El Niño–Southern Oscillation's Impact on Atlantic Basin Hurricanes and U.S. Landfalls

PHILIP J. KLOTZBACH

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

(Manuscript received 20 April 2010, in final form 7 September 2010)

ABSTRACT

El Niño–Southern Oscillation (ENSO) has been shown in many previous papers to impact seasonal levels of Atlantic basin tropical cyclone activity. This paper revisits this relationship by examining a longer period (1900–2009) than has been examined in earlier analyses. Alterations in large-scale climate parameters, especially vertical wind shear, are shown to be the primary reasons why tropical cyclone activity in the Atlantic is reduced in El Niño years. Climate signals are found to be somewhat stronger in the Caribbean than for the remainder of the tropical Atlantic. The focus of the paper then shifts to U.S. landfalls, confirming previous research that U.S. landfalls are reduced in El Niño years. The reduction in landfall frequency is greater along the Florida peninsula and East Coast than it is along the Gulf Coast, especially for major hurricanes. The probability of each state being impacted by a hurricane and major hurricane is given for El Niño, La Niña, and neutral years. The most dramatic probability differences between warm and cold ENSO events lie along the East Coast and, in particular, the state of North Carolina. The relationship between ENSO and the Atlantic multidecadal oscillation (AMO) is also examined. In general, the negative phase of the AMO is characterized by a stronger ENSO modulation signal than a positive phase of the AMO.

1. Introduction

El Niño–Southern Oscillation (ENSO) has been shown to impact overall Atlantic basin tropical cyclone (TC) activity in many studies over the past several decades (e.g., Gray 1984; Goldenberg and Shapiro 1996; Wilson 1999). The primary reason why it is thought that ENSO impacts Atlantic basin hurricanes is because of alterations in the Walker circulation. In warm ENSO events, the Walker circulation is slightly weaker than normal and shifts eastward, thereby increasing upper-level westerly winds over the Caribbean and tropical Atlantic. These increased upper-level westerlies, combined with climatological lower-level easterlies, increase vertical wind shear across the tropical Atlantic (Gray 1984; Goldenberg and Shapiro 1996). Strong levels of vertical wind shear are known to be detrimental to Atlantic TC formation (DeMaria 1996; Frank and Ritchie 2001; Knaff et al. 2004). While weak-to-moderate warm ENSO events may be characterized by active to very active Atlantic hurricane seasons (e.g., 1969 and 2004), strong ENSO events are associated with much-reduced levels of activity (e.g., 1982, 1987, and 1997).

In general, more active Atlantic basin TC seasons have more landfalling U.S. hurricanes (Gray 1984; Klotzbach and Gray 2004). Because of this fact, it would be expected that ENSO would also impact U.S. hurricane landfall numbers. Recent research confirms this conjecture, as it has been demonstrated that El Niño reduces U.S. hurricane landfall numbers (Bove et al. 1998; Elsner and Jagger 2004, 2006; Smith et al. 2007). Bove et al. (1998), using data from 1900 to 1997, found that the probability of a major hurricane making U.S. landfall in an El Niño year was 23% compared with 58% during a neutral year and 63% during a La Niña year. Elsner and Jagger (2004) used the cold tongue index (CTI; 6°S–6°N, 180°–90°W), which is closely related to ENSO, in a Bayesian model prediction for U.S. landfalling hurricanes, with a reduced CTI (e.g., El Niño) associated with fewer landfalling hurricanes. More recently, Elsner and Jagger (2006) utilized the May-June-averaged value of the Southern Oscillation index (SOI) as part of their model to predict annual U.S. hurricane counts. A negative SOI, typically characteristic of a warm ENSO event, was found to reduce the number of landfalling U.S. hurricanes. Smith

---

Corresponding author address: Philip J. Klotzbach, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.
E-mail: philk@atmos.colostate.edu

DOI: 10.1175/2010JCLI3799.1

et al. (2007) found that landfall frequencies in La Niña years were significantly enhanced along the East Coast when compared with neutral years, while little change was seen between La Niña and neutral years for Gulf Coast or Florida landfalls. Pielke and Landsea (1999), using data from the period 1925–1997, showed that the median normalized hurricane damage was approximately 3.3 billion U.S. dollars in La Niña years, 900 million dollars in neutral years, and 150 million dollars in El Niño years.

This paper expands upon earlier research by first documenting the impact of ENSO on overall Atlantic basin hurricane activity over the period 1900–2009. Then, fluctuations in large-scale climate parameters (such as vertical wind shear and midlevel relative humidity), given a particular phase of ENSO, are quantified for both the tropical Atlantic and the Caribbean. Relationships between ENSO and U.S. hurricane landfalls are then examined, for the entire United States coastline, two large regions (the Florida peninsula and East Coast, and the Gulf Coast), and then every coastal state from Maine to Texas. Finally, modulation of these impacts based upon the phase of the Atlantic multidecadal oscillation (AMO) is examined.

Section 2 begins by discussing the various sources of data utilized in this study. Section 3 documents variations in overall Atlantic basin TC activity given a particular phase of ENSO. Section 4 discusses the changes in large-scale climate parameters that are observed given various ENSO phases, both for the Caribbean and the remainder of the tropical Atlantic. The focus of the paper then shifts to fluctuations in U.S. hurricane impacts, for the entire United States coastline as well as for the Florida peninsula and East Coast and the Gulf Coast, individually in section 5. Section 6 examines how the ENSO phase alters the probabilities of hurricane impact for each coastal state, and section 7 examines how ENSO's impacts are altered by phase of the AMO. Section 8 summarizes and provides some ideas for future work.

2. Data

The source for basinwide Atlantic TC statistics is the Atlantic Tracks File database (Jarvinen et al. 1984). This database contains 6-hourly estimates of location and wind speed for all TCs that formed in the Atlantic basin during the period 1851–2009. Underestimates in the data are likely during the earlier portion of the database, as satellite reconnaissance was not available until the mid-1960s, and aircraft reconnaissance was not conducted prior to the mid-1940s (e.g., Landsea 2007; Landsea et al. 2010). These underestimates are likely to be greater for weaker TCs and systems that existed in the eastern part of the Atlantic (where ship traffic was less frequent during the early part of the 1900s). The Atlantic Hurricane Database Reanalysis Project is currently underway (Landsea et al. 2004, 2008), and the reanalysis during the period 1900–25 is included as part of the basinwide TC statistics that are calculated during the period 1900–2009. This reanalysis has altered intensities for some TCs from what was previously available and, consequently, statistics calculated using the reanalyzed data are going to be slightly different than in previous studies. Since El Niño and La Niña events have occurred regularly over the past 110 yr, underestimates in hurricane activity during the earlier portion of the record (e.g., Landsea 2007) should not impact the overall relationships with Atlantic hurricane activity significantly.

For U.S. hurricane landfall statistics, the hurricane impact database from the National Hurricane Center is utilized (current database available online at http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512008.txt; Blake et al. 2007). This dataset lists each hurricane that impacted the U.S. coastline during the period 1851–2008; however, reliable data are not considered available for the entire coastline until 1900 (C. W. Landsea 2009, personal communication). No hurricanes made landfall in the United States in 2009, so the database can be extended to include that year. Impacts are listed based on the Saffir–Simpson scale (Simpson 1974). The hurricane impact database takes into account that several states can be impacted by one hurricane, even if the storm does not make direct landfall in that state. For example, Hurricane Katrina in 2005 impacted Alabama as a category 1 hurricane while making landfall in Louisiana and then Mississippi as a category 3 hurricane, but it is only considered as one landfall for the Gulf Coast. Storms that impacted Texas eastward to northwest Florida (north and west of Tarpon Springs, Florida) are taken as Gulf Coast impacts, while systems impacting the remainder of Florida northward to Maine are taken as Florida peninsula and East Coast impacts. Although one system could impact both the Gulf Coast and the Florida peninsula and East Coast regions and would be counted individually for both subregions, it was only counted as one impact for the U.S. coastline overall (e.g., Hurricane Andrew in 1992).

For ENSO calculations, the Met Office Hadley Centre Sea Ice and Sea Surface Temperature dataset version 1 (HadISST1; Rayner et al. 2003) as calculated through the Climate Explorer (available online at http://climexp.knmi.nl/) is used. The August-October-averaged Niño-3.4 index (5°S–5°N, 120°–170°W) is utilized to define ENSO events during the period 1900–2009 in this study, as this region has been shown to have strong teleconnections with the rest of the globe (Barnston et al. 1997).

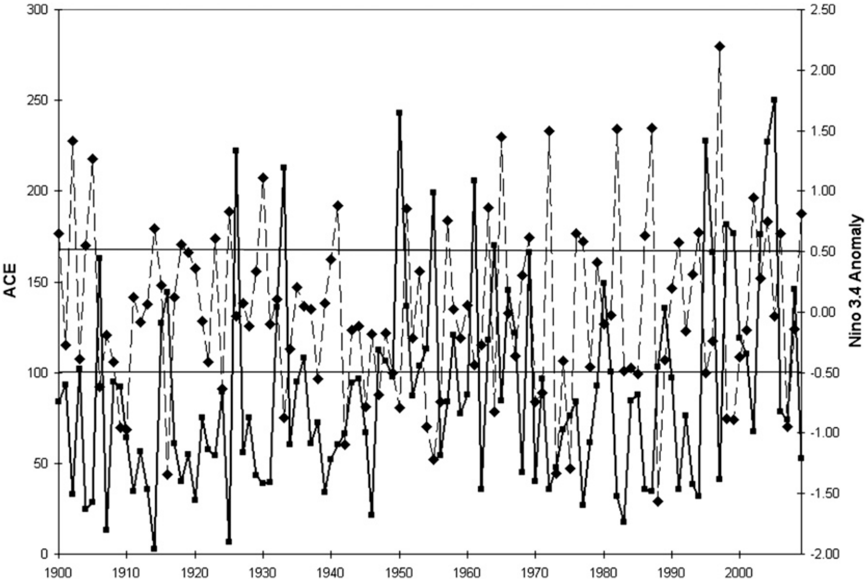

FIG. 1. Annual ACE values (solid line) and August–October Niño-3.4 anomalies (dashed line) from 1900 to 2009. All years above the top line were classified as El Niño years, while all years below the bottom line were classified as La Niña years.

3. ENSO's impacts on Atlantic basin tropical cyclone activity

I begin by tabulating seasonal Atlantic basin TC statistics by year from 1900 to 2009. For the purposes of this analysis, TC activity in January was counted as part of the previous year's activity, since the physical conditions present during the previous hurricane season were likely more responsible for that activity than conditions during the following season. Several different TC statistics were calculated for each Atlantic basin TC season from 1900 to 2009. These statistics were named storms (NS, tropical or subtropical cyclones with maximum sustained winds ≥34 kt), named storm days (NSD, the number of days where a TC has maximum sustained winds ≥34 kt), hurricanes (H, a TC that has maximum sustained winds ≥64 kt), hurricane days (HD, the number of days where a TC has maximum sustained winds ≥64 kt), major hurricanes (MH, a TC that has maximum sustained winds ≥96 kt), major hurricane days (MHD, the number of days where a TC has maximum sustained winds ≥96 kt), and accumulated cyclone energy [ACE, the sum of the square of a named storm's maximum wind speed (in 10^4 kt^2) for each 6-h period of its existence; Bell et al. 2000).

The next step was to classify each year from 1900–2009 as El Niño, neutral, or La Niña. This was done by classifying August–October periods with an SST anomaly of 0.5°C or greater in the Niño-3.4 region as El Niño years, August–October periods with an SST anomaly of −0.5°C or less in the Niño-3.4 region as La Niña years, while the remaining years were classified as neutral years. When this was done, 28 yr were classified as El Niño, 26 yr were classified as La Niña, and all remaining years were treated as neutral years. Figure 1 displays a plot of annual values of ACE and August-October-averaged values of the Niño-3.4 index. The linear correlation between the two indices is −0.35, which is statistically significant at the 99% level using a one-tailed Student's *t* test and assuming that each year represents an individual degree of freedom.

Table 1 displays annually averaged TC statistics for El Niño, neutral, and La Niña years from 1900 to 2009 and the ratios of these statistics for El Niño and La Niña years. All differences in means are statistically significant at the 99% level. Significance tests were conducted using a one-tailed Student's *t* test, since many previous studies have demonstrated that El Niño reduces the number and intensity of Atlantic basin TCs (e.g., Gray 1984; Goldenberg and Shapiro 1996). The La Niña/El Niño ratios are somewhat larger for more intense

TABLE 1. Average per-year number of NS, NSD, H, HD, MH, MHD, and ACE for El Niño, neutral, and La Niña years (as defined in the text). The ratio between La Niña and El Niño years is also provided.

	NS	NSD	H	HD	MH	MHD	ACE
El Niño (28 yr)	7.5	37.3	4.0	14.9	1.5	3.0	62
Neutral (56 yr)	9.5	50.4	5.4	21.3	2.1	5.4	90
La Niña (26 yr)	11.6	62.6	6.5	28.7	3.2	7.2	118
Ratio (La Niña/ El Niño)	1.6	1.7	1.6	1.9	2.1	2.4	1.9

TABLE 2. The probability of major hurricanes occurring in the Atlantic in an El Niño, neutral, and La Niña year given the statistics calculated in Table 1 and assuming a Poisson distribution.

	≥1 MH (%)	≥2 MH (%)	≥3 MH (%)	≥4 MH (%)
El Niño	78	45	20	7
Neutral	87	61	34	16
La Niña	96	82	61	39

TCs, which is to be expected, since weak TCs can likely form in environments that are somewhat more marginal for TC development (such as would be expected to occur in El Niño years).

Elsner and Schmertmann (1993) advocate modeling major hurricane activity as a Poisson process, since these events occur with a known average rate and are independent of the previous event that occurred. In addition, the Poisson distribution limits results to nonnegative integers. Given the average levels of major hurricane activity that occurred for various ENSO phases, one can translate this to the probability of one or more major hurricanes, two or more major hurricanes, and so on, occurring in the Atlantic basin in any particular year. Table 2 provides the probabilities of one or more major hurricanes, two or more major hurricanes, three or more major hurricanes, and four or more major hurricanes occurring in the Atlantic in El Niño, neutral, and La Niña years. The probability of four or more major hurricanes occurring in a La Niña year is 39% compared with only 7% in an El Niño year.

Figure 2 displays the tracks of major hurricanes that occurred in La Niña and El Niño years. Eighty-two major hurricanes and 186 major hurricane days occurred in the 26 La Niña years compared with 43 major hurricanes and 84.75 major hurricane days in the 28 El Niño years. The absence of major hurricane tracks near the East Coast is especially notable in El Niño years, a point that will be addressed in detail later in the manuscript.

4. ENSO's impacts on large-scale climate parameters in the tropical Atlantic and the Caribbean

This paper now examines how ENSO impacts various large-scale climate parameters in the tropical Atlantic and in the Caribbean. One of the primary reasons why El Niño is typically associated with quieter Atlantic basin hurricane seasons is because of an increase in vertical wind shear, associated with an eastward-shifted Walker circulation. The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kistler et al. 2001) is utilized to examine how vertical shear is impacted by various ENSO phases. The reanalysis only extends back to 1948, and therefore using the definition in the previous section (August-October-averaged Niño-3.4 $\geq |0.5|$), 18 yr were

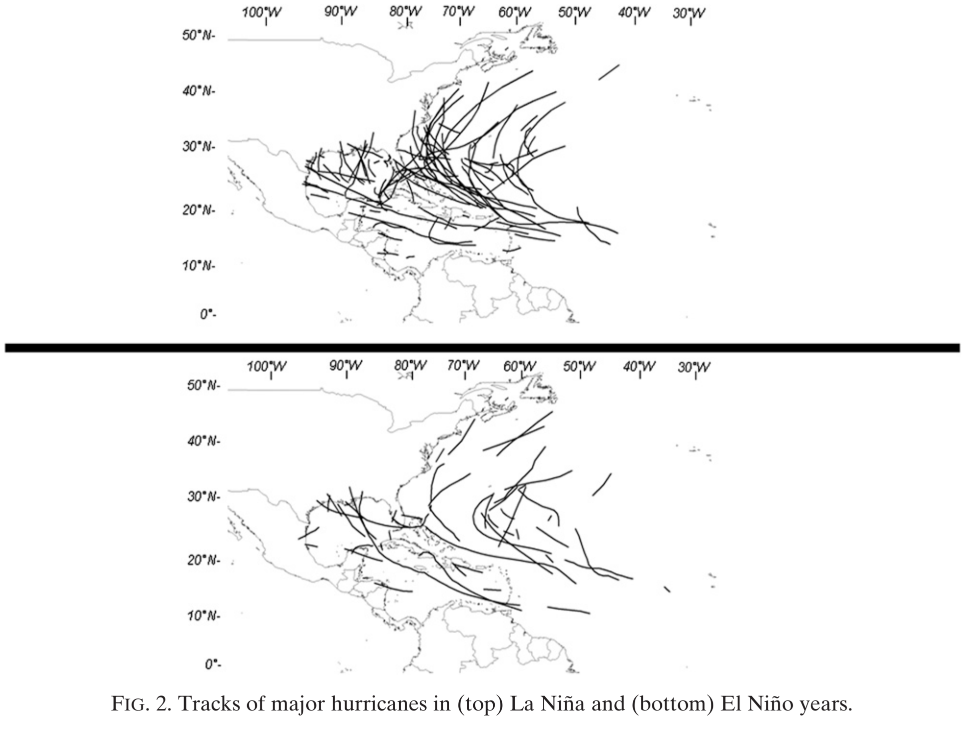

FIG. 2. Tracks of major hurricanes in (top) La Niña and (bottom) El Niño years.

TABLE 3. August–October-averaged values and individual monthly values for August, September, and October of 200-mb *U* (m s^{-1}), 850-mb *U* (m s^{-1}), 200–850-mb *U* shear (m s^{-1}), SLP (mb), SST (°C), 500-mb RH (%), and OLR (W m^{-2}) for El Niño and La Niña years over the period 1948–2009 as calculated over the tropical Atlantic (10°–20°N, 20°–60°W). El Niño minus La Niña differences are also provided. Differences that are significant at the 95% level are highlighted in italics, while differences that are significant at the 99% level are highlighted in bold.

			August–October average				
	200-mb *U*	850-mb *U*	200–850-mb *U* shear	SLP	SST	500-mb RH	OLR
El Niño (18 yr)	2.9	−5.5	8.4	1014.3	27.4	35.5	253.9
La Niña (16 yr)	0.9	−5.7	6.6	1013.9	27.3	37.4	251.2
El Niño–La Niña	*2.0*	0.2	1.8	*0.4*	0.1	−1.9	2.7
			August				
El Niño (18 yr)	−3.6	−5.5	1.9	1014.9	27.0	36.3	256.0
La Niña (16 yr)	−6.5	−5.1	−1.4	1014.1	27.0	39.9	251.0
El Niño–La Niña	**2.9**	0.4	**3.5**	**0.8**	0.0	*−3.6*	*5.0*
			September				
El Niño (18 yr)	2.7	−5.6	8.3	1014.3	27.6	35.4	253.9
La Niña (16 yr)	−0.3	−5.6	5.3	1014.0	27.4	36.8	250.9
El Niño–La Niña	**3.0**	0.0	**3.0**	0.3	0.2	−1.4	3.0
			October				
El Niño (18 yr)	9.7	−5.4	15.1	1013.7	27.7	35.0	251.9
La Niña (16 yr)	9.7	−6.3	16.0	1013.7	27.4	35.4	251.7
El Niño–La Niña	0.0	**−0.9**	−0.9	0.0	0.3	−0.4	0.2

classified as El Niño years and 16 yr were classified as La Niña years during the period 1948–2009.

Table 3 displays August-October-averaged values, as well as individual monthly values for August–October, over the tropical Atlantic (10°–20°N, 20°–60°W) for several large-scale climate fields that have been shown to impact Atlantic basin TC activity on seasonal time scales (Gray 1984; Klotzbach 2007). The fields investigated are 200-mb zonal wind (*U*), 850-mb *U*, 200–850-mb *U* shear, sea surface temperature, outgoing longwave radiation (OLR) and 500-mb relative humidity (RH). The differences between El Niño and La Niña years are also provided. Statistical significance tests were calculated using a two-tailed Student's *t* test. For the August–October average, differences in 200-mb zonal wind and sea level pressure are statistically significant at the 95% level, while all other differences are not statistically significant at the 95% level. When the individual months of August, September, and October are examined, the impacts of ENSO appeared to be stronger during the months of August and September, which are the two months when 90% of all ACE generated in the tropical Atlantic occurs. Differences in 200–850-mb vertical shear are significant at the 99% level during August and September, while the shear differences in October are small (and actually negative). Generally, La Niña years are characterized by somewhat less vertical shear, slightly moister midlevels, lower pressure, and reduced OLR—indicative of a more favorable dynamic and thermodynamic environment for TC formation and intensification.

A similar analysis is now employed for the Caribbean (10°–20°N, 60°–88°W). Table 4 displays values of the same large-scale atmospheric–oceanic fields investigated in Table 3. Differences are generally of a larger magnitude, and higher statistical significance levels are reached for most fields. The August-October-averaged El Niño–La Niña difference for 200-mb *U*, 850-mb *U*, 200–850-mb *U* shear, 500-mb RH, and OLR are statistically significant at the 99% level. The difference in vertical shear is approximately 2 m s^{-1} greater in the Caribbean than it is over the tropical Atlantic, indicating that conditions are more favorable for an active season in the Caribbean during a La Niña year compared with an El Niño year, while conditions are only modestly more favorable over the remainder of the tropical Atlantic. When individual months are examined, ENSO's impacts on Caribbean vertical shear are strongest in August and become statistically insignificant by October. However, both the 500-mb RH and OLR radiation are much more favorable in October in La Niña years than in El Niño years. The linear correlation between monthly ACE and monthly Niño-3.4 values increases somewhat from −0.23 in August and −0.21 in September to −0.30 in October. August and September correlations are significant at the 95% level, while October correlations are significant at the 99% level, using a one-tailed Student's *t* test, given that it is to be expected that El Niño should impact levels of Atlantic basin TC activity. Although the difference in these correlations is minimal, perhaps the combined slightly more favorable dynamic environment and considerably more favorable thermodynamic environment in October are

TABLE 4. As in Table 3, but calculated for the Caribbean (10°–20°N, 60°–88°W). El Niño minus La Niña differences are also provided.

	200-mb *U*	850-mb *U*	200–850-mb *U* shear	SLP	SST	500-mb RH	OLR
August–October average							
El Niño (18 yr)	1.4	−6.0	7.4	1012.4	28.0	40.8	225.8
La Niña (16 yr)	−1.6	−5.2	3.6	1012.1	27.8	42.9	220.3
El Niño–La Niña	**3.0**	**-0.8**	**−3.8**	0.3	0.2	**−2.1**	**5.5**
August							
El Niño (18 yr)	0.2	−7.7	7.9	1013.3	27.8	38.7	228.1
La Niña (16 yr)	−3.7	−6.5	2.8	1012.8	27.8	41.3	222.8
El Niño–La Niña	**3.9**	**−1.2**	**5.1**	0.5	0.0	*−2.6*	*5.3*
September							
El Niño (18 yr)	1.2	−5.6	6.8	1012.2	28.1	43.0	224.9
La Niña (16 yr)	−2.1	−4.8	2.7	1012.0	28.0	43.3	221.3
El Niño–La Niña	**3.3**	*−0.8*	**4.1**	0.2	0.1	−0.3	3.6
October							
El Niño (18 yr)	2.7	−4.6	7.3	1011.6	28.0	40.9	224.3
La Niña (16 yr)	1.0	−4.2	5.2	1011.4	27.7	44.1	216.9
El Niño–La Niña	1.7	0.4	2.1	0.2	**0.3**	**−3.2**	**7.4**

responsible for the stronger correlations than in August and September. The strong relationship between ENSO and Caribbean TC activity is documented in detail in Klotzbach (2011).

The NCEP–NCAR reanalysis monthly composites Web site (available online at http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl) allows for easy construction of vertical cross sections for up to 20 yr of data. It is instructive to examine the vertical zonal wind field in more detail to see how it changes with height in the atmosphere for different phases of ENSO. Figure 3 displays a vertical cross section of the 10 strongest El Niños minus the 10 strongest La Niñas from 1000 to 100 mb averaged from 10° to 20°N from the eastern Pacific into the tropical Atlantic. In the Caribbean, one can clearly see the anomalous easterlies at low levels and stronger westerlies at upper levels and the consequent increase in the vertical shear over this region. Further east in the tropical Atlantic, defined as 10°–20°N, 20°–60°W, upper-level westerlies are somewhat stronger in El Niño years than in either neutral or La Niña years, while very little signal is seen in the trades, similar to results found in Bell and Chelliah (2006). This figure provides additional validation that the vertical shear aspect of ENSO should have a stronger impact in the Caribbean.

5. ENSO's impacts on large-scale areas along the U.S. coastline

ENSO has been shown to impact U.S. landfalls in several previous studies, including Bove et al. (1998), Pielke and Landsea (1999), Elsner (2003), Elsner and Jagger (2006), and Smith et al. (2007). This section revisits this relationship for the entire U.S. coastline, and then it investigates the relationship further by examining landfall differences for the Gulf Coast as well as the Florida peninsula and East Coast. As mentioned previously, the U.S. hurricane impacts database (Blake et al. 2007) is utilized to examine landfall frequency differences.

Table 5 displays the average per-year number of hurricanes and major hurricanes impacting the U.S. coastline for El Niño, neutral, and La Niña years. These per-year average values are also converted into the annual probabilities of one or more hurricanes and major hurricanes making U.S. landfall using the Poisson distribution. Hurricane and major hurricane impact differences between El Niño and La Niña are statistically significant at the 99% level using a one-tailed Student's *t* test, confirming earlier research indicating significant differences in U.S. landfall depending on ENSO phase. The probability of hurricane and major hurricane impacts, given a particular phase of ENSO, differ slightly from those found in Bove et al. (1998), because of a combination of the use of a different ENSO index, 12 more years of hurricane statistics (1998–2009), and the reanalysis of tropical cyclone intensities from 1900 to 1925 (Landsea et al. 2004, 2008).

More dramatic relationships are discovered if only stronger ENSO events are examined. One would expect that stronger events would have a stronger impact on large-scale climate conditions and therefore on Atlantic basin TC activity. The following analysis confirms this hypothesis. Table 6 tabulates the landfalls during the 15 strongest El Niño events since 1900 (Augusts–Octobers having an anomaly of greater than 0.75°C in the Niño-3.4 region) and compares them with the 15 strongest La

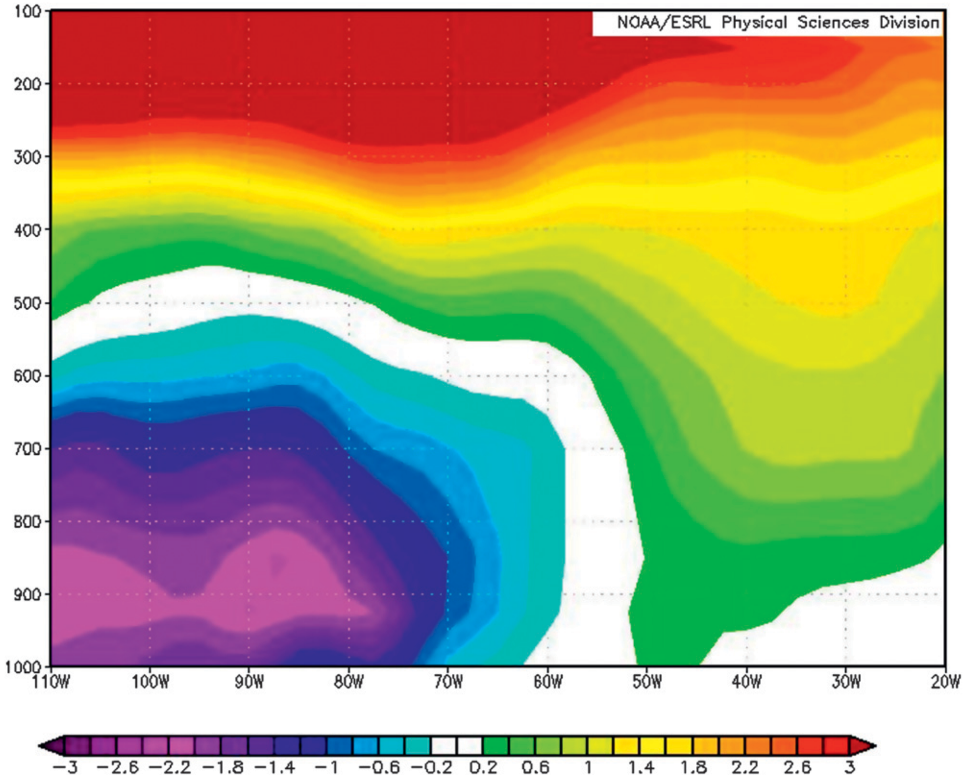

FIG. 3. Vertical cross section (1000–100 mb) of August–October zonal wind differences (m s^{-1}) averaged from 10° to 20°N, 110°–10°W for the 10 strongest El Niños minus the 10 strongest La Niñas from 1948 to 2009.

Niña events since 1900 (Augusts–Octobers having an anomaly of less than −0.78°C in the Niño-3.4 region). Differences between El Niño and La Niña remain statistically significant at the 99% level. A total of 19 major hurricanes made landfall in the 15 strongest La Niña years compared with only 3 major hurricanes in the 15 strongest El Niño years (Fig. 4). It should also be noted that the probability of landfall is reduced considerably when only strong El Niño events are considered, while probabilities of landfall are not increased much when strong La Niña events are examined. This is likely because vertical shear is already favorable when a La Niña event is in progress, and a strong La Niña event may actually generate too much easterly wind at upper levels, imparting easterly shear. On the other hand, a strong El Niño event is associated with especially detrimental westerly vertical shear conditions throughout the tropical Atlantic and especially the Caribbean.

The next step is to investigate hurricane impacts for two large U.S. subregions, which are classified as the Gulf Coast and the Florida peninsula and East Coast. The Gulf Coast is classified as extending from Brownsville, Texas, to Tarpon Springs, Florida, while the Florida peninsula and East Coast include the remainder of the state of Florida and the entire East Coast. Table 7 displays the average per-year number of hurricanes and major hurricanes impacting both the Gulf Coast and the Florida peninsula and East Coast in El Niño, neutral, and

TABLE 5. Average per-year number of hurricane and major hurricane impacts along the U.S. coastline for El Niño, neutral, and La Niña years. These average per-year impacts are converted into the annual probability of one or more hurricane and major hurricane impacts using the Poisson distribution.

	Hurricane impacts (per year)	Major hurricane impacts (per year)	Hurricane impact probability (%)	Major hurricane impact probability (%)
El Niño	1.0	0.3	65	27
Neutral	1.6	0.6	79	45
La Niña	2.7	1.1	93	66

TABLE 6. Average per-year number of hurricane and major hurricane impacts along the U.S. coastline for the 15 strongest El Niño years and the 15 strongest La Niña years. These average per-year impacts are converted into annual probabilities of one or more hurricanes and major hurricanes using the Poisson distribution.

	Hurricane impacts (per year)	Major hurricane impacts (per year)	Hurricane impact probability (%)	Major hurricane impact probability (%)
Strong El Niño	0.7	0.2	49	18
Strong La Niña	2.7	1.3	93	72

La Niña years. Differences between El Niño and La Niña are statistically significant at the 99% level for hurricanes and major hurricanes impacting the Florida peninsula and East Coast and for hurricanes impacting the Gulf Coast, using a one-tailed Student's *t* test. The difference is not significant for major hurricane impacts along the Gulf Coast.

6. ENSO's impacts by coastal state

The impact of ENSO on every coastal state from Texas to Maine is now investigated. Table 8 displays the probability of each state being impacted by a hurricane and a major hurricane in an El Niño year, a neutral year, and a La Niña year, utilizing the hurricane impacts and ENSO databases from 1900 to 2009, along with the Poisson distribution. Probabilities for certain coastal states, especially along the mid-Atlantic coast and New England, should be treated cautiously, as 109 yr of data may not be a long enough time period to establish reliable probabilities in these regions. In addition, Georgia, although not impacted by a major hurricane since 1900, was impacted by two major hurricanes in the 1890s.

The probability of being impacted by a hurricane or a major hurricane is greatest for the state of Florida, regardless of ENSO phase; however, other state's rankings change depending on whether an El Niño is present. For example, the second highest probability state to be impacted by a hurricane in an El Niño year is Louisiana (at 25%), while Louisiana is the fourth most likely state to be impacted by a hurricane in a La Niña year. The largest probability shift between El Niño and La Niña events is the state of North Carolina. The number of hurricanes impacting the state increases by 3.5 times from El Niño (4 hurricane impacts) to La Niña (14 hurricane impacts). No major hurricane has impacted the state of North Carolina in an El Niño year, while 5 major hurricanes have impacted the state of North Carolina in La Niña years, resulting in an annual probability of approximately 17%. The dearth of landfalling hurricane

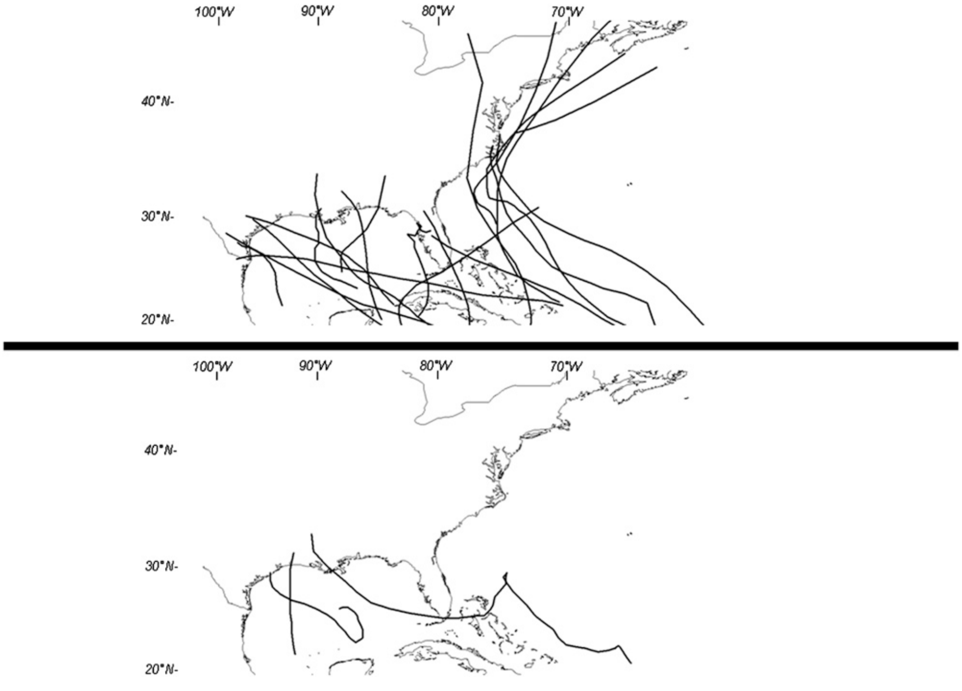

FIG. 4. Tracks of major hurricanes making landfall in the (top) 15 strongest La Niña years and (bottom) 15 strongest El Niño years.

TABLE 7. As in Table 5, but for the Gulf Coast and the Florida peninsula and East Coast (FL + EC).

	Hurricane impacts (per year)	Major hurricane impacts (per year)	Hurricane impact probability (%)	Major hurricane impact probability (%)
El Niño (Gulf Coast)	0.6	0.3	44	22
Neutral (Gulf Coast)	0.9	0.3	60	29
La Niña (Gulf Coast)	1.5	0.5	78	42
El Niño (FL + EC)	0.6	0.1	46	10
Neutral (FL + EC)	0.8	0.3	57	26
La Niña (FL + EC)	1.4	0.6	76	44

activity is clearly evident along the mid-Atlantic coast and New England as well in El Niño years. No major hurricane has impacted a state from Georgia northward to Maine since 1900 in an El Niño year.

7. AMO modulation of ENSO relationships

The AMO has been demonstrated in many previous studies to significantly impact Atlantic basin TC activity through alterations in sea surface temperatures in the tropical Atlantic and Caribbean basin, levels of vertical wind shear, midlevel moisture, and low-level horizontal vorticity (e.g., Goldenberg et al. 2001; Klotzbach and Gray 2008; Wang et al. 2008). A positive phase of the AMO is typically associated with more active TC seasons. Klotzbach and Gray (2008) diagnosed positive phases of the AMO from 1926 to 1969 and from 1995 to 2007 with negative phases from 1900 to 1925 and from 1970 to 1994. Since the past 2 yr have exhibited typical ocean and atmosphere signals characteristic of a positive phase of the AMO, the 2008 and 2009 seasons are also treated as years in a positive phase of the AMO. With the given caveat that subdividing the rather limited period when reliable TC activity is available may limit the statistical significance of the results, additional analysis is now conducted as to how the impacts of ENSO differ between an active and inactive phase of the AMO.

a. AMO modulation of overall Atlantic basin TC activity

Table 9 displays average levels of activity in the Atlantic basin experienced in El Niño, neutral, and La Niña years for positive and negative phases of the AMO. All differences are significant at the 99% level between El Niño-negative AMO and La Niña-positive AMO and El Niño-negative AMO and La Niña-negative AMO. Differences are not significant between El Niño-positive AMO and La Niña-positive AMO. A couple of important points to note are that it typically requires La Niña conditions in the tropical Pacific to get an active Atlantic basin season when the AMO is in its negative phase, while even a weak-to-moderate El Niño event can be active when the AMO is in its positive phase. For example, both the 1951 and 1963 hurricane seasons were

TABLE 8. Probability of one or more hurricanes and major hurricanes impacting every coastal state from Texas to Maine in El Niño (EN), neutral (N), and La Niña (LN) years.

	EN H (%)	EN MH (%)	N H (%)	N MH (%)	LN H (%)	LN MH (%)
Texas	19	10	32	12	46	21
Louisiana	25	13	26	12	34	11
Mississippi	7	4	9	4	21	11
Alabama	7	4	15	4	24	4
Florida	30	13	44	22	68	34
Georgia	<1	<1	7	<1	7	<1
South Carolina	10	<1	15	4	17	14
North Carolina	13	<1	25	9	42	17
Virginia	<1	<1	4	2	7	<1
Maryland	<1	<1	<1	<1	4	<1
Delaware	<1	<1	2	<1	<1	<1
New Jersey	<1	<1	2	<1	<1	<1
New York	10	<1	4	4	11	11
Connecticut	7	<1	4	2	11	7
Rhode Island	4	<1	4	2	7	7
Massachusetts	4	<1	4	<1	11	7
New Hampshire	<1	<1	2	<1	4	<1
Maine	4	<1	4	<1	7	<1

Table 9. Average per-year number of NS, NSD, H, HD, MH, MHD, and ACE for El Niño, neutral, and La Niña years for positive and negative phases of the AMO (as defined in the text). The ratio between La Niña and El Niño years for positive and negative phases of the AMO is also provided.

	NS	NSD	H	HD	MH	MHD	ACE
El Niño/negative AMO (16 yr)	6.0	27.3	3.0	8.2	0.8	0.8	37
Neutral/negative AMO (24 yr)	8.2	43.9	4.6	17.0	1.3	3.6	73
La Niña/negative AMO (11 yr)	10.3	53.1	5.7	22.5	2.5	4.5	91
El Niño/positive AMO (12 yr)	9.4	50.6	5.3	23.8	2.6	6.0	96
Neutral/positive AMO (32 yr)	10.4	55.3	6.0	24.6	2.7	6.8	103
La Niña/positive AMO (15 yr)	12.5	69.6	7.1	33.3	3.6	9.1	138
Ratio (La Niña-positive AMO/El Niño-negative AMO)	2.1	2.5	2.4	4.1	4.8	11.5	3.7
Ratio (La Niña-negative AMO/El Niño-negative AMO)	1.7	1.9	1.9	2.7	3.4	5.6	2.5
Ratio (La Niña-positive AMO/El Niño-positive AMO)	1.3	1.4	1.3	1.4	1.4	1.5	1.4

characterized by accumulated cyclone energy values of greater than 125% of the 1900–2009 average (90 ACE units), while August-October-averaged Niño-3.4 values were greater than 0.8°C. A total of 4 out of 12 yr classified as El Niño had above-average ACE levels when the AMO was positive, while none of the 16 yr that had El Niño conditions when the AMO was negative had ACE values reach average levels (90 ACE units).

Another important point to note is that the degree of activity modulation by ENSO is much greater when the AMO is in its negative phase than when it is in its positive phase. For example, approximately 5 times more major hurricane days occur in a La Niña than in an El Niño when the AMO is negative, while the La Niña/El Niño ratio for major hurricane days is approximately 150% when the AMO is positive. This is likely because the background conditions generated by a negative phase of the AMO are unfavorable, and that combined with an El Niño makes conditions prohibitive for storm formation. Since a positive phase of the AMO generates a much more favorable background condition, somewhat detrimental conditions caused by a weak-to-moderate El Niño may not be enough to significantly reduce activity. However, when El Niño is strong (August-October-averaged Niño-3.4 values greater than 1.0°C), activity is significantly reduced, regardless of AMO phase.

b. AMO modulation of U.S. impacts

Table 10 displays the number of hurricane and major hurricane impacts along the U.S. coastline in El Niño, neutral, and La Niña years for positive and negative phases of the AMO. These per-year averages are also converted to probabilities for one or more hurricane and major hurricane impacts using the Poisson distribution. Differences in landfall are significant at the 99% level for both hurricanes and major hurricanes between El Niño-negative AMO and La Niña-positive AMO. These differences are significant at the 99% level for hurricanes and the 95% level for major hurricanes for El Niño-negative AMO and La Niña-negative AMO. Differences are significant at the 99% level for hurricanes between El Niño-positive AMO and La Niña-positive AMO, while differences are not significant for major hurricanes. As was seen with the overall Atlantic basin activity, ratio differences are much stronger between El Niño and La Niña when the AMO is negative than when the AMO is positive. Readers, however, should interpret these statistics with caution, as a rather small number of years is included with each classification, and U.S. hurricane impacts are a fairly rare event (e.g., fewer than two per year on average).

Lastly, the combined impacts of the AMO and ENSO are examined for the Gulf Coast and the Florida peninsula

Table 10. Average per-year number of hurricane and major hurricane impacts along the U.S. coastline for El Niño, neutral, and La Niña years for both positive and negative phases of the AMO. These average per-year impacts are converted into the annual probability of one or more hurricane and major hurricane impacts using the Poisson distribution.

	Hurricane impacts (per year)	Major hurricane impacts (per year)	Hurricane impact probability (%)	Major hurricane impact probability (%)
El Niño/negative AMO (16 yr)	0.9	0.1	58	12
Neutral/negative AMO (24 yr)	1.4	0.5	75	39
La Niña/negative AMO (11 yr)	2.7	0.9	93	60
El Niño/positive AMO (12 yr)	1.3	0.6	71	44
Neutral/positive AMO (32 yr)	1.7	0.7	82	48
La Niña/positive AMO (15 yr)	2.7	1.2	93	70

TABLE 11. As in Table 10, but for the Gulf Coast and the Florida peninsula and East Coast (FL + EC).

	Hurricane impacts (per year)	Major hurricane impacts (per year)	Hurricane impact probability (%)	Major hurricane impact probability (%)
El Niño/negative AMO (Gulf Coast)	0.4	0.1	31	12
Neutral/negative AMO (Gulf Coast)	0.9	0.4	60	31
La Niña/negative AMO (Gulf Coast)	1.7	0.6	82	47
El Niño/positive AMO (Gulf Coast)	0.8	0.5	56	37
Neutral/positive AMO (Gulf Coast)	0.9	0.3	61	27
La Niña/positive AMO (Gulf Coast)	1.3	0.5	74	37
El Niño/negative AMO (FL + EC)	0.6	0.0	43	—
Neutral/negative AMO (FL + EC)	0.6	0.2	46	19
La Niña/negative AMO (FL + EC)	1.1	0.3	66	24
El Niño/positive AMO (FL + EC)	0.7	0.3	49	22
Neutral/positive AMO (FL + EC)	1.0	0.4	63	31
La Niña/positive AMO (FL + EC)	1.7	0.8	81	55

and East Coast. Table 11 displays the average per-year number of hurricanes and major hurricanes impacting both the Gulf Coast and the Florida peninsula and East Coast in El Niño, neutral, and La Niña years, for negative and positive phases of the AMO. These per-year values are also converted to annual probabilities. Differences between El Niño-negative AMO and La Niña-positive AMO are statistically significant at the 99% level for hurricanes and major hurricanes impacting the Florida peninsula and East Coast while El Niño-La Niña differences are not significant when both are considered in either the positive or negative AMO phase. For the Gulf Coast, differences between El Niño-negative AMO and La Niña-positive AMO are statistically significant at the 99% level for hurricanes and the 95% level for major hurricanes, while the relationship between El Niño-negative AMO and La Niña-negative AMO is significant at the 99% level. All other relationships are not statistically significant at the 95% level.

8. Summary and future work

This paper began by investigating the influence of El Niño–Southern Oscillation (ENSO) on large-scale Atlantic basin hurricane activity and on large-scale climate parameters known to impact tropical cyclones (TCs). Atlantic basin hurricane activity is significantly reduced in El Niño years compared with La Niña years, agreeing with many previous studies. The largest impacts of ENSO on large-scale climate fields were shown to be in the Caribbean, with smaller signals observed over the remainder of the tropical Atlantic. The large-scale field that appears to be impacted the most by the phase of ENSO is the 200–850-mb vertical shear field, with considerably more shear present in El Niño years, especially over the Caribbean. As would be expected given the marked reduction in overall Atlantic hurricane activity, landfalling frequency along the U.S. coastline is less in El Niño years as well. A total of 19 major hurricanes made landfall along the U.S. coastline in the 15 coldest ENSO events, compared with only 3 major hurricanes in the 15 warmest ENSO events. While most states' probabilities of being impacted by a hurricane are greater in La Niña than in El Niño, the state with the most dramatic increase in likelihood of landfall in a La Niña year is the state of North Carolina. Relationships between the phase of ENSO and the phase of the Atlantic multidecadal oscillation (AMO) are also examined. Very strong differences for both Atlantic basin TCs as well as U.S. landfalls are seen when comparing El Niño and the negative phase of the AMO with La Niña and the positive phase of the AMO. In general, El Niño–La Niña relationships are stronger in the negative phase of the AMO than in the positive phase of the AMO.

This paper expounds upon previous research by describing in more detail the impact that ENSO has on Atlantic basin hurricanes as well as U.S. landfalls. The signal of ENSO appears to be strongest in both large-scale climate features as well as tropical cyclone activity over the Caribbean. This information will be utilized to improve seasonal forecasts issued by the Tropical Meteorology Project, of which the author is currently the lead forecaster. Separate forecasts for the Caribbean basin only will be introduced, with primary emphasis placed on the ENSO–Caribbean TC relationship.

Acknowledgments. I would like to acknowledge funding provided by NSF Grant ATM-0346895 and by the Research Foundation of Lexington Insurance Company (a member of the American International Group). I would like to thank the three anonymous reviewers as well as the editor for their helpful comments that improved the manuscript. I would also like to thank William

Gray for his helpful comments on an earlier version of this manuscript.

REFERENCES

Barnston, A. G., M. Chelliah, and S. B. Goldenberg, 1997: Documentation of a highly ENSO-related SST region in the equatorial Pacific. *Atmos.–Ocean,* **35,** 367–383.

Bell, G. D., and M. Chelliah, 2006: Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *J. Climate,* **19,** 590–612.

——, and Coauthors, 2000: Climate assessment for 1999. *Bull. Amer. Meteor. Soc.,* **81,** S1–S50.

Blake, E. S., E. N. Rappaport, and C. W. Landsea, 2007: The deadliest, costliest and most intense United States tropical cyclones from 1851 to 2006 (and other frequently requested hurricane facts). NOAA Tech. Memo. NWS TPC-5, 45 pp.

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

DeMaria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.,* **53,** 2076–2088.

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

——, and C. B. Schmertmann, 1993: Improving extended-range seasonal predictions of intense Atlantic hurricane activity. *Wea. Forecasting,* **8,** 345–351.

——, and T. H. Jagger, 2004: A hierarchical Bayesian approach to seasonal hurricane modeling. *J. Climate,* **17,** 2813–2827.

——, and ——, 2006: Prediction models for annual U.S. hurricane counts. *J. Climate,* **19,** 2935–2952.

Frank, W. M., and E. A. Ritchie, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev.,* **129,** 2249–2269.

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

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.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

Klotzbach, P. J., 2007: Recent developments in statistical prediction of seasonal Atlantic basin tropical cyclone activity. *Tellus,* **59A,** 511–518.

——, 2011: The influence of El Niño–Southern Oscillation and the Atlantic multidecadal oscillation on Caribbean tropical cyclone activity. *J. Climate,* **24,** 721–731.

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

——, and ——, 2008: Multidecadal variability in North Atlantic tropical cyclone activity. *J. Climate,* **21,** 3929–3935.

Knaff, J. A., S. A. Seseske, M. DeMaria, and J. L. Demuth, 2004: On the influences of vertical wind shear on symmetric tropical cyclone structure derived from AMSU. *Mon. Wea. Rev.,* **132,** 2503–2510.

Landsea, C. W., 2007: Counting Atlantic tropical cyclones back to 1900. *Eos, Trans. Amer. Geophys. Union,* **88,** doi:10.1029/2007EO180001.

——, 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. Murnane and K.-B. Liu, Eds., Columbia University Press, 177–221.

——, and Coauthors, 2008: A reanalysis of the 1911–20 Atlantic hurricane database. *J. Climate,* **21,** 2138–2168.

——, G. A. Vecchi, L. Bengtsson, and T. Knutson, 2010: Impact of duration thresholds on Atlantic tropical cyclone counts. *J. Climate,* **23,** 2508–2519.

Pielke, R. A., Jr., and C. W. Landsea, 1999: La Niña, El Niño, and Atlantic hurricane damages in the United States. *Bull. Amer. Meteor. Soc.,* **80,** 2027–2033.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.,* **108,** 4407, doi:10.1029/2002JD002670.

Simpson, R. H., 1974: The hurricane disaster—Potential scale. *Weatherwise,* **27,** 169–186.

Smith, S. R., J. Brolley, J. J. O'Brien, and C. A. Tartaglione, 2007: ENSO's impact on regional U.S. hurricane activity. *J. Climate,* **20,** 1404–1414.

Wang, C., S.-K. Lee, and D. B. Enfield, 2008: Atlantic warm pool acting as a link between Atlantic multidecadal oscillation and Atlantic tropical cyclone activity. *Geochem. Geophys. Geosyst.,* **9,** Q05V03, doi:10.1029/2007GC001809.

Wilson, R. M., 1999: Statistical aspects of major (intense) hurricanes in the Atlantic basin during the past 49 hurricane seasons (1950-1998): Implications for the current season. *Geophys. Res. Lett.,* **26,** 2957–2960.