The Influence of El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation on Caribbean Tropical Cyclone Activity

PHILIP J. KLOTZBACH

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

(Manuscript received 4 March 2010, in final form 7 June 2010)

ABSTRACT

Caribbean basin tropical cyclone activity shows significant variability on interannual as well as multidecadal time scales. Comprehensive statistics for Caribbean hurricane activity are tabulated, and then large-scale climate features are examined for their impacts on this activity. The primary interannual driver of variability is found to be El Niño–Southern Oscillation, which alters levels of activity due to changes in levels of vertical wind shear as well as through column stability. Much more activity occurs in the Caribbean with La Niña conditions than with El Niño conditions. On the multidecadal time scale, the Atlantic multidecadal oscillation is shown to play a significant role in Caribbean hurricane activity, likely linked to its close relationship with multidecadal alterations in the size of the Atlantic warm pool and the phase of the Atlantic meridional mode. When El Niño–Southern Oscillation and the Atlantic multidecadal oscillation are examined in combination, even stronger relationships are found due to a combination of either favorable or unfavorable dynamic and thermodynamic factors. For example, 29 hurricanes tracked into the Caribbean in the 10 strongest La Niña years in a positive Atlantic multidecadal oscillation period compared with only two hurricanes tracking through the Caribbean in the 10 strongest El Niño years in a negative Atlantic multidecadal oscillation period.

1. Introduction

Tropical cyclones are a frequent occurrence in the Caribbean basin, and these systems can often have devastating impacts. Some of the most devastating hurricanes of all time have occurred in the Caribbean, including the deadliest hurricane of all time (the Great Hurricane of 1780, which killed 22 000 people); Hurricane Mitch (1998), which was responsible for approximately 9000 deaths (Guiney and Lawrence 1999); and Hurricane Fifi (1974) and the Dominican Republic Hurricane of 1930—each responsible for approximately 8000 deaths (Rappaport and Fernandez-Partagas 1994).

Recently, Hurricane Gustav (2008) was responsible for 100 deaths in Haiti, Jamaica, and the Dominican Republic (Beven and Kimberlain 2009) and is estimated to have incurred $210 million in damage in Jamaica, and Hurricane Ike (2008) a few weeks later was even more devastating, with $3–$4 billion in damage caused in Cuba alone (Berg 2009). Hurricane Jeanne made landfall in the Dominican Republic in 2004, and flooding associated with this system triggered devastating mudslides that were responsible for over 3000 deaths in Haiti (Beven 2004).

Large-scale climate features such as the El Niño–Southern Oscillation (ENSO) (Gray 1984; Goldenberg and Shapiro 1996; Wilson 1999; Klotzbach 2007), the Atlantic meridional mode (AMM) (Kossin and Vimont 2007; Vimont and Kossin 2007), and the Atlantic multidecadal oscillation (AMO) (Goldenberg et al. 2001; Klotzbach and Gray 2008) have all been shown to have significant impacts on Atlantic basin tropical cyclones. More active seasons are associated with La Niña conditions, a positive phase of the AMM, and a positive phase of the AMO.

The primary reasons why ENSO is thought to impact Atlantic basin tropical cyclone activity is through alterations in vertical wind shear (e.g., Gray 1984) along with alterations in fluctuations in tropospheric and surface temperature (Tang and Neelin 2004). Because tropospheric temperature anomalies tend to lead surface temperature anomalies by several months, the potential intensity (Emanuel 1986) for tropical cyclone formation tends to be lower following an El Niño onset, as upper-level temperatures warm prior to sea surface temperatures (Wallace et al. 1998). Consequently, the

---

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

DOI: 10.1175/2010JCLI3705.1

likelihood of an active season is reduced with warm ENSO conditions.

Recent research has extended these basinwide studies on ENSO to localized areas. For example, Bove et al. (1998) found an increased likelihood of United States landfall in La Niña years and a decreased likelihood in El Niño years. Smith et al. (2007) found that landfall frequencies in La Niña years were significantly enhanced along the U.S. East Coast when compared with neutral years, whereas little change was seen between La Niña years and neutral years for Gulf Coast or Florida landfalls. Pielke and Landsea (1999), using data from 1925 to 1997, showed that the median normalized hurricane damage for the United States was much greater in La Niña years than in El Niño years.

Research on the impacts of various large-scale climate phenomena on Caribbean tropical cyclones is much more limited. Tartaglione et al. (2003) showed that probabilities of hurricane landfall in the Caribbean tend to be increased during the cold phase of ENSO, likely because of reductions in vertical wind shear and increases in low-level vorticity. They subdivided the Caribbean into three regions—northern, eastern, and western—and found a significant reduction of storm frequency in the northern Caribbean during El Niño years, while the frequency of storms in the eastern and western Caribbean was not altered significantly.

The AMM has been shown to impact Atlantic basin tropical cyclones through alterations in vertical shear, convergence, low-level vorticity, and sea surface temperature. While the AMM has its maximum amplitude during the spring months, it also appears as an important driver of Atlantic basin tropical cyclone activity during the late summer and early fall (Kossin and Vimont 2007; Vimont and Kossin 2007).

Although ENSO and the AMM have fairly direct, well-documented relationships with Atlantic basin tropical cyclone activity, extensive examination of the physical reasoning why the AMO impacts Atlantic basin tropical cyclones has only occurred recently. The AMO has been hypothesized to be driven by fluctuations in the strength of the Atlantic thermohaline circulation, with a positive phase of the AMO associated with a stronger thermohaline circulation (Gray et al. 1997). Vimont and Kossin (2007) hypothesize that the AMO excites the AMM on decadal time scales. Wang et al. (2008) documented that the AMO is closely related to decadal fluctuations in the size of the Atlantic warm pool (AWP). Larger-than-normal areas of the AWP (defined as the area of water greater than 28.5°C in the Caribbean Sea, Gulf of Mexico, and western North Atlantic) are associated with significantly more favorable dynamic and thermodynamic conditions for tropical cyclones. In the Caribbean, a larger-than-normal AWP is strongly positively correlated with a weaker subtropical high, consequently reducing the strength of the Caribbean low-level jet (Wang and Lee 2007). In this analysis, we focus on the AMO as opposed to the AMM or AWP since the AMO signal is known months in advance. The AMM or AWP—although generally positive and larger, respectively, when the AMO is positive—can be of opposite sign for any particular year. For example, even though the AMO was positive in 2000 and an active hurricane season was experienced, the AMM was negative that year during August and September.

This paper goes beyond earlier research by tabulating probabilities of landfall based on climatological data for every island in the Caribbean and the east coast of Central America. This study then focuses on how Caribbean activity is altered by phase of ENSO and the AMO. Full-year hurricane statistics are utilized in this study to document the level of skill that would be available, given the knowledge of the AMO and a perfect forecast for August–October ENSO. The forecast skill of cutting-edge ENSO models from 1 June for August–October is very high, with a correlation of 0.89 between forecasts and observations for the Niño-3.4 region for a 1 June forecast issued over the period from 1993 to 2007 from the EUROpean Seasonal to Inter-annual Prediction (EUROSIP) ensemble (F. Vitart, 2008, personal communication).

The remainder of this paper is organized as follows. Section 2 discusses the data utilized. Section 3 displays climatological probabilities of landfall for each island in the Caribbean and for the east coast of Central America. Section 4 examines the relationship between ENSO and overall Caribbean basin activity, while section 5 examines the relationship between the AMO and overall Caribbean basin activity. Section 6 examines the combined impact of ENSO and the AMO on Caribbean basin activity, and section 7 completes the paper with conclusions and some ideas for future work.

2. Data

The source for all hurricane data utilized in this study is the National Hurricane Center Atlantic Tracks file database (Jarvinen et al. 1984). This dataset contains 6-hourly estimates of wind speed and location for all tropical cyclones that occurred in the Atlantic basin from 1851 to 2009. The database is currently being reanalyzed as part of the Atlantic Hurricane Database Re-analysis Project, as documented in Landsea et al. (2004, 2008), and this study incorporates the reanalyzed data from 1900 to 1920 as part of the climatological

TABLE 1. The number of named storms (NS), hurricanes (H), and major hurricanes (MH) that tracked within 50 and 100 miles of every island in the Caribbean and along the east coast of Central America during the period 1900 to 2008. The probability of one or more NS, H, and/or MH impacting a landmass in a particular year given the climatological statistics and a Poisson distribution is also provided in parentheses.

	NS (50 miles)	H (50 miles)	MH (50 miles)	NS (100 miles)	H (100 miles)	MH (100 miles)
Anguilla	32 (25%)	16 (14%)	6 (5%)	66 (45%)	34 (27%)	10 (9%)
Antigua and Barbuda	44 (33%)	23 (19%)	8 (7%)	70 (47%)	33 (26%)	11 (10%)
Aruba	9 (8%)	3 (3%)	0 (<1%)	16 (14%)	7 (6%)	5 (4%)
The Bahamas	137 (72%)	66 (45%)	31 (25%)	177 (80%)	81 (52%)	38 (29%)
Barbados	28 (23%)	4 (4%)	2 (2%)	58 (41%)	11 (10%)	4 (4%)
Belize	47 (35%)	21 (18%)	9 (8%)	57 (41%)	23 (19%)	9 (8%)
Cape Verde	9 (8%)	3 (3%)	0 (<1%)	14 (12%)	3 (3%)	0 (<1%)
Cayman Islands	50 (37%)	28 (23%)	10 (9%)	76 (50%)	42 (32%)	14 (12%)
Costa Rica	3 (3%)	1 (1%)	0 (<1%)	9 (8%)	4 (4%)	2 (2%)
Cuba	136 (71%)	68 (46%)	32 (25%)	177 (80%)	86 (55%)	42 (32%)
Dominica	32 (25%)	11 (10%)	5 (4%)	65 (45%)	25 (20%)	8 (7%)
Dominican Republic	65 (45%)	33 (26%)	9 (8%)	98 (59%)	46 (34%)	17 (14%)
Grenada	27 (22%)	5 (4%)	3 (3%)	36 (28%)	6 (5%)	3 (3%)
Guadeloupe	38 (29%)	19 (16%)	7 (6%)	73 (49%)	33 (26%)	11 (10%)
Guatemala	37 (29%)	12 (10%)	3 (3%)	48 (36%)	20 (17%)	9 (8%)
Haiti	57 (41%)	26 (21%)	10 (9%)	85 (54%)	39 (30%)	16 (14%)
Honduras	88 (55%)	24 (20%)	12 (10%)	117 (66%)	39 (30%)	17 (14%)
Jamaica	55 (40%)	25 (20%)	11 (10%)	76 (50%)	36 (28%)	16 (14%)
Martinique	37 (29%)	9 (8%)	1 (1%)	61 (43%)	19 (16%)	7 (6%)
Mexico	170 (79%)	68 (46%)	23 (19%)	209 (85%)	97 (59%)	33 (26%)
Montserrat	33 (26%)	17 (14%)	5 (4%)	62 (43%)	31 (25%)	11 (10%)
Netherlands Antilles	8 (7%)	1 (1%)	0 (<1%)	22 (18%)	8 (7%)	4 (4%)
Nicaragua	35 (27%)	14 (12%)	8 (7%)	58 (41%)	19 (16%)	9 (8%)
Panama	2 (2%)	0 (<1%)	0 (<1%)	8 (7%)	1 (1%)	0 (<1%)
Puerto Rico	42 (32%)	17 (14%)	5 (4%)	74 (49%)	36 (28%)	14 (12%)
Saint Kitts and Nevis	34 (27%)	19 (16%)	4 (4%)	65 (45%)	32 (25%)	12 (10%)
Saint Lucia	36 (28%)	7 (6%)	1 (1%)	61 (43%)	13 (11%)	4 (4%)
Saint Vincent and the Grenadines	47 (35%)	8 (7%)	4 (4%)	66 (45%)	12 (10%)	4 (4%)
Trinidad and Tobago	15 (13%)	4 (4%)	2 (2%)	35 (27%)	6 (5%)	3 (3%)
Turks and Caicos	41 (31%)	17 (14%)	9 (8%)	72 (48%)	31 (25%)	12 (10%)
U.K. Virgin Islands	40 (31%)	18 (15%)	5 (4%)	72 (48%)	32 (25%)	13 (11%)
U.S. Virgin Islands	45 (34%)	18 (15%)	5 (4%)	73 (49%)	37 (29%)	14 (12%)

calculations, which are based on the period from 1900 to 2008. The geographical information system (GIS) version of the Atlantic Tracks file database is available from the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (available online at http://csc-s-maps-q.csc.noaa.gov/hurricanes/download.jsp). For this analysis, the hurricane statistics associated with a particular year run from 1 February to 31 January, as storms that form in January are more likely associated with the climate conditions from the previous year (e.g., 2005).

The Hadley Centre Sea Ice and SST dataset version 1 (HadISST1) (Rayner et al. 2003) as calculated through the Climate Explorer (available online at http://climexp.knmi.nl/) is the SST dataset used for ENSO calculations. The August–October-averaged Niño-3.4 index (5°S–5°N, 120°–170°W) is utilized to define ENSO events over the period from 1900 to 2008 in this study, as it has been shown that the SST anomalies in this region have significant impacts on climate around the globe (Barnston et al. 1997). The older HadISST1 dataset was utilized for ENSO calculations owing to its interpolation characteristics, since some data during the earlier part of the record were unavailable in the Second Hadley Centre SST dataset (HadSST2) dataset, which does not use interpolation.

The positive versus negative decades for the AMO were defined in the same way as done in Klotzbach and Gray (2008). They utilized a combined measure of SST in the far North Atlantic and sea level pressure (SLP) in the tropical and subtropical Atlantic to arrive at their AMO index. According to their definition, positive multidecadal periods of the AMO extended from 1926 to 1969 and 1995 to 2006, whereas negative multidecadal periods extended from 1900 to 1925 and 1970 to 1994. The generalized characteristics of the positive AMO have continued for the past couple of years; therefore, 2007 and 2008 are considered to be a part of the current positive phase of the AMO. Other definitions of the AMO have been utilized in the literature (e.g., Enfield et al. 2001), but these studies generally arrived at similar periods for positive and negative phases of the AMO.

3. Climatological Caribbean and Central American landfall probabilities

The calculation of climatological probabilities of landfall for various islands in the Caribbean and landmasses in Central America was undertaken using the ArcMap software available from the Environmental Systems Research Institute (ESRI). ArcMap is a widely used GIS tool that has numerous spatial calculation capabilities. In this paper, I used ArcMap to select the tracks of all tropical cyclones that tracked within 50 and 100 miles of each island/landmass in the Caribbean/Central America over the period from 1900 to 2008. The maximum intensity that was reached by the tropical cyclone when it was within 50 or 100 miles of the particular island/landmass was assigned as its landfall intensity.

The next step in this analysis was to translate the number of tropical cyclones impacting each island into an annual probability. Elsner and Schmertmann (1993) proposed using the Poisson distribution in forecasts of the annual number of Atlantic basin major hurricanes, since the Poisson distribution limits outcomes to individual nonnegative integers. Tartaglione et al. (2003) utilized the Poisson distribution when calculating probabilities of Caribbean landfall in their analysis, while Klotzbach and Gray (2009) utilize the Poisson distribution for issuing annual probabilities for U.S. landfall. I therefore utilize the Poisson distribution, defined as follows, when calculating landfall probabilities for various islands in the Caribbean and countries of Central America:

$$\mathrm{EP} = p^{-x}/e^{p}x!, \tag{1}$$

where EP is the expected probability, p is the annual average number of tropical cyclones that have occurred in the past 109 years, and x is any particular number of storms expected in the upcoming year. For example, the Poisson formula can tell you the probability of exactly zero, one, two, three, or more hurricanes for the upcoming year.

Given this formula, probabilities of any specific number of tropical cyclones impacting an island or landmass in a given year can be easily calculated. Table 1 tabulates the number of named storms, hurricanes (maximum 1-min sustained winds greater than or equal to 64 kt), and major hurricanes (maximum 1-min sustained winds greater than or equal to 96 kt) that tracked within 50 and 100 miles of each island in the Caribbean and the east coast of Central America over the period from 1900 to 2008. It also displays the probability of one or more named storms, hurricanes, and major hurricanes being within 50 and 100 miles of each island or landmass based on the climatological statistics from 1900 to 2008 and using the Poisson distribution. For all islands where no storm of a particular magnitude tracked within 50 or 100 miles, the probability was set as less than 1% since there is a chance in the future that a storm could impact that area. It is important to note when examining these probabilities that larger countries or islands tend to have higher probabilities. However, if a major hurricane tracks within 50 miles of Cuba, it does not necessarily mean that the entire island will be impacted, whereas a major hurricane tracking within 50 miles of Saint Lucia would impact the entire island.

TABLE 2. Probability of one or more major hurricanes (MH) tracking within 50 miles of every island in the Caribbean and along the east coast of Central America over time periods of 5, 10, 25 and 50 yr, given the climatological statistics of the period between 1900 and 2008.

	Time period			
Island(s)	5 yr	10 yr	25 yr	50 yr
Anguilla	26%	45%	77%	95%
Antigua and Barbuda	33%	55%	86%	98%
Aruba	<1%	<1%	<1%	<1%
The Bahamas	78%	95%	>99%	>99%
Barbados	9%	18%	39%	63%
Belize	36%	59%	89%	99%
Bermuda	22%	39%	71%	92%
Cape Verde	<1%	<1%	<1%	<1%
Cayman Islands	39%	63%	92%	99%
Costa Rica	<1%	<1%	<1%	<1%
Cuba	79%	96%	>99%	>99%
Dominica	22%	39%	71%	92%
Dominican Republic	36%	59%	89%	99%
Grenada	14%	26%	52%	77%
Guadeloupe	29%	50%	82%	97%
Guatemala	14%	26%	52%	77%
Haiti	39%	63%	92%	99%
Honduras	45%	70%	95%	>99%
Jamaica	42%	66%	93%	>99%
Martinique	5%	9%	22%	39%
Mexico	68%	90%	>99%	>99%
Montserrat	22%	39%	71%	92%
Netherlands Antilles	<1%	<1%	<1%	<1%
Nicaragua	33%	55%	86%	98%
Panama	<1%	<1%	<1%	<1%
Puerto Rico	22%	39%	71%	92%
Saint Kitts and Nevis	18%	33%	63%	86%
Saint Lucia	5%	9%	22%	39%
Saint Vincent and the Grenadines	18%	33%	63%	86%
Trinidad and Tobago	9%	18%	39%	63%
Turks and Caicos	36%	59%	89%	99%
U.K. Virgin Islands	22%	39%	71%	92%
U.S. Virgin Islands	22%	39%	71%	92%

The reader will note that, in general, the probability of a particular country having a major hurricane track within 50 miles is fairly small in a given year. However, these probabilities grow considerably when longer periods of time are considered. It is important to consider longer-period odds when building a home or other structure.

TABLE 3. Tropical cyclone activity occurring in the Caribbean by year from 1900 to 2008. Statistics are provided for the number of named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), major hurricanes (MH), major hurricane days (MHD), and accumulated cyclone energy (ACE).

Year	NS	NSD	H	HD	MH	MHD	ACE
1900	4	5.00	1	0.50	0	0.00	4.0
1901	6	16.00	1	0.25	0	0.00	13.2
1902	0	0.00	0	0.00	0	0.00	0.0
1903	3	4.00	1	3.50	1	3.25	15.5
1904	3	5.00	1	0.50	0	0.00	4.3
1905	3	5.75	0	0.00	0	0.00	4.3
1906	5	14.75	3	6.50	2	0.75	24.7
1907	1	2.00	0	0.00	0	0.00	1.0
1908	4	12.50	3	7.75	0	0.00	22.2
1909	7	17.75	3	5.25	1	0.75	23.0
1910	3	8.50	2	5.50	0	0.00	14.9
1911	1	7.00	1	2.25	0	0.00	9.5
1912	2	11.25	1	6.25	1	1.75	21.2
1913	3	4.75	0	0.00	0	0.00	3.5
1914	0	0.00	0	0.00	0	0.00	0.0
1915	3	11.00	3	8.00	2	3.50	34.6
1916	9	23.50	6	8.75	0	0.00	35.8
1917	2	6.25	1	2.75	1	0.25	10.6
1918	3	12.00	1	2.00	0	0.00	12.2
1919	1	2.00	0	0.00	0	0.00	1.2
1920	1	1.50	0	0.00	0	0.00	0.9
1921	3	8.00	2	5.00	2	2.50	19.7
1922	3	4.00	2	2.25	1	1.25	8.6
1923	1	0.25	0	0.00	0	0.00	0.1
1924	5	11.25	2	5.25	1	0.75	21.4
1925	1	2.75	0	0.00	0	0.00	1.3
1926	7	16.50	3	4.25	1	0.50	19.7
1927	2	2.75	0	0.00	0	0.00	1.6
1928	4	12.50	2	4.00	1	2.25	24.4
1929	0	0.00	0	0.00	0	0.00	0.0
1930	1	3.50	1	2.50	1	1.50	12.1
1931	7	19.00	2	1.75	1	0.25	20.0
1932	5	20.75	2	10.25	2	4.50	43.9
1933	15	45.75	7	9.75	1	0.25	47.6
1934	4	7.25	1	0.75	0	0.00	5.2
1935	2	12.75	2	7.75	1	0.75	24.6
1936	3	1.25	0	0.00	0	0.00	0.7
1937	2	2.00	0	0.00	0	0.00	1.0
1938	5	8.25	2	3.75	0	0.00	13.5
1939	4	8.00	1	1.25	0	0.00	7.9
1940	3	6.00	0	0.00	0	0.00	3.6
1941	1	4.75	1	3.00	1	1.00	11.5
1942	4	15.50	2	4.25	0	0.00	19.6
1943	4	7.50	2	3.25	0	0.00	10.8
1944	5	13.75	3	8.75	1	1.50	28.4
1945	9	10.50	3	2.50	0	0.00	13.0
1946	2	1.75	1	0.25	0	0.00	1.7
1947	5	8.00	2	0.75	1	0.50	7.4
1948	4	3.75	2	1.25	0	0.00	4.7
1949	6	7.50	1	1.25	0	0.00	7.5
1950	4	7.75	3	3.75	2	1.50	16.3
1951	3	9.50	3	7.00	2	1.25	23.7
1952	3	4.00	2	2.00	1	0.50	7.7
1953	5	7.75	1	0.25	1	0.25	6.9
1954	4	14.75	2	10.00	1	5.00	39.7
1955	6	14.00	5	10.00	4	6.00	48.2
1956	1	1.75	1	1.75	0	0.00	4.8
1957	0	0.00	0	0.00	0	0.00	0.0
1958	4	5.00	3	2.25	1	0.25	9.1
1959	1	1.25	0	0.00	0	0.00	0.8
1960	2	6.50	2	5.00	1	1.25	16.9
1961	4	13.00	3	8.00	2	4.75	37.5
1962	0	0.00	0	0.00	0	0.00	0.0
1963	3	8.75	2	6.75	1	4.00	28.3
1964	3	5.25	1	3.25	1	3.00	20.8
1965	1	0.25	0	0.00	0	0.00	0.1
1966	4	6.25	3	5.50	1	2.75	22.4
1967	1	9.50	1	6.25	1	3.75	27.3
1968	1	0.50	0	0.00	0	0.00	0.5
1969	4	6.75	2	3.25	1	0.25	11.9
1970	2	4.25	1	0.50	0	0.00	4.0
1971	4	13.00	2	3.50	1	1.00	19.5
1972	1	0.25	0	0.00	0	0.00	0.2
1973	2	0.50	0	0.00	0	0.00	0.4
1974	4	7.50	2	4.50	1	1.25	18.4
1975	1	5.00	1	0.50	0	0.00	4.1
1976	1	0.50	0	0.00	0	0.00	0.6
1977	1	1.00	0	0.00	0	0.00	0.8
1978	3	5.75	1	2.50	1	1.00	11.4
1979	3	7.50	1	3.25	1	3.00	26.0
1980	2	4.25	1	2.75	1	2.75	20.9
1981	4	4.00	1	0.50	0	0.00	3.7
1982	2	0.00	1	0.00	0	0.00	0.0
1983	0	0.00	0	0.00	0	0.00	0.0
1984	1	2.25	1	1.00	0	0.00	3.2
1985	2	1.00	1	0.50	0	0.00	1.1
1986	1	1.25	0	0.00	0	0.00	1.0
1987	2	3.50	1	1.25	1	0.50	6.1
1988	3	14.25	2	8.50	2	4.75	41.7
1989	3	6.50	2	3.25	1	2.25	16.4
1990	3	7.00	1	0.75	0	0.00	7.8
1991	0	0.00	0	0.00	0	0.00	0.0
1992	0	0.00	0	0.00	0	0.00	0.0
1993	3	6.00	0	0.00	0	0.00	3.5
1994	2	4.00	0	0.00	0	0.00	2.8
1995	6	9.75	3	5.00	3	2.25	23.2
1996	8	18.00	7	5.50	0	0.00	22.3
1997	1	1.25	1	1.25	0	0.00	2.7
1998	3	12.50	2	8.50	2	4.50	44.2
1999	4	9.50	2	6.00	1	2.00	24.2
2000	3	6.25	2	4.00	1	1.25	13.2
2001	5	12.25	2	4.25	2	1.75	23.2
2002	2	6.75	1	0.50	0	0.00	6.4
2003	3	5.50	1	0.25	0	0.00	5.8
2004	5	12.50	4	8.00	2	6.50	50.8
2005	8	19.50	4	10.00	4	6.50	57.9
2006	2	4.75	1	0.25	0	0.00	4.4
2007	4	11.00	2	7.00	2	5.75	46.8
2008	6	13.50	3	5.00	2	1.00	21.6

Table 2 displays the probability of each island or landmass having one or more major hurricanes tracking within 50 miles over 5-, 10-, 25-, and 50-yr periods, respectively. The probabilities for longer periods are calculated by taking the individual-year probability and then using the binomial distribution function:

$$1 - (1 - \text{one-year probability})^{\text{number of years}}. \quad (2)$$

Note that the probabilities are greater than 90% for most countries when a time period of 50 yr is considered. Therefore, it is imperative that hurricane-resistant structures be constructed throughout the Caribbean and in Central America.

4. Impacts of ENSO on Caribbean landfall frequency

As mentioned in the introduction, both ENSO (e.g., Gray 1984; Goldenberg and Shapiro 1996; Wilson 1999; Klotzbach 2007) and the AMO (Gray et al. 1997; Goldenberg et al. 2001; Klotzbach and Gray 2008) have been shown to impact Atlantic basin storm activity, whereas the focus on impacts in the Caribbean has been primarily limited to ENSO (e.g., Tartaglione et al. 2003). This study now examines the impact of these indices on tropical cyclone activity in the Caribbean, defined as 10°–20°N, 60°–88°W for the purposes of this study. Table 3 displays the number of named storms, named storm days (number of days where tropical cyclones are at least of named storm strength), hurricanes, hurricane days (number of days where tropical cyclones are at least of hurricane strength), major hurricanes, major hurricane days (number of days where major hurricanes are at least of major hurricane strength), 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] that were accrued in the Caribbean by year from 1900 to 2008. Activity in the Caribbean varies drastically from year to year, with eight years having no named storm activity over the period from 1900 to 2008 and 1933 having an impressive 15 named storms tracking through the region. The status of 1933 is even more impressive considering that no other year in the database had more than 9 named storms (1916 and 1945) in the region, and 2005 (the most active season on record with 28 total named storms in the Atlantic basin) only had 8 named storms in the Caribbean. The most active year in the Caribbean from an ACE perspective was 2005, followed by 2004, 1955, and then 1933.

To examine the impacts of ENSO on Caribbean tropical cyclone activity, I utilize the August–October-averaged Niño-3.4 index. The linear correlation between the August–October Niño-3.4 index and Caribbean ACE is −0.41 over the period from 1900 to 2008, which is significant at the 99% level, although only explaining about 17% of the variability over the period of the record. As will be demonstrated below, stronger signals can be obtained when examining relatively strong warm and cold ENSO events.

The 25 warmest August–October months are classified as El Niño years, the 25 coldest August–October months are classified as La Niña years, and all other years are classified as neutral years. Using this definition, all events cooler than −0.50°C are classified as La Niña, with all events greater than 0.56°C classified as El Niño. Figure 1 displays a time series of the August–October Niño-3.4 values over the period from 1900 to 2008, with El Niño events higher than the top line and La Niña events lower than the bottom line. Gray (1984) documented that the impacts of increased vertical shear driven by El Niño events was quite strong in the Caribbean, while Tang and Neelin (2004) documented a strong upper-tropospheric warming and concomitant decrease in potential intensity over the Caribbean associated with warm ENSO events. Therefore, one would expect to see dramatic differences in storm occurrence in the Caribbean between El Niño years and other years.

It has been suggested recently that ENSO events can be broken up into two types: eastern Pacific ENSO events, discussed in detail in Rasmusson and Carpenter (1982), and central Pacific ENSO events, termed El Niño–Modoki and discussed in Ashok et al. (2007). I have taken the Ashok et al. classifications and assigned the August–October months of 1986, 1990, 1991, 1992, 1994, 2002, and 2004 as El Niño–Modoki. The seven most recent warm ENSO August–October months that are not Modoki are 1969, 1972, 1976, 1982, 1987, 1997, and 2006. The August–October Caribbean basin-averaged shear for both cases is 7.4 m s^{-1}, indicating that both types of ENSO have a similar impact on the level of vertical shear experienced in the Caribbean. For both types of ENSO, the median ACE in the Caribbean was three units, indicating that both types of ENSO also have a similar impact on overall activity experienced in the Caribbean. Therefore, central and eastern Pacific ENSO events are not separated in this analysis.

I also examined the differences between the 10 warmest and 10 coldest ENSO events since it is to be expected that the strongest events may have the most significant impacts on the strength of vertical wind shear alterations and hence on hurricane activity. Table 4 displays the average per-year number of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days, and ACE for the 10 warmest, 25 warmest, neutral, 25 coldest, and 10 coldest years in the Niño-3.4

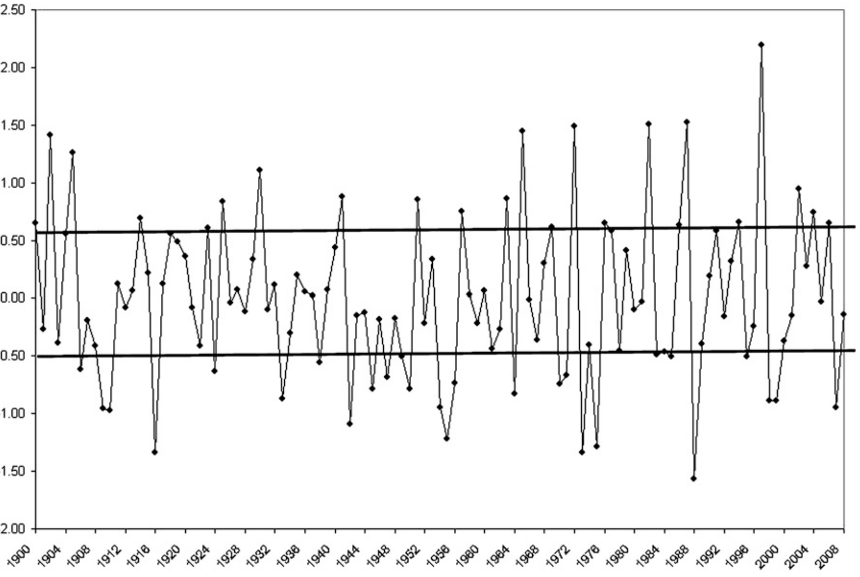

FIG. 1. The August–October-averaged Niño-3.4 index from 1900 to 2008. All years above 0.56°C are classified as El Niño events, all years between the two lines are classified as neutral events, and all years below −0.5°C are classified as La Niña events.

region. The 25 coldest/25 warmest and 10 coldest/10 warmest ratios are also provided. In general, the ratios are between 2.5:1 and 3.5:1 for the 25 coldest/25 warmest ENSO events, indicating large differences in activity between warm and cold years. All means between the 25 warmest and 25 coldest years are statistically significant at the 95% level, using a one-tailed Student's *t* test and assuming that each year represents an additional degree of freedom. A one-tailed Student's *t* test is utilized given that, a priori, one would expect a decrease in storm activity during warm episodes and an increase in activity during cold episodes (e.g., Gray 1984). All remaining statistical significance tests are done with this same assumption. Ratios extend from 3.3:1 for major hurricanes to 7.3:1 for major hurricane days for the 10 coldest versus 10 warmest years. All means between the 10 warmest and 10 coldest years are statistically significant at the 95% level except for major hurricanes (significant at the 90% level). Figure 2 shows the tracks of major hurricanes for the 10 coldest and 10 warmest ENSO years, illustrating the dramatic impacts of ENSO discussed in this section.

Figure 3 displays the probabilities of one or more tropical cyclones tracking into the Caribbean in the 10 warmest, 25 warmest, neutral, 25 coldest, and 10 coldest ENSO events using statistics over the period from 1900 to 2008 and the Poisson distribution. The probability of one or more hurricanes and major hurricanes tracking through the Caribbean increase dramatically from 39% and 26% in the 10 warmest ENSO years to 92% and 63% in the 10 coldest ENSO years, respectively. These probabilities certainly bear out the discussion in the preceding sections that ENSO plays a very important role in modulating Caribbean tropical cyclone activity.

This difference in storm activity has been attributed to changes in vertical wind shear over the Caribbean (10°–20°N, 60°–88°W). To verify this assertion, I next examine the difference in 200–850-mb zonal wind over the Caribbean during the months of August–October for the 10 warmest and 10 coldest ENSO events over the period from 1948 to 2008 using the National Centers for Environmental Prediction–National Center for Atmospheric

TABLE 4. The average per-year number of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days, and ACE for the 10 coldest, 25 coldest, neutral, 25 warmest and 10 warmest August-October periods in the Niño-3.4 region. The 25 coldest/25 warmest ratio and 10 coldest/10 warmest ratio are also provided. All mean differences between the 25 coldest and 25 warmest, and 10 coldest and 10 warmest are statistically significant at the 95% level differently using a one-tailed Student's *t* test except for the ratio between major hurricanes for the 10 coldest and 10 warmest August–October periods (significant at the 90% level).

	NS	NSD	H	HD	MH	MHD	ACE
10 coldest	4.3	12.5	2.5	6.0	1.0	2.2	27.4
25 coldest	4.6	11.4	2.3	4.7	0.9	1.5	21.8
Neutral	3.2	1.4	0.7	7.3	2.8	1.0	13.3
25 warmest	1.6	3.3	0.7	1.4	0.4	0.6	6.9
10 warmest	1.2	2.6	0.5	0.9	0.3	0.3	4.3
Ratio (25 coldest/25 warmest)	2.9	3.4	3.2	3.4	2.4	2.4	3.1
Ratio (10 coldest/10 warmest)	3.6	4.8	5.0	6.7	3.3	7.3	6.3

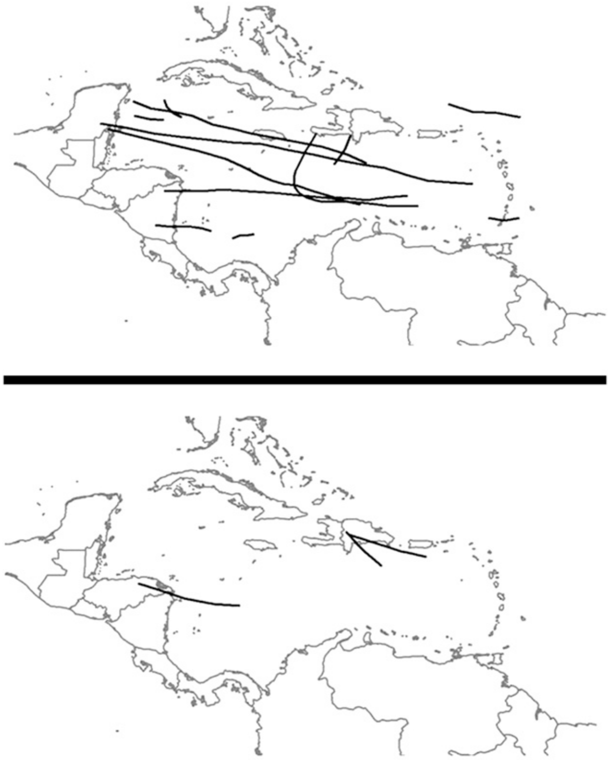

FIG. 2. (top) Tracks of major hurricanes in the 10 coldest ENSO years (22.25 major hurricane days) and (bottom) major hurricanes in the 10 warmest ENSO years (3 major hurricane days).

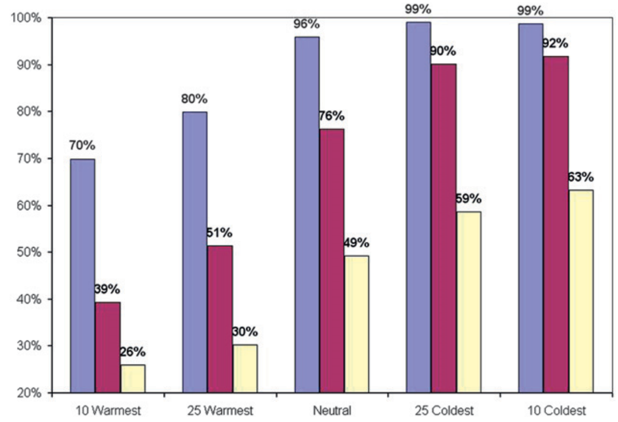

FIG. 3. Probabilities of one or more named storms (blue bars), hurricanes (red bars), and major hurricanes (yellow bars) tracking through the Caribbean given various phases of ENSO.

Research (NCEP–NCAR) reanalysis (Kistler et al. 2001). The NCEP–NCAR reanalysis is only available since 1948, which is why this is the period examined in this paper. For the 10 warmest events since 1948, the average 200–850-mb zonal wind shear in the Caribbean was 7 m s^{-1} compared with only 3 m s^{-1} in the 10 coldest events since 1948. This difference in shear is statistically significant at the 99% level, confirming previous research discussing the importance of Caribbean vertical shear fluctuations driven by ENSO phase (e.g., Gray 1984).

5. Impacts of the AMO on Caribbean landfall frequency

The AMO has been thought to impact Atlantic basin tropical cyclone activity through alterations in large-scale features over the tropical Atlantic including sea surface temperatures, vertical wind shear, low-level convergence, and the position of the intertropical convergence zone (Vimont and Kossin 2007; Klotzbach and Gray 2008; Grossmann and Klotzbach 2009). I begin analyzing the AMO's impacts on activity over the Caribbean basin using the AMO periods as first identified by Goldenberg et al. (2001) and updated by Klotzbach and Gray (2008). They classified the period from 1900 to 1925 as a cold AMO phase, from 1926 to 1969 as a warm AMO phase, from 1970 to 1994 as a cold AMO phase, and from 1995 to 2008 as a warm AMO phase. Table 5 displays the average per-year activity that occurred in the Caribbean during these four periods. As was seen for basinwide activity in Klotzbach and Gray (2008, their Table 2), the difference in activity in the Caribbean is much stronger between the 1995–2008 and the 1970–94 period than between the 1926–69 and 1900–25 period. None of the differences between 1926–69 and 1900–25 is statistically significant at the 90% level, whereas all of the differences between 1995–2008 and 1970–94 are statistically significant at the 95% level. The 1995–2008 period has been very active in the Caribbean when compared with tropical cyclone statistics since 1900. Given that activity during the earlier part of the twentieth century may have been underestimated (e.g., Landsea et al. 2006; Knutson et al. 2010), according to the best-track dataset, four of the most active years in the Caribbean for ACE have occurred since 1998 (1998, 2004, 2005, and 2007). It is also of importance to note that 9 of the 10 most active ACE years in the Caribbean occurred when the AMO was judged to be in its positive phase. The only exception was 1988, which was characterized by the strongest La Niña event since 1900 as defined by the August–October Niño-3.4 index.

6. Impacts of a combined ENSO/AMO index on Caribbean landfall frequency

As has been shown in the previous two sections, both ENSO and the AMO play an important role in altering levels of Caribbean tropical cyclone activity. These relationships are greater when these two indices are

TABLE 5. The average per-year number of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days, and ACE that occurred during the periods 1900–25, 1926–69, 1970–94, and 1995–2008, respectively. Ratios between the 1926–69 and 1900–25 time periods and between the 1995–2008 and 1970–94 time periods are provided.

	NS	NSD	H	HD	MH	MHD	ACE
1900–25 (AMO cold)	3.0	1.3	0.5	7.6	2.8	0.6	11.8
1926–69 (AMO warm)	3.6	1.7	0.7	8.2	3.3	1.1	14.8
1970–94 (AMO cold)	2.0	0.8	0.4	4.0	1.3	0.7	7.7
1995–2008 (AMO warm)	4.3	2.5	1.4	10.2	4.7	2.3	24.8
Ratio (1926–69/1900–25)	1.2	1.3	1.5	1.1	1.2	1.9	1.3
Ratio (1995–2008/1970–94)	2.1	3.3	3.8	2.6	3.5	3.4	3.2

treated in combination. Table 6 displays the average per-year activity that occurred in the Caribbean during the 10 warmest and 10 coldest ENSO events when the AMO was positive (e.g., 1926–69, 1995–2008) and when the AMO was negative (1900–25, 1970–94). The impacts of ENSO are reduced slightly when the AMO is positive. For example, when the AMO is positive, the 10 coldest − 10 warmest ENSO difference average ACE is reduced from 32 to 14 units (44% as much ACE), whereas when the AMO is negative, the 10 coldest − 10 warmest difference in ACE is reduced from 18.9 to 1.9 (10% as much). Similar differences are seen for hurricanes (48% versus 9%) and hurricane days (45% versus 5%). The signal is much weaker for named storms, which is to be expected, given that weaker tropical cyclones can form in years with large-scale climate conditions that are not particularly conducive. Even though El Niño is unfavorable for tropical cyclones, in a positive AMO phase some tropical cyclones can still form and intensify, given that other large-scale climate parameters such as tropical Atlantic sea surface temperatures are likely still somewhat favorable for tropical cyclone formation. A negative AMO phase and El Niño combine to provide large-scale climate features that are especially hostile for tropical cyclones.

ENSO clearly dominates over the AMO on an interannual basis. Note the especially drastic relationship between a warm ENSO event and a negative AMO compared with a cold ENSO event and a positive AMO. All of these means are statistically significantly different at the 99% level. Dramatic differences are also seen when converting these values to probabilities using the Poisson distribution. For example, given the statistics of the 1900–2008 period, the probability of one or more hurricanes impacting the Caribbean when the AMO is positive and one of the 10 strongest cold ENSO events is in progress is 95%, whereas when the AMO is negative and one of the 10 strongest warm ENSO events is in progress, the probability is reduced to only 18%.

Figure 4 displays the tracks of hurricanes that occurred in the Caribbean during the 10 coldest ENSO years in a warm AMO phase (29 hurricanes) and in the 10 warmest ENSO years in a cold AMO phase (2 hurricanes). Sixty-five hurricane days occurred during the 10 coldest ENSO years in a warm AMO phase, compared with only 1.75 hurricane days in the 10 warmest ENSO years in a cold AMO phase. Therefore, given the knowledge of which AMO phase one is currently in combined with an accurate prediction of ENSO provides a very powerful predictor for Caribbean tropical cyclone activity.

7. Conclusions and future work

This paper examines Caribbean tropical cyclone activity over the period from 1900 to 2008. Probabilities of named storms, hurricanes, and major hurricanes impacting every island in the Caribbean and every country in Central America are presented. The impacts of the El Niño–Southern Oscillation (ENSO) and the Atlantic multidecadal oscillation (AMO) on levels of Caribbean activity are then examined in detail. Many more tropical cyclones occur in the Caribbean during La Niña events than during El Niño events, confirming previous studies on the issue (Gray 1984; Tartaglione et al. 2003). The AMO is also shown to impact the number of tropical cyclones occurring in the Caribbean, with the recent positive AMO period from 1995 to 2008 showing significantly

TABLE 6. As in Table 5, but for during the 10 coldest ENSO events when the AMO was positive, the 10 warmest ENSO events when the AMO was positive, the 10 coldest ENSO events when the AMO was negative, and the 10 warmest ENSO events when the AMO was negative. The ratio between the 10 coldest AMO events when the AMO was positive and the 10 warmest ENSO events when the AMO was negative is also provided.

	NS	NSD	H	HD	MH	MHD	ACE
10 coldest ENSO + positive AMO	5.6	14.7	2.9	6.5	1.4	2.8	32.0
10 warmest ENSO + positive AMO	1.9	5.2	1.4	2.9	0.7	1.4	14.0
10 coldest ENSO + negative AMO	4.1	11.3	2.2	4.4	0.7	0.8	18.9
10 warmest ENSO + negative AMO	1.4	2.2	0.2	0.2	0.1	0.1	1.9
Ratio (10 coldest ENSO + positive AMO)/(10 warmest ENSO + negative AMO)	4.0	6.7	14.5	37.1	14.0	56.0	16.7

FIG. 4. (top) Tracks of hurricanes in the 10 coldest ENSO years with a positive AMO phase (65 hurricane days) and (bottom) tracks of hurricanes in the 10 warmest ENSO years with a negative AMO phase (1.75 hurricane days).

more storms than the previous negative AMO period from 1970 to 1994. When the AMO and ENSO are considered in combination, the relationships are of an even stronger magnitude.

Other large-scale climate factors besides the AMO and ENSO clearly also play a role in impacting Caribbean hurricane activity. As mentioned earlier, the AMO only signals active versus inactive multidecadal periods for tropical cyclones. On an interannual basis, other factors such as tropical Atlantic sea surface temperatures (Saunders and Lea 2008), the size of the Atlantic warm pool (Wang et al. 2008), and tropical Atlantic sea surface temperature gradients and low-level trade wind strength as measured by the Atlantic meridional mode (Vimont and Kossin 2007) also play a critical role in influencing levels of Atlantic basin and Caribbean hurricane activity.

Some research has been conducted into the potential impact of the AMO on multidecadal fluctuations of ENSO. Timmermann et al. (2005) document a weakening of ENSO events with a weakening of the thermohaline circulation (e.g., a negative phase of the AMO), whereas Dong et al. (2006) document the opposite impact (e.g., a positive phase of the AMO weakens ENSO events). The disagreement may be because Timmermann et al. (2005) focus on changes in the large-scale ocean circulation, while Dong et al. (2006) focus on atmospheric changes. Further documentation of these relationships will help in better understanding the impacts of both of these modes on Caribbean basin hurricane activity.

In the future, I intend to investigate the relationship between ENSO and the AMO on specific Caribbean islands. In addition, given the very strong impact of ENSO on Caribbean tropical cyclone activity, seasonal forecasts for Caribbean-only activity will be considered in future years. Viewing the Caribbean as a separate area for prediction from the remainder of the Atlantic basin may add skill to the currently issued Atlantic basin seasonal forecasts by the author and W. M. Gray of the Tropical Meteorology Project at Colorado State University.

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 William Gray, Eric Blake, and Chris Landsea for helpful discussions on Caribbean tropical cyclone activity. I would like to acknowledge the two anonymous reviewers for helpful comments that significantly improved the manuscript.

REFERENCES

Ashok, K., S. K. Behera, S. A. Rao, H. Weng, and T. Yamagata, 2007: El Niño Modoki and its possible teleconnection. *J. Geophys. Res.,* **112,** C11007, doi:10.1029/2006JC003798.

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

Berg, R., 2009: Tropical cyclone report: Hurricane Ike. National Hurricane Center Rep., 55 pp.

Beven, J. L., 2004: Tropical cyclone report: Hurricane Frances. National Hurricane Center Rep., 28 pp.

——, and T. B. Kimberlain, 2009: Tropical cyclone report: Hurricane Gustav. National Hurricane Center Rep., 38 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.

Dong, B., R. T. Sutton, and A. A. Scaife, 2006: Multidecadal modulation of El Niño–Southern Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures. *Geophys. Res. Lett.,* **33,** L08705, doi:10.1029/2006GL025766.

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

Emanuel, K. A., 1986: An air–sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.,* **43,** 585–604.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble, 2001: The Atlantic multi-decadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.,* **28,** 2077–2080.

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.

——, J. D. Sheaffer, and C. W. Landsea, 1997: Climate trends associated with multidecadal variability of Atlantic hurricane activity. *Hurricanes: Climate and Socioeconomic Impacts,* H. F. Diaz and R. S. Pulwarty, Eds., Springer-Verlag, 15–53.

Grossmann, I., and P. J. Klotzbach, 2009: A review of North Atlantic modes of natural variability and their driving mechanisms. *J. Geophys. Res.,* **114,** D24107, doi:10.1029/2009JD012728.

Guiney, J. L., and M. B. Lawrence, 1999: Tropical cyclone report: Hurricane Mitch. National Hurricane Center Rep., 19 pp.

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: Revised prediction of seasonal Atlantic basin tropical cyclone activity from 1 August. *Wea. Forecasting,* **22,** 937–949.

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

——, and ——, 2009: Extended range forecast of Atlantic seasonal hurricane activity and landfall strike probability for 2010. Colorado State University Dept. of Atmospheric Science Rep., 34 pp.

Knutson, T. R., and Coauthors, 2010: Tropical cyclones and climate change. *Nat. Geosci.,* **3,** 157–163, doi:10.1038/ngeo779.

Kossin, J. P., and D. J. Vimont, 2007: A more general framework for understanding Atlantic hurricane variability and trends. *Bull. Amer. Meteor. Soc.,* **88,** 1767–1781.

Landsea, C. W., and Coauthors, 2004: The Atlantic hurricane database re-analysis 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.

——, B. A. Harper, K. Hoarau, and J. Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science,* **313,** 452–454, doi:10.1126/science.1128448.

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

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.

Rappaport, E. N., and J. Fernandez-Partagas, 1994: The deadliest Atlantic tropical cyclones, 1492-1994. NOAA Tech. Memo. 4, 42 pp.

Rasmusson, E. M., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.,* **110,** 354–384.

Rayner, N. A., D. E. Parker, E. B. Holland, 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.

Saunders, M. A., and A. S. Lea, 2008: Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. *Nature,* **451,** 557–560, doi:10.1038/nature06422.

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.

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., S. R. Smith, and J. J. O'Brien, 2003: ENSO impact on hurricane landfall probabilities for the Caribbean. *J. Climate,* **26,** 2925–2931.

Timmermann, A., S.-I. An, U. Krebs, and H. Goosse, 2005: ENSO suppression due to weakening of the North Atlantic thermohaline circulation. *J. Climate,* **18,** 3122–3139.

Vimont, D. J., and J. P. Kossin, 2007: The Atlantic Meridional Mode and hurricane activity. *Geophys. Res. Lett.,* **34,** L07709, doi:10.1029/2006GL029683.

Wallace, J. M., T. P. Mitchell, E. M. Rasmusson, V. E. Kousky, E. S. Sarachik, and H. von Storch, 1998: On the structure and evolution of ENSO-related climate variability in the tropical Pacific: Lessons from TOGA. *J. Geophys. Res.,* **103,** 14 241–14 259.

Wang, C., and S.-K. Lee, 2007: Atlantic warm pool, Caribbean low-level jet, and their potential impact on Atlantic hurricanes. *Geophys. Res. Lett.,* **34,** L02703, doi:10.1029/2006GL028579.

——, ——, 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.