Climatology and Interannual Variability of North Atlantic Hurricane Tracks

LIAN XIE AND TINGZHUANG YAN

Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina

LEONARD J. PIETRAFESA

College of Physical and Mathematical Sciences, North Carolina State University, Raleigh, North Carolina

JOHN M. MORRISON

Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina

THOMAS KARL

National Climatic Data Center, Asheville, North Carolina

(Manuscript received 15 December 2004, in final form 28 March 2005)

ABSTRACT

The spatial and temporal variability of North Atlantic hurricane tracks and its possible association with the annual hurricane landfall frequency along the U.S. East Coast are studied using principal component analysis (PCA) of hurricane track density function (HTDF). The results show that, in addition to the well-documented effects of the El Niño–Southern Oscillation (ENSO) and vertical wind shear (VWS), North Atlantic HTDF is strongly modulated by the dipole mode (DM) of Atlantic sea surface temperature (SST) as well as the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO). Specifically, it was found that Atlantic SST DM is the only index that is associated with all top three empirical orthogonal function (EOF) modes of the Atlantic HTDF. ENSO and tropical Atlantic VWS are significantly correlated with the first and the third EOF of the HTDF over the North Atlantic Ocean. The second EOF of North Atlantic HTDF, which represents the "zonal gradient" of North Atlantic hurricane track density, showed no significant correlation with ENSO or with tropical Atlantic VWS. Instead, it is associated with the Atlantic SST DM, and extratropical processes including NAO and AO. Since for a given hurricane season, the preferred hurricane track pattern, together with the overall basinwide hurricane activity, collectively determines the hurricane landfall frequency, the results provide a foundation for the construction of a statistical model that projects the annual number of hurricanes striking the eastern seaboard of the United States.

1. Introduction

The number of hurricanes that form each year in the Atlantic Ocean is quite variable, ranging from 2 in 1982 to 12 in 1969, with an average of 6 since 1950. Not surprisingly, the East Coast of the United States also experiences high year-to-year variability in the number of landfalling hurricanes. Previous hurricane climatology studies found that the interannual variability of hurricane activity in the Atlantic basin is generally associated with several local and remote factors including the El Niño–Southern Oscillation (ENSO; Gray 1984a,b; 1990), vertical wind shear (VWS) in the troposphere [typically between 850 and 200 hPa within the critical 10° to 20°N latitude belt stretching from North Africa to Central America; termed the "main development region" (MDR; Gray et al. 1993)], Western Africa rainfall anomalies (Landsea et al. 1996), sea level pressure (SLP) anomalies over the Caribbean Sea and tropical western Atlantic, quasi-biennial oscillation (QBO; Gray 1984a), and North Atlantic Oscillation (NAO; Elsner 2003). Above (below) average hurricane activity is known to be associated with a reduction (increase) of VWS and above (below) normal SST in the

Corresponding author address: Dr. Lian Xie, NCSU/MEAS, Box 8208, Raleigh, NC 27695-8208.
E-mail: lian_xie@ncsu.edu

MDR, the presence of La Niña (El Niño), low (high) SLP over the Caribbean Sea, and increased (decreased) rainfall in the Sahel region of West Africa. Such revelations have enabled the National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center (CPC) to issue seasonal extended-range outlooks for the level of hurricane activity with forecasts of total numbers and of major (Saffir–Simpson categories 3–5) events. While the corroborated statistical accuracy of these predictions is beyond the scope of this study, suffice it to say that these outlooks have generally shown skill and have been received with a high level of credibility by both the news media and the public.

Improvement in community weather prediction models, coupled with rapid strides in NOAA's observing capability and advances in numerical model data assimilation techniques, have led to significantly improved hurricane track guidance in recent years (Marks and Shay 1998). However, there still exist large uncertainties in the capability of actually predicting the exact path of an individual event, let alone the likely paths of a projected family of annual events. Although the level of annual hurricane activity in the North Atlantic can now be predicted months in advance using both statistical (Klotzbach and Gray 2004, and references therein) and dynamic (see http://iri.columbia.edu/forecast/tc_fcst/) models, it is still a challenge to predict with any confidence whether hurricanes that occur in a given season will cluster across a preferred area swath, for example, the Gulf of Mexico versus the southern or eastern seaboard of the United States versus the central North Atlantic. To respond to this challenge, statistical modeling of regional hurricane frequency in the North Atlantic was exploited recently. Lehmiller et al. (1997) outlined a statistical approach to seasonal prediction of the likely locations of Atlantic basin hurricanes. Their study was further advanced by Jagger et al. (2002) by developing a space–time statistic model that was used to hindcast the probabilities of hurricane occurrence within each 6° latitude × 6° longitude boxes over the Atlantic basin using ENSO and NAO indices as predictors. Their models indicated some useful skill above climatology. However, the focus of their studies was on the development of statistic models using known climatic predictors, not on the identification of important new climatic predictors. Furthermore, neither Lehmiller et al. (1997) nor Jagger et al. (2002) investigated the spatial/temporal modes of hurricane tracks, let alone the association of such modes with climatic variables. It would be of great benefit to society if the preferred paths of hurricanes could also be predicted in advance of the onset of hurricane season.

With the best-track dataset, the frequency of occurrence of hurricanes can be studied using track density functions (TDFs) as proposed by Anderson and Gyakum (1989), who studied the extratropical cyclones over the Pacific Ocean. The method creates a TDF based on track locations and then characterizes the nonseasonal variability of this field using a standard empirical orthogonal function (EOF) analysis. The output of the EOF analysis is then applied to extract the dominant factors that affect track patterns or EOF modes of the TDF. This method is especially useful for understanding the characteristics of the landfalling hurricanes since landfalling hurricane frequency obviously depends on both total number of hurricanes that occur in the Atlantic basin and on the track patterns. By comparing the controlling factors derived from the hurricane TDF (HTDF) EOF analysis with other atmospheric and oceanic environmental factors, hurricane variability and regime patterns can be constructed. The primary purpose of this paper is to describe and diagnose both global and local environmental conditions that may contribute to the interannual variability of Atlantic hurricane tracks. The relationships between the variation of these hurricane-influencing factors and the dominant components of HTDF EOFs provide a physical basis for developing a prediction scheme for hurricane landfall frequency along the U.S. East Coast (Yan et al. 2005, manuscript submitted to *J. Climate*, hereafter Y05).

2. Data and methodology

NOAA maintains the "best-track" database (HURDAT) at the National Climatic Data Center (NCDC) for all Atlantic tropical cyclones since 1851. For each storm, as the record allows, the data file contains the 6-hourly (0000, 0600, 1200, and 1800 UTC) center locations (latitude and longitude in tenths of degrees), intensities (maximum 1-min surface wind speeds in knots and minimum central pressures in hPa), and an indicator of whether the system was purely tropical, subtropical, or extratropical. Hurricane data collected after 1944 were analyzed in this study because observed hurricane positions were much more accurate via routine military reconnaissance following World War II. The term "North Atlantic hurricane activity" used in this paper refers to the total number of tropical cyclones that formed in the North Atlantic and reached hurricane intensity. The phrase "landfalling hurricane" refers to any hurricane whose center either crossed the coastline or moved within 0.5° latitude (approximately 50 km) of the coastline, such as Hurricane Emily of 1993.

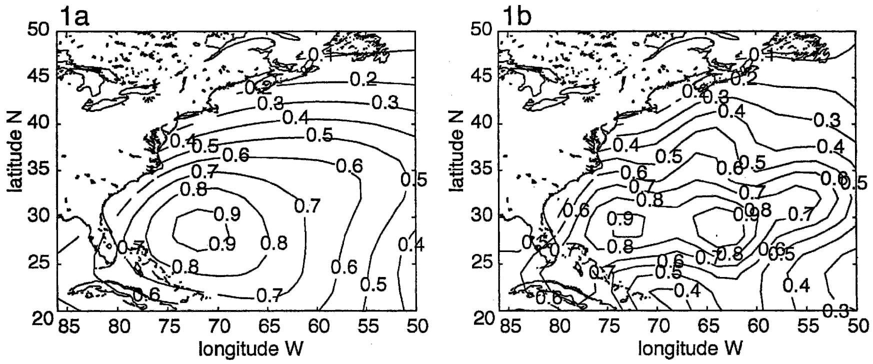

FIG. 1. HTDF field (unit: cyclones day^{-1} in a 2° × 2° box). (a) Normalized mean spatial distribution of HTDF. (b) Normalized standard deviation of HTDF.

Climatic indices including the NAO and the Arctic Oscillation (AO) are obtained from the Climate Prediction Center (CPC) of the NOAA National Centers for Environmental Prediction (NCEP). (The NAO index is available online at http://www.cpc.ncep.noaa.gov/data/teledoc/nao.html, and the AO index is downloaded from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html.)

The primary analysis methodology used in this study is based on principal component analysis (PCA), which employs EOF in keeping with Lorenz (1956). In particular, singular value decomposition (SVD) is used to compute the EOFs, which greatly simplifies computational requirements (Kelly 1988). This method has been widely used in meteorological and oceanic data analysis (Rasmusson et al. 1981; Anderson and Gyakum 1989; Knappenberger and Michaels 1993; Lee and Cornillon 1995). EOF analysis determines a set of orthogonal functions that characterizes the covariability of the time series. The advantage of EOF analysis is that it provides a compact description of the spatial and temporal variability of data series in terms of orthogonal functions, or statistical "modes."

Analysis of these EOF modes could provide physical insight into the data that will be useful in identifying the principal factors that influence hurricane track pattern.

3. Hurricane track density function and EOF analysis

The construction of the HTDF is accomplished by evaluating a summation of all daily hurricane tracks in the dataset on a 2° × 2° grid, based on the time and location of individual hurricanes (Anderson and Gyakum 1989).

$$C(\mathbf{x}, t) = \sum_j W(\mathbf{x} - \mathbf{x}_j, t - t_j), \qquad (3.1)$$

where

$$W(\Delta\mathbf{x}, \Delta t) = \cos^2\frac{|\Delta\mathbf{x}|}{S_x}\cos^2\frac{|\Delta t|}{S_t} \quad \text{when} \quad \frac{|\Delta\mathbf{x}|}{S_x} < \frac{\pi}{2}$$

$$\text{and} \quad \frac{|\Delta t|}{S_t} < \frac{\pi}{2} \quad W(\Delta\mathbf{x}, \Delta t) = 0.$$

As in Anderson and Gyakum (1989), $\mathbf{x}_j$ is the position of the jth cyclone observation, which is valid at time t_j; $W(\Delta\mathbf{x}, \Delta t)$ is a weighting function, which defines the space and time smoothed cyclone track density; and S_x and S_t are space and time resolutions, which, in this paper, are set to $16/\pi$ and $36/\pi$, respectively.

The 2° × 2° resolution grid covers the U.S. southeast coast from 20° to 50°N and from 50° to 86°W. While the tracks were detected by HTDF with a 6-h sampling interval, the temporal resolution of the HTDF is one day (24 h). The time domain of the computation was from 1 June to 30 November, and this 183-day period is defined as one "hurricane season."

a. Spatial and temporal distribution of dominant EOFs of Atlantic HTDF

Once the hurricane track density field is constructed, a nonseasonal anomaly field is then computed by subtracting the climatology from the 61-yr (1944–2004) dataset at each grid box. The spatial distribution of mean and standard deviation of the cyclone track density anomaly field are displayed in Figs. 1a,b.

Next, we compute the EOFs of the HTDF within the study domain. This computation was carried out with daily time resolution on the 2° × 2° analysis grid using an iterative singular decomposition technique where a first-guess field is repeatedly projected through the dataset in time and then space until convergence is reached. After an EOF has been found, the corresponding variance is removed and the process is repeated to find the next most important EOF. The top

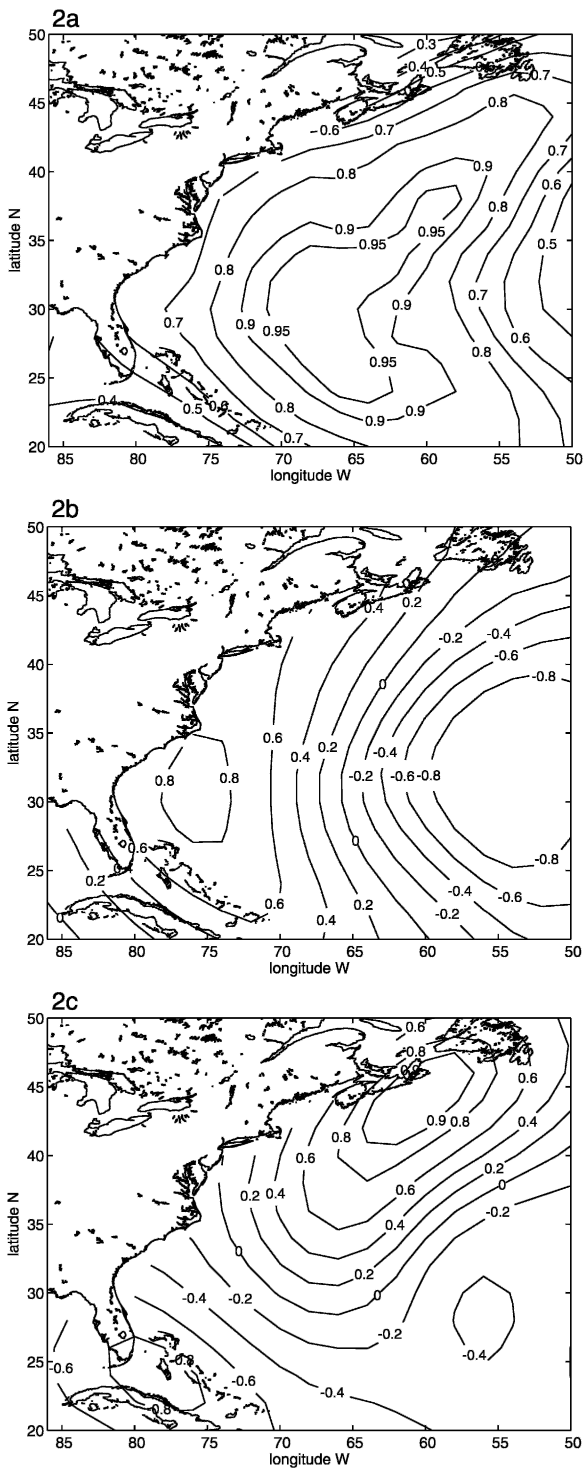

FIG. 2. HTDF EOFs: (a) HTDF field associated with EOF1 (30.47%), (b) HTDF field associated with EOF2 (12.89%), and (c) HTDF field associated with EOF3 (9.72%).

three EOFs of the HTDF are shown in Figs. 2a–c. They explain 30.47%, 12.89%, and 9.72% of the total variance, respectively.

The most reliable way of assessing the statistical significance of EOFs is to carry out a Monte Carlo (MC) experiment. One approach is to randomly assign scrambling starting data for each of the cyclones in the dataset and compare the residual variances of the dominant EOFs with their counterparts as it was done in Anderson and Gyakum (1989). Our experiment is designed to randomly generate subsets of the original dataset (subset sizes > one-fourth of the original size) and compare the EOFs for different subsets against the ones for the full dataset using spatial correlation coefficients. Results indicated that the first three EOFs retained their rank in the hierarchy and exhibited substantial levels of similarity—98 of the 100 Monte Carlo control runs matched their counterparts by a spatial correlation coefficient of at least 0.85, representing a substantial statistical significance of the first three leading EOFs.

To interpret the physical meanings of the EOFs and their spatial and temporal variability, it is important to check if any of the EOFs do not represent the physical fields. One approach for simplifying the interpretation of an EOF analysis is the technique of factor rotation, which has been widely used in meteorological applications (Horel 1981; Anderson and Gyakum 1989). In this study, the rotated EOFs are computed by using the VARIMAX program. For detailed discussions of EOF rotation, the readers should consult Cureton and D'Agostino (1983) and Richman and Lamb (1985). When an EOF rotation is carried out, one needs to choose the truncation point, M, for the description of the field by using the first M-order EOF components. Figure 3a demonstrates the variance explained by the first five unrotated EOFs, and the variance for rotations when M takes the value 2, 3, 4, and 5, respectively. The first three rotated EOFs explain a similar amount of variance as those explained by the first four or five EOFs involved in the rotation. Additionally, the space and time structures of the first three rotated EOFs are nearly identical to the cases where M takes 4 or 5. Thus, $M = 3$ is a reasonable truncation point. The temporal distributions of the top three EOFs and the rotated EOFs of Atlantic HTDF (Fig. 3b) are also nearly identical, which further shows the reliability of the first three leading EOFs. As we will show below, the periods of amplitude maxima and minima represent distinct clustering of Atlantic hurricane tracks.

The spatial distribution of EOF1 (Fig. 2a) is characterized by a single high positive value over the study domain. A large positive weight represents an above-

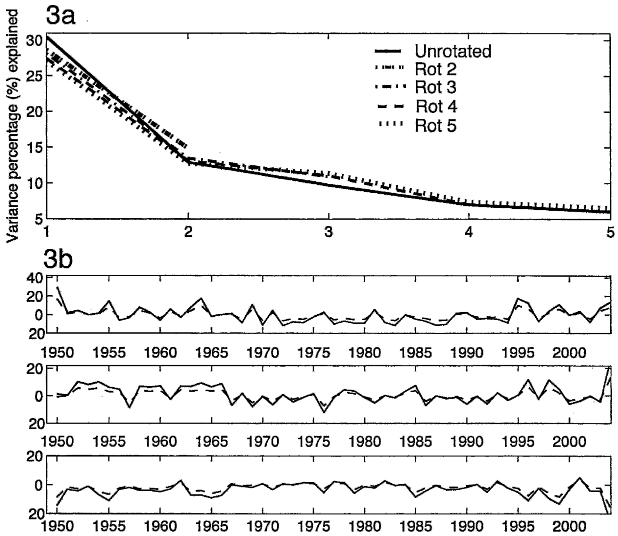

FIG. 3. (a) Variance explained by the first five unrotated EOFs, and the variance for rotations when M takes the value of 2, 3, 4, and 5, respectively; (b) time series of the amplitudes (weights) of the three leading HTDF EOFs and rotated EOFs. Solid line represents rotated EOFs.

normal hurricane track density in the region (referred to as Mode 1+ hereafter), and a negative weight indicates a below-normal hurricane track density (referred to as Mode 1− hereafter). The spatial pattern of EOF2 (Fig. 2b) shows that its values are positive in the western region and negative in the eastern region of the study domain. This zonal gradient depicts the zonal movement of the hurricanes. A large positive weight of EOF2 (referred to as Mode 2+ hereafter) corresponds to above-normal HTDF near the coast on the western side of the study region, whereas a negative weight (referred to as Mode 2− hereafter) corresponds to the opposite pattern. The spatial pattern of EOF3 is shown in Fig. 2c. It shows a large positive center in the northeast region coupled with negative values in the southwest region of the study area. In general, the value of EOF3 increases from south to north, indicating a north–south gradient. A large positive weight in this mode (referred to as Mode 3+ hereafter) indicates that hurricanes tend to move to the northeast and spare the U.S. southeast coast, whereas a negative weight (referred to as Mode 3− hereafter) represents conditions when hurricanes prefer to move southwestward and make landfall along the U.S. southeast coast.

b. Track patterns associated with HTDF EOFs

It is well known that atmospheric circulation patterns play a key role in the steering of hurricane motion. To a first approximation, hurricanes can be thought of as being steered by the surrounding environmental flow throughout the depth of the troposphere (from the surface to about 12 km). At tropical latitudes (equatorward of 20°–25°), hurricanes generally move toward the northwest because of beta drift (Chan 2005).

To further diagnose possible effects of atmospheric circulation on the HTDF over the tropical Atlantic Ocean, hurricane tracks during the positive/negative amplitude periods were analyzed using the first three dominant rotated EOF modes of HTDF. As defined in Section 3a, case type $i+$ refers to periods when the ith EOF component has a large positive weight (specifically, larger than half of the maximum amplitude of the ith EOF component); type $i-$ refers to periods when the ith EOF component has a large negative weight (less than half of the minimum amplitude of the ith EOF component), where i could be 1, 2, or 3. The periods chosen are the largest-weight cases where the anomaly extended over the whole life span of the specific hurricane.

Figures 4a and 4b represent, respectively, the track patterns associated with Mode 1+ and Mode 1− (dashed line in Fig. 4b represents tracks of tropical

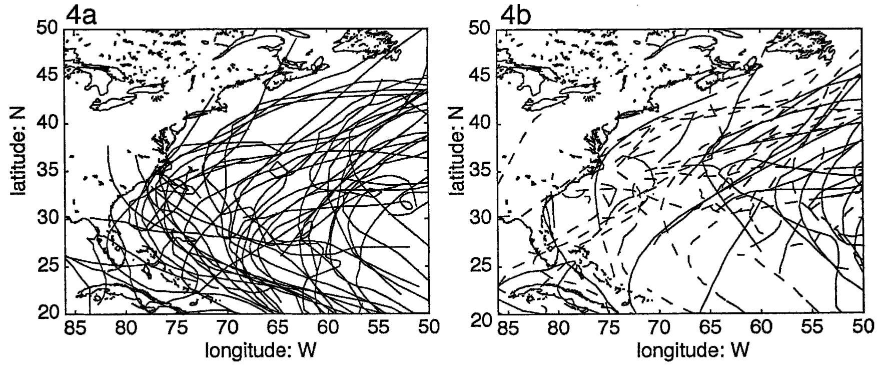

FIG. 4. Composite hurricane tracks associated with HTDF Mode 1+ and Mode 1−. Track pattern associated with (a) Mode 1+ and (b) Mode 1−. Solid curves indicate hurricane intensity, whereas the broken curves indicate tropical storm intensity.

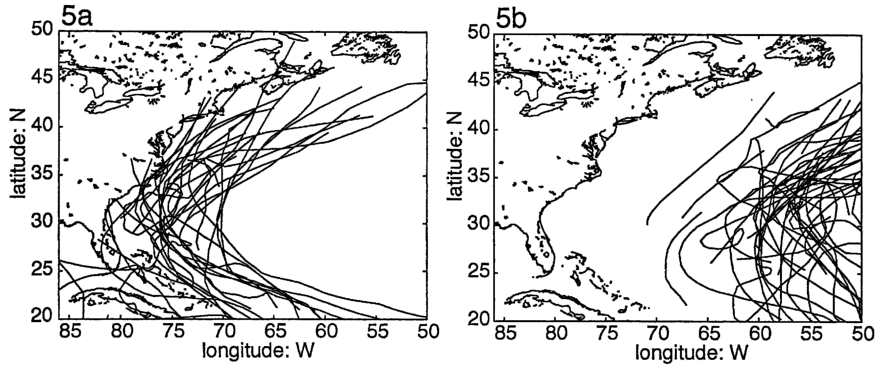

FIG. 5. Same as in Fig. 4, but for Mode 2+ and Mode 2−.

storms with maximum wind greater than 39 mph and less than 74 mph). By examining each individual hurricane, it appears that approximately 88% of the total hurricanes captured by Mode 1+ are major hurricanes [with maximum sustained 1-min surface winds of at least 111 mph, according to the National Hurricane Center (NHC)], whereas only about 30% of Mode 1− hurricanes are major hurricanes. Mode 1+ hurricanes also have higher probability (3 out 10) to strike the east coast than Mode 1− hurricanes (1 out of 10). This is probably due to the fact that Mode 1+ hurricanes generally have a life span averaging more than 7 days, and as a result, over 90% of them traveled over across at least half of the study region, whereas the average life span for Mode 1− hurricanes is only about 4 days, and more than half of these storms did not travel through half of the study region. Additionally, over 50% of Mode 1+ hurricanes occurred in September, whereas only about a third of the mode 1− hurricanes developed in September.

HTDF track patterns associated with Mode 2+ and Mode 2− are shown in Figs. 5a and 5b, respectively. During periods of Mode 2+, 42% of the hurricanes successfully crossed the U.S. southwest coastline (Fig. 5a), however all of the tracks associated with periods of Mode 2− stayed off the coast (Fig. 5b). Mode 2 is clearly associated with the hurricane track gradient in the east–west (landward–seaward) direction.

Figures 6a,b depict the track patterns associated with Mode 3+ and Mode 3−, respectively. Mode 3+ hurricanes are more likely to occur in the northeast portion of the study region, while Mode 3− hurricanes tend to move toward the southeast coast of the United States. About 90% of the hurricanes captured by Mode 3+ crossed 35°N, while more than 8% of Mode 3− hurricanes passed the region south of 25°N, resulting in more landfall hurricanes along the southeast coast of the United States during this time period. Out of 34 (62%) Mode 3− hurricanes, 21 made landfalls along the U.S. southeast coast and the Caribbean Islands. These Mode 3− hurricanes are also generally stronger than the Mode 3+ hurricanes that moved to the north. As shown in Fig. 7, the maximum hurricane wind speed (minimum center pressure) associated with Mode 3− in the southern portion of the domain is generally stronger (lower) than the Mode 3+ hurricanes in the north. This finding is consistent with that of Elsner (2003) in which Atlantic hurricane tracks are clustered into a

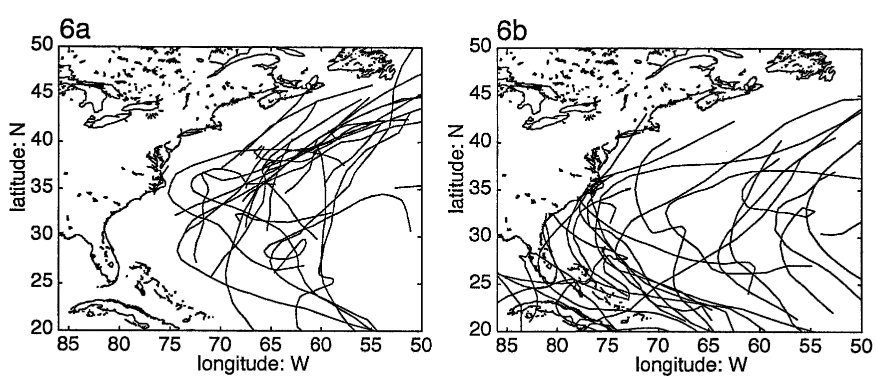

FIG. 6. Same as in Fig. 4, but for Mode 3+ and Mode 3−.

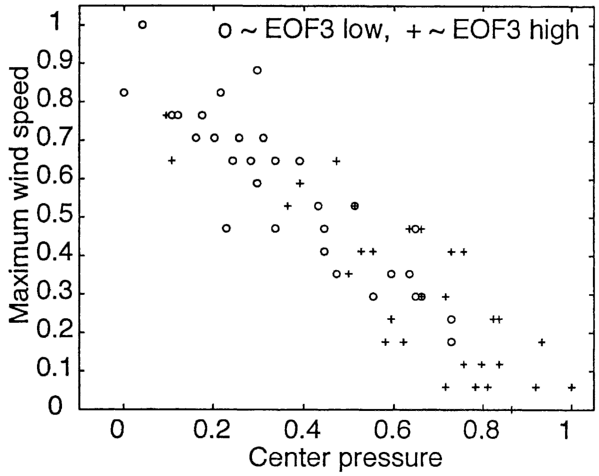

FIG. 7. Maximum wind distribution associated with EOF3 high/low (normalized).

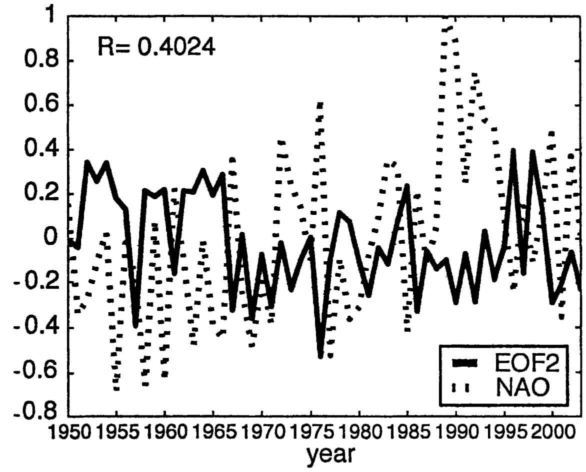

FIG. 8. Overlay of HTDF EOF2 and NAO index.

"southern group" and a "northern group," and the storms in the southern group were found to be generally stronger.

4. Factors affecting the first three EOF components of HTDF

a. North Atlantic Oscillation

The NAO is one of the oldest known climatic weather patterns depicting the pressure differences between the Azores and Iceland. The NAO is most important in the cold season and has two phases (Barnston and Livezey 1987). The positive NAO phase corresponds to higher (lower) surface pressure in the subtropical Azores high (Icelandic low), whereas the negative NAO phase depicts the opposite. Elsner (2003) examined the hurricane tracks across the North Atlantic and classified hurricane tracks into north and south regions based on the NHC historical hurricane best-track data (HURDAT) from 1944 to 2002. He found that the 2-month (May and June) average NAO index is well correlated with North Atlantic hurricane tracks during the following hurricane season. As shown in Fig. 2b, the second EOF of the HTDF is associated with the west–east gradient of the hurricane track density. The correlation coefficient between the HTDF and the mean of the NAO Index from January to June was computed. The NAO index used in this study is the monthly NAO index produced by NOAA CPC. Figure 8 shows the overlay of HTDF EOF2 amplitude and the NAO time series. They are negatively correlated ($R = -0.4024$) and exceed the 95% confidence level. Additionally, HTDF EOF3 and NAO are positively correlated (Table 1). Since Mode 2+ and Mode 3− are associated with westward-moving and southward-moving storms, respectively, it clearly indicates that the negative phase of NAO favors more landfall hurricanes along the U.S. southeast coast. This is perhaps because the negative phase of NAO is associated with a more southwest position of the North Atlantic subtropical high pressure system (Elsner 2003), which tends to steer hurricanes more to the U.S. southeast coast than the northeast coast and thus creating a more favorable condition for hurricanes to make landfall along the U.S. southeast coast.

b. Arctic Oscillation

The AO, alternatively known as the Northern Hemisphere annular mode (NHA), is the dominant pattern of nonseasonal SLP variations to the north of 20°N. It is a large-scale mode of climate variability characterized by SLP anomalies of one sign in the Arctic and anomalies of opposite sign centered about 37° – 45°N. Periods of relatively "high" AO index are accompanied by below-normal Arctic SLP and enhanced surface westerlies in the north Atlantic. Opposite circulation

TABLE 1. Pearson correlations between HTDF EOF components and climate factors [Prob > |*r*| under H0: Rho = 0; (*N* = 55, 1950–2004)].

Coefficient	EOF1	EOF2	EOF3
ENSO (Jan–Jun)	*−0.3050*	−0.0071	*0.2671*
NAO (Jan–Jun)	−0.1420	**−0.4024**	*0.2627*
AO (Jan–Jun)	−0.0076	**−0.3679**	0.1782
SSTDM (Jun–Jul)	**0.5536**	**0.4054**	**−0.5038**
VWS (Aug–Oct)	**−0.5936**	−0.1755	0.2110

Note: Coefficient exceeds 95% confidence level if |*R*| > 0.261 (shown in italics). Exceeds 99% confidence level if |*R*| > 0.340 (in bold). SSTDM: Atlantic SST dipole mode.

TABLE 2. Pearson cross-correlation coefficients (r) among climate factors in Table 1 (N = 55, 1950–2004).

Factors	SST DM	TotalHur	ENSO	NAO	AO	VWS
SST DM	**1.0000**	**0.5654** *<0.001*	−0.1955 *0.1487*	−0.2467 *0.0694*	−0.0921 *0.5037*	**−0.6404** *<0.001*
TotalHur	**0.5654** *<0.001*	**1.0000**	−0.1116 *0.4129*	−0.2154 *0.1143*	−0.1324 *0.3353*	**−0.5380** *<0.001*
ENSO	−0.1955 *0.1487*	−0.1116 *0.4129*	**1.0000**	0.0770 *0.5727*	−0.1398 *0.3040*	0.2658 *0.0477*
NAO	−0.2467 *0.0694*	−0.2154 *0.1143*	0.0770 *0.5727*	**1.0000**	**0.8772** *<0.001*	−0.1620 *0.2372*
AO	−0.0921 *0.5037*	−0.1324 *0.3353*	−0.1398 *0.3040*	**0.8772** *<0.001*	**1.0000**	−0.0168 *0.9030*
VWS	**−0.6404** *<0.001*	**−0.5380** *<0.001*	0.2658 *0.0477*	−0.1620 *0.2372*	−0.0168 *0.9030*	**1.0000**

Note: Numbers in italic are p values. $P < 0.05$ is the traditional indicator of statistical significance. Values of r with $p < 0.001$ are shown in bold. TotalHur: Annual landfall Atlantic hurricane frequency along U.S. East Coast.

pattern with a deep trough and weak westerlies in the North Atlantic is associated with "low" AO index conditions (Thompson and Wallace 2000). Mean monthly AO index from January to June computed by NOAA CPC is used as the AO index in this paper. The correlation coefficients between the AO index and HTDF EOF2 were computed for the period extending from 1950 to 2004. The correlation is negative and exceeds the 95% confidence level (Table 1). This suggests that, similar to NAO, AO is associated with the zonal mode of HTDF. During the positive phase of AO, strong westerlies in the North Atlantic tend to steer the hurricanes offshore, whereas during the negative phase of AO, more landfall hurricanes are expected along the U.S. East Coast. As Wallace (2000) suggested, the AO and NAO are a pair of related phenomena known as the Northern Hemisphere annular mode. They represent two different aspects of the same phenomenon, and their effects on hurricane activity are similar in the North Atlantic region. As such, these two indices are closely correlated (r = 0.88, p <0.0001; Table 2).

c. The 200-hPa geopotential height

Since Atlantic hurricane tracks are largely associated with the atmospheric circulation over the North Atlantic and North America (Arakawa et al. 1981), it is important to understand the large-scale patterns of the geopotential height (GHT) anomaly fields associated with the landward-moving (EOF 2+) and offshore-moving (EOF 2−) hurricanes. Figures 9a and 9b represent the 200-hPa composite GHTs associated with HTDF Mode 2+ and Mode 2−, respectively. These figures demonstrate how large-scale atmospheric circulation influences the zonal mode of hurricane motion. The 200-hPa GHT anomaly fields were constructed from NCEP–National Center for Atmospheric Research (NCAR) reanalysis daily average 200-hPa pressure level data (Kalnay et al. 1996) by compositing the data for the period of time coincident with HTDF Mode 2+ and Mode 2−, respectively. As stated previously, average of the maximum (minimum) weight of Mode 2 was used as the threshold weight to select the time periods of Mode 2+ (Mode 2−). During the Mode 2+ periods, there is a stronger ridge (positive anomaly) along the southeast U.S. coast, which is favorable for westward tracking of hurricanes and gave them a better chance of making landfall (Fig. 9a). During the Mode 2− periods, there is a deeper trough (negative anomaly) over the entire southeast coast of the United States, which acts to steer the hurricanes northeastward

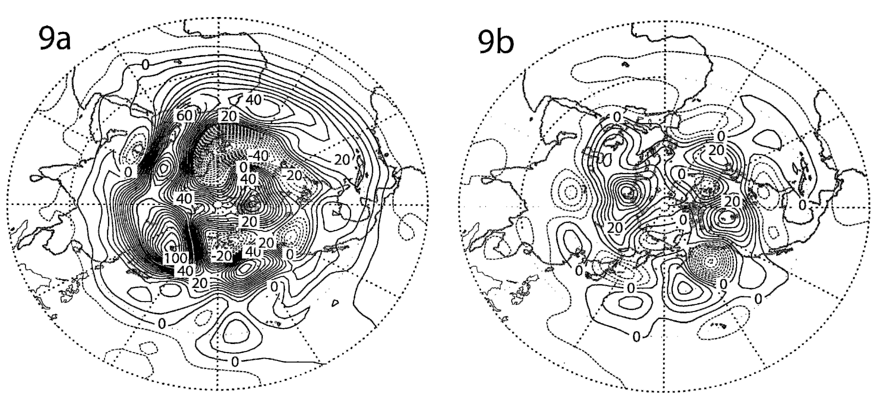

FIG. 9. Composite GHT anomalies at 200 hPa for composite during (a) Mode 2+ and (b) Mode 2−.

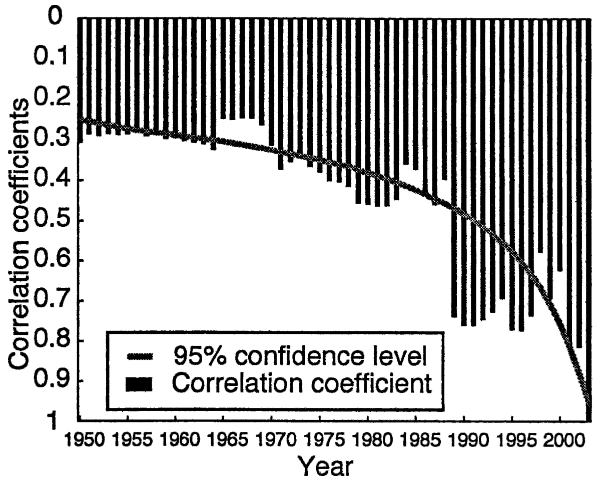

FIG. 10. Correlation coefficients between HTDF EOF1 and ENSO. The horizontal axis shows the starting year of the time series during which the correlation is computed. All time series have the some ending year, which is the last year on the axis.

and away from the coast (Fig. 9b). Thus, an approaching deep midlatitude trough is a typical signal for northeastward-moving hurricanes, whereas a strengthened, westward positioned subtropical high signals a higher probability of landfall storms along the U.S. East Coast.

d. El Niño–Southern Oscillation

ENSO is perhaps, the most studied climatic effect on Atlantic tropical cyclones (Gray 1984a,b). Goldenberg et al. (2001) summarized the scientific advances in Atlantic hurricane climatology and variability studies and indicated that the SST variability in the central and eastern equatorial Pacific Ocean associated with ENSO play a key effect on the development of Atlantic hurricanes. Decreased hurricane activity is associated with strong El Niño seasons and enhanced activity during La Niña periods (Gray 1984a,b). In addition to direct ENSO effects on the formation of hurricanes, equatorial Pacific climate extremes during the ENSO cycle may also affect the position and intensity of the upper-atmospheric jet stream, which may, in turn, affect the intensities and tracks of Atlantic hurricanes.

ENSO monthly indexes (1950–2004) derived from the Japan Meteorological Agency (JMA) SST anomalies, which are annual mean SST anomalies for the area 4°S–4°N, 150°–90°W (Meyers et al. 1999), are used here as the ENSO index (also known as Niño-3 SST anomalies). The correlation coefficients between the first EOF of the HTDF and the ENSO index are displayed in Fig. 10 as a function of the year when the correlation began. The solid line represents the 95% confidence level. In general the correlation coefficients are above the 95% confidence level, suggesting the existence of a robust relationship between these two time series. This strong negative implies that fewer and weaker hurricanes occur in El Niño years, while more frequent and stronger hurricanes occur in La Niña years. This is consistent with earlier findings summarized by Goldenberg et al. (2001).

HTDF EOF3 has a positive correlation with the ENSO index (Table 1), suggesting that favorable landfall conditions usually occur in La Niña years along the U.S. southeast coast, whereas conditions unfavorable for hurricane landfall often occurs in El Niño years. Interestingly, no significant correlation between HTDF EOF2 and the ENSO index was found, which implies that while ENSO may play a major role in modulating the interannual variability of Atlantic basin hurricane activity, its effect is less important in modulating the zonal gradient of the HTDF.

e. Vertical wind shear in the Atlantic hurricane main development region

It is well known that weak vertical shear of the horizontal wind between the upper and lower troposphere (typically between 850 and 200 hPa) is one of the local conditions required for TC formation and development (Landsea 2000). Active hurricane seasons in the Atlantic basin are generally associated with a reduction of VWS within the critical 10° to 20°N latitude belt stretching from North Africa to Central America (Fig. 11) [termed the main development region by Gray et al. (1993)]. During August–October, VWS in the Atlantic basin's MDR normally exhibits a strong westerly component and exceeds the critical 7.5–10 m s^{-1} threshold for hurricane formation (Gray et al. 1993). This large shear is caused by a combination of upper-level (200

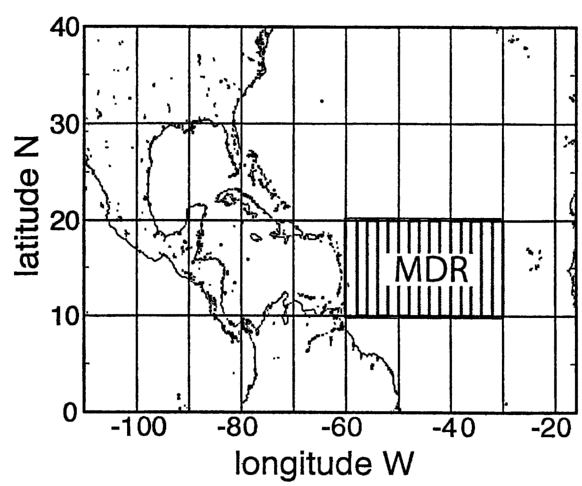

FIG. 11. MDR (redrawn from Goldenberg and Shapiro 1996).

hPa) westerly winds in association with a mean tropical upper-tropospheric trough (Sadler 1976; Fitzpatrick et al. 1995), and low-level (850 hPa) easterly trade winds. Thus, very active hurricane seasons require that the VWS in this region be substantially reduced from the climatological mean. According to Landsea et al. (1996), remote climatic factors can significantly affect the interannual variability of Atlantic basin hurricane activity, primarily through their low-frequency modulation of the distribution of VWS. ENSO alters the global atmospheric circulation affecting tropical cyclone frequencies by changing the lower-troposphere vorticity sources and the vertical wind shear (Landsea 2000). Strong VWS usually inhibits the formation and intensification of the hurricanes by preventing the axis-symmetric organization of deep convection. Goldenberg et al. (2001) noticed the recent increase in Atlantic hurricane activity and attributed it to the increases in Atlantic SST and the decreases in VWS.

Following the work of Goldenberg et al. (2001), the percentage of the south-central portion of the MDR where VWS is less than 6 m s^{-1} was used to represent the VWS index. The correlation between the VWS index and the first three modes of the HTDF EOFs shows that the interannual variability of VWS is inversely correlated to Mode 1 of the HTDF (Table 1), suggesting that fewer and weaker hurricanes are usually observed in years with stronger VWS, and fewer hurricanes move toward the U.S. southeast coast in years with stronger VWS. Notice that this correlation coefficient is well above the 99% confidence level ($p < 0.01$). No significant correlation was found between Mode 2 of HTDF and the VWS index, which is consistent with the results discussed in section 2.

It should be noted that the tropical Atlantic VWS itself is correlated significantly with ENSO ($R = \geqslant 0.2658$, $p = 0.0477$), West Sahel rainfall (WSR) ($R = -0.48$, $p = 0.0002$), as well as the tropical Atlantic SST dipole mode (DM) as we will show below ($R = -0.64$, $p < 0.0001$). Thus, the effect of tropical Atlantic VWS on hurricanes is likely reflected in these cross-correlated parameters (ENSO, Atlantic SST DM, and WSR; Table 2).

f. Atlantic SST dipole mode

The interhemispheric gradient of anomalous SST (Atlantic SST DM), which is primarily linked to the latent heat flux anomalies, has a decadal time scale (Carton et al. 1996). Previous studies on the effects of Atlantic SST dipole mode concerned mainly the decadal climatic variability (Chang et al. 1997). Many studies have shown that tropical North Atlantic SST correlates positively with major hurricane activity (Gray et al. 1993; Landsea et al. 1996; Goldenberg et al. 2001). Since North Atlantic HTDF is determined by the total number of hurricanes in the North Atlantic basin and the track of these storms, it is reasonable to assume that the EOFs of North Atlantic HTDF are associated with the SST anomalies in the tropical Atlantic. This hypothesis is confirmed by the strong correlations between the first three EOFs of the North Atlantic HTDF and the first EOFs of tropical Atlantic SST (Table 1), which depicts the well-known dipole structure (Servain 1991). The correlation coefficients for the entire time series are well above the 99% confidence level. The Atlantic SST dipole structure associated with Atlantic SST EOF1 is characterized by opposite SST anomalies between the tropical North and tropical South Atlantic (Servain 1991). The Atlantic SST Dipole indices used in this study is the average SST anomaly differences in June and July between tropical North Atlantic and the tropical South Atlantic, which extends roughly from 30°S to 30°N and from 10°E to 45°W (Sutton et al. 2000). There is a strong connection between the Atlantic SST dipole mode and the overall interannual variability of Atlantic hurricanes (Table 1) as well as the interannual variability of Atlantic landfall hurricane frequency (Table 2) (Xie et al. 2005). The strong negative correlation between the Atlantic SST dipole mode and the third mode of HTDF (Table 1) suggests that the positive phase of the Atlantic SST dipole mode corresponds to above-normal hurricane landfall in the southeast United States, whereas the negative phase corresponds to fewer landfall hurricanes. It is interesting to note that the Atlantic SST dipole mode also has significant association with HTDF EOF2 (Table 1). This implies that the east–west distribution of HTDF is likely not only caused by extratropical factors, such as NAO (AO) as discussed in sections 4a and 4b, but also by tropical Atlantic SST as well.

5. Discussion and conclusions

In this paper, Atlantic hurricane track density has been studied by analyzing the spatiotemporal statistics of the North Atlantic HTDF. The leading EOF modes of HTDF demonstrated well-behaved correlations with one or more physical factors that are associated with Atlantic Ocean hurricane activities. These correlations reveal some important associations between North Atlantic HTDF and a set of tropical, extratropical, oceanic, and atmospheric physical parameters that appear to be of use in seasonal hurricane landfall forecasting. Specific findings are summarized below.

1) The overall North Atlantic hurricane activity depicted by, among others, the first EOF of the North

Atlantic HTDF is well correlated with the ENSO index [Nino-3 SST anomaly (SSTA)], the Atlantic SST dipole mode, and the VWS in the Atlantic hurricane MDR. The Atlantic SST dipole mode is previously known to affect the decadal variability of North Atlantic climate. This study revealed the presence of a strong correlation (exceeds 99% confidence level) between the interannual variability of North Atlantic hurricane activity and the Atlantic SST dipole mode. The positive phases of the Atlantic SST dipole mode correspond to above normal hurricane activity in the North Atlantic Ocean, and vice versa. Although ENSO and VWS are previously known to be associated with North Atlantic hurricane activity, this association is confirmed through HTDF EOF analysis. It is shown that the ENSO index has a negative correlation with the first EOF of the North Atlantic HTDF. The significance of the correlation exceeds the 95% significance level. There are fewer Atlantic hurricanes spawned in strong El Niño years and an above average number of hurricanes during La Niña years.

2) The second EOF of the North Atlantic HTDF depicts an east–west (zonal) gradient of HTDF. It is especially relevant to hurricane landfall frequency along the U.S. East Coast. It is found that this zonal gradient of North Atlantic HTDF is influenced by the NAO (AO) and the Atlantic SST DM, suggesting the possibility of using NAO (AO) and Atlantic SST DM index as predictors for hurricane landfall frequency along the U.S. East Coast. When the NAO is in a negative (positive) phase, there tends to be more (fewer) hurricanes making landfall along the U.S. East Coast.
3) The third EOF of North Atlantic HTDF depicts a southwest–northeast-oriented gradient in the HTDF field. It is negatively correlated with the number of hurricane landfalls along the U.S. southeast coast. The third EOF of North Atlantic HTDF is also negatively correlated with the Atlantic SST DM and positively correlated with the NAO index, which implies more frequent hurricane landfalls along the U.S. southeast coast during positive Atlantic SST DM, and negative NAO.

Based on the parameters discussed above, it is possible to construct a statistical model for predicting the number of landfall hurricanes for the U.S. East Coast or a specified area (Y05). It should be noted that there are other factors, such as the quasi-biennial oscillation (QBO) and western Africa rainfall, that are suggested as predictors for North Atlantic hurricane activity (Gray 1984a,b; Goldenberg et al. 2001), but are not examined here. It is possible that the effects of QBO and western Africa rainfall on the North Atlantic HTDF are indirectly implied by the VWS and the Atlantic SST DM. The effects of QBO and western Africa rainfall on Atlantic HTDF will be analyzed more thoroughly in the future.

Acknowledgments. The authors acknowledge support for this study from the National Science Foundation, WOCE AIMS program, and U.S. National Oceanic and Atmospheric Administration Grant NAO3NES4400015 through a Cooperative Agreement (Climate & Weather Impacts on Society and the Environment) via the Charleston Coastal Services Center and the National Climatic Data Center.

REFERENCES

Anderson, J. R., and J. R. Gyakum, 1989: A diagnostic study of Pacific basin circulation regimes as determined from extratropical cyclone tracks. *Mon. Wea. Rev.,* **117,** 2672–2686.

Arakawa, H., C. A. Buenafe, and H. D. Hamilton, 1981: Comparison of tropical cyclone movement and environmental steering. *Mon. Wea. Rev.,* **109,** 908–909.

Barnston, A. G., and R. E. Livezey, 1987: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Wea. Rev.,* **115,** 1083–1127.

Carton, J. A., X. H. Cao, B. S. Giese, and A. M. Da Silva, 1996: Decadal and interannual SST variability in the tropical Atlantic Ocean. *J. Phys. Oceanogr.,* **26,** 1165–1175.

Chan, J. C. L., 2005: The physics of tropical cyclone motion. *Annu. Rev. Fluid Mech.,* **37,** 99–128.

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. *Nature,* **385,** 516–518.

Cureton, E. E., and R. B. D'Agostino, 1983: *Factor Analysis, an Applied Approach.* Lawrence Elburn, 457 pp.

Elsner, J. B., 2003: Tracking hurricanes. *Bull. Amer. Meteor. Soc.,* **84,** 353–356.

Fitzpatrick, P. J., J. A. Knaff, C. W. Landsea, and S. V. Finley, 1995: A systematic bias in the aviation model's forecast of the Atlantic tropical upper-tropospheric trough: Implications for tropical cyclone forecasting. *Wea. Forecasting,* **10,** 433–446.

Goldenberg, S. B., and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and west African rainfall with Atlantic major hurricane activity. *J. Climate,* **9,** 1169–1187.

——, C. W. Landsea, M. A. Mestas-Nunez, and W. M. Gray, 2001: The recent increase in Atlantic Hurricane activity: Causes and implications. *Science,* **293,** 474–479.

Gray, W. M., 1984a: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 hPa quasi-biennial oscillation influences. *Mon. Wea. Rev.,* **112,** 1649–1668.

——, 1984b: Atlantic seasonal hurricane frequency. Part II: Forecasting its variability. *Mon. Wea. Rev.,* **112,** 1669–1683.

——, 1990: Strong association between West African rainfall and U.S. landfall of intense hurricanes. *Science,* **249,** 1251–1256.

——, C. W. Landsea, P. W. Mielke Jr., and K. J. Berry, 1993: Predicting Atlantic seasonal tropical cyclone activity by 1 August. *Wea. Forecasting,* **8,** 73–86.

Horel, J. D., 1981: A rotated principal component analysis of the interannual variability of the Northern Hemisphere 500 mb height field. *Mon. Wea. Rev.,* **109,** 2080–2092.

Jagger, H. T., X. Niu, and J. B. Elsner, 2002: A space–time model for seasonal hurricane prediction. *Int. J. Climatol.,* **22,** 451–465.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kelly, K. A., 1988: Comment on "Empirical orthogonal function analysis of advanced very high resolution radiometer surface temperature patterns in Santa Barbara Channel" by G. S. E. Lagerloef and R. L. Bernstein. *J. Geophys. Res.,* **93C,** 15 753–15 754.

Klotzbach, P. J., and W. M. Gray, 2004: Updated 6–11-month prediction of Atlantic basin seasonal hurricane activity. *Wea. Forecasting,* **19,** 917–934.

Knappenberger, P. C., and P. J. Michaels, 1993: Cyclone tracks and wintertime climate in the mid-Atlantic region of the USA. *Int. J. Climatol.,* **13,** 509–531.

Landsea, C. W., 2000: El Niño–Southern Oscillation and the seasonal predictability of tropical cyclones. *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts,* H. F. Diaz and V. Markgraf, Eds., Cambridge University Press, 149–181.

——, N. Nicholls, W. M. Gray, and L. A. Avila, 1996: Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophys. Res. Lett.,* **23,** 1697–1700.

Lee, T., and P. Cornillon, 1995: Temporal variation of meandering intensity and domain-wide lateral oscillations of the Gulf Stream. *J. Geophys. Res.,* **100,** 13 603–13 613.

Lehmiller, G. S., T. B. Kimberlain, and J. B. Elsner, 1997: Seasonal prediction models for North Atlantic basin hurricane location. *Mon. Wea. Rev.,* **125,** 1780–1791.

Lorenz, E. N., 1956: Empirical orthogonal functions and statistical weather prediction. Scientific Rep. 1, Statistical Forecasting Project, MIT, Cambridge, MA, 48 pp.

Marks, F. D., and L. K. Shay, 1998: Landfalling tropical cyclones: Forecast problems and associated research opportunities: Report of the Fifth Prospectus Development Team to the U.S. Weather Research Program. *Bull. Amer. Meteor. Soc.,* **79,** 305–323.

Meyers, S. D., J. J. O'Brien, and E. Thelin, 1999: Reconstruction of monthly SST in the tropical Pacific Ocean during 1868–1993 using adaptive climate basis functions. *Mon. Wea. Rev.,* **127,** 1599–1612.

Rasmusson, E. M., P. A. Arkin, W.-Y. Chen, and J. B. Jalickee, 1981: Biennial variations in surface temperature over the United States as revealed by singular decomposition. *Mon. Wea. Rev.,* **109,** 587–598.

Richman, M. B., and P. J. Lamb, 1985: Climate pattern analysis of three- and seven-day summer rainfall in the central United States: Some methodological considerations and a regionalization. *J. Climate Appl. Meteor.,* **24,** 1325–1343.

Sadler, J. C., 1976: A role of the tropical upper tropospheric trough in early season typhoon development. *Mon. Wea. Rev.,* **104,** 1266–1278.

Servain, J., 1991: Simple climate indices for the tropical Atlantic Ocean and some applications. *J. Geophys. Res.,* **96,** 15 137–15 146.

Sutton, R. T., S. P. Jewson, and D. P. Rowell, 2000: The elements of climate variability in the tropical Atlantic region. *J. Climate,* **13,** 3261–3284.

Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate,* **13,** 1000–1016.

Wallace, J. M., 2000: North Atlantic Oscillation/Annular Mode: Two paradigms—One phenomenon. *Quart. J. Roy. Meteor. Soc.,* **126,** 791–805.

Xie, L., T. Yan, and L. J. Pietrafesa, 2005: The effect of Atlantic sea surface temperature dipole mode on hurricanes: Implications for the 2004 Atlantic hurricane season. *Geophys. Res. Lett.,* **32,** L03701, doi:10.1029/2004GL021702.