Characteristics of Landfalling Tropical Cyclones in the United States and Mexico: Climatology and Interannual Variability

Joshua Larson

Williams College, Williamstown, Massachusetts

Yaping Zhou

NASA Goddard Space Flight Center, Greenbelt, Maryland

R. Wayne Higgins

Climate Prediction Center, Camp Springs, Maryland

(Manuscript received 5 August 2003, in final form 16 September 2004)

ABSTRACT

The climatology and interannual variability of landfalling tropical cyclones and their impacts on precipitation in the continental United States and Mexico are examined. The analysis is based on National Hurricane Center 6-hourly tropical cyclone track data for the Atlantic and eastern Pacific basins and gridded daily U.S. precipitation data for the period August–October 1950–98. Geographic maps of total tropical cyclone strike days, and the mean and maximum percentage of precipitation due to tropical cyclones, are examined by month. To make the procedures objective, it is assumed that precipitation is symmetric about the storm's center. While this introduces some uncertainty in the analysis, sensitivity tests show that this assumption is reasonable for precipitation within 5° of the circulation center.

The relationship between landfalling tropical cyclones and two leading patterns of interannual climate variability—El Niño–Southern Oscillation (ENSO) and the Arctic Oscillation (AO)—are then examined. Relationships between tropical cyclone frequency and intensity and composites of 200-hPa geopotential height and wind shear anomalies are also examined as a function of ENSO phase and AO phase using classifications devised at the Climate Prediction Center.

The data show that tropical cyclone activity in the Atlantic basin is modulated on both seasonal and intraseasonal time scales by the AO and ENSO and that impact of the two modes of climate variability is greater together than apart. This suggests that, during La Niña conditions, atmospheric circulation is more conducive to activity in the main development region during AO-positive conditions than during AO-negative ones and that, during El Niño conditions, atmospheric circulation appears even less conducive to tropical cyclone development during the negative phase of the AO than during the positive phase.

1. Introduction

Fluctuations in Atlantic basin and northeast Pacific tropical cyclone (TC) frequency have significant impacts on human life and property. Since TCs can bring tremendous amounts of precipitation in short time periods, tropical cyclone precipitation (TCP) can be a significant portion of total summer precipitation along the U.S. East Coast and Gulf Coast, small portions of the U.S. West Coast, and the Mexican west and east coasts, in addition to areas well inland. Therefore, an accurate understanding of the climatology and interannual variability of landfalling TCs will aid monthly and seasonal long-lead forecasts.

The Atlantic hurricane season officially begins 1 June and ends 30 November. The peak of the hurricane season, and the statistical peak of TC-related precipitation along the U.S. East Coast, occurs from mid-August to early October (Herbert and Taylor 1979; Landsea 1993). Meanwhile, the hurricane season in the Northeast Pacific basin starts somewhat earlier in the year, with activity usually beginning in late May or early June and often continuing through late October or early November; TC activity in this basin peaks in late August and early September.

Recent improvements in seasonal hurricane forecasts (Gray et al. 1993; Elsner and Schmertmann 1993) have made it attractive for forecasters to use this information in their seasonal precipitation forecasts. Several studies

Corresponding author address: Dr. R. W. Higgins, Analysis Branch, Climate Prediction Center, NOAA/NWS/NCEP, Camp Springs, MD 20746.
E-mail: wayne.higgins@noaa.gov

have shown that the interannual variability of tropical cyclone activity in the Atlantic basin is strongly related to the ENSO cycle and to the stratospheric quasi-biennial oscillation (QBO; Gray 1984). In addition, Gray et al. (1997) noted that strong multidecadal fluctuations in the strength and tracks of TCs are linked to sea surface temperatures (SSTs) in the northern Atlantic Ocean. More recently, studies have shown that TC activity in all of the tropical ocean basins is modulated by the Madden–Julian oscillation (MJO) on intraseasonal time scales (e.g., Maloney and Hartmann 2000; Higgins and Shi 2001). When MJO-related wind anomalies in the lower troposphere of the tropical eastern Pacific are westerly, hurricane development in the Gulf of Mexico and the western Caribbean is 4 times more likely than when MJO-related winds are easterly (Maloney and Hartmann 2000).

The impact of ENSO on precipitation in the United States and Mexico is well documented (Roeplewski and Halpert 1986). Its impact on tropical cyclone activity in both the Atlantic and eastern Pacific basins is significant (e.g., Klotzbach and Gray 2003; Kimberlain 1999; Chu 2004), and it has considerable influence on monthly and seasonal precipitation totals over the United States and Mexico (e.g., Ropelewski and Halpert 1986, 1987); as a result, ENSO is an important factor in long-lead monthly and seasonal forecasts. Finally, while the Arctic Oscillation (AO) has been the subject of many recent studies, most have investigated and emphasized its role during the cold season when the AO is thought to be most active. However, the AO also accounts for a significant portion of the total variance in atmospheric circulation during the warm season (Thompson et al. 2000).

In this paper, the fraction of total precipitation due to landfalling tropical cyclones along the Atlantic and Pacific coasts of the United States and Mexico was computed from gridded daily precipitation data for the United States and Mexico together with TC track data for the Atlantic and northeast Pacific basins for the period 1950–98. In addition, a climatology was established and the influence of ENSO and the AO on precipitation totals associated with landfalling TCs in the Atlantic basin was then considered.

The methodology and datasets used in this study are discussed in section 2. The climatology of landfalling tropical cyclones and their impacts on precipitation in the United States and Mexico are discussed in section 3. Relationships between ENSO, landfalling TCs, and precipitation are discussed in section 4. A similar analysis is presented in section 5 for the AO. In section 6, the combined effects of ENSO and the AO on TC activity are investigated. The results are summarized and are discussed in section 7.

2. Methodology and data

This study uses the Atlantic and Northeast Pacific Tropical Cyclone (HURDAT) dataset from the National Hurricane Center (Neumann et al. 1999). This dataset contains 6-hourly records of low center locations and intensities (maximum 1-min surface wind speeds and minimum central pressures) for all tropical storms and hurricanes from 1950 to 1998 in these two areas. When considering TC-related precipitation, both hurricanes and tropical storms are included regardless of whether an individual cyclone's intensity remains strong enough to be classified as a tropical storm (sustained winds $>$ 39 mph or 17 m s^{-1}) or hurricane (sustained winds $>$ 74 mph or 33 m s^{-1}) by the time it makes landfall. Therefore, we use the term "tropical cyclone" to cover all cases. The gridded daily precipitation dataset for the United States and Mexico compiled by Higgins et al. (2000b) is used for the precipitation analysis. This gridded daily analysis typically includes 10 000–12 000 daily reports at a horizontal resolution of (latitude, longitude) = (1°, 1°), with the best coverage over the eastern two-thirds of the United States (more information available online at http://www.cpc.ncep.noaa.gov/products/precip/realtime/).

An objective procedure was used to relate observed precipitation to landfalling tropical cyclones (referred to as TCP). The radius of a TC, defined by the location and area of threshold wind speed, varies widely (radii between 100 and 1100 km have been observed) and is not necessarily proportional to TC intensity. In some cases the precipitation shield is roughly symmetric about the center of the TC. In many cases, such as those in which interactions with midlatitude disturbances or fronts are present or in which vertical wind shear is relatively strong, the precipitation shield is asymmetric. For the purposes of an objective procedure that determines TCP for each landfalling TC over a multiyear period, we assume that the precipitation shield is symmetric about the storm center. In this study, precipitation within 5° of the center of a tropical cyclone is considered to be TCP. We note that this is very close to the 550-km radius chosen by Douglas and Englehart (2001), who found that in 90% of the cases the distance between the center of a storm and the outer edge of its cloud shield is less than 550–600 km. Sensitivity tests show that TCP levels off when a radius near 5° is employed and that further increases of the radius make relatively little difference to the TCP values (we tested the sensitivity of the results for radii varying between 2.5° and 7.5°). Radii smaller than 5° unnecessarily exclude much of the TCP in the vicinity of many storms. It is important to note that, as the center of TCs rarely propagates more than 600 km within 6 h, the radius specified is large enough to cover areas along the storm track. In other words, by this definition we included precipitation not only within 5° of the TC center, but also within 5° along the storm track.

In section 4, a classification of Pacific cold (La Niña) and warm (El Niño) episodes during each August–October (ASO) season, constructed by the Climate Prediction Center (CPC) for the period 1950–2001, is

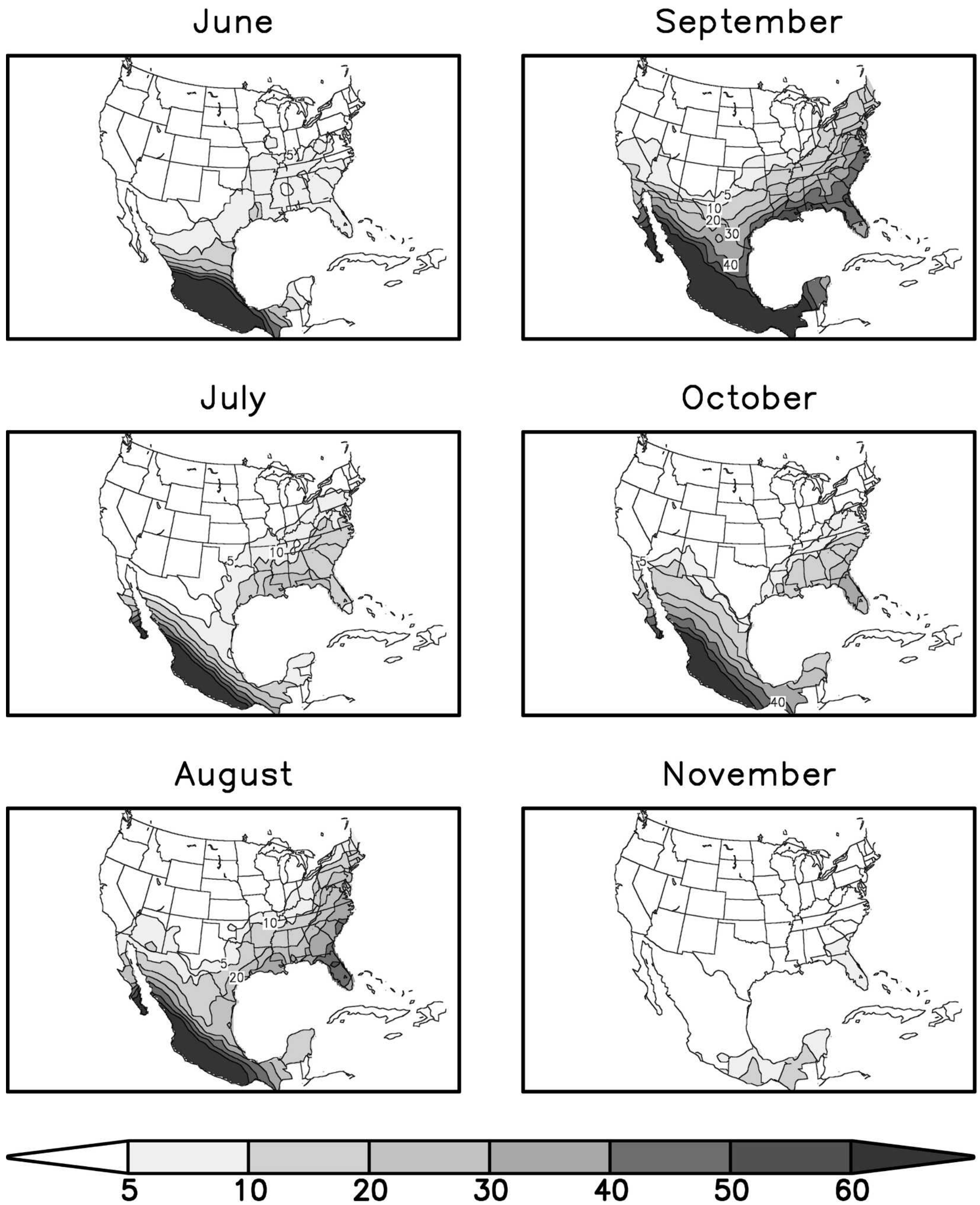

FIG. 1. Total number of TC strike days by month during the period Jun to Nov 1950–98: (a) Jun, (b) Jul, (c) Aug, (d) Sep, (e) Oct, and (f) Nov.

used to relate TC activity and the ENSO phase. This ENSO classification is based on the pattern and magnitude of SST anomalies in the tropical Pacific and can be found on the CPC's Web site. For the purposes of this study, no distinction is made among weak, moderate, and strong events (except in Figs. 8 and 9 where the moderate and strong events are considered). There are 20 (13) ASO seasons with El Niño (La Niña) conditions present, and the remaining 18 are classified as ENSO neutral.

In section 5, standardized seasonal values of an AO index are computed for all ASO seasons from 1950 to 2001 and related to TC activity. The AO index used was developed by H.-K. Kim (2004, personal communication) and is based on the methodology of Thompson and Wallace (2000). The daily AO index was first constructed by projecting daily 1000-hPa geopotential height anomalies poleward of 20°N onto the leading pattern of the AO, which is the leading EOF of monthly

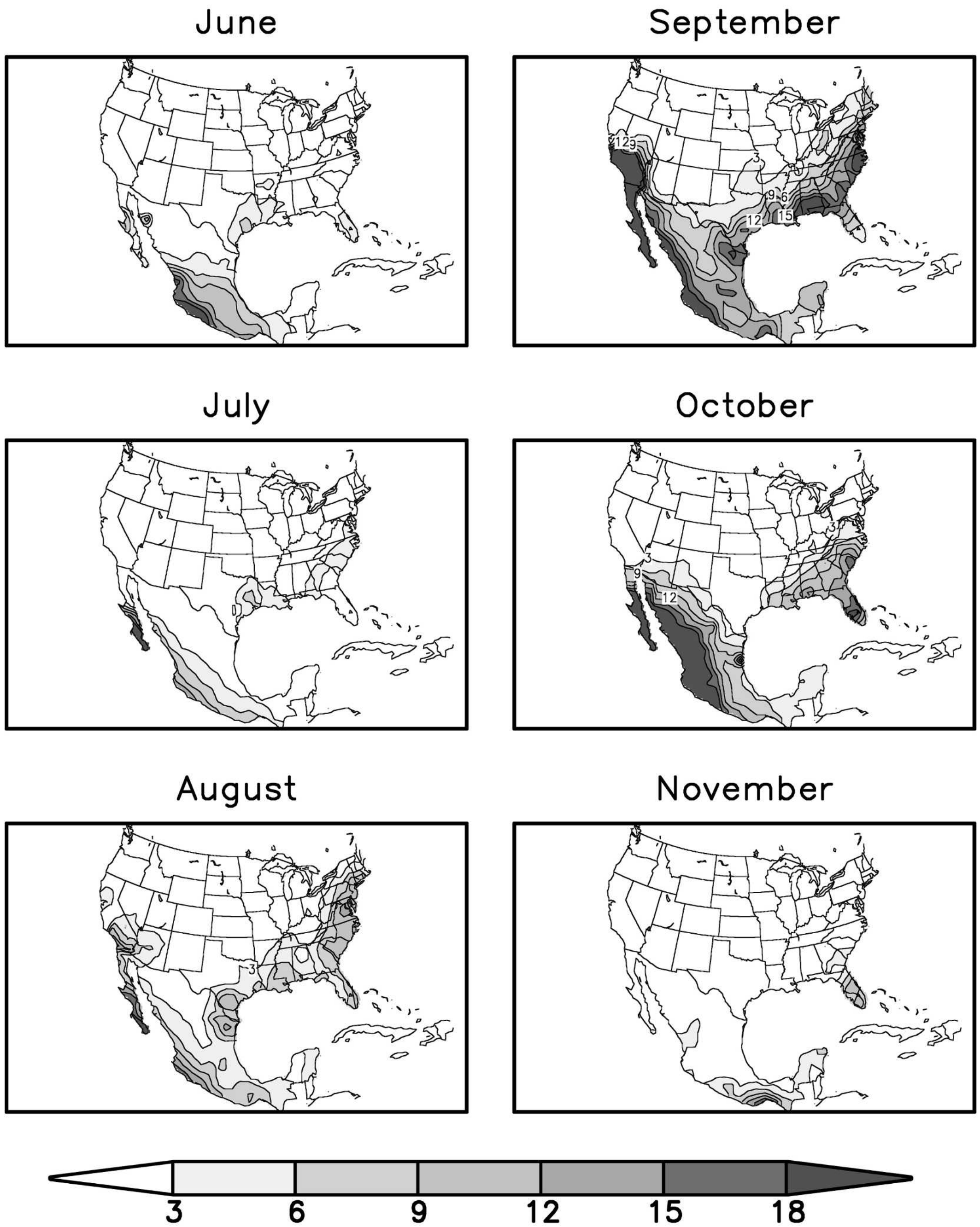

FIG. 2. As in Fig. 1 but for mean fraction (in percent) of total monthly precipitation due to TCs. Results are based on TC strike days.

mean 1000-hPa geopotential heights. Seasonal values of the index were then constructed from the daily values.

3. Landfalling tropical cyclones and precipitation

The number of TC strike days, defined as days on which tropical cyclones approach within 5° of a particular land-based grid point, at a given location is an overall indicator of the local level of TC activity, though this measure will always be somewhat higher than the number of storms that actually make landfall. During the period 1950–98 most of southern and western Mexico averages more than one strike day per year (or more than 60 strikes in the 49-yr record) during the months of June–October (Fig. 1). The highest frequencies creep northwestward along the southwest coast of Mexico

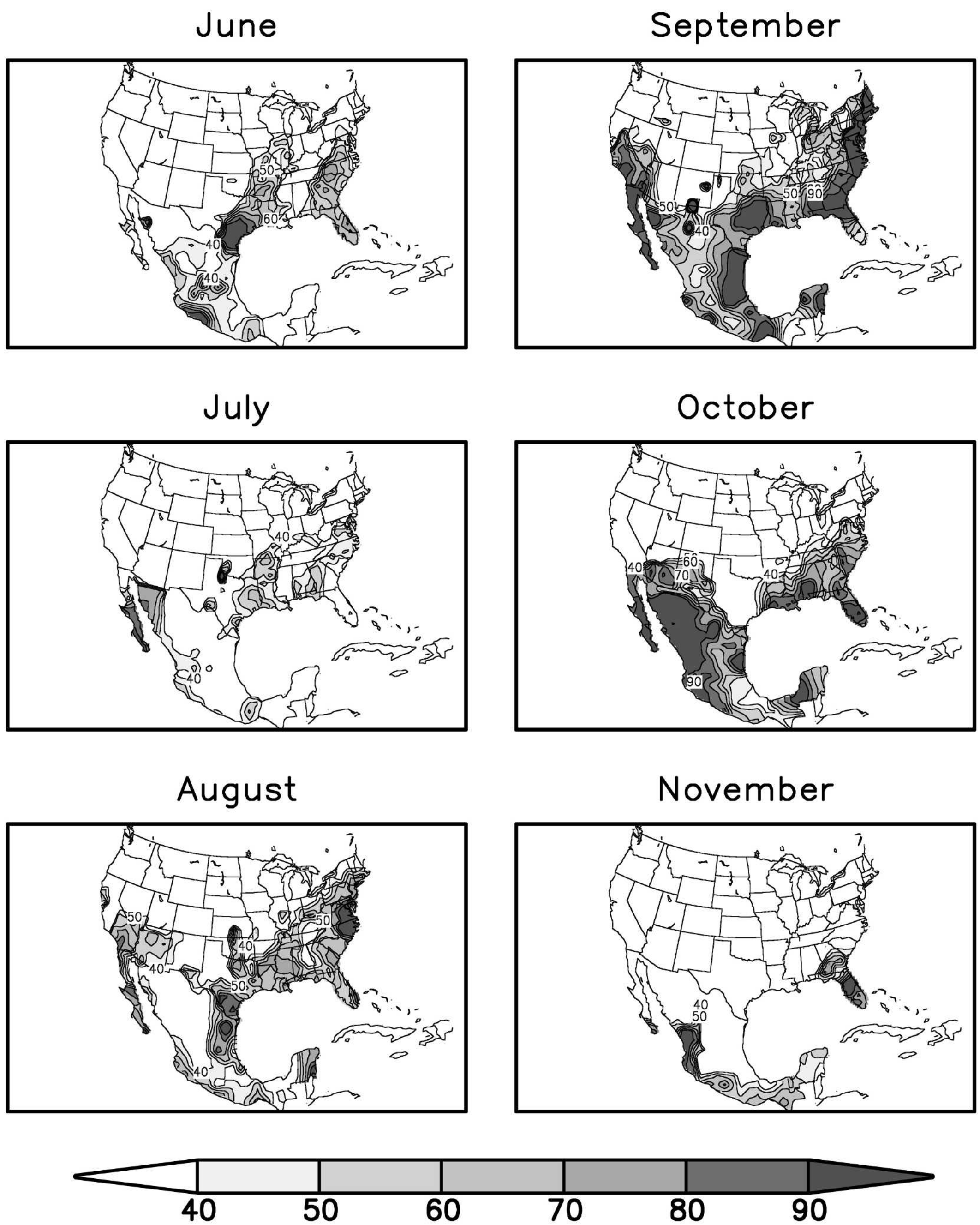

Fig. 3. As in Fig. 2 but for maximum fraction.

from June (Fig. 1a) to September (Fig. 1d) and then retreat to the south thereafter, with a dramatic decrease in November (Fig. 1f). In the United States, TC strike days peak in September along the eastern seaboard and Gulf Coast, with more than 50 strikes during the period at some locations (see also Landsea 1993). Even locations as far north as Maryland and Delaware have experienced more than 30 TC strike days in September (Fig. 1d).

The mean fraction of total monthly precipitation due to TCs (Fig. 2) exceeds 10% during September (Fig. 2d) along the southwest coast of Mexico, the U.S. Gulf Coast, and the U.S. East Coast as far north as southern New Jersey. During this month, at some locations, more than 20% of the total precipitation is due to TCs. In these regions the fractions are much lower in June and July (Figs. 1a,b), except along portions of the southwest coast of Mexico where total precipitation

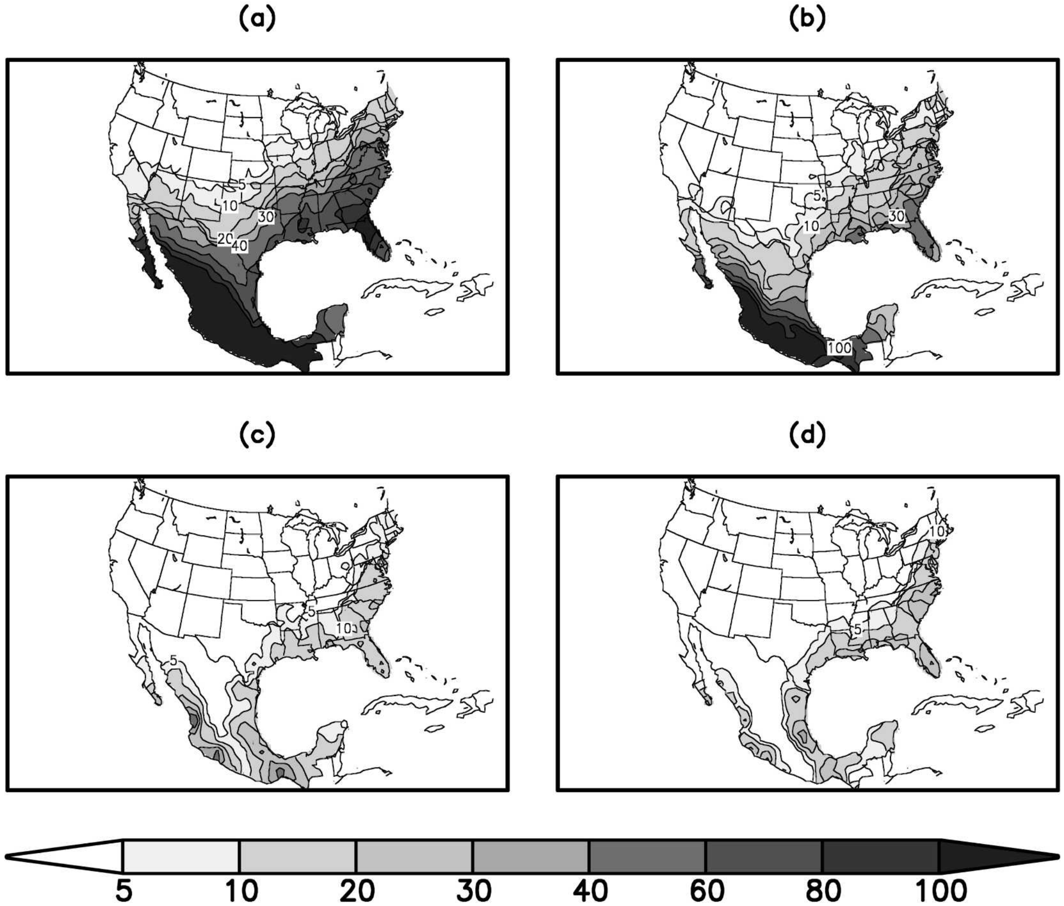

FIG. 4. Number of days during Jun–Nov 1950–98 with TCP in the following ranges: (a) TCP < 10 mm day^{-1}, (b) 10 mm day^{-1} $<$ TCP $<$ 25 mm day^{-1}, (c) 25 mm day^{-1} $<$ TCP $<$ 40 mm day^{-1}, and (d) TCP $>$ 40 mm day^{-1}.

during this time is much lower. October values remain high from Florida to the Carolinas and in southwest Mexico, consistent with TC strike days (Fig. 1e). In fact, the percentage of TCP in western Mexico is higher in October than in September even though the total number of TC strike days decreases; this apparent discrepancy is actually due to a dramatic decrease in total precipitation in southwest Mexico during October as the monsoon season comes to an end.

The maximum fraction of total monthly precipitation due to TCs in any particular month has been up to 100% of monthly precipitation in many coastal areas (Fig. 3), especially during September and October (Figs. 3d,e). To understand this statistic, recognize that one TC can produce the equivalent of many months of rainfall in a short period of time (e.g., Tropical Storm Allison in 2001 in southeast Texas). The maximum fraction peaks along much of the U.S. coastline in September and along the west coast of Mexico in October. Even in November, TCP can contribute greater than 90% of all precipitation in parts of central Florida and west-central coastal sections of Mexico (Fig. 3f).

The pattern of the number of TC days during June–November 1950–98 with small precipitation amounts (Fig. 4a) resembles the pattern of total strike days in September (Fig. 1, upper right), implying that many TCs produce relatively small precipitation amounts. Composites for larger daily precipitation amounts (e.g., Figs. 4b–d) indicate that Atlantic basin landfalling TCs tend to deliver heavier rainfall more frequently than do eastern Pacific storms.

4. ENSO and TC activity in the Atlantic and eastern Pacific basins

It is reasonably well known that El Niño events are associated with an increase in tropical cyclone activity in the eastern North Pacific and a decrease in TC activity in the Atlantic basin (e.g., Gray 1984; Gray et al. 1993; Goldenberg and Shapiro 1996; Kimberlain 1999; Chu 2004). Conversely, La Niña events are associated with a decrease in TC activity in the eastern Pacific basin and an increase in TC activity in the Atlantic basin. The Tahiti–Darwin Southern Oscillation index (SOI) is one measure of the influence of ENSO in the tropical and subtropical atmosphere. If values of the

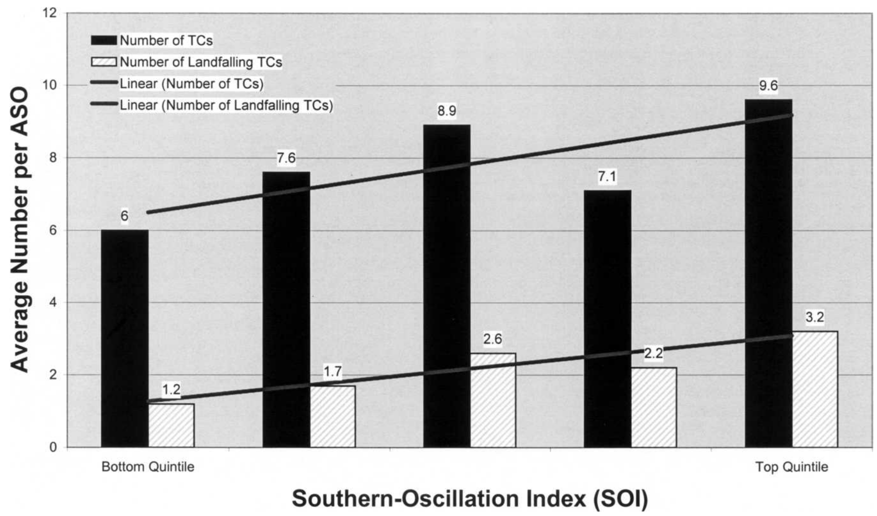

Fig. 5. Relationship between the SOI and the number of TCs (number of landfalling TCs) per ASO season in the Atlantic basin. Results are based on ASO 1950–2001.

SOI are organized by quintile, there is a statistically significant increase in the number of TCs that develop as well as in the number of landfalling TCs as the SOI becomes increasingly positive. A correlation ($r = 0.35$, significant at the 99% confidence level) between ENSO and the number of TCs that develop over the Atlantic basin is clearly evident (Fig. 5). The total number of TCs (number of landfalling TCs) is proportional to the SOI; that is, there are fewer total TCs (landfalling TCs) when the SOI is most negative and vice versa.

In addition, a correlation between SOI values and the percentage of TCs that make landfall is also seen: as the SOI goes from negative to positive, the percentage of TCs that make landfall increases (Fig. 6). Following the trend line one sees that for the lowest quintile of SOI (moderate and strong El Niño ASO periods), an average of approximately 18% of TCs in the Atlantic basin make landfall during ASO, while for the top quintile of SOI (moderate and strong La Niña ASO periods), an average of 32% of TCs make landfall. It is important to recognize that the statistic "*percentage* landfalling storms" can skew the results, especially in situations when there are relatively few TCs (e.g., El Niño) compared to situations when there are more TCs (La Niña).

An analysis of eastern Pacific tropical cyclone activity (Fig. 7, left column) indicates that El Niño conditions (Fig. 7a) bring appreciably more precipitation farther north than La Niña conditions (Fig. 7b). A dramatic increase in TCP is noted in the southwestern

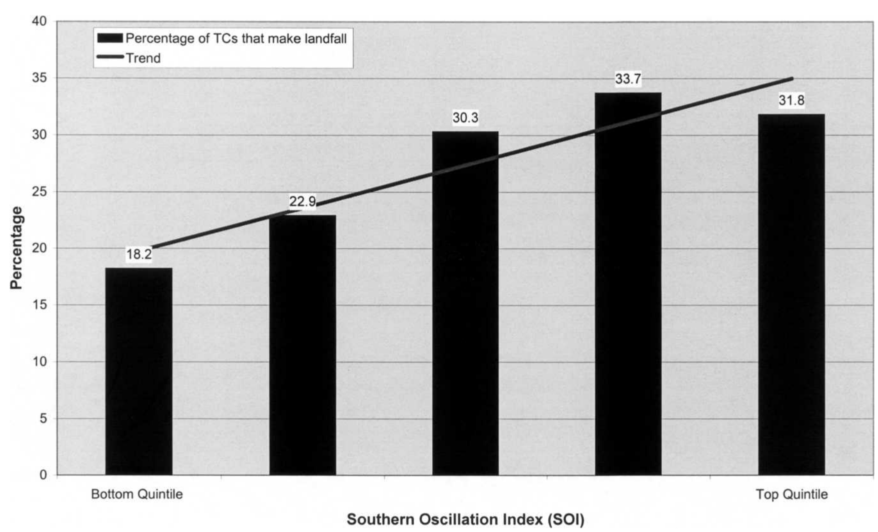

Fig. 6. As in Fig. 5 but for the percentage of TCs that make landfall.

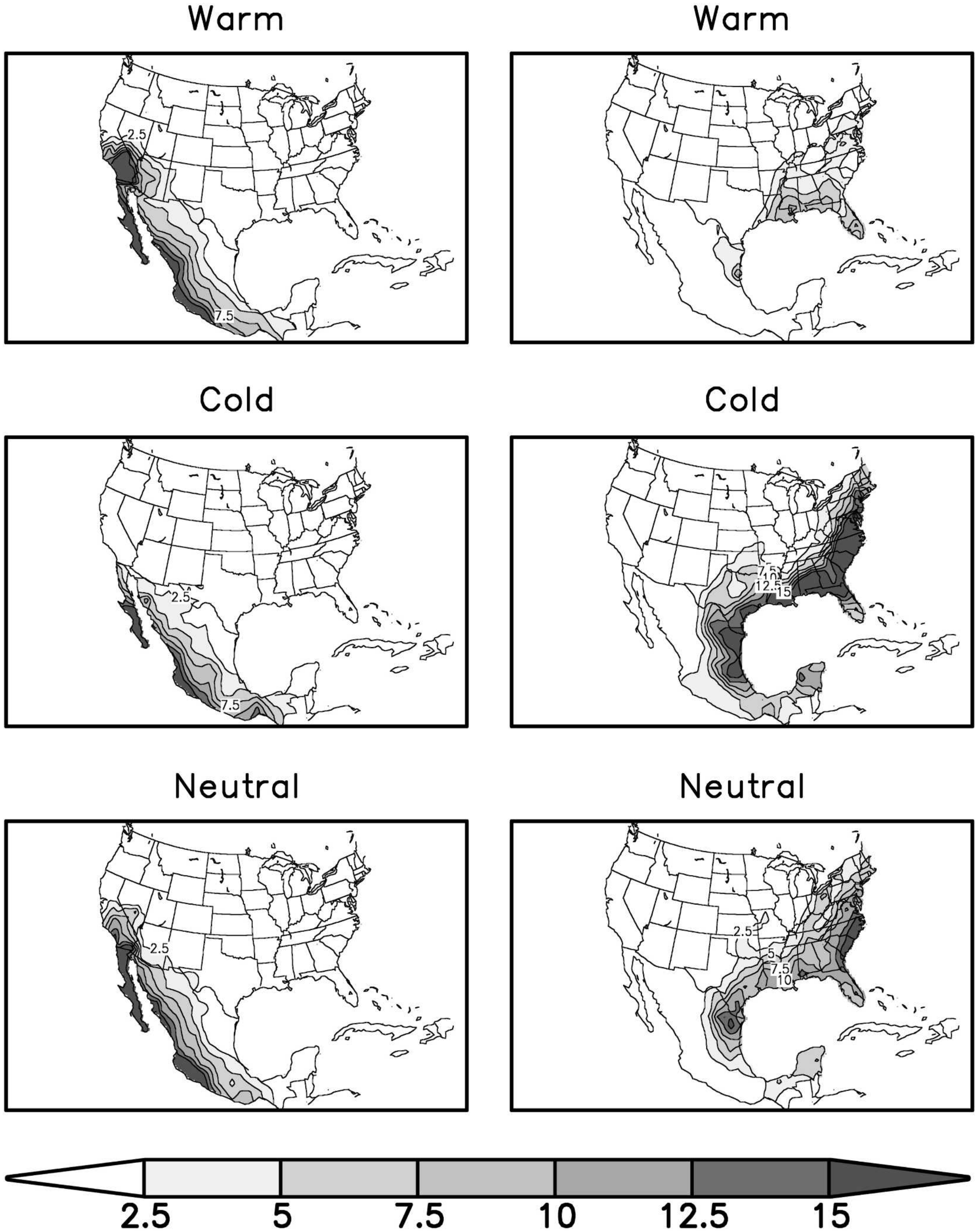

FIG. 7. Mean fraction (in percent) of total precipitation due to TCs by ENSO phase during the period Aug–Oct 1950–98 for landfalling storms along the West Coast [left column: (a) warm, (b) cold, and (c) neutral] and East Coast [right column: (d) warm, (e) cold, and (f) neutral].

United States during El Niño, especially the southern half of California, as well as parts of Nevada and much of New Mexico, compared to La Niña events. However, results in the southwestern United States should be interpreted with caution, as precipitation amounts are very low in this region independent of ENSO phase. Climatologically, 15% or more of the precipitation is TCP for much of the southern half of California during El Niño events. During La Niña episodes, TCP is limited to Mexico, while TCP in the southwestern United States is nonexistent. For ENSO-neutral conditions the TCP (Fig. 7e) is similar to El Niño conditions, with up to 10% of precipitation during ASO due to TCs as far north as central California and central Nevada.

TABLE 1. Statistics illustrating relationships between ENSO phase and the frequency and intensity of TC activity in the Atlantic basin. Results are based on ASO 1950–2001.

Average number of	El Niño (20 events)	Neutral (19 events)	La Niña (13 events)
TCs per ASO	6.9	8.42	9.3
Hurricanes per ASO	4.25	5.47	5.8
Landfalling TCs per ASO	1.34	2.32	2.87
Landfalling hurricanes per ASO	0.6	1.16	1.92

The mean number of tropical cyclones forming in the Atlantic basin during each ASO period between 1950 and 2001 is 8.1. Using the classification of El Niño and La Niña events discussed in section 2, we find that the mean number of TCs per ASO during La Niña is 9.3, while the mean number per ASO during El Niño is 6.9—a difference of 25%. During El Niño episodes, roughly 19% of all TCs that develop in the Atlantic basin (or Gulf of Mexico) make landfall in the United States (Table 1). This fraction increases to roughly 28% for ENSO-neutral conditions and to 31% for La Niña conditions; the difference between La Niña and El Niño is significant at the 90% confidence level, as determined by a Student's t test (with a null hypothesis of equal means). An analysis of Atlantic basin TC-related precipitation during ASO 1950–98 (Fig. 7, right column) shows a significant reduction in TCP, typically in the range of 5%–10% of total precipitation depending on the location, during El Niño (Fig. 7b) as compared to La Niña (Fig. 7d), typically in excess of 15% of total precipitation. TCP during ENSO-neutral conditions averages between that for El Niño and La Niña episodes at most locations (Fig. 7f).

It is well known that TC activity in the Atlantic basin is affected by ENSO through changes in the atmospheric circulation over the basin. During El Niño

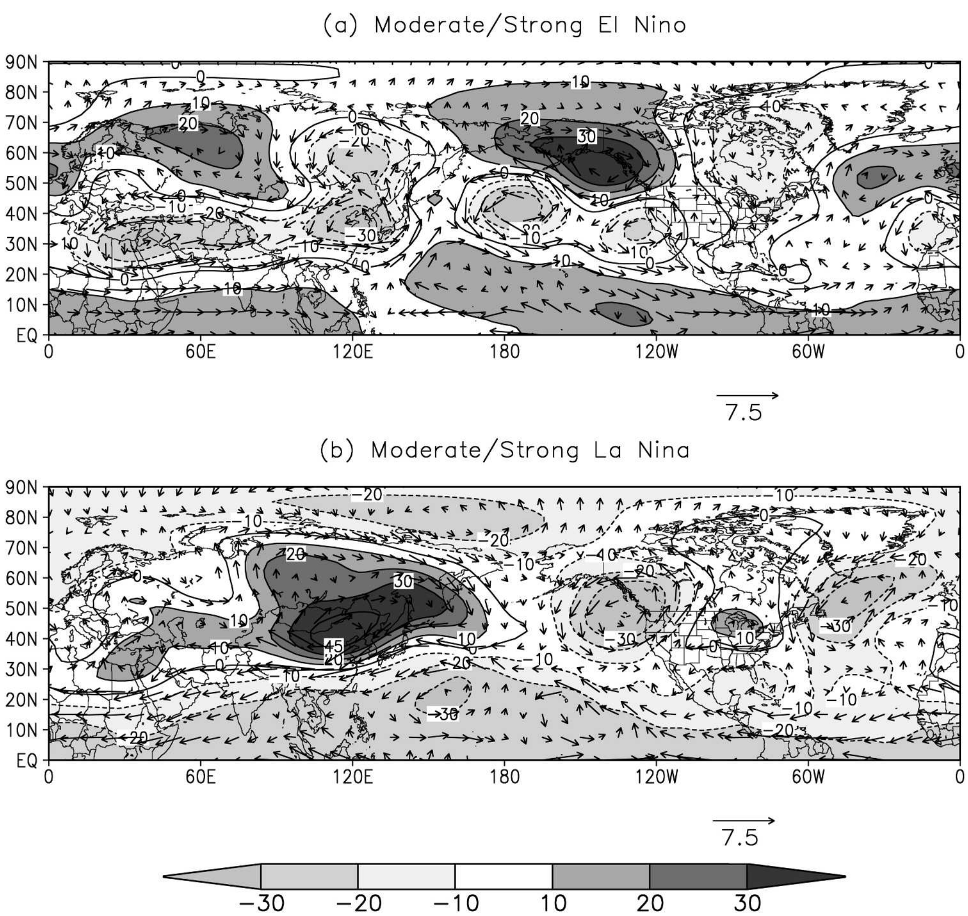

FIG. 8. Composites of seasonal mean 200-hPa geopotential height anomalies (m) and 200-hPa wind anomalies (m s^{-1}) for moderate to strong (a) El Niño and (b) La Niña episodes during ASO 1950–98.

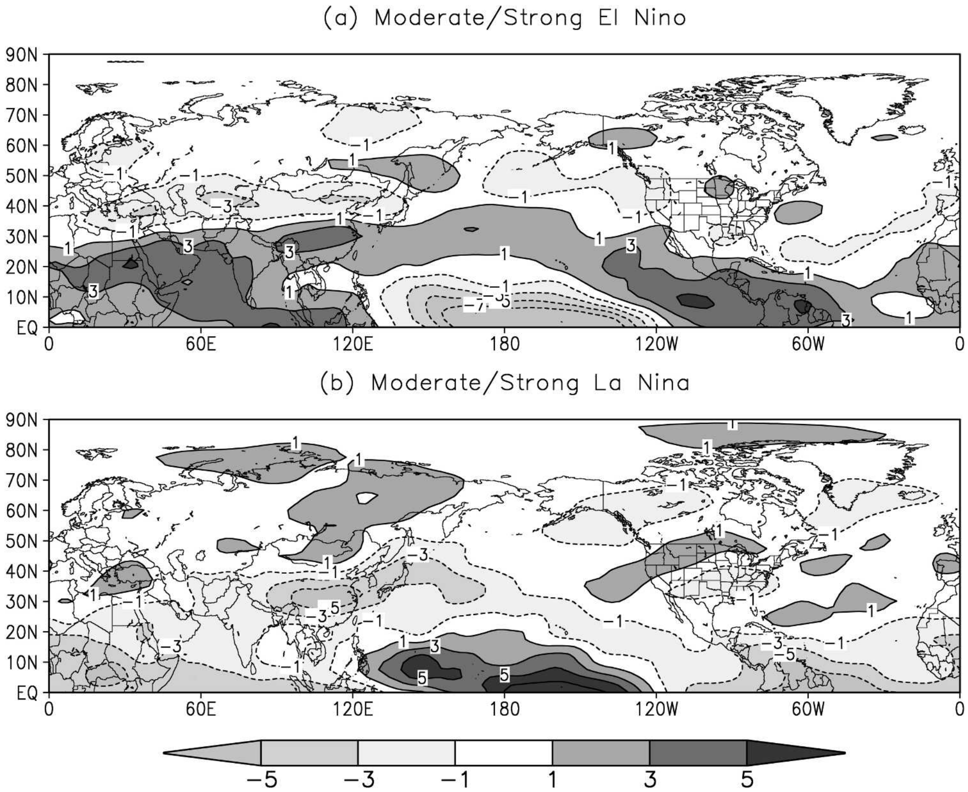

FIG. 9. As in Fig. 6 but for seasonal-mean wind shear anomalies (m s^{-1}) (difference in mean zonal wind anomalies between 200 and 850 hPa).

events, increased upper-level westerly winds lead to increased vertical wind shear and a resultant decrease in TC activity (Gray 1984; Shapiro 1987). During La Niña events, reduced upper-level westerlies and decreased vertical wind shear favor enhanced TC activity. Note, too, that ENSO also influences the number of U.S. landfalling TCs that develop over the Atlantic basin (e.g., Bove et al. 1998). It has been demonstrated that there is a three-to-one ratio in continental U.S. landfalling major hurricanes—those of category 3, 4, or 5 on the Saffir–Simpson scale—during non–El Niño years compared to El Niño years (Gray 1984). The relationship between ENSO phase and TC activity is supported by composites of seasonal mean 200-hPa geopotential height anomalies, 200-hPa wind anomalies (Fig. 8), and wind shear anomalies (Fig. 9) for moderate to strong El Niño (La Niña) episodes during ASO 1950–98. These composites show westerly (easterly) wind anomalies over the main development region of the Atlantic basin (roughly 10°–20°N, 20°–60°W) during El Niño (La Niña). In addition, they show positive vertical shear anomalies in the range from 1 to 3 m s^{-1} over much of the main development region during El Niño (due to enhanced westerlies aloft) and negative vertical shear anomalies in the range from –3 to –5 m s^{-1} over this same region for La Niña (due to suppressed westerlies aloft).

5. The Arctic Oscillation and Atlantic basin TC activity

The Arctic Oscillation is marked by opposing fluctuations in surface pressure over the polar cap region (60°–90°N) and midlatitudes (30°–60°N), together with opposing fluctuations in the strength of tropospheric westerlies at subpolar (near 60°N) and subtropical (near 30°N) latitudes (Thompson and Wallace 2000). We note that the North Atlantic Oscillation (NAO) correlates strongly with the AO and may be viewed as the projection of the AO into the North Atlantic sector throughout the annual cycle (e.g., Higgins et al. 2000a). Thompson and Wallace (2000) showed that the AO has far-reaching effects on winter weather over the United States, Europe, and Asia. They also noted that the AO accounts for a significant portion of the total variance of the atmospheric circulation during portions of the warm season. To date, however, there has been relatively little study of the effects of the AO on summer weather (e.g., Thompson et al. 2000).

The positive phase of the AO is characterized by below-normal heights over northern North America and Greenland, above-normal heights over Europe, and a strengthening of the Hudson Bay low over high latitudes; over the eastern United States there is a weakening of the Hudson Bay low, along with en-

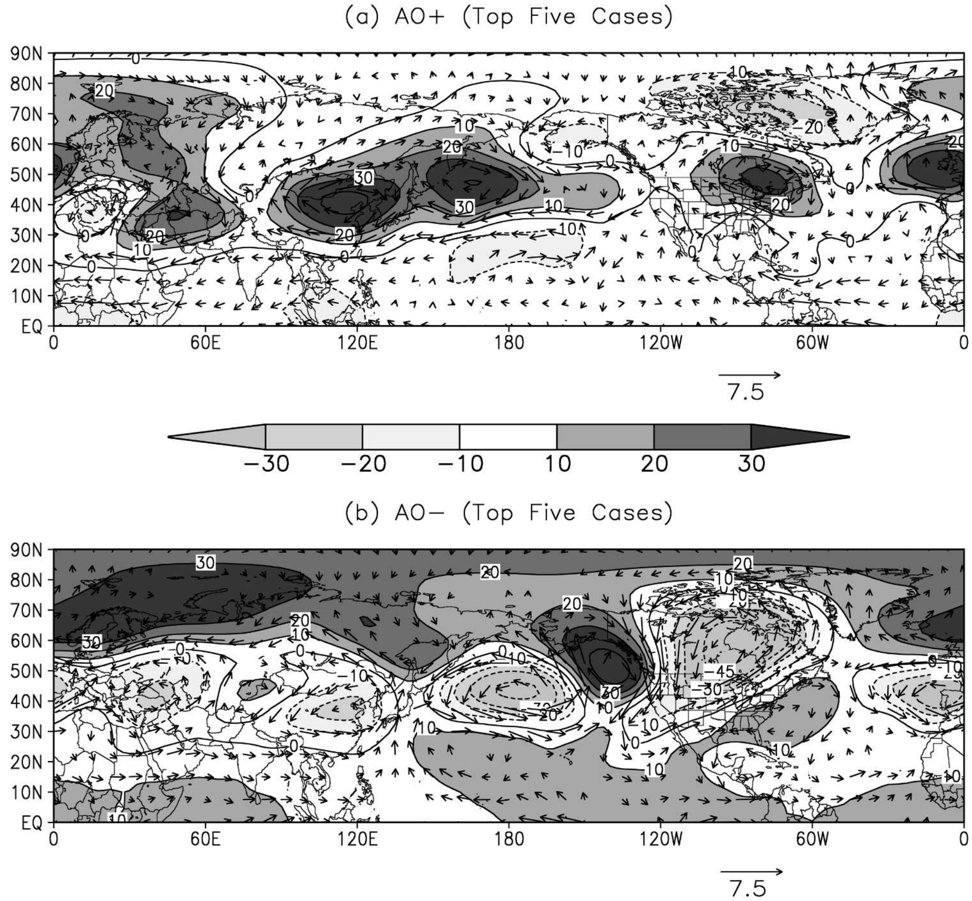

Fig. 10. Composites of seasonal mean 200-hPa geopotential height anomalies (m) and 200-hPa wind anomalies (m s^{-1}) for (a) the five strongest AO-positive ASO seasons (1951, 1987, 1972, 1993, and 1959) and (b) the five strongest AO-negative ASO seasons (1989, 1955, 1978, 1953, and 1961). Results are based on ASO 1950–2001.

hanced subtropical ridging over the southeast. These features are visible in the composites of seasonal-mean wind shear anomalies, computed as the difference in mean zonal wind anomalies between 200 and 850 hPa (Fig. 11a). Enhanced ridging in this region is associated with a strengthening and westward extension of the mean Bermuda high over the western Atlantic and southeast United States as well as a northeastward shift of the Bermuda high over the eastern North Atlantic. Over Africa and Asia we note a large-scale pattern of above-normal heights associated with upper-level easterly wind anomalies extending from the central North

Table 2. Top 10 most active ASO periods based on the number of observed TCs. (Top 7 phases in boldface).

Most active ASO periods; ranking	No. of TCs	AO conditions
1995 (1)	16	**AO positive**
2000 (2)	15	**AO positive**
1969 (3)	14	AO negative
1990 (=4)	13	AO neutral
1950 (=4)	13	AO-negative
2001 (=6)	12	**AO positive**
1998 (=6)	12	**AO positive**
1955 (=6)	12	**AO positive**
1988 (=9)	11	**AO positive**
1971 (=9)	11	**AO positive**

Table 3. Top 10 least active ASO periods based on the number of observed TCs. (Top 7 phases in boldface).

Least active ASO periods; ranking	No. of TCs	AO Conditions
1986 (=1)	3	**AO negative**
1997 (=1)	3	**AO negative**
1972 (=3)	4	**AO negative**
1960 (=3)	4	**AO negative**
1994 (=3)	4	AO positive
1983 (=3)	4	AO positive
1982 (=3)	4	AO positive
1966 (=8)	5	**AO negative**
1968 (=8)	5	**AO negative**
1962 (=5)	5	**AO negative**

TABLE 4. Statistics illustrating relationships between AO phase and the frequency and intensity of TC activity in the Atlantic basin, 17 events in each tercile. Results are based on ASO 1950–2000.

Average number of	AO negative (bottom tercile)	AO neutral (middle tercile)	AO positive (top tercile)
TCs per ASO	7.18	7.53	9.24
hurricanes per ASO	4.82	4.94	5.47
landfalling TCs per ASO	1.82	1.76	2.94

Pacific (vicinity of the date line) westward across central Africa (Fig. 10a). Over Africa this anomaly pattern reflects an amplified tropical easterly jet (TEJ), which is a well-known feature of active hurricane seasons.

The negative phase of the AO features generally opposite circulation anomalies in these main areas. Key aspects of this phase include upper-level westerly wind anomalies over the eastern half of the United States, a reduced overall strength of the TEJ, and an overall southward shift and weakening of the mean Bermuda high (Fig. 10b).

We find that the AO has a strong relationship with TC activity in the Atlantic basin. For example, 7 of the 10 most active ASO periods during 1950–2001 featured the positive phase of the AO (Table 2). Those seven years averaged 13 TCs per ASO season compared to the long-term average of 8.1. Conversely, 7 of the 10 least active ASO periods during 1950–2001 featured the negative phase of the AO and averaged four TCs per ASO season (Table 3). If seasonal values of the AO time series are ranked and the top, middle, and bottom tercile of the distribution is used to define the AO-positive, AO-neutral, and AO-negative years, respectively, we find that there is an average of 9.2 TCs per ASO season during the AO-positive years and 7.2 TCs per ASO season during AO-negative years (Table 4). In addition, an average of 4.8 hurricanes develop per ASO season during AO-negative conditions, whereas an average of nearly 5.5 hurricanes develop per ASO season during AO-positive conditions—some 15% more. Finally, AO-negative ASO periods average 1.8 landfalling TCs, whereas AO-positive ASO periods av-

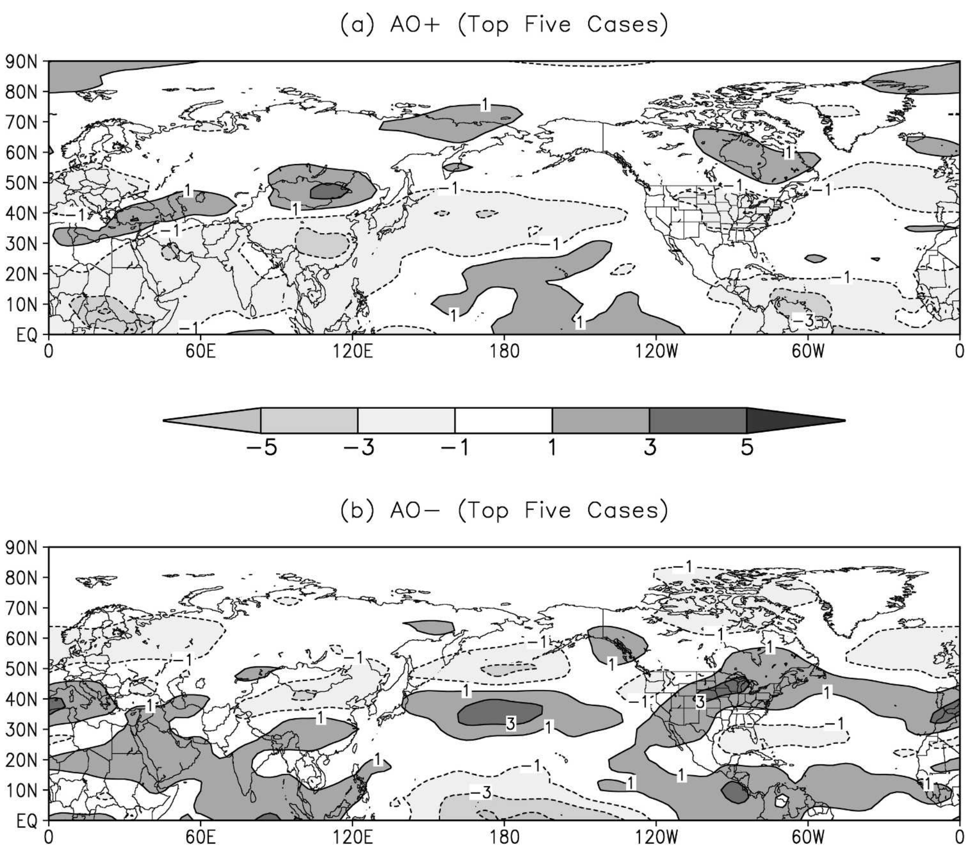

FIG. 11. As in Fig. 10 but for seasonal-mean zonal wind shear anomalies (m s^{-1};) (difference in mean zonal wind anomalies between 200 and 850 hPa).

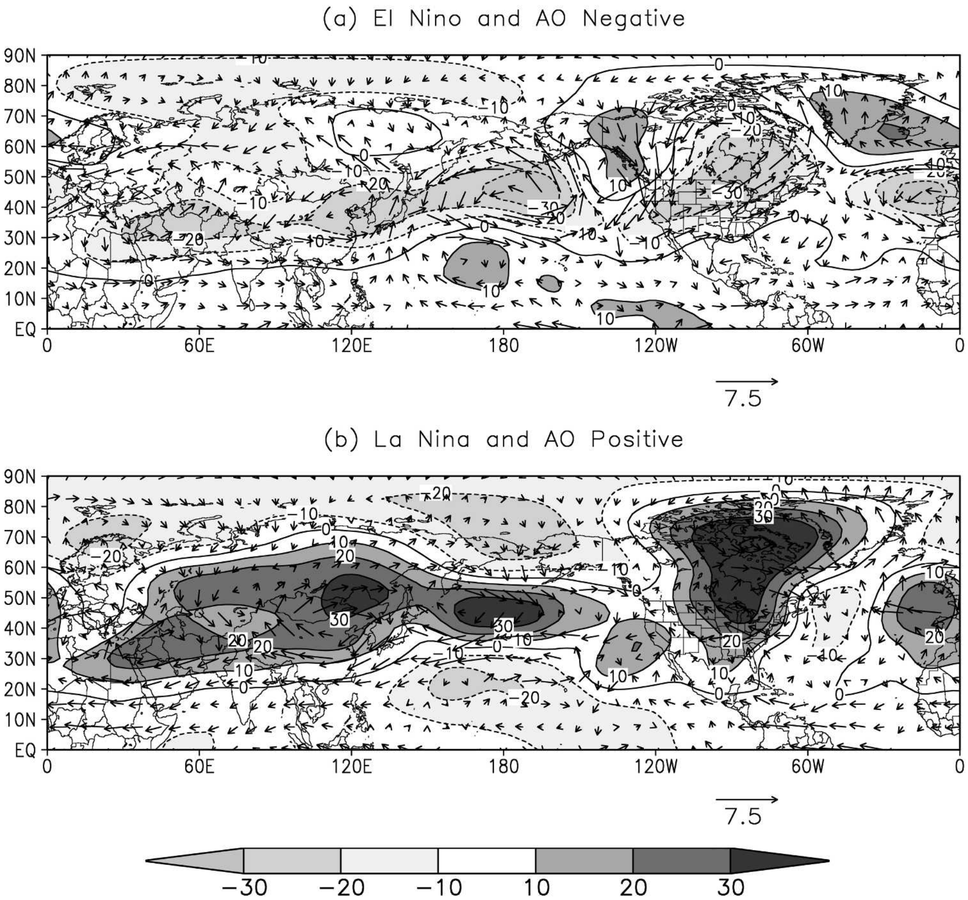

FIG. 12. Composites of seasonal mean 200-hPa geopotential height anomalies (m) and 200-hPa wind anomalies (m s^{-1}) for (a) El Niño and AO-negative ASO seasons (1951, 1966, 1968, 1969, 1972, 1976, 1986, 1987, 1993) and (b) La Niña and AO-positive ASO seasons (1954, 1955, 1970, 1971, 1973, 1988, 1998). Results are based on ASO 1950–98.

erage 2.9 such storms—some 60% more. We note that the composite means for AO-negative and AO-positive ASO periods are significantly different from each other at the 95% level (based on a Student's *t* test) for both average number of TCs and average number of landfalling TCs (Table 4) and that the correlation between seasonal values of the AO and the number of TCs during ASO 1950–2000 is $r = 0.40$, which is significant at the 99.5% confidence level as determined by a *t* test. Lagged correlations are not statistically significant, indicating that spring values of the AO index are not a reliable predictor of summer TC activity.

The association between AO-positive conditions and enhanced TC activity in the Atlantic basin may be due to enhanced midlatitude ridging across the North Atlantic and easterly upper-level wind anomalies in the Tropics (Fig. 10a). These conditions are associated with reduced westerly wind shear (Fig. 11a), which is more conducive to TC development. The association between AO-negative conditions and suppressed TC activity in the Atlantic basin may be due to enhanced troughing in midlatitudes and westerly zonal wind anomalies in the Tropics (Fig. 10b). These conditions favor enhanced westerly wind shear (Fig. 11b) over the main development region (between 5° and 15°N). Thus, the direction of the wind flow aloft and the associated wind shear over the main development region (MDR) are two major factors that help explain the AO–TC relationship.

6. Combined effects of ENSO and the AO

From previous analysis, both La Niña and the positive phase of the AO are associated with atmospheric conditions known to favor increased Atlantic hurricane activity and the likelihood of U.S. hurricane landfall. Conversely, both El Niño and the negative phase of the AO are associated with atmospheric conditions that tend to suppress TC activity. Composite circulations for La Niña/AO-positive conditions show expansive upper-level ridging across eastern North America and easterly wind anomalies across most of North America (Fig. 12b). They also show an expanded upper-level ridge across Europe and northern Africa. These conditions

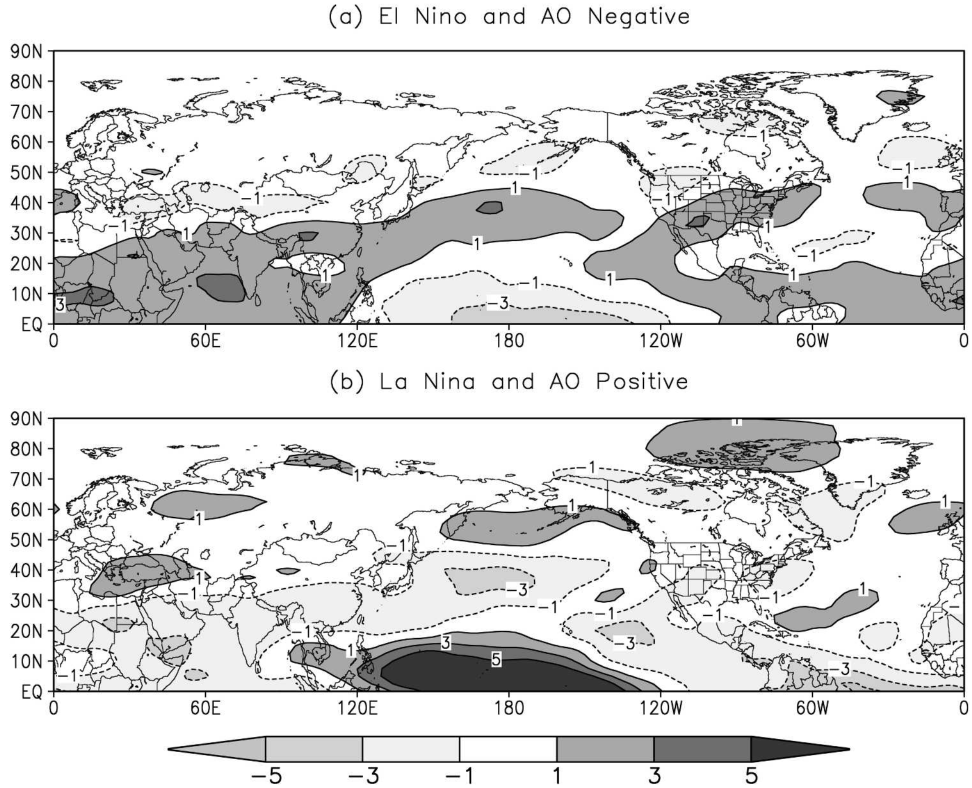

FIG. 13. As in Fig. 12 but for seasonal-mean zonal wind shear anomalies (m s^{-1}; difference in mean zonal wind anomalies between 200 and 850 hPa).

are associated with an enhanced TEJ and below-average vertical wind shear across the heart of the main development region (Fig. 13b).

While the AO index used here is a seasonal one, it is well known that the AO concentrates much of its variance on subseasonal time scales. This implies that there will be periods during a particular season that are favorable (unfavorable) for TC development depending in part on the phase of the AO. During La Niña conditions, atmospheric circulation is more conducive to activity in the MDR during AO-positive conditions than during AO-negative ones. Similarly, for El Niño conditions, atmospheric circulation appears even less conducive to hurricane development during AO-negative conditions than during AO-positive ones. These statistics are further supported in Table 5. Note that, during ENSO-neutral and AO-negative ASO periods, an average of only 6.7 TCs develop whereas, during ENSO-neutral and AO-positive ASO periods, an average of 10.3 TCs develop as compared to the long-term average of 8.0.

Composites of seasonal mean 200-hPa geopotential height anomalies for ENSO-warm years coupled with AO-negative conditions (Fig. 12a) and ENSO-cold years coupled with AO-positive conditions (Fig. 12b), as well as seasonal mean wind shear anomalies for these same two combinations (Fig. 13), once again show very clearly the specific conditions that favor TC activity as discussed in the previous composites. These composites are consistent with the earlier ones in Figs. 8–9 and Figs. 10–11, though it is difficult to say which mode of variability might be dominating the composites in Figs. 12 and 13; further analysis similar to that in Goldenberg and Shapiro (1996) is necessary.

7. Summary

Geographic maps of total tropical cyclone strike days, and the mean and maximum percentage of precipitation due to TCs, were examined by month. Depending on the location and the month, it was found that (in the mean) up to 15% (20%) of summer precipitation along the U.S. Gulf Coast (Mexican coast)

TABLE 5. Average number of TCs in the Atlantic basin per ASO for combinations of ENSO and AO phase. Results are based on ASO 1950–2000. The 1950–2000 mean number of TCs during ASO is also given for reference.

ENSO and AO phases	Average number of TCs per ASO
ENSO neutral and AO negative	6.73
1950–2000 mean	7.98
ENSO neutral and AO positive	10.30

was due to landfalling TCs. It is important to note that there is some uncertainty in the results due to the assumption of a symmetric precipitation shield about the TC center. However, sensitivity tests showed that our choice of a 5° radius captured the vast majority of TC-related precipitation. Choice of a particular radius is necessary to make the procedure objective.

Our study shows that El Niño–Southern Oscillation (ENSO) has a direct effect not only on the number of tropical cyclones that develop during a given hurricane season, but also on the number of TCs that make landfall (as well as on the amount and fraction of precipitation directly attributable to TCs). La Niña events typically lead to an average 15% increase in the number of TCs that develop in the Atlantic basin, whereas El Niño events typically lead to an average 10% reduction in the number of TCs. There is a statistically significant correlation, of $r = 0.35$ at the 99% confidence level, between the Tahiti–Darwin SOI and the number of TCs that develop during ASO. During El Niño events only 20% of all TCs make landfall in the Atlantic basin during ASO, whereas during La Niña events nearly one-third of all TCs make landfall. The decrease (increase) in the number of landfalling TCs during El Niño (La Niña) is consistent with increased (decreased) westerly wind in the upper troposphere, increased (decreased) vertical wind shear, and decreased (increased) overall TC activity.

The Arctic Oscillation has a more significant correlation to TC activity ($r = 0.4$, statistically significant at the 99% level) than ENSO. Seven of the 10 most active TC seasons during ASO 1950–2001 featured the positive phase of the AO; conversely, 7 of the 10 least active TC seasons featured the negative phase of the AO. Our data show that, on average, AO-positive seasons have a nearly 15% increase in the number of TCs that develop compared to normal, while AO-negative seasons on average have a nearly 10% reduction in the number of TCs that develop. The association between AO-positive conditions and enhanced TC activity in the Atlantic basin may be due to enhanced midlatitude ridging across the North Atlantic and easterly wind anomalies in the Tropics: These conditions favor reduced westerly wind shear, which is inherently conducive to TC development. The opposite appears to be true during most AO-negative ASO periods, leading to a reduction in the number of TCs that develop. While both ENSO and AO are largely independent of each other (e.g., Higgins et al. 2000a), they show strong relationships to TC activity in the Atlantic basin during ASO; the combined effects of the two modes are even more notable. There is a 35% difference between TC frequency during El Niño events coupled with AO-negative conditions compared to La Niña events coupled with AO-positive conditions. Several improvements to the current analysis are envisioned. Daily AO data would allow us to resolve the subseasonal flips in the Arctic Oscillation. This would allow us to relate the AO to individual TCs more directly and might reveal a more significant correlation. In addition, analyzing landfalling TC activity with respect to the phase of the Madden–Julian oscillation (MJO) might produce interesting results. Finally, future studies should aim to determine which mode of climate variability—ENSO or AO—dominates during La Niña/AO-positive or El Niño/AO-negative periods. Wind anomalies and wind shear anomalies are similar during El Niño and AO-negative periods and during La Niña and AO-positive periods over the MDR, so it is difficult to attribute atmospheric effects to a particular mode.

Acknowledgments. We gratefully acknowledge Dr. Wei Shi of the Climate Prediction Center for help in accessing the precipitation data used in this study. We also thank Drs. Gerry Bell, Vernon Kousky, and Hyun-Kyung Kim for input and guidance on preliminary versions of the manuscript. In addition, we thank two anonymous reviewers, who provided numerous helpful suggestions that considerably improved the quality of the manuscript.

REFERENCES

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

Chu, P. S., 2004: ENSO and tropical cyclone activity. *Hurricanes and Typhoons: Past, Present, and Potential*, R. J. Murnane and K. B. Liu, Eds., Columbia University Press, 297–332.

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

Douglas, A. V., and P. J. Englehart, 2001: The role of eastern North Pacific tropical storms in the rainfall climatology of western Mexico. *Int. J. Climatol.,* **21,** 1357–1370.

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.

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.

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

——, J. D. Sheaffer, and C. W. Landsea, 1997*: Hurricanes: Climate and Socioeconomic Impacts.* Springer, 292 pp.

Herbert, P., and G. Taylor, 1979: Everything you always wanted to know about hurricanes. *Weatherwise,* **32,** 61–67.

Higgins, R. W., and W. Shi, 2001: Intercomparison of the principal modes of interannual and intraseasonal variability of the North American monsoon system. *J. Climate,* **14,** 403–417.

——, A. Leetmaa, Y. Xue, and A. Barnston, 2000a: Dominant factors influencing the seasonal predictability of U.S. precipitation and surface air temperature. *J. Climate,* **13,** 3994–4017.

——, W. Shi, E. Yarosh, and R. Joyce, 2000b: *Improved United States Precipitation Quality Control System and Analysis*. NCEP/Climate Prediction Center Atlas 7, 40 pp. [Available online at http://www.cpc.ncep.noaa.gov/research_papers/ncep_cpc_atlas/7/index.html.]

Kimberlain, T. B., 1999: The effects of ENSO on North Pacific and North Atlantic tropical cyclone activity. Preprints, *23d Conf. on Hurricanes and Tropical Meteorology*, Dallas, TX, Amer. Meteor. Soc., 250–253.

Klotzbach, P. J., and W. M. Gray, 2003: Forecasting September Atlantic basin tropical cyclone activity. *Wea. Forecasting,* **18,** 1109–1128.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.,* **121,** 1703–1713.

Maloney, E. D., and D. L. Hartmann, 2000: Modulation of hurricane activity in the Gulf of Mexico by the Madden–Julian Oscillation. *Science,* **287,** 2002–2004.

Neumann, C. J., B. R. Jarvinen, C. J. McAdie, and G. R. Hammer, 1999: *Tropical Cyclones of the North Atlantic Ocean, 1871–1998*. National Climatic Data Center, 256 pp.

Ropelewski, C. F., and M. S. Halpert, 1986: North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Mon. Wea. Rev.,* **114,** 2352–2362.

Shapiro, L. J., 1987: Month-to-month variability of the Atlantic tropical circulation and its relationship to tropical storm formation. *Mon. Wea. Rev.,* **115,** 2598–2614.

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

——, J. M. Wallace, and G. C. Hegerl, 2000: Annular modes in the extratropical circulation. Part II: Trends. *J. Climate,* **13,** 1018–1036.