NOTES AND CORRESPONDENCE

ENSO's Impact on Regional U.S. Hurricane Activity

SHAWN R. SMITH, JUSTIN BROLLEY, JAMES J. O'BRIEN, AND CARISSA A. TARTAGLIONE

Center for Ocean–Atmospheric Prediction Studies, The Florida State University, Tallahassee, Florida

(Manuscript received 5 December 2005, in final form 19 June 2006)

ABSTRACT

Regional variations in North Atlantic hurricane landfall frequency along the U.S. coastline are examined in relation to the phase of El Niño–Southern Oscillation (ENSO). ENSO warm (cold) phases are known to reduce (increase) hurricane activity in the North Atlantic basin as a whole. Using best-track data from the U.S. National Hurricane Center, regional analysis reveals that ENSO cold-phase landfall frequencies are only slightly larger than neutral-phase landfall frequencies along the Florida and Gulf coasts. However, for the East Coast, from Georgia to Maine, a significant decrease in landfall frequency occurs during the neutral ENSO phase as compared to the cold phase. Along the East Coast, two or more major (category 3 or above) hurricanes never made landfall in the observational record (1900–2004) during a single hurricane season classified as an ENSO neutral or warm phase.

1. Introduction

Atlantic basin hurricane landfall frequency, categorized by phases of El Niño–Southern Oscillation (ENSO), is examined for regional variations along the U.S. coastline. The work is motivated by a need to better understand regional variations in hurricane landfalls in an era of increasing hurricane activity and growing coastal population (Pielke and Landsea 1998; Changnon et al. 2000). Goldenberg et al. (2001) noted that hurricane activity across the Atlantic basin between 1995 and 2000 was nearly double the activity during the preceding 24 yr (1971–94). Above-normal hurricane numbers in 2004 and 2005 reflect a continuation of active Atlantic hurricane seasons. Clearly, regional landfall probabilities would be useful to many government agencies [e.g., the Federal Emergency Management Agency (FEMA) and local governments] as they plan for potential hurricane emergencies. To achieve maximum benefit, the results of the presented research must be combined with a 3–6-month lead time forecast of the ENSO phase that will onset during the Atlantic hurricane season.

Corresponding author address: Mr. Shawn R. Smith, Center for Ocean–Atmospheric Prediction Studies, The Florida State University, Tallahassee, FL 32306-2840.
E-mail: smith@coaps.fsu.edu

DOI: 10.1175/JCLI4063.1

The presented results expand upon the data and results contained in the master's thesis of Tartaglione (2002). The authors focus on differences in landfall frequency, landfall probability distributions, and the location where U.S. landfalling hurricanes are first classified as tropical storms only for the three phases of ENSO. The authors acknowledge that other climate modes, including the Atlantic Multidecadal Oscillation (AMO; e.g., Goldenberg et al. 2001; Sutton and Hodson 2005) and the North Atlantic Oscillation (NAO; Xie et al. 2005), likely play a role in hurricane frequency in the Atlantic, but these modes will not be explicitly treated in this analysis. Separating hurricane landfalls by ENSO phase and landfall region already limits the sample size for statistical testing. Further simultaneous separation using the AMO or NAO would further limit the ability to test for significant variability in regional landfalls. The primary update to Tartaglione (2002) is the use of the reanalyzed Atlantic hurricane best-track data for 1900–2004 (Landsea et al. 2004). The authors specifically limit discussion of cause and effect relationships, noting up front that this manuscript focuses on statistical relationships and that additional research is required.

The impact of ENSO on basin-wide North Atlantic hurricane activity has been well documented. ENSO warm-phase (El Niño) conditions reduce hurricane activity in the North Atlantic basin (Gray 1984). The main factor Gray (1984) credited for the suppression of tropical cyclone development in the North Atlantic during El Niño is a strengthening of the upper-level westerlies over the equatorial Atlantic and Caribbean Sea. These westerly anomalies, estimated at 2–7 m s^{-1} during El Niño years, result in increased vertical wind shear, which is known to suppress tropical cyclone formation and growth (Gray 1968). Recently, Tang and Neelin (2004) have correlated the reduction in hurricanes during ENSO warm phases to changes in column static stability over the Atlantic. Conversely, ENSO cold-phase (La Niña) conditions tend to increase hurricane activity primarily due to weaker upper-level westerlies and reduced vertical wind shear.

Bove et al. (1998) also showed a decrease (increase) in hurricane landfall probabilities in the United States during El Niño (La Niña) events. For the period of record 1900–97, the mean number of hurricanes to make landfall in the United States annually was 1.04 during El Niño years, 1.61 during neutral years, and 2.23 during La Niña years (Bove et al. 1998). For the same period, Bove et al. (1998) found the probability of two or more North Atlantic hurricanes making landfall anywhere along the U.S. coastline to be 28% during El Niño, 48% during the neutral phase, and 66% during La Niña.

The previous studies do not analyze hurricane landfall probabilities for the United States on a regional scale. Regional differences in the effects of ENSO on hurricane landfalls in the Caribbean have been observed (Tartaglione et al. 2003; Landsea et al. 1999). El Niño (La Niña) decreases (increases) hurricane landfall activity relative to the neutral phase for the entire Caribbean region. Regionally, no differences were observed in hurricane landfall probabilities between the El Niño and neutral phases in the eastern and western Caribbean, while more landfalls occurred during the neutral versus warm phases in the northern Caribbean (Tartaglione et al. 2003). More recently, Klotzbach and Gray (2006) have begun providing forecast landfall probabilities for regions along the U.S. coastline; however, the role of ENSO is not directly included in their probability calculation but indirectly through their forecasts of net tropical cyclone activity.

As a follow-up to Tartaglione et al. (2003), hurricane landfall probabilities for the period 1900–2004 are calculated separately for Florida, the Gulf Coast, and the East Coast to assess the regional impact of ENSO on U.S. landfalls. The East Coast was defined as extending from the Florida–Georgia border northward to the Maine–Canada border. The Florida coastline extends from the Florida–Alabama border around Florida to the Florida–Georgia border, and the Gulf Coast spans from the Texas–Mexico border eastward to the Florida–Alabama border.

The analysis reveals a significant increase in the probability of hurricane landfalls along the East Coast during ENSO cold versus neutral phases. Surprisingly, there is virtually no difference in the probability of hurricane landfalls in Florida or along the Gulf Coast during ENSO cold versus neutral years. The probability of an East Coast landfall during ENSO neutral phases is nearly identical to the landfall probability for ENSO warm phases. Along the Gulf Coast and in Florida the landfall probabilities are reduced for warm versus neutral ENSO phases.

2. Methods

The Atlantic basin best-track hurricane dataset (HURDAT; Jarvinen et al. 1984; Neumann et al. 1993; Landsea et al. 2004) is used to identify hurricanes making landfall in the United States. The authors use all hurricanes (winds $\geq$ 64 kt) noted by HURDAT as making at least one landfall along the Florida, Gulf of Mexico, or East coasts. Only hurricanes (storms with winds $\geq$ 64 kt) defined by HURDAT as having a U.S. landfall are considered. The authors note that the list of U.S. landfalls derived from HURDAT includes a few hurricanes whose center never crossed the coastline (termed hurricane strikes) but were included as landfalls because 1-min wind speeds of at least hurricane force (64 kt) impacted the coast (C. Landsea 2006, personal communication). The term landfall in this paper is used to encompass both hurricane strikes and hurricanes whose center (eye) crossed the coastline. The record of landfalling hurricanes is more accurate than the record of all hurricanes because, prior to the deployment of satellites in the 1960s, open-ocean hurricanes may not have been identified if they failed to hit land. It is unlikely that any U.S. hurricane landfall was missed during the twentieth century. In addition, landfalling hurricanes are of more interest to the general public because they directly impact lives and property. The authors also use the Saffir–Simpson hurricane intensity scale listed in HURDAT to identify major (category 3–5) hurricanes.

Each landfalling storm is categorized following the method of Bove et al. (1998) as occurring during the onset summer of a warm, cold, or neutral ENSO phase. The phases of ENSO are defined using the Japan Meteorological Agency (JMA) index of equatorial Pacific sea surface temperatures (SST). Warm and cold phases classified by the JMA index compare favorably with many modern ENSO studies (Trenberth 1997;

TABLE 1. ENSO phases for hurricane seasons (June–November) based on the JMA index and the method of Bove et al. (1998). Row indicates decade, and column indicates year. W = warm, N = neutral, and C = cold ENSO phase.

	0	1	2	3	4	5	6	7	8	9
190	N	N	W	C	W	W	C	N	C	C
191	C	W	N	W	N	N	C	N	W	N
192	N	N	C	N	C	W	N	N	N	W
193	W	N	N	N	N	N	N	N	C	N
194	W	N	C	N	C	N	N	N	N	C
195	N	W	N	N	C	C	C	W	N	N
196	N	N	N	W	C	W	N	C	N	W
197	C	C	W	C	C	C	W	N	N	N
198	N	N	W	N	N	N	W	W	C	N
199	N	W	N	N	N	N	N	W	C	C
200	N	N	W	N	N					

Hanley et al. 2003). The JMA defines the 12-month period October through September as a warm (cold) phase when the 5-month running average SST anomaly over the tropical Pacific, from 4°S–4°N, 150°W–90°, is greater than 0.5°C (less than −0.5°C) for at least 6 consecutive months including October–December (JMA 1991). As an example, the hurricane season of June–November 1997 is split across the 1996 ENSO neutral event (June–September) and the onset of the 1997 ENSO warm event (October–November). By the criteria of Bove et al. (1998), the hurricane season of June–November 1997 is classified as occurring during the onset of an ENSO warm phase. All hurricane seasons that are not categorized as occurring during the onset of an ENSO warm or cold phase are classified as neutral seasons. Using this method, 25 of the hurricane seasons in the 105-yr period are classified as cold phases, 23 are designated warm phases, and 57 are categorized as neutral (Table 1).

The number of landfalls and landfall probabilities are determined for each ENSO phase and coastal region. Landfall counts are made for all hurricanes and for major hurricanes. If a hurricane makes landfall in Florida and then along the Gulf Coast, it is counted as a landfall in each of the two regions; however, the same hurricane is counted only once when considering all regions as a whole. In addition to counts of landfalls in each region, hurricane landfall probabilities for the 105-yr period of record are calculated using inverse cumulative frequency distributions (ICFDs).

The count of hurricane landfalls during a hurricane season is a discrete random variable; therefore, differences in the landfall frequency between ENSO phases can be tested in terms of two Poisson populations. Following the method used by Patten et al. (2003) and Tartaglione et al. (2003), a Z test based on a joint Poisson distribution (Lehmann 1986) is formulated to test the null hypothesis that the two rates of occurrence of hurricane landfalls between two ENSO phases are statistically similar. The alternative hypothesis assumes that the landfall rates of occurrence are significantly different. The Z-test statistic, with a continuity correction, is

$$Z = \left| \frac{x - 0.5 - \left(\dfrac{tn_x}{n_x + n_y}\right)}{\sqrt{t\left(\dfrac{n_x}{n_x + n_y}\right)\left(\dfrac{n_y}{n_x + n_y}\right)}} \right|. \qquad (1)$$

Considering the comparison of ENSO cold versus neutral phases, x = the number of landfalls occurring in n_x cold-phase years, y = the number of landfalls in n_y neutral-phase years, and $t = x + y$. The Z test is valid when $t > 25$ and is evaluated for significance levels of 90% or higher.

ENSO phase shifts in the mean and median location where hurricanes making landfall in the United States are first classified within the HURDAT as a tropical storm or stronger (winds ≥ 34 kt) are identified for each coastal region. Standard error bars ($s/\sqrt{n}$) are applied to the mean latitude and longitude of tropical storm classification. Box plots of the tropical storm classification latitude and longitude reveal these distributions to be asymmetric (see Fig. 7); therefore, a nonparametric statistical test is used to reveal significant shifts in the median classification location. The test method is based on a 2 × 2 contingency table (Bhattacharyya and Johnson 1977). The null hypothesis tested states that median tropical storm classification latitude and longitude between two ENSO phases are statistically equal versus the alternate hypothesis that the medians are different. Mean and median locations of tropical storm classification are also provided for major hurricanes; however, the small sample size precludes the application of significance tests.

3. Results

The number of hurricane landfalls in the three coastal regions shows a clear pattern of interannual variability (Fig. 1). A total of 53 hurricanes made landfall along the East Coast between 1900 and 2004, with 18 making landfall during the 25 ENSO cold events, 10 during the 23 warm events, and 25 during the 57 neutral events (Fig. 1a). Landfalls along the East Coast show clear active and inactive periods, with only two landfalls from 1917 to 1932 and only one from 1961 to 1970. During the same time period, 67 hurricanes made landfall in Florida (Fig. 1b). There were 20, 7, and 40 land-

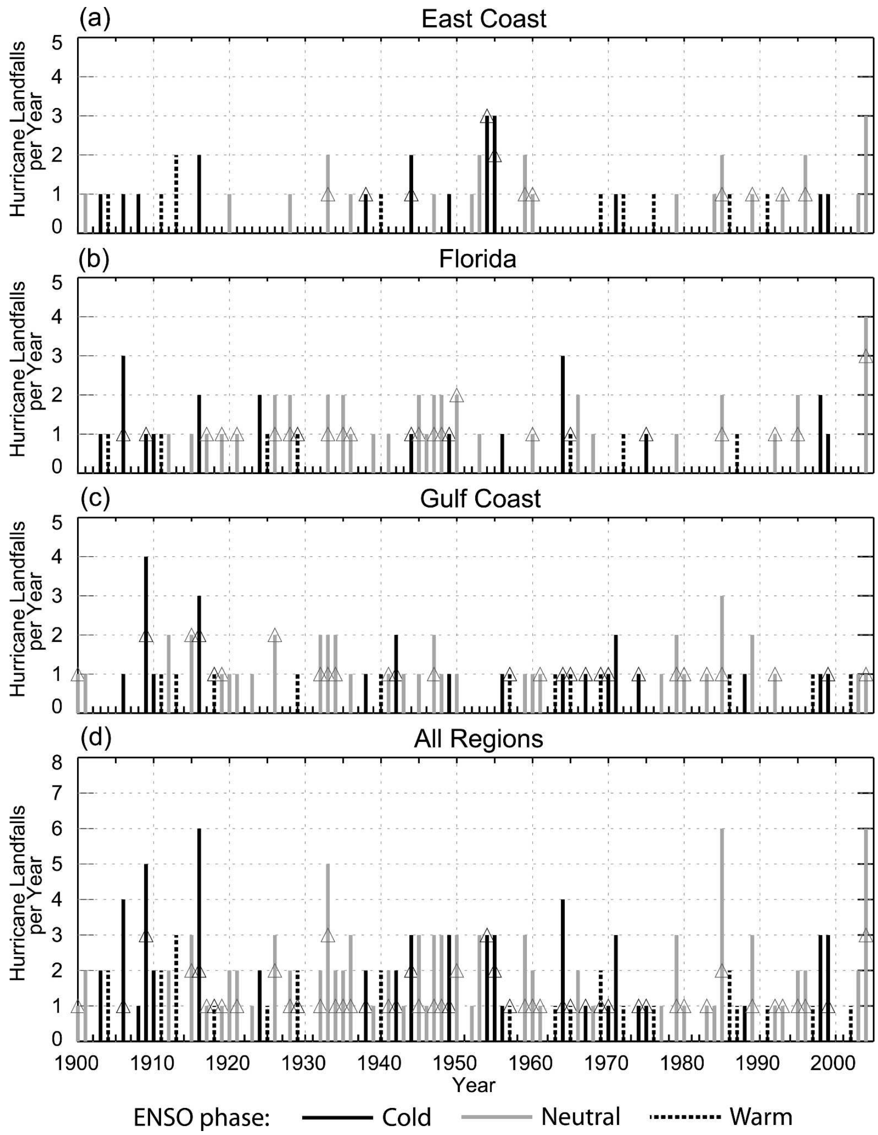

Fig. 1. The number of hurricanes that made landfall along the (a) East Coast (except Florida), (b) Florida coast, (c) Gulf Coast (except Florida), and (d) the entire U.S. coastline during each year between 1900 and 2004. ENSO cold, neutral, and warm phases are indicated by black, gray, and black dashed bars, respectively. Triangles indicate the number of category 3, 4, and 5 hurricanes while bars indicate the total of all hurricane categories.

falls during the cold, warm, and neutral ENSO phases, respectively. The record in Florida shows nearly twice the landfalls (41) from 1900 to 1950 that occurred from 1951 to 2001 (22 landfalls). The Gulf Coast experienced the most landfalls (77) from 1900 to 2004 (Fig. 1c), with 23, 12, and 42 landfalls during the cold, warm, and neutral ENSO phases, respectively. Gulf Coast landfalls are distributed fairly evenly through the 105-yr period record. The totals for all regions combined (57 cold-, 94 neutral-, and 26 warm-phase landfalls) show a drop in landfalls from 1960 to 1995 (Fig. 1d), which coincides with the decrease in Atlantic major hurricanes from the mid-1960s to 1994 noted by Goldenberg et al. (2001).

Landfall frequency per year for the entire U.S. coastline from 1900 to 2004 (Fig. 2d) compares favorably with the results of Bove et al. (1998). Regionally, the highest frequencies occur during ENSO cold phases for each of the three coastal regions (Figs. 2a–c). The landfall counts result in an average of 0.72, 0.80, and 0.92 hurricane landfalls per season, respectively, for the East Coast, Florida, and the Gulf Coast during ENSO cold phases. Comparing landfall frequencies during ENSO

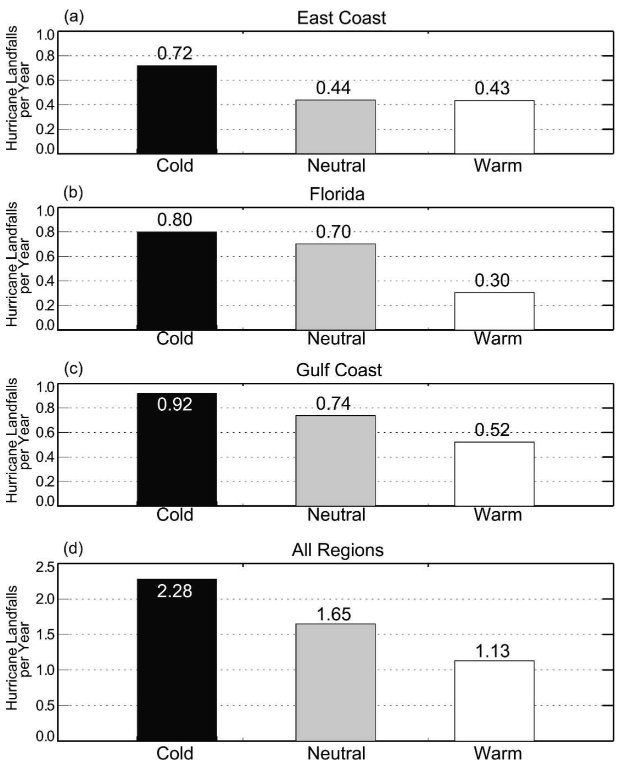

FIG. 2. Average number of hurricane landfalls per year (a) on the East Coast (except Florida), (b) in Florida, (c) along the Gulf Coast (except Florida), and (d) along the entire U.S. coastline from 1900 to 2004 during years classified as cold, neutral, or warm ENSO phases. As an example of how to interpret these averages, approximately one (0.92) landfall occurs per ENSO cold phase vs one landfall for every two ENSO warm phases (0.52) along the Gulf Coast.

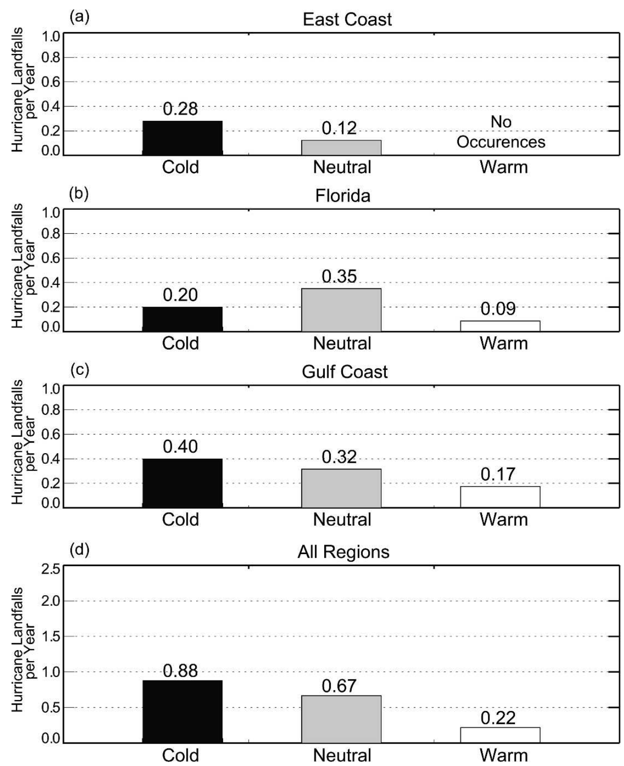

FIG. 3. Average number of major (category 3, 4, or 5) hurricane landfalls per year (a) on the East Coast (except Florida), (b) in Florida, (c) along the Gulf Coast (except Florida), and (d) along the entire U.S. coastline from 1900 to 2004 during years classified as cold, neutral, or warm ENSO phases. Within the 1900–2004 period, there were no occurrences of major hurricane landfalls along the East Coast during ENSO warm phases.

cold versus neutral phases reveals a significant decrease only for hurricanes making landfall along the East Coast. Applying the Z test from (1) allows rejection of the hypothesis that East Coast landfall frequencies are equal during ENSO cold and neutral phases at a significance level of greater than 90%. During a neutral phase along the East Coast (Fig. 2a), only 0.44 hurricane landfalls occur per season, which can be interpreted as approximately four landfalls for every 10 neutral phases. This compares to seven landfalls for every 10 ENSO cold phases along the East Coast. Differences in ENSO cold versus neutral landfall probabilities are notably smaller for Florida and the Gulf Coast (Figs. 2b,c). These results suggest that there is a significant change in formation location and/or steering patterns during neutral years that limits East Coast landfalls.

The probability of hurricane landfalls within each of the three coastal regions is lowest for ENSO warm phases (Fig. 2). The authors expected this result based on previous work, but clear regional variations also exist for the warm versus neutral ENSO phases. First, the probability of hurricane landfall along the East Coast is nearly identical for warm and neutral ENSO phases (Fig. 2a). In addition, the difference in landfall probabilities in Florida between warm (0.30) and neutral (0.70) phases is significant at the 99% level (based on the Z test).

Limiting the analysis to major hurricane landfalls again reveals the Gulf Coast to have the most landfalls (32) as compared to Florida (27) and the East Coast (14). Major hurricane landfall frequency for the combined U.S. coast from 1900 to 2004 mirrors the results for all hurricanes, with more (less) landfalls during cold (warm) phases relative to neutral. Regionally, the highest landfall frequencies occur during the cold ENSO phase for the East and Gulf Coasts (Figs. 3a,c); however, the neutral phase dominates major hurricane landfalls in Florida (Fig. 3b). The number of landfalls represents a summary of rare events during the 1900–2004 period of record and the totals are too small to allow the application of the Z test for major hurricanes. Clearly the warm-phase sample is too small to draw any

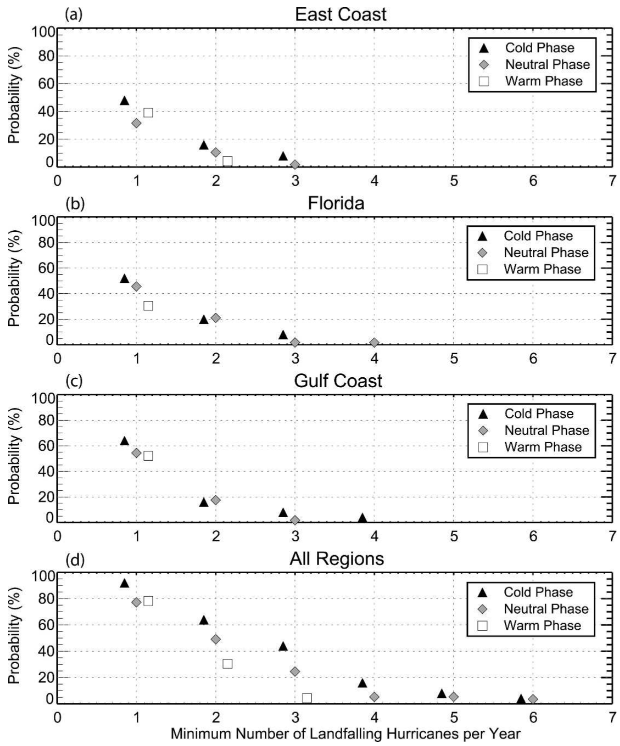

FIG. 4. ICFD of hurricanes making landfall (a) on the East Coast (except Florida), (b) in Florida, (c) on the Gulf Coast (except Florida), and (d) along the entire U.S. coastline for ENSO cold, neutral, and warm phases from 1900 to 2004. ICFD shows the probability of *x* or more hurricanes making landfall within 1 yr, where *x* is the abscissa on the plot. For all cases, the probability of zero or more hurricanes is 100% by definition and is not plotted.

regional conclusions beyond the fact that the rare event of a major hurricane landfall is even more infrequent during ENSO warm phases based on the 1900–2004 period of record. Based on the small sample available, the authors note that the only years between 1900 and 2004 with two or more major hurricane landfalls along the East Coast (1954 and 1955) are classified as ENSO cold phases (Fig. 1a). In Florida from 1900 to 2004, only two ENSO neutral years have had multiple major hurricane landfalls (1950 and 2004), while two ENSO cold and two ENSO neutral years (1909 and 1916; 1915 and 1926, respectively) had two major hurricane landfalls on the Gulf Coast (Fig. 1).

The ICFDs from the 1900–2004 period confirm a higher probability of hurricanes making landfall during cold versus neutral ENSO phases along the East Coast. During a cold phase, the probability of two or more hurricanes hitting the East Coast is 16% versus only 10% during a neutral phase (Fig. 4a). In Florida, the probability of two or more hurricanes making landfall is nearly identical for the cold (20%) and neutral (21%) phases (Fig. 4b). Probabilities of two or more landfalls along the Gulf Coast are also similar during a cold (16%) and neutral (17%) phase. The authors note that no ENSO warm-phase season during the 1900–2004 record has produced more than one hurricane landfall in Florida or along the Gulf Coast (Fig. 4). In addition, when considering the combined coastline, only cold and neutral phases have exhibited four, five, or six hurricane landfalls in a single year.

The analysis above clearly shows regional differences in landfall frequencies during ENSO phases. The differences led the authors to question whether there are variations in the location where landfalling hurricanes first reach tropical storm status during the three ENSO phases. Identifying variations in tropical storm classification location will help focus future research into the variability of physical processes (e.g., air–sea fluxes of heat and moisture) that enhance or suppress hurricane activity.

Plotting the location where each U.S. landfalling hurricane was first classified as a tropical storm or stronger in the HURDAT reveals differences by ENSO phase (Fig. 5). Most striking is the expected reduction in the number of tropical cyclones forming during ENSO warm phases (Fig. 5c). The overall mean (Fig. 6) and median (Fig. 7) position of first classification as a tropical storm is shifted to the north and west for hurricanes making landfall along the entire U.S. coastline during a warm phase, relative to cold or neutral phases. Nonparametric tests reject the hypothesis that the all-regions warm-phase median latitude is equal to the neutral (and cold)-phase median with a confidence of greater than 90%. For the East Coast, the northward shift (relative to neutral phase) in median latitude and the westward shift (relative to neutral and cold phases) in median longitude during a warm phase reject the hypothesis of equal medians at the 99% and 95% level, respectively (Table 2; Fig. 7). Similar significance can be expected for the East Coast mean latitude and longitude where the range of 2 times the standard error on the mean for the cold and neutral phases falls outside the same range for the warm phase (Fig. 6). The authors also note that no hurricane making landfall in the United States during ENSO warm phases was first classified as a tropical storm east of 50°W from 1900 to 2004 (Fig. 5c).

Overall, the difference in median tropical storm classification position for cold- versus neutral-phase landfalling hurricanes is small (only 1.0° latitude and 1.5° longitude); however, significant regional variations are present (Table 2; Fig. 7). Hurricanes making landfall in Florida exhibit a 12.8° westward shift in median tropical storm classification location during ENSO cold versus neutral phases (Table 2). This significant westward shift

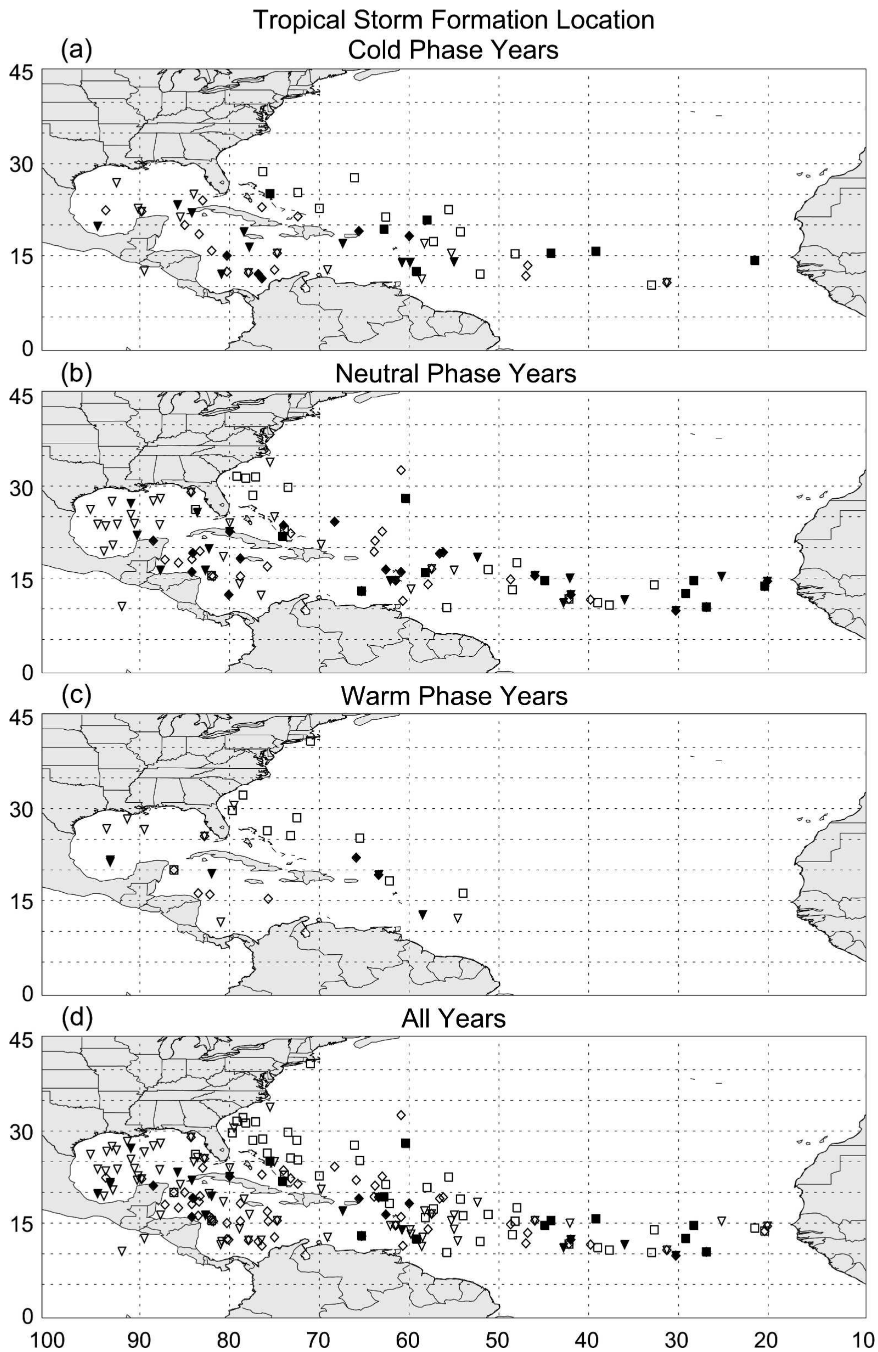

FIG. 5. Location at which hurricanes making landfall in the United States are first designated as a tropical storm (or stronger) within the HURDAT for ENSO (a) cold, (b) neutral, and (c) warm phases and (d) all years combined. Landfall location is separated into East Coast (square), Florida (diamond), and Gulf Coast (inverted triangle). Open symbols are hurricanes that made landfall as a category-1 or -2 storm, and closed symbols are hurricanes that made landfall as a category-3, -4, or -5 storm. Note that storms may move across land as a tropical storm and make landfall in a different region as a hurricane.

(90% level) brings developing tropical storms closer to the Florida coast and increases the probability of these storms making landfall as hurricanes in Florida during ENSO cold phases.

East Coast landfalling hurricanes, except those forming during a warm phase, typically form farther east than those that strike Florida or the Gulf Coast (Figs. 5–7). In fact, the median longitude of tropical storm

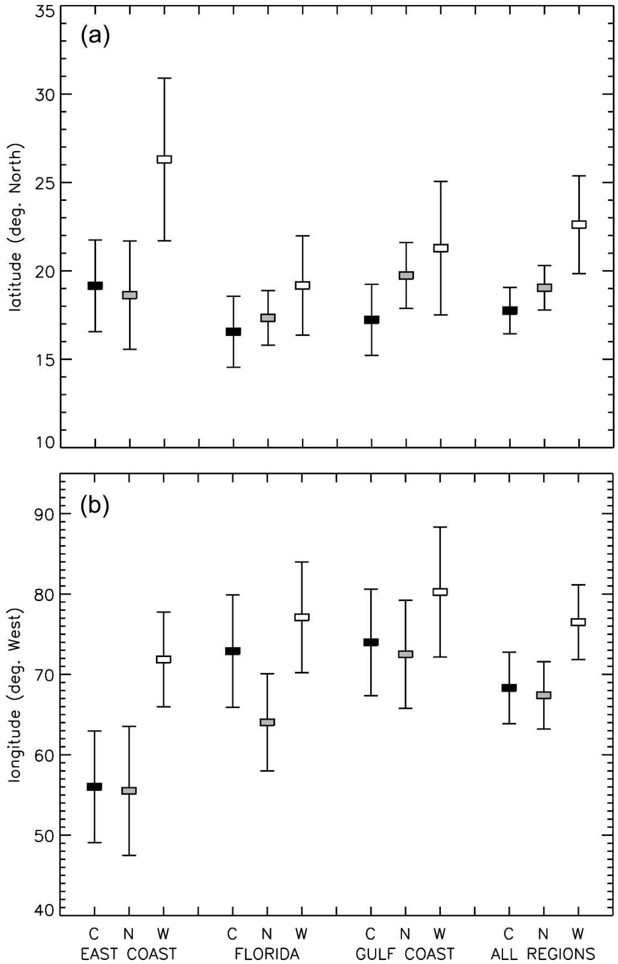

Fig. 6. Mean (a) latitude and (b) longitude at which hurricanes making landfall in the United States are first classified in HURDAT as a tropical storm. Means are separated into cold (C, black), neutral (N, gray), and warm (W, white) ENSO phases and are grouped by landfall region. Error bars represent 2 times the standard error of the mean ($s/\sqrt{n}$).

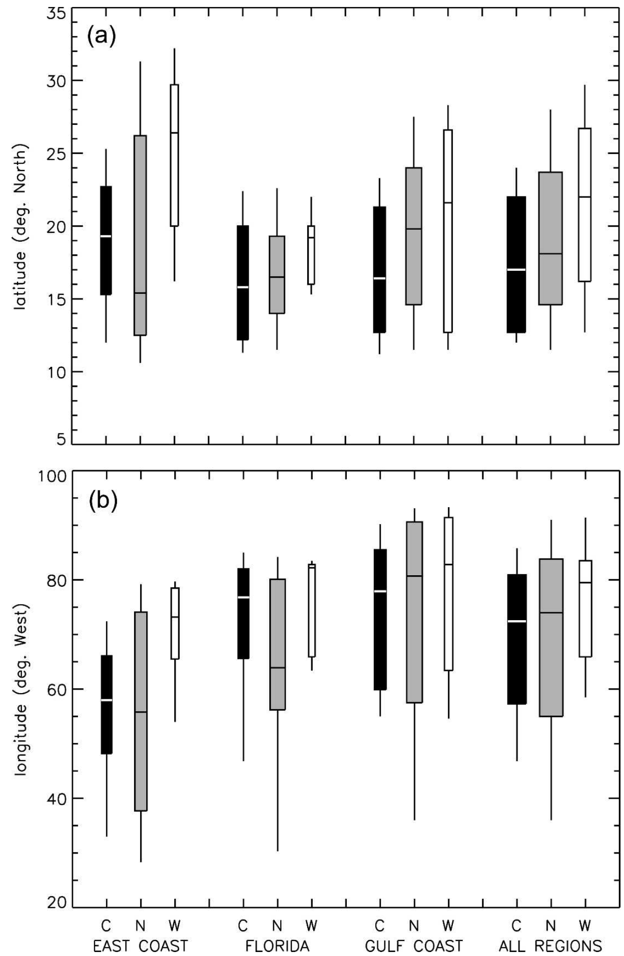

Fig. 7. Box plots showing the median and interquartile range for the (a) latitude and (b) longitude at which hurricanes making landfall in the United States are first classified in HURDAT as a tropical storm. Box plots are separated into cold (C, black), neutral (N, gray), and warm (W, white) ENSO phases and are grouped by landfall region. Upper (lower) whiskers extend to the 90th (10th) percentile value and the box width is proportional to the $\sqrt{n}$.

classification during cold and neutral ENSO phases is near or less than the 25th percentile longitude for both Florida and Gulf Coast landfalling hurricanes (Fig. 7). Tropical cyclones that form in the far eastern Atlantic have more time to be influenced by upper-level troughs as they travel across the Atlantic, thereby increasing the likelihood that they will reach a more northern latitude and impact the East Coast. During the ENSO cold phase, the 19.0° difference in median longitude of tropical storm classification between hurricanes making East Coast versus Florida landfall is significant at the 99% level. During the neutral phase, the East Coast versus Florida median longitude difference is only 8.0°, but this difference grows to 17.1° when considering only major hurricanes. Major hurricanes making landfall during the neutral phase in Florida have a median tropical storm classification longitude of 62.0° versus 44.9°W for East Coast major hurricanes during the neutral phase (Table 2). A classification location closer to the United States may partially explain Florida having the highest probability (35%) of a major hurricane landfall during ENSO neutral phases (Fig. 3b) over the 1900–2004 period of record.

Along the East Coast, the reduction in hurricane landfalls during ENSO neutral phases may be related to variations in the number of hurricanes that are first classified as tropical storms in the eastern tropical North Atlantic Ocean. When considering all hurricanes that make landfall in the United States over the 105-yr period of record there is a 16% probability per year that hurricanes first classified as a tropical storm east of

TABLE 2. Mean, standard error ($s/\sqrt{n}$), and median of the latitude (°N) and longitude (°W) at which U.S. landfalling hurricanes first achieve tropical storm (or stronger) status according to the best-track data. The number of hurricane landfalls (n) is determined by separating landfalls by coastal region (e.g., East Coast, Florida, and Gulf of Mexico) and ENSO phase. Summary statistics for all regions are also presented, but note that the totals are not cumulative due to the method of counting only one landfall for the combined region even if a hurricane makes landfall in multiple subregions. The statistics are shown for (top) all and (bottom) major hurricanes when n ≥ 5.

All landfalling hurricanes

ENSO phase		Cold		Neutral		Warm	
		Lat	Lon	Lat	Lon	Lat	Lon
East Coast	Mean	19.1	56.0	18.6	55.5	26.3	71.9
	Std error	1.3	3.5	1.5	4.0	2.3	2.9
	Median	19.1	57.6	15.4	55.8	26.0	72.8
	n	18	18	25	25	10	10
Florida	Mean	16.6	72.9	17.3	64.0	19.2	77.1
	Std error	1.0	3.5	0.8	3.0	1.4	3.4
	Median	15.6	76.6	16.4	63.8	19.2	82.2
	n	20	20	40	40	7	7
Gulf Coast	Mean	17.2	74.0	19.7	72.5	21.3	80.2
	Std error	1.0	3.3	0.9	3.4	1.9	4.0
	Median	16.4	77.9	19.6	80.3	21.4	82.4
	n	23	23	42	42	12	12
All regions	Mean	17.8	68.3	19.0	67.4	22.6	76.5
	Std error	0.7	2.2	0.6	2.1	1.4	2.3
	Median	17.0	72.4	18.0	73.9	21.8	79.0
	n	57	57	94	94	26	26

Major landfalling hurricanes

ENSO phase		Cold		Neutral		Warm	
		Lat	Lon	Lat	Lon	Lat	Lon
East Coast	Mean	17.6	51.5	16.8	46.0	—	—
	Std error	1.7	6.7	2.3	7.1	—	—
	Median	15.7	58.0	14.6	44.9	—	—
	n	7	7	7	7	0	0
Florida	Mean	15.1	71.8	16.6	59.3	—	—
	Std error	1.6	3.8	0.9	4.9	—	—
	Median	15.0	76.4	16.0	62.0	—	—
	n	5	5	20	20	2	2
Gulf Coast	Mean	17.1	74.5	16.8	58.8	—	—
	Std error	1.2	4.1	1.2	5.7	—	—
	Median	16.7	78.1	15.3	56.9	—	—
	n	10	10	18	18	4	4
All regions	Mean	16.8	66.6	17.1	59.5	19.0	72.6
	Std error	0.8	3.6	0.8	3.6	1.7	6.5
	Median	16.0	66.5	16.0	61.2	19.4	65.9
	n	22	22	38	38	5	5

50°W will make landfall on the East Coast regardless of ENSO phase. The probability drops to 13% for Florida and 9% for Gulf Coast landfalls, respectively. In other words, one hurricane reaching tropical storm status east of 50°W makes landfall on the East Coast every 6 yr versus one in every 10 yr along the Gulf Coast. When we consider the actual number of landfalling hurricanes first classified as tropical storms east of 50°W, we find that 5 (11), 3 (9), and 1 (8) made landfall along the East Coast, in Florida, and along the Gulf Coast during ENSO cold (neutral) phases (Fig. 5). Based on there being only 2.4 times as many neutral-phase years as cold-phase years from 1900 to 2004, it is surprising that 8 times as many hurricanes classified as tropical storms east of 50°W during a neutral phase make landfall on the Gulf Coast. The increase during neutral phases (relative to cold phases) in landfalls along the Florida and Gulf coasts for hurricanes classified as tropical storms east of 50°W allows the authors to hypothesize that a variation in the steering flow exists during neutral phases. The hypothetical variation in the steering flow seems to keep tropical cyclones forming in the eastern tropical North Atlantic on a more southerly track during a neutral ENSO phase, thereby decreasing the probability of East Coast landfalls.

Recent work by Xie et al. (2005) reveals that hurricanes favor tracks moving more to the southwest (northeast) during ENSO cold (warm) phases. This pattern favors landfalls along the East Coast during ENSO cold phases. Xie et al. (2005) do not comment on tracks during ENSO neutral phases; however, separating hurricane landfall locations along the East Coast by state boundaries reveal that hurricanes tend to hit farther south during an ENSO neutral phase than during cold phases. For the 1900–2004 period, both Georgia and South Carolina have more landfalls during ENSO neutral versus cold phases. Georgia averages one landfall for every 20 neutral-phase years while there are no occurrences, from 1900 to 2004, of a hurricane landfall in Georgia during a cold phase. In South Carolina, an average of one hurricane makes landfall for every six (eight) ENSO neutral (cold) phase years. From North Carolina through Massachusetts there are more landfalls during ENSO cold versus neutral phases, excluding Delaware and New Jersey, which recorded no landfalls. The more southerly landfall location on the East Coast during ENSO neutral phases combined with the result that 8 times as many hurricanes reaching tropical storm status east of 50°W during a neutral phase make landfall on the Gulf Coast versus the East Coast imply that a more southerly track for hurricanes is favored during ENSO neutral phases, thus decreasing the likelihood of an East Coast landfall.

4. A look at 2005

The authors' primary analysis was completed during the extremely active 2005 hurricane season, so 2005 data are not included in the results above. We now compare the 2005 hurricane season to the 1900–2004

Table 3. Statistics for hurricanes making landfall along the U.S. coastline during the 2005 hurricane season. Note that Katrina made landfall in two regions: category 1 in Florida and category 3 along the Gulf Coast. (Source: HURDAT 2005 update.)

Name	Landfall region	Saffir–Simpson category at landfall	Location at tropical storm classification
Cindy	Gulf Coast	1	25.1°N, 90.2°W
Dennis	Florida	3	13.0°N, 65.9°W
Katrina	Florida	1	24.5°N, 76.5°W
	Gulf Coast	3	
Ophelia	East Coast	1	27.9°N, 78.8°W
Rita	Gulf Coast	3	22.2°N, 72.3°W
Wilma	Florida	3	16.9°N, 79.6°W

results. The JMA index and the method of Bove et al. (1998) classify the 2005 hurricane season as a neutral ENSO phase. A recent update of the HURDAT data to include the 2005 season reveals that six hurricanes made landfall along the U.S. coastline (Table 3). The 2005 hurricane season marks only the fourth time since 1900 that six hurricanes made U.S. landfall (other years are 1916, 1985, and 2004). The 2005 season also marks the first occurrence since 1900 of four hurricanes classified as major at landfall.

By region, one, three, and three hurricane landfalls occurred along the East Coast, in Florida, and along the Gulf Coast, respectively. The fact that only one of the seven landfalls occurred along the East Coast is consistent with the authors' findings of reduced East Coast landfall probabilities during ENSO neutral phases (Fig. 2). The location at which each of these five hurricanes reached tropical storm strength, clustered between 60° and 80°W longitude, also contributed to the reduced probability that they would make landfall along the East Coast (none of these cyclones first reached tropical storm strength in the favored East Coast landfall region east of 50°W). Finally, the authors note that the only occurrences from 1900 to 2005 of multiple major hurricane landfalls in Florida (Fig. 1b; Table 3) are during ENSO neutral years (1950, 2004, and 2005). Multiple major hurricane landfalls along the Gulf Coast (Fig. 1c; Table 3) are almost equally likely during the cold (1909 and 1916) and neutral (1915, 1926, and 2005) phases.

5. Conclusions

The regional differences in Atlantic hurricane landfall probabilities along the U.S. coast are identified with respect to the warm, neutral, and cold phases of ENSO. Combining forecasts of the ENSO phase that will onset during a hurricane season with the landfall frequencies from 1900 to 2004, one can determine whether the probability of a hurricane landfall is the highest along the East Coast, in Florida, or along the Gulf Coast. Local, state, and federal emergency management agencies, particularly with respect to coastal areas, should benefit from the results of this study.

Residents of the East Coast are most likely to see a landfalling hurricane during a season that precedes a La Niña winter. The landfall probability during ENSO cold phases (0.72) drops to 0.44 during neutral phases for East Coast landfalls. In Florida and along the Gulf Coast, there is little difference observed in the frequency of hurricane landfalls between cold and neutral events. As expected from previous works, landfall probabilities are smallest during ENSO warm phases in all regions.

Exploring the possible physical mechanisms that may explain the decrease in hurricane landfalls along the East Coast during neutral years are beyond the scope of this work. Variations in the landfall location of hurricanes first reaching tropical storm status in the eastern tropical North Atlantic Ocean are revealed between ENSO cold and neutral phases. Overall hurricanes reaching tropical storm strength in the eastern tropical Atlantic are more likely to strike the East Coast; however, hurricanes reaching tropical storm strength in this region during ENSO neutral phases have a higher than expected probability of striking Florida or the Gulf Coast. Clearly variations in location where landfalling hurricanes first reach tropical storm strength alone cannot account for variations in regional U.S. landfalls and future research must investigate changes in steering flow during ENSO phases. The strength, position, and shape of the subtropical Atlantic surface anticyclone and its relationship to phases of the North Atlantic Oscillation and Atlantic multidecadal oscillation should be considered. Further investigation is needed to gain a better understanding of the mechanisms suppressing East Coast hurricane landfalls during ENSO neutral years.

Acknowledgments. Funding for this research was provided by the National Oceanic and Atmospheric Administration (NOAA) Office of Global Programs through an Applied Research Center. Additional funding for this work was provided by NASA and the USDA. The authors thank Mark Bourassa for his insight into statistical methods, Melissa Griffin for her helpful suggestions, and Shane Prorok for his contribution to the 2005 hurricane analysis. The authors also express their gratitude to Christopher Landsea and the two anonymous reviewers for their constructive comments on this manuscript.

REFERENCES

Bhattacharyya, G. K., and R. A. Johnson, 1977: *Statistical Concepts and Methods*. John Wiley and Sons, 639 pp.

Bove, M. C., J. B. Elsner, C. W. Landsea, X. Niu, and J. J. O'Brien, 1998: Effect of El Niño on U.S. landfalling hurricanes, revisited. *Bull. Amer. Meteor. Soc.,* **79,** 2477–2482.

Changnon, S. A., R. A. Pielke Jr., D. Changnon, R. T. Sylves, and R. Pulwarty, 2000: Human factors explain the increased losses from weather and climate extremes. *Bull. Amer. Meteor. Soc.,* **81,** 437–442.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science,* **293,** 474–479.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.,* **96,** 669–700.

——, 1984: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.,* **112,** 1649–1668.

Hanley, D. E., M. A. Bourassa, J. J. O'Brien, S. R. Smith, and E. R. Spade, 2003: A quantitative evaluation of ENSO indices. *J. Climate,* **16,** 1249–1258.

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis, 1984: A tropical cyclone data tape for the North Atlantic Basin, 1886–1983: Contents, limitations, and uses. NOAA Tech. Memo. NWS NHC 22, 21 pp.

JMA, 1991: Climate charts of sea surface temperatures of the Western North Pacific and the global ocean. Marine Department, Japan Meteorological Agency, 51 pp.

Klotzbach, P. J., and W. M. Gray, cited 2006: Extended range forecast of Atlantic seasonal hurricane activity and U.S. landfall strike probability for 2006. [Available online at http://typhoon.atmos.colostate.edu/Forecasts/2006/april2006/.]

Landsea, C. W., R. A. Pielke Jr., A. M. Mestas-Nuñez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change,* **42,** 89–129.

——, and Coauthors, 2004: The Atlantic hurricane database reanalysis project: Documentation for the 1851–1910 alterations and additions to the HURDAT database. *Hurricanes and Typhoons: Past, Present and Future,* R. J. Murname and K.-B. Liu, Eds., Columbia University Press, 177–221.

Lehmann, E. L., 1986: *Testing Statistical Hypotheses*. 2d ed. Wiley and Sons, 600 pp.

Neumann, C. J., B. R. Jarvinen, C. J. McAdie, and J. D. Elms, 1993: Tropical cyclones of the North Atlantic Ocean. National Climatic Data Center, Asheville, NC, in cooperation with the National Hurricane Center, Coral Gables, FL, 193 pp.

Patten, J. M., S. R. Smith, and J. J. O'Brien, 2003: Impacts of ENSO on snowfall frequencies in the United States. *Wea. Forecasting,* **18,** 965–980.

Pielke, R. A., Jr., and C. W. Landsea, 1998: Normalized hurricane damages in the United States: 1925–95. *Wea. Forecasting,* **13,** 621–631.

Sutton, R. T., and D. L. R. Hodson, 2005: Atlantic Ocean forcing of North American and European summer climate. *Science,* **309,** 115–118.

Tang, B. H., and J. D. Neelin, 2004: ENSO influence on Atlantic hurricanes via tropospheric warming. *Geophys. Res. Lett.,* **31,** L24204, doi:10.1029/2004GL021072.

Tartaglione, C. A., 2002: Regional effects of ENSO on US hurricane landfalls. M.S. thesis, Dept. of Meteorology, The Florida State University, 45 pp.

——, S. R. Smith, and J. J. O'Brien, 2003: ENSO impact on hurricane landfall probabilities for the Caribbean. *J. Climate,* **16,** 2925–2931.

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.,* **78,** 2771–2777.

Xie, L., T. Yan, L. J. Pietrafesa, J. M. Morrison, and T. Karl, 2005: Climatology and interannual variability of North Atlantic hurricane tracks. *J. Climate,* **18,** 5370–5381.