Interannual and Decadal Variability of Landfalling Tropical Cyclones in the Southeast Coastal States of the United States

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ABSTRACT

The interannual variability of the Atlantic tropical cyclone (TC) frequency is well known. Separately, recent studies have also suggested that a much longer, multidecadal (40–60 year) trend might be emerging from the recent increase in Atlantic TC activity. However, the overall structure of the intrinsic frequencies (or temporal modes) of Atlantic TC activity is not yet known. The focus of this study is to systematically analyze the intrinsic frequencies of Atlantic TC activity using hurricane and tropical storm landfall data collected along the southeast coast (SEC) of the United States. Based on an Empirical Mode Decomposition (EMD) analysis of the frequency of landfall TCs along the SEC from 1887–1999, we have found that Atlantic TC activity has four primary, temporal modes. The interannual and multidecadal modes reported in the published literature are two such modes. After identifying all primary modes, the relative importance of each mode and its physical cause can be analyzed. For example, the most energetic mode is the interannual mode (2–7 year period). This mode is known to be associated with the 2–7 year El Niño / La Niña cycle. The average number of annual landfalling TCs along the SEC decreased by 24% during El Niño years, but did not show significant increase during weak and moderate La Niña years. However, intense La Niña years were generally associated with more than average landfalling TCs along the SEC. The effects of El Niño and La Niña also became more significant when only hurricanes were considered. The significance of the effects of El Niño and La Niña on landfalling TCs and hurricanes in different US southeast coastal states showed significant differences.

Key words: tropical cyclone, empirical mode decomposition, El Niño, decadal variability

1. Introduction

The fact that Atlantic tropical cyclone (TC) activity varies at on interannual (2–7 year) time scale is well documented (e.g., Gray 1984a; Shapiro 1987). These authors also showed that a leading cause for the interannual variability of Atlantic TC activity is the El Niño / Southern Oscillation (ENSO) phenomenon. The ENSO phenomenon is known to affect the vertical wind shear via its influence on the Walker circulation over the tropical Atlantic Ocean resulting in a stronger (weaker) shear during El Niño (La Niña) years and hence an unfavorable (favorable) condition for Atlantic TC development. ENSO events are also

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correlated to the interannual changes of landfalling TC frequency along the United States (US) southeast coast (SEC). Pielke and Landsea (1999) documented the economic consequences due to hurricanes striking the US southeastern coastal states, finding La Niña years exhibiting much more damage than El Niño years. In addition to ENSO, several other factors were also found to affect the interannual changes of Atlantic TC frequency. These factors include: the lower stratospheric quasi–biennial oscillation (QBO) which affects vertical wind shear; western Africa rainfall anomalies which reflect the intensity of African waves known to be the seeds of most intense Atlantic hurricanes; and local factors such as sea level pressure, middle and lower tropospheric moisture, and tropical Atlantic sea surface temperature (SST) (Gray 1984a; Shapiro 1989; Gray 1990; Landsea et al. 1992). These studies have led to the development of statistical prediction models for seasonal Atlantic TC activity (Gray 1984b; Gray et al. 1993).

Separately, Goldenberg et al. (2001) pointed out the existence of a multidecadal (40–60 year) period in the activity of major Atlantic hurricanes since 1944. This is evidenced by the relatively quiescent period of 1970–1994 and the resurgence of TC activity in the Atlantic Ocean since 1995. *Goldenberg et al. (2001) suggest that the multidecadal variability of* Atlantic TC activity is caused by the variability of tropical Atlantic SST and vertical wind shear that occur at a similar time scale.

Two important questions remain unanswered. First, in addition to the interannual and the decadal variability, are there other preferred frequencies of Atlantic TC activity? The overall structure and the significance of all major temporal modes of Atlantic TC activity are poorly understood. Second, at the interannual time scale, although a negative correlation between the annual number of TC occurrence and eastern tropical Pacific SST anomaly exists, it is not known whether a similar correlation exists between the Atlantic TC landfall frequency along different sections of the US southeastern seaboard and the eastern tropical Pacific SST anomaly.

The above two issues are the focus of this study. First, the interannual variability of landfalling TCs in three US southeastern coastal states (North Carolina, South Carolina, and Florida) and its correlation with the ENSO phenomenon are analyzed. Then, the overall structure and the dominant frequencies of the temporal variability of landfalling TCs along the US SEC are investigated by using the Empirical Mode Decomposition (EMD) method (Huang et al. 1998).

2. The EMD method

Empirical Mode Decomposition (EMD), a recent mathematical development (Huang et al. 1998), has been shown to be very useful in the analysis of nonlinear and non–stationary data. The basic idea of EMD is the decomposition of a time series into a finite set of ' intrinsic mode functions' (IMFs) that admit a well–behaved Hilbert transform. Each mode is represented as a function of both instantaneous frequency and amplitude, and hence, describes the scale and energy characteristics at any time. The sum of all modes gives the full description of the frequency and time characteristics of the signal. Below, we will provide a brief description of the EMD method.

An arbitrary, realvalued time series, $f(t)= L^2(R)$,, has Hilbert transform $g(t)$,

$$g(t)=\frac{1}{\pi}P\int_{-\infty}^{+\infty}\frac{f(t')}{t-t'}dt' , \tag{1}$$

where P is the Cauchy principal value. A unique analytic function $z(t)$ can be defined by the complex conjugate pair $f(t)$ and $g(t)$,

$$z(t)=f(t)+ig(t)=a(t)e^{i\theta(t)} , \tag{2}$$

where $a(t)$ and $\theta(t)$ are the local amplitude and phase, respectively, defined by

$$a(t)=[f^2(t)+g^2(t)]^{1/2} , \quad \theta(t)=\arctan\left[\frac{g(t)}{f(t)}\right] . \tag{3}$$

From (3), the local or instantaneous frequency can be derived as

$$\omega=\frac{d\theta(t)}{dt} . \tag{4}$$

In contrast to the EMD method, traditional Fourier Analysis (FA) transfers the time series from the time domain to the frequency domain with constant amplitude and frequency, without any resolution in the time domain. FA describes the structures of a signal in the frequency domain globally, so the frequency structure of the signal is constant in time. The EMD method also differs from the Wavelet Analysis (WA) method (Chan 1995). In recent years, WA has been used in the analysis of non–stationary signals such as the ENSO time series (Torrence and Webster 1999). While WA provides definite resolutions in both the time and frequency domains, and can also be used to study local structures of signals, it is an adjustable–window FA and is thus basically a linear analysis. Explaining a nonlinear phenomenon by adding non–existing harmonics is a process lacking in physical content.

The challenge in EMD analysis is the identification of the IMFs from the original signal. Huang et al. (1998) proposed a simple sifting process to extract the IMFs. This process uses the envelopes defined by the local maxima and minima of the time series separately. An upper (and lower) envelope is generated through all local maxima (and minima) and connected by an upper (lower) cubic spline. The difference between the signal $f(t)$ and the mean of the upper and lower envelopes m_1 is h_1. Huang et al. (1998) provided a criterion to determine if h_1 is an IMF. If h_1 is not, the same procedure is repeated k times until h_1 becomes the IMF $h_{1,k}$, which is the first mode. Following the above procedure, we obtain all of the modes. The last mode is either the lowest frequency trend or a constant. Thus, a mean or zero reference is not needed for application of the EMD method. For more details and examples of EMD analysis, the readers should consult Huang et al. (1998) and Huang et al. (1999).

3. Data

The Atlantic TC landfall data are derived from the US National Oceanic and Atmospheric Administration's (NOAA) historical hurricane database (Jarvinen et al. 1984) available online at: http: / / www.nhc.noaa.gov. We chose to employ the TC landfall data since it is more reliable than TC data for open ocean areas, particularly prior to the start of routine aircraft TC reconnaissance (Goldenberg et al. 2001). In this study, landfalling TCs along the US East Coast (EC) are hurricanes and tropical storms that made landfall along the east and west coasts of Florida (FL), and the Atlantic coast of Georgia (GA), South Carolina (SC), North Carolina (NC) and Virginia (VA). Similarly, landfalling TCs along the US SEC are those TCs that made landfall along the Gulf Coast states or along the US Atlantic coast from Florida to Virginia. Landfalling TCs in a given state (NC, SC, FL) refers to hurricanes and tropical storms that either made a direct hit along the coast of that state or entered that state after making initial landfall elsewhere. Hurricanes that moved along the coast with eyewalls partially encountering the coastline are also counted as landfalling TCs.

The El Niño / La Niña years since 1925 are based on Pielke and Landsea (1999). It is based on the tropical Pacific SST anomalies in the Nino 3.4 region (referred to as the Nino 3.4 SSTA, hereafter). The more complete ENSO time series from 1887–1999 is based on the Japan Meteorological Agency (JMA) SST anomalies (referred to as the JMA index hereafter), which are annual mean SST anomalies for the area 4°S–4°N and 150°–90°W (Meyers et al. 1997).

4. Results

4.1 *Climatology and interannual variability*

Figure 1a shows the annual TC landfall frequency along the US SEC from 1887 to 1999, superimposed with the JMA index. The correlation coefficients between the TC time series and the JMA index (black curve) and the Nino 3.4 SSTA (gray curve) are displayed in Fig. 1b as a function of the year when the correlation began. For example, the correlation coefficient indicated by the thick black curve represents the correlation between the TC series and the JMA index from 1899–1999. Figure 1b shows that the TC time series is negatively correlated with the JMA index as well as with the Nino 3.4 SSTA. The correlation between the TC time series and JMA index agrees well with that between the TC time series and the Nino 3.4 SSTA, and both exceeded the 95% significance level, except during the period from 1956 to 1974. Thus, in the following description, the JMA index will be used when we refer to ENSO events since it has a longer record. For the US SEC as a whole, an average of 3.23 TCs made landfall annually (Table 1). The mean annual frequency of landfalling TCs along the US SEC decreased by 24% to 2.47 events per year (e / yr) during El Niño years, confirming the well-documented effect of El Niño on landfalling TCs along the US SEC. The impact of all La Niña events on landfalling TCs along the US SEC is relatively small. However, the effect is considerably enhanced when only intense La Niña events are considered, namely an increase in the annual frequency of landfalling TCs in the SE by 26% from 3.23 e / yr to 4.06 e / yr. On the other hand, intense El Niño events are no more significant than weak and moderate El Niño events in modulating SE landfalling TC frequency.

When only hurricanes are considered (i.e., excluding all tropical storms), the effects of El Niño and La Niña become more significant. On average, the annual frequency of landfalling hurricanes along the SEC decreased by 28% (increased by 34%) from 1.52 e / yr during normal years to 1.09 (2.03) e / yr in El Niño (La Niña) years. This conclusion can also be reached by considering the landfalling TCs (hurricanes) along the US East Coast from Florida to Virginia.

The significance of the effects of El Niño and La Niña on landfalling TCs varies from state to state. For the top three states that experienced the most landfalling TCs along the US East Coast (FL, NC, and SC), the effect of ENSO is most significant in NC. The correlation between TC landfall frequency in NC and the ENSO index generally exceeded that between the SEC TC and the ENSO index, particularly after 1917 (Fig. 1b). In NC, the annual frequency of landfalling TCs is 0.81 e / yr during normal years, 0.56 e / yr during El Niño

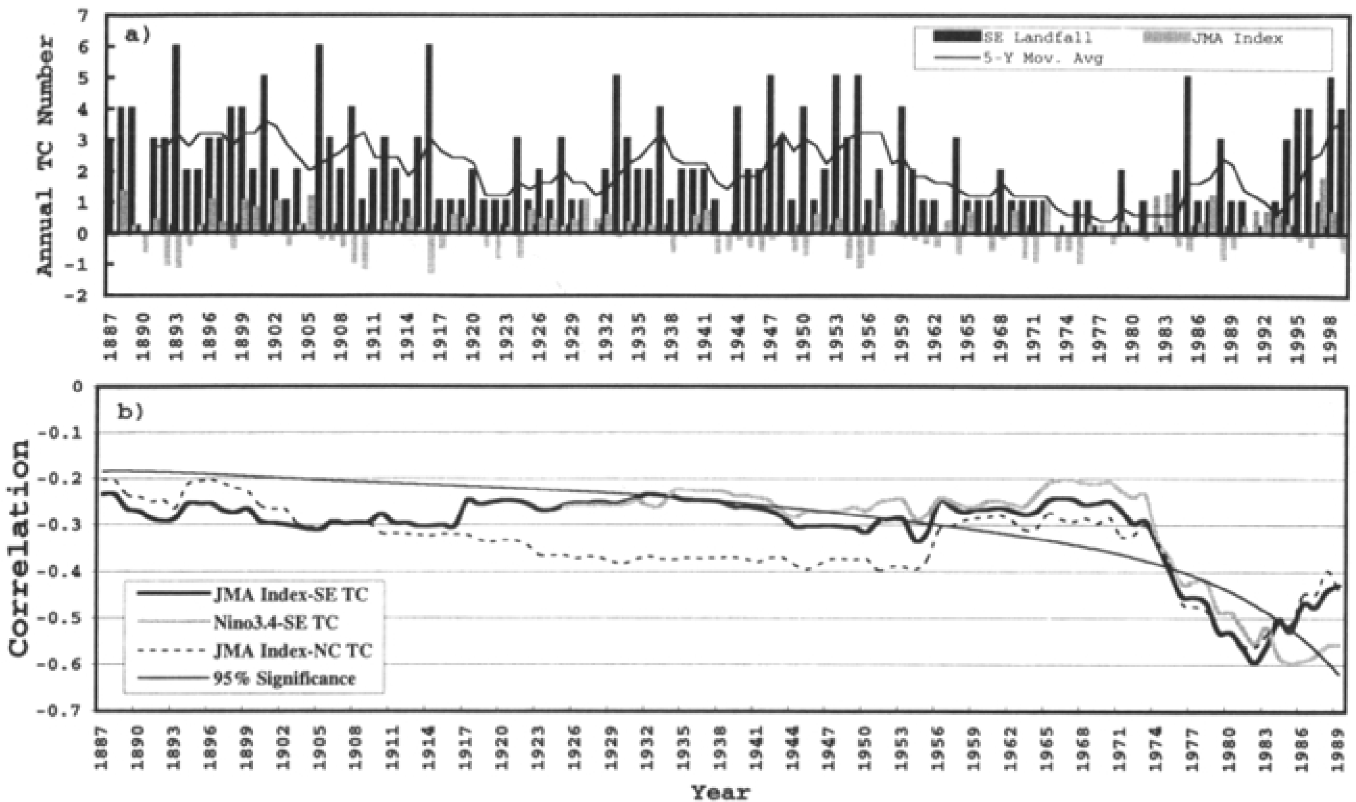

Fig. 1. (a) Annual number of landfalling tropical cyclones (TCs) along the U.S. Southeast Coast (US SEC) from 1887–1999 (dark bar) and the 5–year moving average (gray curve). The tropical Pacific Nino 3.4 SST anomalies (gray bar) (from Pielke and Landsea 1999) and the JMA index (narrow bar) (Meyers et al. 1997) are superimposed. (b) Correlation between US SEC landfalling TCs and JMA index (black curve), as well as the correlation with the Nino 3.4 SST anomaly (gray curve). The correlation is displayed as a function of the year when the correlation began. The 95% significance level is indicated by the thin curve. The thin broken curve indicates the correlation coefficients between annual NC landfalling TC frequency and the JMA ENSO index.

Table 1. Statistics of annual landfalling TC and hurricane numbers along the SEC

	Normal Yrs	El Niño Yrs	Intense El Niño Yrs	La Niña Yrs	Intense La Niña Yrs
SE TC	3.23	2.47	2.67	3.41	4.06
SE Hurricane	1.52	1.09	1.17	2.03	2.40
NC TC	0.81	0.5	0.67	1.24	0.87
NC Hurricane	0.29	0.12	0.17	0.44	0.53
FL TC	1.60	1.09	1.33	1.5	1.93
FL Hurricane	0.64	0.47	0.67	0.97	1.07
SC TC	0.22	0.18	N / A	0.25	N / A
SC Hurricane	N / A	N / A	N / A	N / A	N / A

Note: N / A indicates insufficient sample size for statistical analysis.

years, and 1.24 e / yr during La Niña years. This represents a 30% reduction (53% increase) of landfalling TCs in NC during El Niño (La Niña) years. The annual landfalling TC rates in SC during normal, El Niño, and La Niña years were 0.22, 0.18, and 0.25 e / yr, respectively, which indicates that the number of TCs that made landfall in SC decreased by 14% (increased by 18%) during El Niño (La Niña) years. The annual number of landfalling TCs in FL during normal, El Niño, and La Niña years were 1.6, 1.09, and 1.5 e / yr, respectively. This indicates that the annual number of landfalling TCs in FL decreased by 31% during El Niño years, but increased by a mere 6% during La Niña years. As a result, the overall correlation between annual landfall TC frequency in FL and the JMA ESNO index between 1887 and 1999 is relatively small (not shown). However, when only intense La Niña events were considered, the average number of TCs that made landfall in FL per intense La Niña year reached 20% more than normal. The difference in the ENSO's effect on landfalling TC frequencies between different regions of the SEC may be due to different responses of the TC's steering flow pattern to SST anomalies in the eastern equatorial Pacific. However, this hypothesis remains to be confirmed.

4.2 *Empirical modes*

Apart from the interannual change associated with the ENSO cycle, there is apparent variability at lower frequencies in the time series of landfalling TCs along the U.S. southeastern seaboard as indicated by the 5-year moving average shown in Fig. 1. The 18-year period, 1965 to 1983, was relatively quiescent. During this period, only 1968 had two TCs and the rest had either one or no TCs. Only a total of 14 named storms, or an average of 0.74 e / yr made landfall along the US SEC. This is consistent with the findings of Landsea et al. (1999) which reported low activity of landfalling major hurricanes along the U.S. east coast during this period. Alternatively, the periods of 1887–1916 and 1944–1960, and the recent period since 1994, were marked by above normal landfalling TCs. Such long-term trends suggest the presence of multidecadal oscillations in landfalling TCs along the US SEC. There were also brief periods of increased activity during the periods of 1932–1941 and 1984–1988, each lasting from several years to about a decade. Except during the relatively quiescent period of 1965–1983, active Atlantic hurricane seasons with 5 or more TCs making landfall along the US SEC occurred every 5 to 16 years with a median interval of 10 years. This suggests the existence of decadal oscillation in landfalling Atlantic TCs along the US SEC.

In order to extract the information of intrinsic modes of various frequencies from the original time series displayed in Fig. 1, an EMD analysis has been carried out on the 113-year

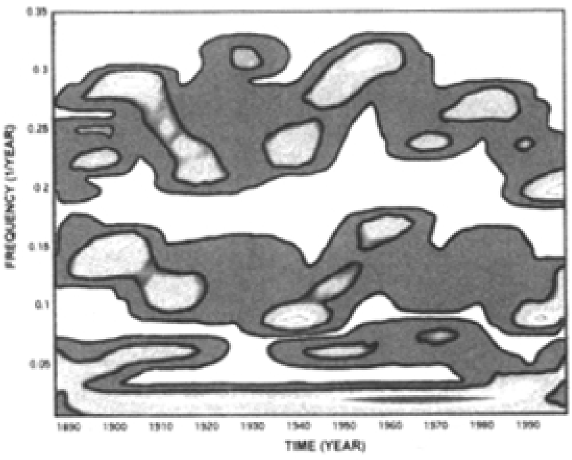

Fig. 2. The Hilbert spectrum of Landfalling TCs along the U.S. Southeast Coast.

US SEC TC time series. Figure 2 shows the Hulbert spectrum power or Hilbert spectrum (Huang et al., 1998) in the time–frequency domain. Four dominant frequency bands are depicted. These frequency bands, in cycles per year (c / yr), are: the interannual band (MOD1), approximately from 0.2 to 0.32 c / yr; the quasi–decadal band (MOD2), from about 0.075 to 0.125 c / yr; the 1st multi–decadal band (MOD3), roughly from 0.025 to 0.05 c / yr; and the 2nd multidecadal band (MOD4), concentrated between 0.02 to 0.025 c / yr.

These frequency bands display considerable shifts and interruptions in time. For example, within the interannual band, the dominant frequencies shifted from 0.3 c / yr in 1895 to 0.22 c / yr in 1925 and shifted back to higher frequencies (~ 0.3 c / yr) between 1950 and 1960. After 1970, the dominant interannual frequencies shifted downward again to 0.2–0.25 c / yr. Frequency shifts also occurred in the quasi–decadal and multi–decadal bands. The quasi–decadal band was almost absent for the periods of 1920–1930 and 1965–1985. The first multidecadal band was also interrupted between 1920 and 1940. The second multidecadal band was perhaps the most stable mode, which persisted over the entire time series with periods between 40–60 years. The persistence of this mode makes its detedtion possible even with relatively short records. For example, Goldenberg et al. (2001) was able to reveal this mode with only a 57–year record.

The temporal variability of landfalling TCs along the US SEC is analyzed by examining the structure of each mode. Figure 3 shows the temporal structure of the EMD modes. Consistent with the energy distribution shown in the Hilbert Spectrum (Fig. 2), the EMD analysis of U.S. SEC landfalling TCs suggests the existence of an interannual mode (Fig. 3a) and three decadal modes (Figs. 3b–c). The interannual mode (MOD1) exhibits a period of approximately 2–7 years (Fig. 3a). The largest amplitude of this mode reached 2.3 e / yr, making it the most significant mode.

The quasi–decadal mode (MOD2) has a period of 8–12 years (Fig. 3b). Over the past 113 years, this mode shows main frequency peaks (exceeding 1 e / yr) around the years 1893, 1901, 1906, 1916, 1934, 1953, 1959, 1985, and 1999. It is worth noting that all of these peaks correspond to the years with above normal TC activities in the southeast as shown in Fig. 1,

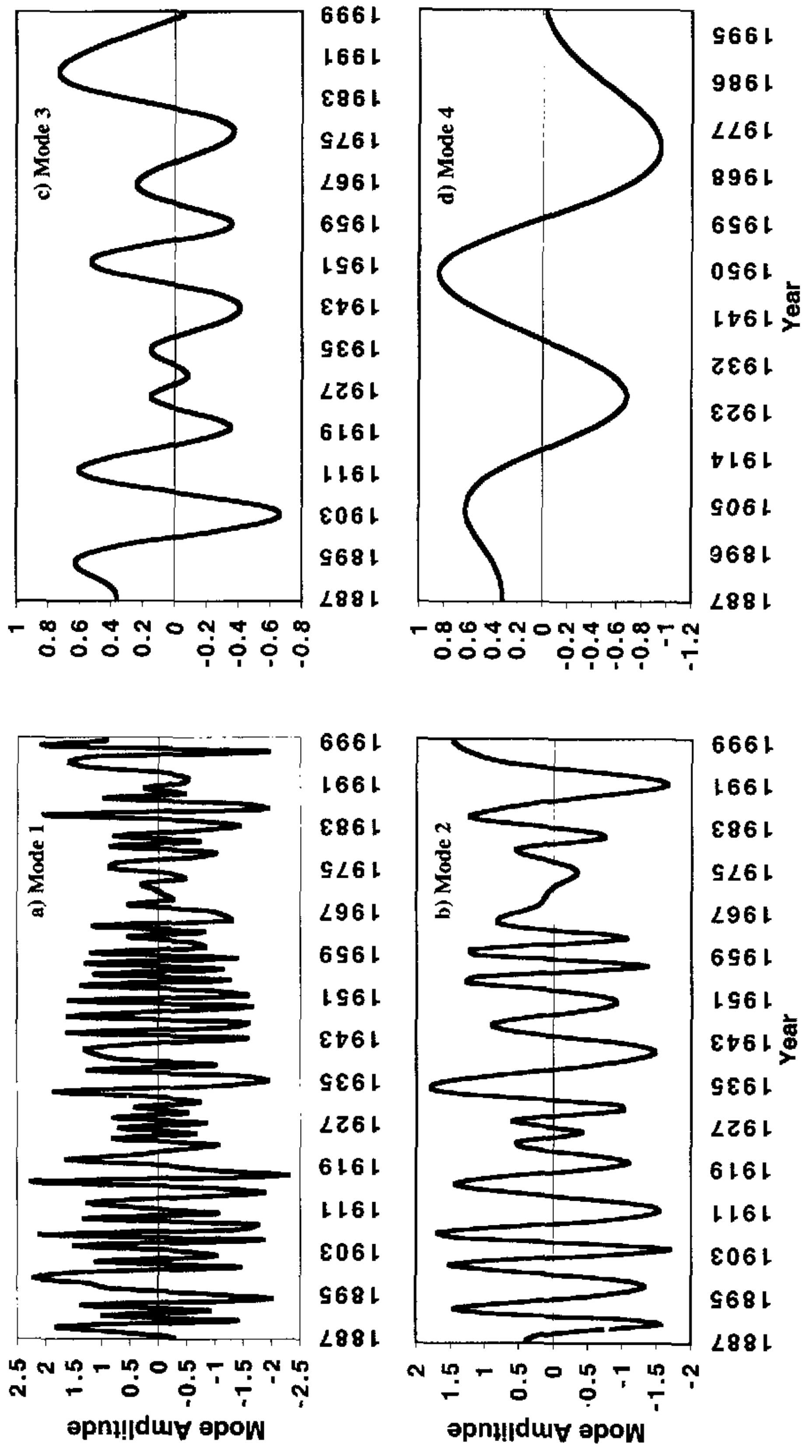

Fig. 3. The EMD modes of landfalling tropical cyclones along the U.S. Southeast Coast.

which suggests that this quasi–decadal mode play an important role in determining the major peaks in the original landfall TC time series. The 1st multi–decadal TC mode (MOD3) has a dominant period of about 20–40 years (Fig. 3c). The amplitude of this mode is between 0.1 e / yr and 0.8 e / yr. It depicts major peaks near 1893 and 1985, and major dips centered around 1911 and 1974. The time series of the 2nd multidecadal mode (MOD4) is plotted in Fig. 3d. The amplitude of this mode is between 0.6 and 0.8 e / yr. The main peaks occur around 1904 and 1948, while major dips occur around 1925 and 1974. In recent years, this mode is in a near–normal condition, but the trend is rising. Thus, the recent increase in landfalling TCs along the US SEC is mainly the result of the combination of positive interannual and decadal modes and the return of the 40–60–year mode from a negative to a near–normal condition. It should be cautioned, however, that since the decadal and multi–decadal modes have relatively smaller amplitudes than the interannual mode, TC landfall frequency at any given year in the next few decades can be either normal, above normal, or below normal even though the long–term trend may be positive. The relatively few landfalling TCs in the SEC States in 2000 and 2001 testifies to this.

5. Conclusions and remarks

The results presented in this study reveal the existence of four dominant modes in Atlantic TC variability. For the first time, the relative significance of all four dominant modes can be analyzed by their respective contribution to the overall variability of Atlantic TC activity. We find that the most significant mode is the interannual mode, which contributes on average plus or minus two TCs each year to the total landfalling TC frequency along the SEC of the United States, but such modulation differs from state to state. The reason for the regional differences is likely related to changes in large–scale atmospheric circulation patterns in response to interannual climatic forcing signals, such as ENSO. Shifts in large–sale circulation patterns alter the steering flow and thus affect landfalling TC locations. The total number of TCs that make landfall along the SEC of the United States is also strongly modulated by three other decadal and multidecadal modes.

Goldenberg et al. (2001) predicted that the recent increase in Atlantic hurricane activity since 1995 will continue for another 10 to 40 years, and thus there will be increased hurricane risk along the US Atlantic coast. Their prediction was based on the multidecadal variation of tropical Atlantic SST and its correlation with major Atlantic hurricane activity. The results from our study indicate that although the multidecadal trends suggest that anabove–normal nombe of landfalling TCs along the US SEC may continue into the early 21st Century, the annual number of tropical storms and hurricanes that will make landfall in this region will be strongly modulated by interannual and quasi–decadal modes. The results also suggest that the modulation of the annual number of landfalling TCs by ENSO events will differ significantly from one SEC state to another. Thus, long–term climatic changes of Atlantic TC or hurricane activity will have significantly different implications for different U.S. coastal regions or states.

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