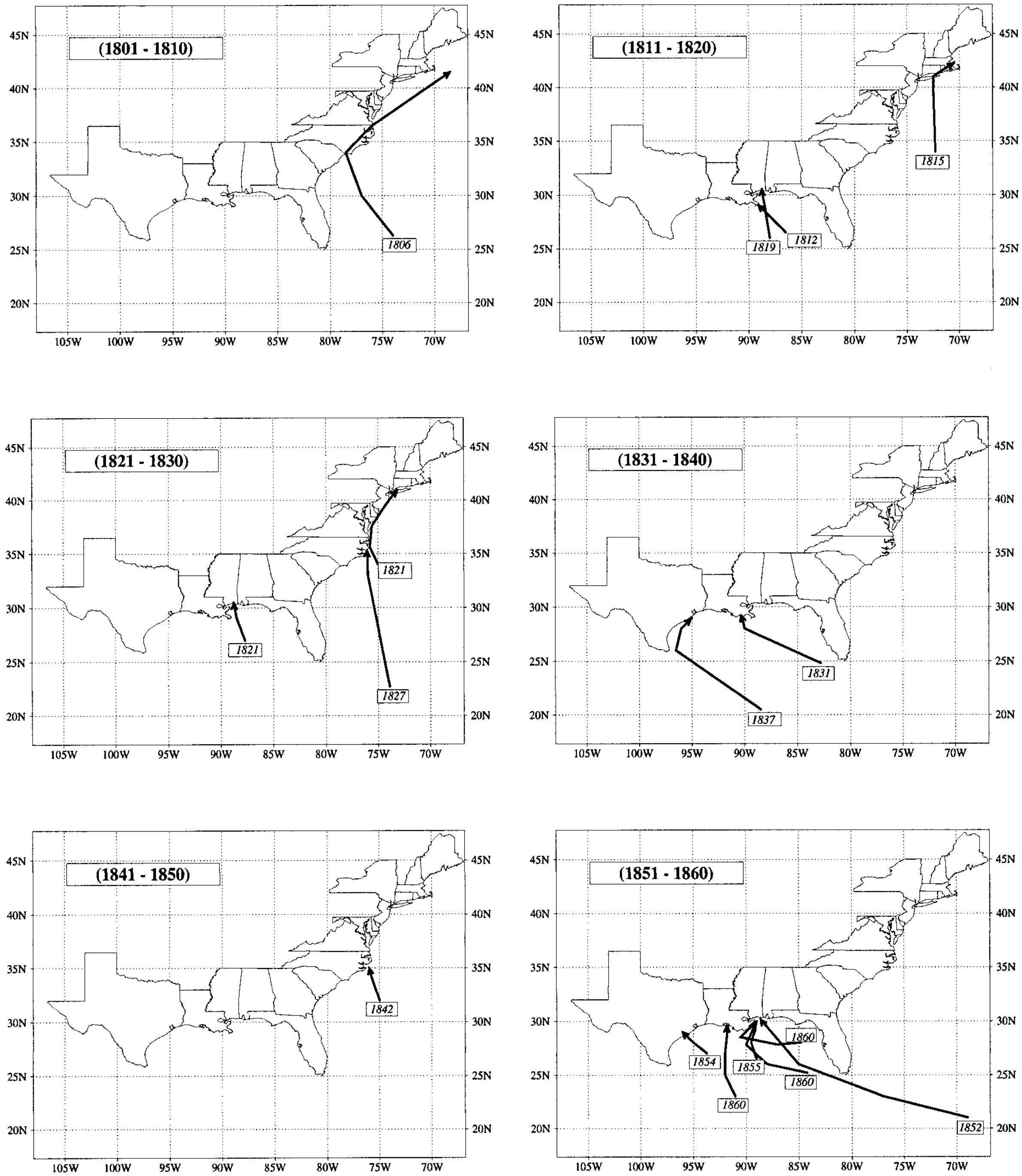

FIG. 6. Major hurricanes along the U.S. coastline (excluding FL, GA, and SC) in 10-yr intervals over the period 1801–60.

fication for considering the Gulf and East Coasts separately as there is a gap between clusters 2 and 4. Note that points in the Gulf Coast cluster align along the immediate coast, whereas points in the East Coast cluster scatter throughout the western North Atlantic, with many located offshore. In excluding the eastern Gulf Coast (Florida) we are further justified by the results of Vega and Binkley (1993) that show an avoidance of tracks over northwestern Florida for storms originating in the Gulf of Mexico and the western Caribbean.

Although our grouping (Gulf Coast: TX–AL and East Coast: NC–ME) could be done in different ways, it balances the twin constraints of exclusivity and sample size. It would be unlikely for a single hurricane to make landfall along both the northwestern Gulf and north-

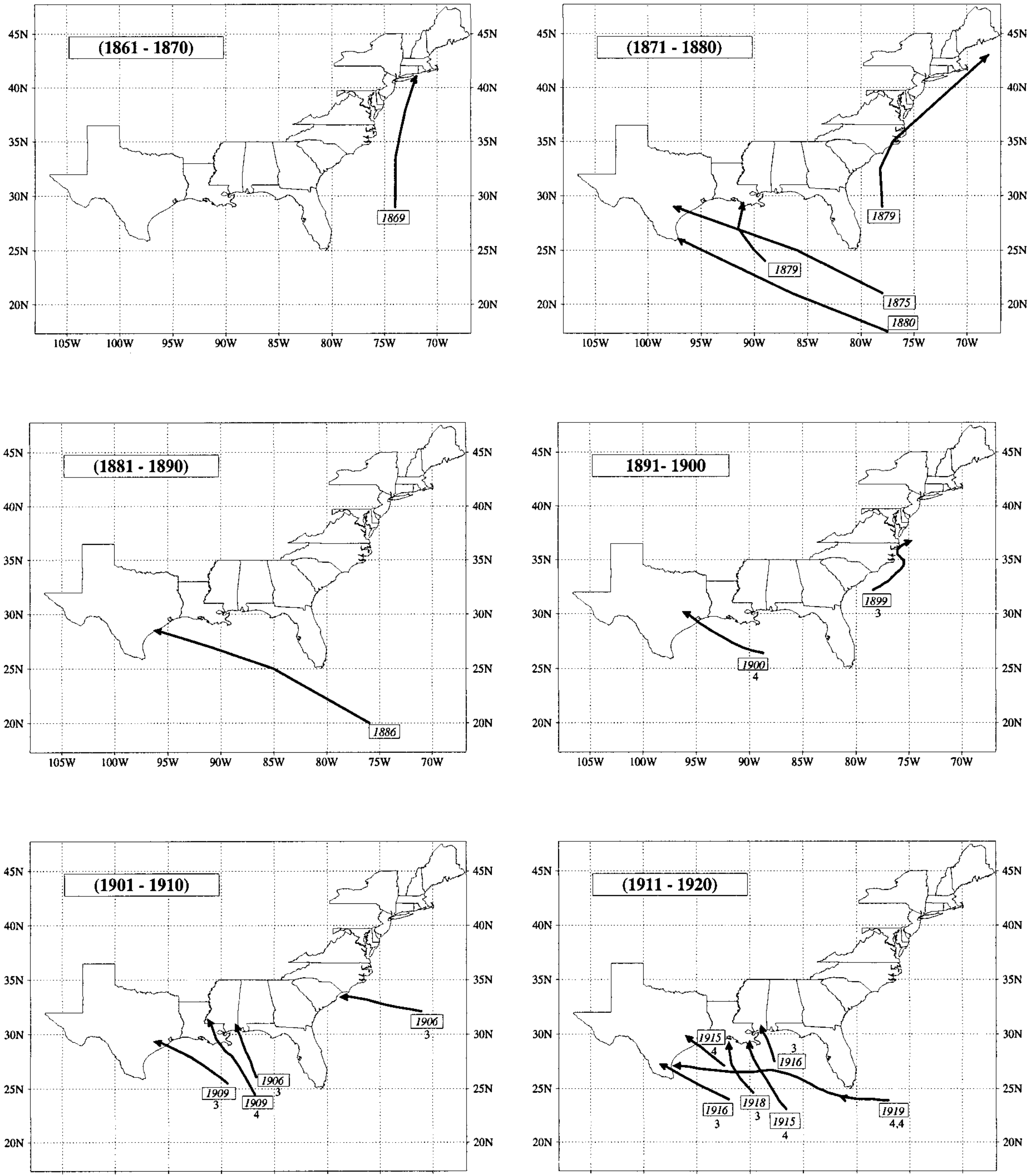

FIG. 7. Major hurricanes along the U.S. coastline (excluding FL, GA, and SC) in 10-yr intervals over the period 1861–1920.

eastern seaboard. Both regions cover a large enough stretch of coastline to have a representative number of major storms. Moreover, both regions have historical records extending back through the nineteenth century. Florida is excluded in the present analysis as the number of major hurricanes to hit the state would overwhelm the statistics of the region it is placed, and because it can be hit by a major hurricane traveling east or west. The historical records are particularly reliable for catastrophic events. Indeed, our focus is on explanation of regional patterns of major hurricane activity. A major hurricane has winds of at least 50 m s^{-1} (100 kt). It is estimated that the strongest 20% of the storms cause 80% of the damage. The present analysis is aimed at a better understanding of climate factors associated with these castastrophic storms.

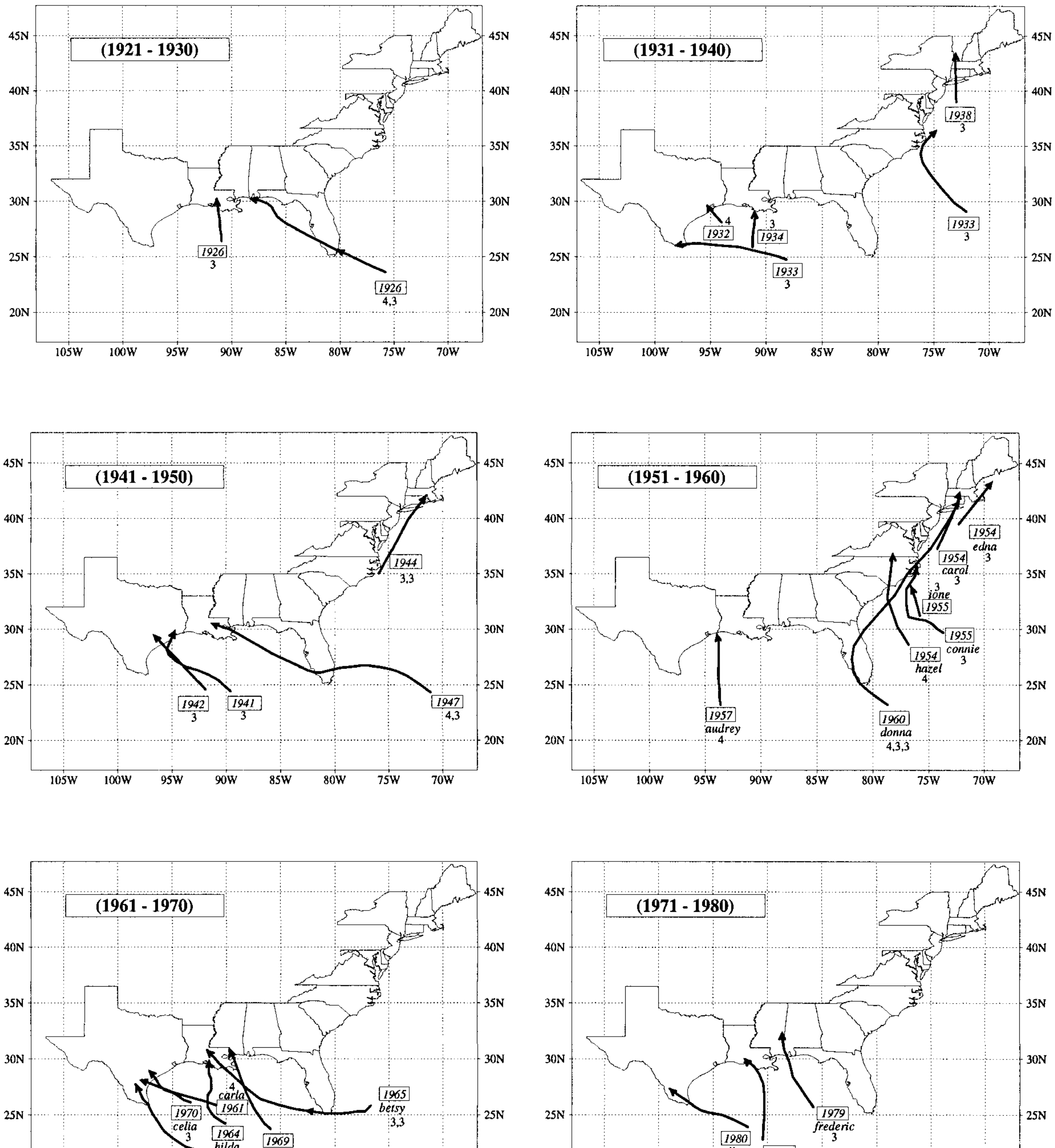

FIG. 8. Major hurricanes along the U.S. coastline (excluding FL, GA, and SC) in 10-yr intervals over the period 1921–80.

a. Seasonal variations

We begin our analysis of the historical record with a look at seasonal variations. Tables 1, 2, and 3 list the major hurricanes that have affected the two regions since 1801. The list includes the year, date, and name of each storm. The date refers to the date of landfall. The lists are a combination of three datasets, as explained in the previous section. Over the 198-yr period (1801–1998) there are 21 major East Coast U.S. hurricanes. Of these, 19 (90%) made landfall during August or September with 50% more landfalls in September than in August (Table 4). One East Coast major hurricane made landfall in July and one hit during October. In comparison, 47 major hurricanes hit the U.S. coastline from Texas to Alabama during the recent bicentennial period with 81% of the strikes occurring during August or September.

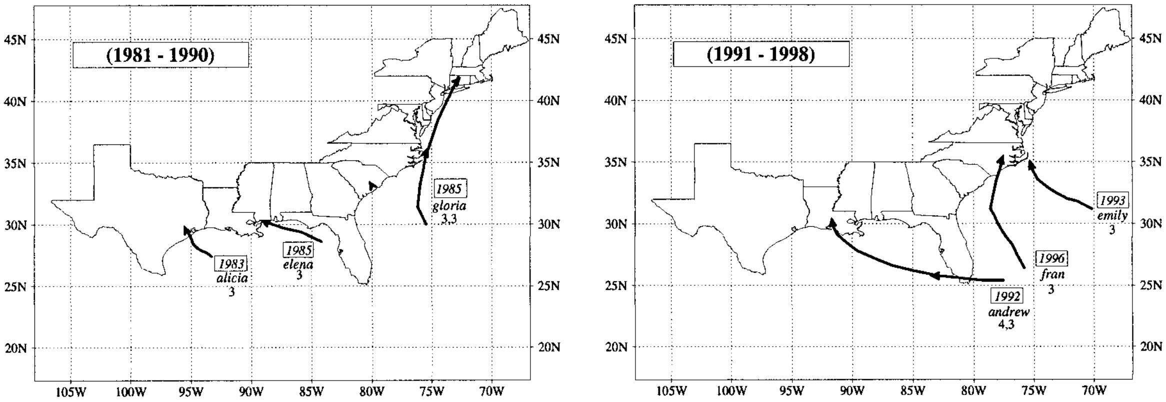

Fig. 9. Major hurricanes along the U.S. coastline (excluding FL, GA, and SC) in 10-yr intervals over the period 1981–98.

However, in contrast to the East Coast, September sees only 25% more hits than August. Over the entire U.S. coastline, September is more active than August by a margin of 2 to 1. For the Gulf Coast no month has a simple majority (exceeds 50% of the seasonal activity). The Gulf Coast has a predominantly east–west orientation that makes it less sensitive to subtle shifts in track recurvature that are unrelated to large-scale climatic changes.

Most noteworthy are the early season strikes along the Gulf. Better than 10% of all major Gulf Coast storms hit before 1 August. Normalized by the start of the season, as defined by the occurrence of the first tropical storm, only two of the nine major East Coast hurricanes since 1951 were designated as the first, second, or third tropical storm of the season. This compares to 10 of the 13 Gulf Coast major hurricanes over the same period. The formation of early season major hurricanes is coincident with a more southerly displaced jet stream and subtropical high, with most storms originating over the Gulf of Mexico and western Caribbean Sea. The average strike date for major Gulf Coast (East Coast) hurricanes is 30 August (6 September). If the start of the season is defined as the date of the occurrence of the first hurricane, and the number of days from this date to each landfall is recorded for all major hurricanes, then we find that Gulf Coast landfalls occur significantly earlier (p value $= 0.017$ using a one-sided t test).

b. *Decadal variations*

The occurrence of major landfalling hurricanes is a rare event, not likely to happen every year, particularly over limited subregions of the coastline. Variations in occurrence can be examined over time by considering events over a group of years. Here we look at the hurricanes in 10-yr intervals beginning in 1801 (Figs. 6–9). All known storms that have made landfall as major hurricanes in the two regions are plotted.[1] Some interesting patterns emerge. In particular the first two decades of the twentieth century featured many Gulf storms with no storms along the northeast coastline (see also Gray et al. 1997). During the 1930s and 1940s there was activity all along the U.S. coastline, but during the 1950s the focus shifted almost exclusively to the East Coast. The pattern shifted again during the 1960s and 1970s, with most storms making landfall to the west of Florida. The 1980s and 1990s show a return of major hurricanes to the northeast.

These plots hint at an inverse relationship between activity in the Gulf and the East Coast. That is, decades of heightened activity at low latitudes along the Gulf are coincident with less activity at higher latitudes along the northeast coast. To test whether or not Gulf Coast and East Coast major landfalls are in fact independent on the decadal timescale we create a 20×2 contingency table containing the decadal number of hurricanes in both regions. The maximum likelihood equivalent of the chi-square statistic for the data in the table is 34.53 with a p value of 0.016, guiding us to reject the null hypothesis of independence with the caveat that the expected frequencies are small during most decades. The dependence arises from the inverse relationship between activity across latitudes.

The latitudinal variation in major hurricane landfalls might be related to their longitude of formation. Tropical storms that become hurricanes over the eastern Atlantic are more likely to reach the coastline at a higher latitude, whereas storms that develop farther west are more likely to make landfall at lower latitudes along the Gulf Coast. Patterns of tropical cyclone activity over the Caribbean during the twentieth century suggest this is the case. In the 1910s and 1920s, when major hurricanes occurred

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[1] The prelandfall tracks for storms before 1871 are based on their impact on islands and shipping and are thus less reliable and less comprehensive.

along the Gulf Coast, the main Caribbean activity was located farther to the south and west. Activity shifted eastward over the Caribbean during the 1940s and 1950s (Walsh and Reading 1991) creating a greater threat to the East Coast.

Here we have established a geographic pattern in the covariability of major hurricane occurrences across the North Atlantic. The variability shows up on the seasonal, decadal, and millennial timescales. Recent research has identified a possible mechanism for the millennial-scale variability related to atmospheric pressure patterns across the North Atlantic.

5. Relation to the North Atlantic oscillation

Based on the above analyses we speculate that the latitudinal variations in hurricane activity on the interannual to decadal timescale might be linked to geographic variations in SLPs across the North Atlantic [see also Vega and Binkley (1993)]. The proximal stearing of hurricanes is the positioning of the subtropical ridges across the North Atlantic. A strong, broad high pressure ridge situated over the western North Atlantic keeps the deep tropical hurricanes from recurving northward. This is a situation conducive to major Gulf storms. With the ridge farther north and east, the East Coast is in the path of recurving major hurricanes, although most remain out to sea. This is consistent with the suggestion of Walsh and Reading (1991) that the Caribbean is more vulnerable to tropical cyclone activity when the subtropical high is positioned farther to the west and south. Ultimately the position and strength of the subtropical high is related to a principal north–south dipole in SLPs as measured by the NAO.

The NAO is a coherent north-to-south seesaw pattern in sea level pressures between Iceland and the Azores. When pressures are low over Iceland (Icelandic low) they tend to be high over the Azores (Azores high) and vice versa. The NAO represents a significant regional climate fluctuation (Lamb and Peppler 1987; Wallace and Gutzler 1981; Bjerknes 1964) and appears as an important pattern of global interannual variability (Hurrell and van Loon 1997; Mann and Park 1994). The intensity of the NAO determines the position and orientation of the midlatitude jetstream through variations in horizontal pressure gradients. Salient to this study is the fact that the out-of-phase relationship in SLPs across latitudes spans an extended range of timescales (Rajagopalan et al. 1998).

It is likely that the NAO is the atmospheric component of an atmosphere–ocean coupling. An excited NAO is associated with a zonal (west to east) temperature gradient featuring above-normal values over Greenland and below-normal values over northern Europe, with a relaxed NAO associated with a reversal in the zonal temperature gradient. An excited NAO mode is also associated with stronger westerly winds and higher than normal SSTs for a large part of the northern North Atlantic. Greater sea ice is noted in the Davis Strait and less sea ice in the Denmark Strait (Barlow et al. 1993).

Because of the inverse relationship, an index of the NAO is commonly taken as the difference in pressures (NAO index $= \mathrm{SLP}_{\mathrm{Azores}} - \mathrm{SLP}_{\mathrm{Iceland}}$). When pressures are simultaneously high over the Azores and low over Iceland the value of the NAO index is large. Although NAO pressure differences are strongest during the boreal winter, the signal is robust during spring and summer (Rogers 1990). Hurrell and van Loon (1997) show that the signal-to-noise ratio of the NAO index computed using Stykkisholmur, Iceland, and Ponta Delgada, Azores (see Jones et al. 1997), is 1.5 for the 3-month averaged pressure anomalies from July through September. Figure 10 shows the NAO index based on normalized July average pressures at these two stations. The pressures are normalized by subtracting the mean and dividing by the standard deviation over the 133-yr period (1865–1997). Large fluctuations are noted from year to year in the July values. A 10-yr running mean shows periods of excited (large positive) and relaxed (weak negative) NAO. In particular, the period from the mid-1920s through the 1930s featured very high values of the NAO index with the 1960s and 1970s featuring lower values. The 1950s was also a period of high values of the NAO index.

More quantitatively we retrospectively examine the years in which major hurricanes occurred over the Gulf and East Coasts in terms of the NAO. Thirteen of the years for which NAO values are available had at least one East Coast major storm. This compares with 32 years with at least one Gulf Coast major hurricane. Of these, 4 years (1879, 1906, 1933, and 1985) had both an East and Gulf Coast major landfall. The average July NAO index value during years with Gulf Coast storms is $+0.183$ compared to $+0.975$ during years with East Coast storms. The p value based on a one-sided t test is 0.039, guiding us to reject the null hypothesis that the difference is due to chance. A one-sided test is justified on the basis that the hypothesis generated from the paleoclimate data suggested East Coast activity is more likely when the subtropical high is located farther north and east. Removing the overlap years increases the p value only slightly to 0.043. Similarly, for years in which pressure values are available for Iceland and at least one East Coast major hurricane, the average SLP is 1008.9 mb. This compares with 1010.0 mb for years with at least one Gulf Coast major hurricane. A deeper Icelandic low is associated with an intensified NAO.

Another way to look at the differences in hurricane activity with respect to the phases of the NAO is through a bootstrap analysis. For the East Coast the 13 values of the NAO are resampled with replacement 10^4 times. For the Gulf Coast, 10^4 samples of 13 yr each are taken from the 32 values. Using the same number of years ensures equal areas under the curves. The bootstrap distributions are shown in Fig. 11. Years of East Coast major hurricane activity are more likely to have above-

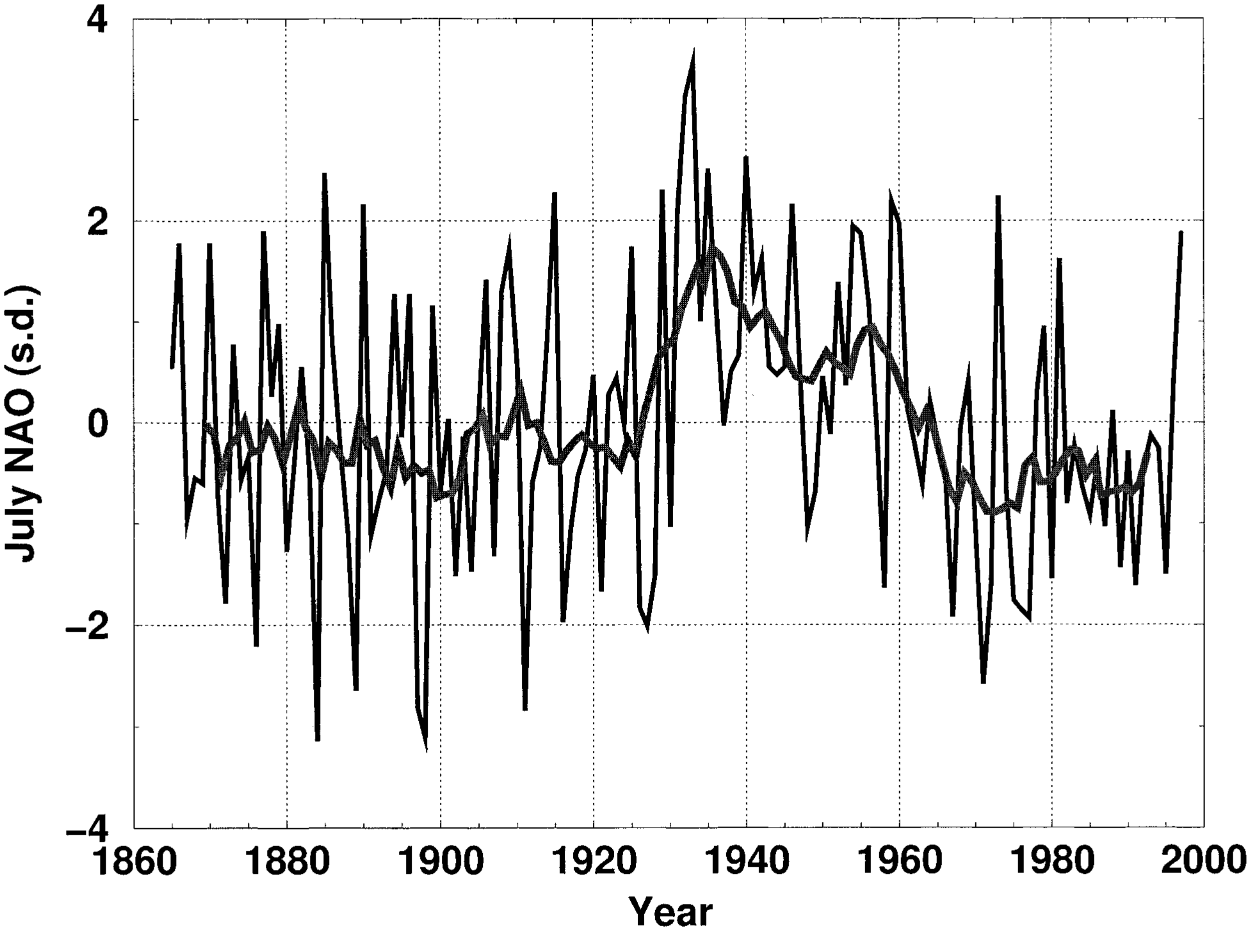

FIG. 10. Jul values of the NAO based on the difference in normalized sea level pressures between Ponta Delgada, Azores, and Stykkisholmur, Iceland. The values are differences in standardized deviations. The thick line is a 10-yr running average.

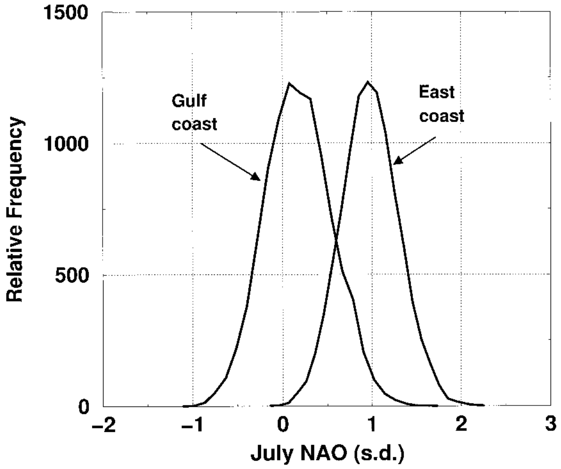

FIG. 11. Bootstrap distributions of the Jul NAO values for years with at least one major hurricane along the Gulf (TX–AL) and for years with at least one major hurricane along the East Coast (NC–ME). The ordinate values are relative frequency from 10^4 samples.

normal values of the NAO index compared with years in which the Gulf Coast gets hit. The 90% confidence interval around the mean value of the NAO index for Gulf Coast years is (-0.417, $+0.806$), which compares with an interval of ($+0.448$, $+1.518$) for East Coast years. The 20-yr period 1951–70 offers a striking contrast in major hurricane activity along the U.S. coastline, as shown in Fig. 8. The 1950s featured six East Coast major hurricanes and only one Gulf Coast storm, while the following decade featured six Gulf Coast major hurricanes and no East Coast storms. The July NAO index averaged $+0.918$ during the 1950s and -0.377 during the 1960s. Moreover, the second decade of the twentieth century (1911–20) saw six major Gulf Coast hurricanes when the summertime NAO index averaged -0.390 for the decade. These differences in the NAO imply contrasting North Atlantic climate regimes responsible for variations in major hurricane activity along the U.S. coastline.

The North Atlantic Ocean displays variations across a spectrum of temporal scales. In general, variations in North Atlantic SLPs respond to changes in SST patterns.

However, on the interannual to decadal timescales SSTs can respond to SLPs through variations in air–sea fluxes (Delworth 1996). On the decadal and longer timescales ocean dynamics are driving the system (Grötzner et al. 1998). Secular variations in principal large-scale SSTs over the North Atlantic during the past century indicate a cold ocean until about 1930 followed by warming through the 1950s with a return to cold conditions during the 1960s (Kushnir 1994). The cold conditions have recently given way to a warmer North Atlantic. These SST variations are roughly inversely correlated to Iceland SLPs. Thus the NAO serves as a proximal cause to shifts major hurricane tracks on long timescales, with the ultimate explanation linked to variations in SSTs. In turn, variations in basinwide SSTs are linked to changes in ocean circulation.

The interdecadal pattern of SSTs is focused in areas surrounding Iceland where North Atlantic deep water formation occurs (Kushnir 1994). Warm surface waters moving northward are cooled by heat loss to the atmosphere. More importantly, the water arrives with high salinity (greater density) creating subsidence and a return flow at depth. The counterbalancing deep, dense return flow crosses the Iceland–Scotland ridge via the Faeroe Bank channel into the Iceland basin, combining with a similar dense flow through the Denmark Strait (Bianchi and McCave 1999) before exiting the Atlantic basin. This large-scale meridional overturning circulation is the North Atlantic component of the global thermal haline circulation. Both model and observations indicate the circulation fluctuates on interdecadal timescales (Weaver and Sarachik 1991; Delworth et al. 1993) and is sensitive to a regional balance of fresh- and saltwater (Broecker et al. 1990). Variations in the deep water transport influence tropical and subtropical ocean circulations including the latitudinal position of the warm Gulf Stream waters across the western North Atlantic. On longer timescales there is evidence of a quasiperiodicity at approximately 1500 yr in this global ocean circulation (Bianchi and McCave 1999). This corresponds to the timescale of changes in major hurricane activity along the Gulf Coast as inferred from the geologic record.

6. Summary

Major landfalling hurricanes are of significant societal concern. The changing threat of a category-4 or -5 hurricane over highly developed New England needs to be quantified. Although we do not address the vulnerability on the scale of individual cities, we attempt to document and to explain what causes the differences in the likelihood of major hurricanes along the northern Gulf Coast and eastern seaboard. The results reaffirm an earlier finding that periods of above-normal activity along the Gulf Coast appear to be out of phase with periods of above-normal major hurricane activity along the northeast coast (Elsner and Kara 1999). This is consistent with an inverse correlation in hurricane activity across latitudes. A novel finding is that the inverse relationship can be identified on several different timescales.

Recent findings from paleotempestology have linked variations in catastrophic hurricane activity along the Gulf Coast to low-frequency shifts in the position of the subtropical high over the North Atlantic. Historical records also suggest a connection between the position of the subtropical high and tropical cyclone activity over the Caribbean (Walsh and Reading 1991). As tropical cyclones tend to recurve around the subtropical ridge, the location of the ridge determines the corridors of hurricane activity. When the high is located farther west and south, storms that develop remain at low latitudes and track through the Caribbean Sea rather than recurve toward the East Coast. On the other hand, when the high is farther east and north, major hurricanes are steered across the western Atlantic. We expand on this finding to show that such shifts occur on the interannual and interdecadal timescales, as inferred by fluctuations in the NAO. The intensity of the NAO is linked to variations in the jet stream and thus to regional climate anomalies across Europe and North America. An excited NAO is associated with a hypothesized ‘‘fingerprint’’ of global warming featuring relatively warm continents and cool oceans. It is proposed that these findings and elucidations will lead to improvements in the specificity of hurricane climate forecasts. We are currently developing a dynamic probability model using a maximum likelihood approach.

7. Conclusions

The principal findings of this study are as follows.

1) Spatial variations in major hurricane activity across the North Atlantic occur on millennial, decadal, and seasonal timescales.
2) On decadal and longer timescales, when hurricane activity is above (below) average at high (low) latitudes it is below (above) average at low (high) latitudes.
3) These variations are linked proximally to the position of the subtropical high and to the intensity of the NAO.
4) An excited (relaxed) NAO is associated with higher (lower) latitude recurving (nonrecurving) hurricanes.
5) The Gulf Coast (East Coast) is more susceptible to a major hurricane strike during a relaxed (excited) NAO.

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