The 2006 North Atlantic Hurricane Season
A Climate Perspective

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1. Overview

The 2006 Atlantic hurricane season produced ten tropical storms (TS), five hurricanes (H) and two major hurricanes (MH) [categories 3-5 on the Saffir-Simpson scale (Simpson (1974)] (Fig. 1). These values are slightly below the 1950-2000 averages of 11 TS, 6 H, and 2.5 MH. Only three Atlantic tropical storms, Alberto, Beryl, and Ernesto, struck the continental U.S. during 2006. This was the first year since 2001 that no hurricanes struck the continental United States.

A widely-used measure of seasonal activity is the National Oceanic and Atmospheric Administration's (NOAA's) Accumulated Cyclone Energy (ACE) index (Bell et al. 2000). The ACE index accounts for the combined strength and duration of tropical cyclones (TC) during the season. The 2006 ACE index was 90% of the 1950-2000 median value (87.5 x 10^4 kt^2),

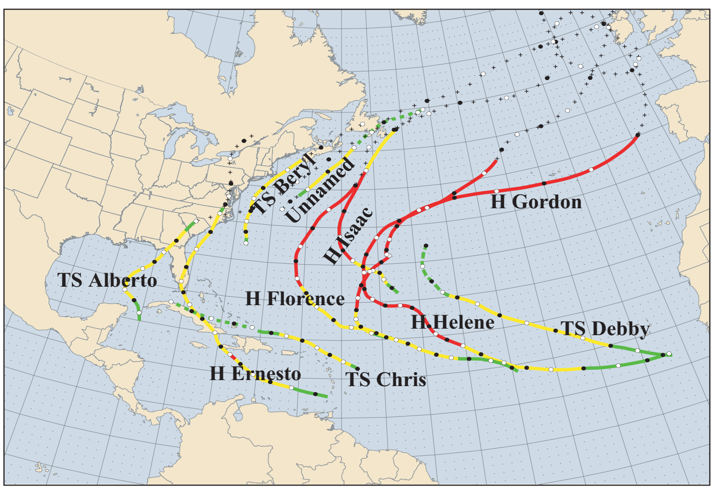

Fig. 1. Atlantic tropical storm and hurricane tracks during 2006. Shading indicates strength, with green indicating tropical depression intensity, yellow indicating tropical storm intensity, and red indicating hurricane intensity.

indicating a near-normal season (Fig. 2). However, this value is well below the previous three seasons which averaged 247% (Bell et al. 2005), and less than one-third of the record high (284%) seen in 2005 (Bell et al. 2006).

The regional atmospheric and oceanic anomalies during the climatological peak months (August-October, ASO) of the 2006 hurricane season are shown schematically in Fig. 3. To the first order, the reduced activity reflected the competing influences of two dominant climate factors. The first dominant factor is El Niño, which suppressed activity mainly during September and October through anomalous upper-level convergence and sinking motion across the Caribbean Sea (Fig. 4). Anomalous circulation features not related to El Niño accentuated this

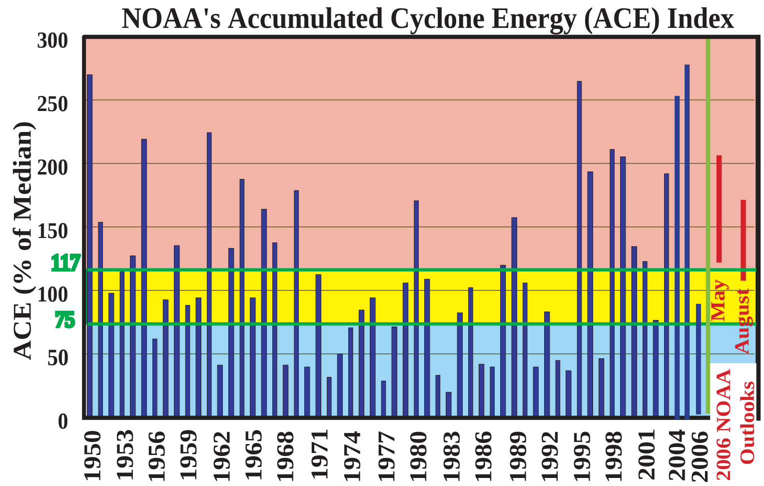

Fig. 2. NOAA's Accumulated Cyclone Energy (ACE) index expressed as percent of the 1951-2000 median value (87.5 x 10^4 kt^2). ACE is a wind energy index, and is calculated by summing the squares of the 6-hourly maximum sustained wind speed in knots ($Vmax^2$) for all periods while the system is a tropical storm, subtropical storm, or hurricane. Season types are indicated by the background shading, with pink, yellow, and blue indicating NOAA's classifications for above-, near-, and below-normal seasons, respectively.

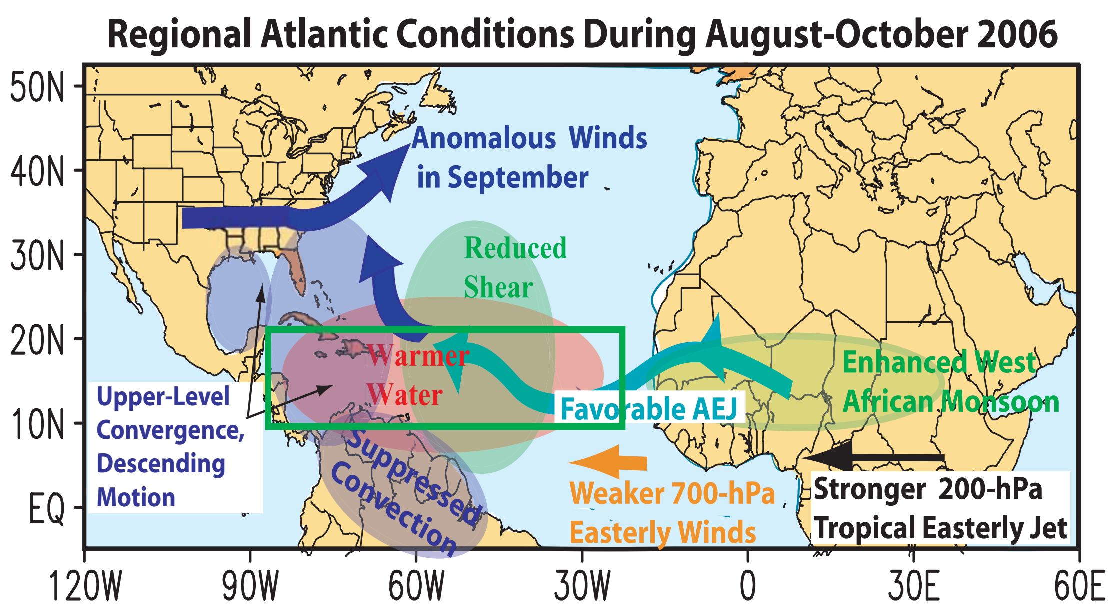

Fig. 3. Schematic of conditions during August-October 2006. The near-normal season mainly reflected the competing influence of El Niño and the ongoing conditions associated with the current active hurricane era that began in 1995. El Niño contributed to anomalous upper-level convergence and anomalous sinking motion over the Caribbean Sea. The active hurricane era conditions again prevailed across the central and eastern tropical Atlantic, the West African monsoon region, and the Amazon Basin.

signal at times, and also contributed to the reduced activity. The second dominant climate factor is the set of ongoing oceanic and atmospheric conditions over the eastern half of the tropical Atlantic, western Africa, and the Amazon Basin. These conditions have been conducive to above normal hurricane seasons since 1995, and they were again very pronounced during 2006.

2. Dominant climate patterns

a. El Niño

El Niño's suppressing influence on Atlantic hurricane activity is well documented (Gray 1984, Tang and Neelin 2004, Bell and Chelliah 2006), and is clearly evident during the current active hurricane era that began in 1995. During 1995-2006, nine of twelve hurricane seasons are in the above normal tercile, which is defined as ACE larger than 117% of the median. The three exceptions are all El Niño years (1997, 2002, and 2006).

During 2006, there were no late-season (Oct-Nov) tropical cyclones (TC), resulting in the third earliest end (following 1983 and 1993) to seasonal activity since routine daily satellite coverage began in 1966. Historically, El Niño suppresses the late season activity over the Caribbean Sea and western tropical Atlantic Ocean. This impact is especially significant during active hurricane eras (Fig. 5), when the mean Oct-Nov ACE index for El Niño years is almost five times less than for non-El Niño years. In the absence of El Niño, an active era features an average of one hurricane per season during Oct-Nov., and roughly one MH every other season. During El Niño, these averages drop to one short-lived hurricane every three seasons, and no MH. In contrast, during inactive hurricane eras, conditions are normally so unfavorable during Oct-Nov that neither El Niño nor La Niña has a strong impact on late season activity. For example, there has never been a late-season

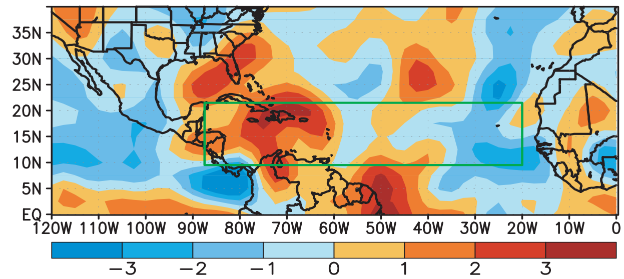

Fig. 4. August-October 2006: Anomalous 300-hPa vertical motion (x 10^{-2} Pa s^{-1}). Anomalous sinking motion is indicated by positive (red shading) values, and anomalous ascending motion is indicated by blue shading. Green box denotes the Main Development Region. Anomalies are departures from the 1971-2000 period monthly means.

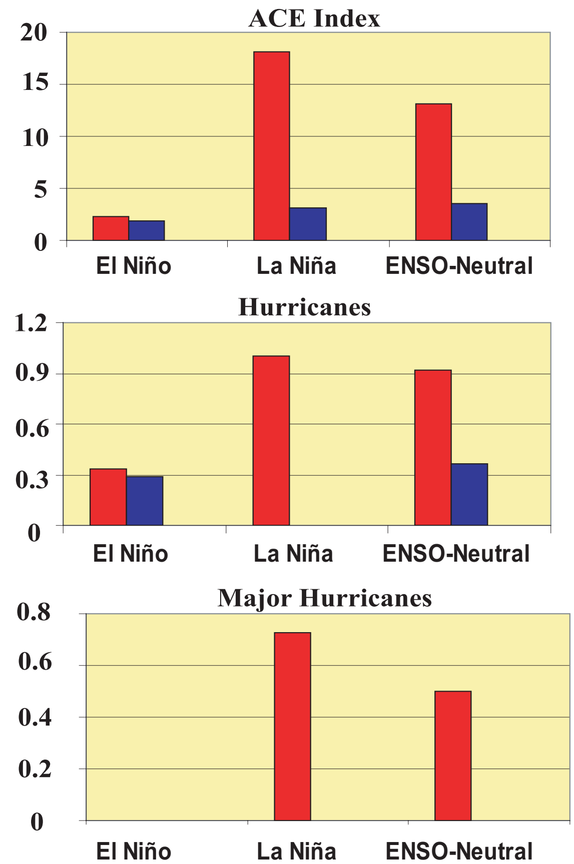

Fig. 5. October-November mean tropical cyclone (TC) activity forming over the Caribbean Sea as a function of active/ inactive hurricane era and ENSO: a) the ACE index, b) hurricanes, and c) major hurricanes. The active era means (red) are based on the periods 1951-1970 and 1995-2005. The inactive era means (blue) are based on the years 1971-1994.

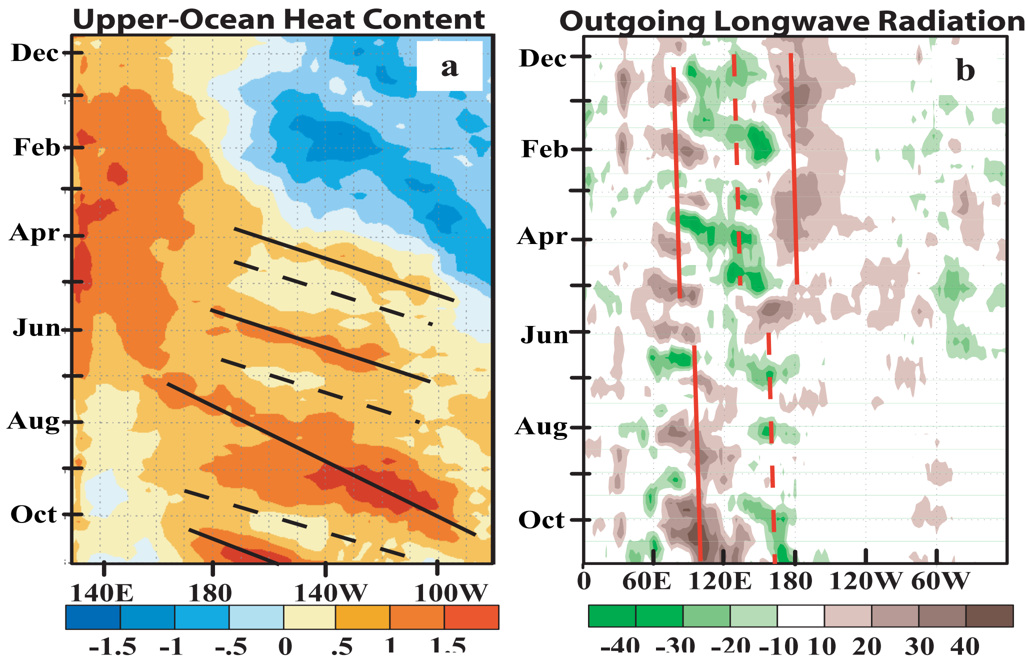

Fig. 6. Time-longitude sections calculated between 5°N-5°S of anomalous (a) upper-ocean heat content (°C) and (b) Outgoing Longwave Radiation (OLR, W m^2). In (a) dashed and solid black lines indicate the warm and cool phases of equatorial oceanic Kelvin Waves, respectively. Heat content anomalies are departures from the 1982-2004 pentad means, and OLR anomalies are departures from the 1979-2000 pentad means.

MH form in the Caribbean Sea during an inactive hurricane era, regardless of El Niño or La Niña.

A time-longitude section of upper-ocean heat content illustrates the rapid development of El Niño during the 2006 Atlantic hurricane season (Fig. 6a). Before the season began, anomalously cold temperatures had disappeared from the central equatorial Pacific. By June a series of Kelvin waves began contributing to a progressive warming in the central and east-central equatorial Pacific. A particularly strong equatorial Kelvin wave during September led to additional significant warming and the development of El Niño. During this period, there was a sharp transition in the distribution of anomalous convection across the equatorial Pacific (Fig. 6b), with the El Niño-like pattern of suppressed convection over the

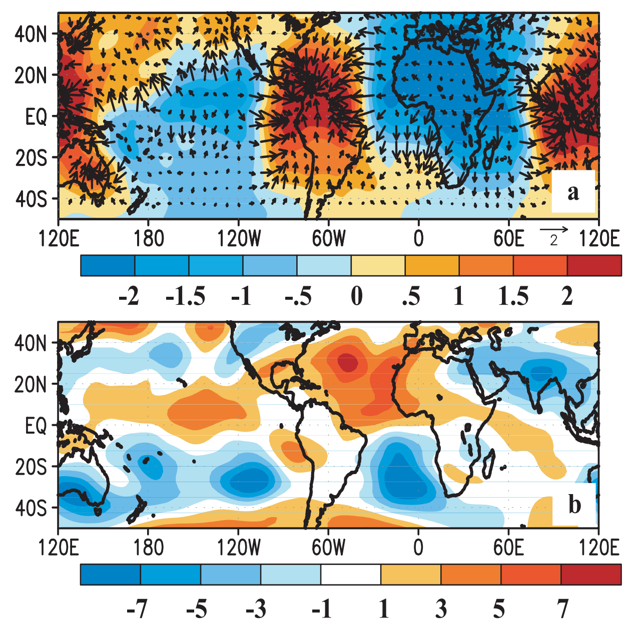

Fig. 7. August – October 2006: (a) Anomalous 200-hpa velocity potential (x 10^6 m^2 s^{-1}) and divergent wind vectors (m s^{-1}), and (b) Anomalous 200-hpa streamfunction (contour interval is 2 x 10^6 m^2 s^{-1}). In (b), anomalous ridges are indicated by positive values (red) in the NH and negative values (blue) in the SH. Anomalous troughs are indicated by negative values in the NH and positive values in the SH. Anomalies are departures from the 1971-2000 period monthly means.

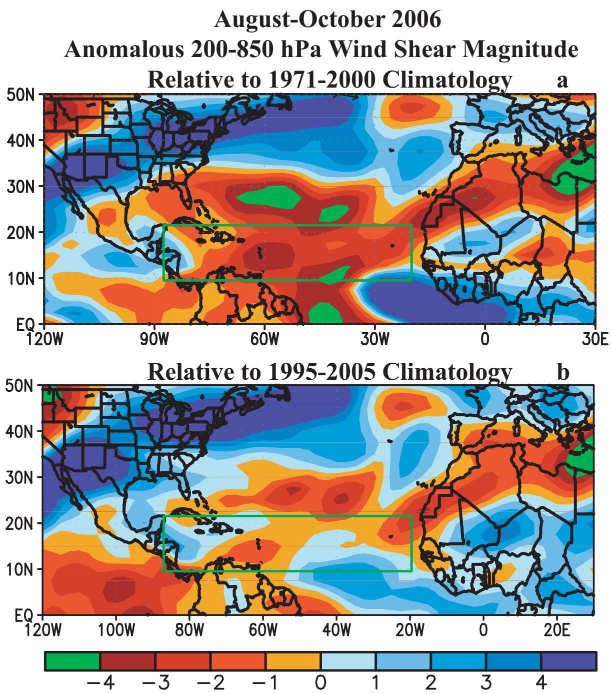

Fig. 8. August-October 2006: Anomalous strength of the total 200-850 hPa vertical wind shear, calculated with respect to (a) the 1971-2000 and (b) the 1995-2005, period monthly means. Red shading indicates below-average strength of the vertical shear. Green box denotes the Main Development Region.

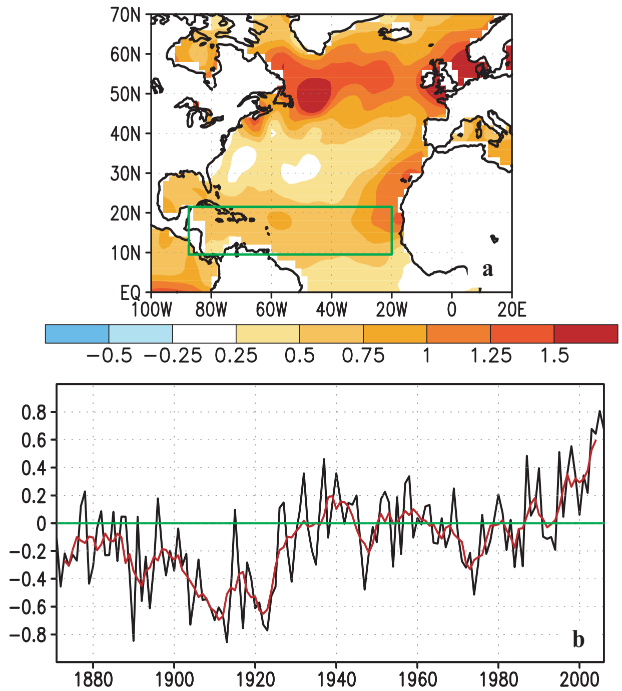

Fig. 9. (a) Sea-surface temperature (SST) anomalies (°C) during August-October 2006, and (b) Time series of area-averaged SST anomalies for the Main Development Region [green boxed region shown in (a)]. Red line in (b) shows the corresponding 5-yr running mean. Anomalies are departures from the 1971-2000 period monthly means.

western Pacific and enhanced convection near the date line beginning to establish itself during July.

The large-scale El Niño signal during ASO 2006 is evident in the patterns of anomalous 200-hPa velocity potential (Fig. 7a) and streamfunction (Fig. 7b). In the tropics velocity potential anomalies are related to the upper-level divergent circulation and anomalous convection. Negative velocity potential anomalies across the central and east-central equatorial Pacific reflect the El Niño-related enhanced convection and anomalous upper-level divergence. Positive values over both the western Pacific/ Indonesia region and the Caribbean Sea reflect compensating anomalous upper-level convergence and suppressed convection. Another characteristic El Niño signature is anomalous upper-level ridges (positive streamfunction anomalies in NH, negative in SH) in the subtropics of both hemispheres flanking the region of enhanced convection over the central equatorial Pacific. However, this feature was not evident until October.

El Niño's typical impacts over the western tropical Atlantic Ocean and Caribbean Sea include increased vertical wind shear between 200-850-hPa and anomalous sinking motion in the middle and upper atmosphere. During ASO 2006 El Niño appears to have suppressed TC activity mainly by contributing to anomalous upper-level convergence and sinking motion across the Caribbean Sea. This suppressing influence was particularly notable during September and October, when only one TC developed over the Caribbean Sea despite low wind shear (< 8 m s^{-1}) (Fig. 8a) and a continuation of anomalously warm sea-surface temperatures (SSTs, Fig. 9). During September these same conditions, but with no anomalous sinking motion, led to the formation of several hurricanes and major hurricanes over the central and eastern tropical Atlantic Ocean.

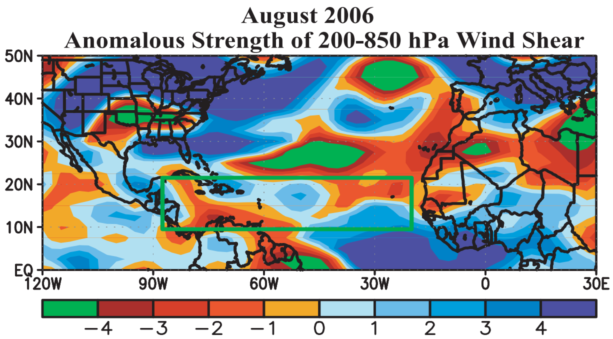

Fig. 10. August 2006: Anomalous strength of the total 200-850 hPa vertical wind shear (m s^{-1}) Green box denotes the Main Development Region. Anomalies are departures from the 1971-2000 period monthly means.

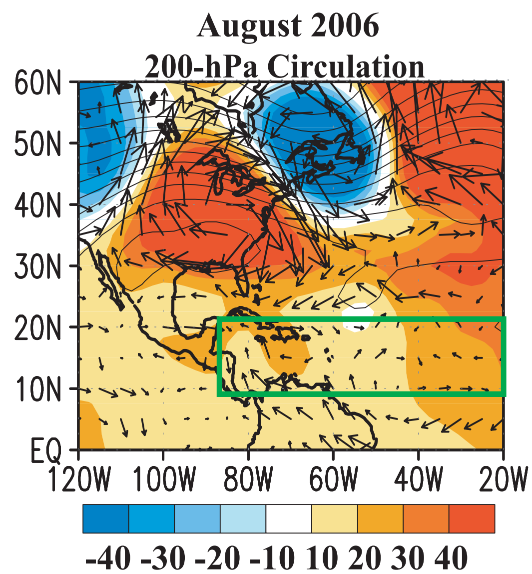

Fig. 11. August 2006: 200-hPa heights (contour interval is 60 m), height anomalies (shading), and vector wind anomalies. Green box denotes the Main Development Region. Anomalies are departures from the 1971-2000 period monthly means.

For the entire Main Development Region (MDR, green box), which encompasses the tropical Atlantic Ocean and Caribbean Sea (Goldenberg and Shapiro 1996), area-averaged SSTs during ASO were 0.68°C above average, the second warmest in the historical record dating back to 1871 (Fig. 9b). The reduced activity, in spite of this anomalous warmth, is consistent with previous findings indicating that local atmospheric circulation anomalies, rather than local SST anomalies, are the dominant contributor to seasonal fluctuations in Atlantic hurricane activity (Shapiro and Goldenberg 1998, Bell and Chelliah 2006).

The vertical wind shear pattern during ASO 2006 primarily reflected anomalously weak shear (relative to the period 1971-2000) throughout the MDR in association with the ongoing active hurricane era (Fig. 8a). A modest El Niño-related increase in wind shear is perhaps evident over the western Caribbean Sea, but only when the departures are calculated relative to the current active era (Fig. 8b). As with the 200-hPa streamfunction anomalies, there is little indication that El Niño affected the vertical wind shear prior to October. Even then, there is little evidence that the increased shear contributed to the shut-down in activity. For example, the main suppressing influence from strong vertical shear (> 8 ms^{-1}) occurred in August, prior to the time when El Niño began affecting this field (Fig. 10). During September and October, the shear was quite weak across the Caribbean Sea, and was therefore not a suppressing factor. It is not clear why the El Niño signal was manifested mainly in the upper-level divergence and vertical motion fields, as opposed to the 200-850 hPa vertical shear, as is typical for most episodes.

b. Mid-latitude and tropical variability

Although El Niño appears to be a primary cause for the reduced TC activity, highly variable circulation features not linked to El Niño also helped to suppress the activity. During August increased vertical wind shear in association with an enhanced mid-oceanic trough led reduced activity across the central MDR (Fig. 11). During September a deep trough near the U.S. east coast contributed to anomalous sinking motion over the Gulf of Mexico (Fig. 12). During October, an enhanced upper-level ridge over the south-central U.S. and western Gulf of Mexico contributed to the anomalous sinking motion over the Gulf of Mexico and

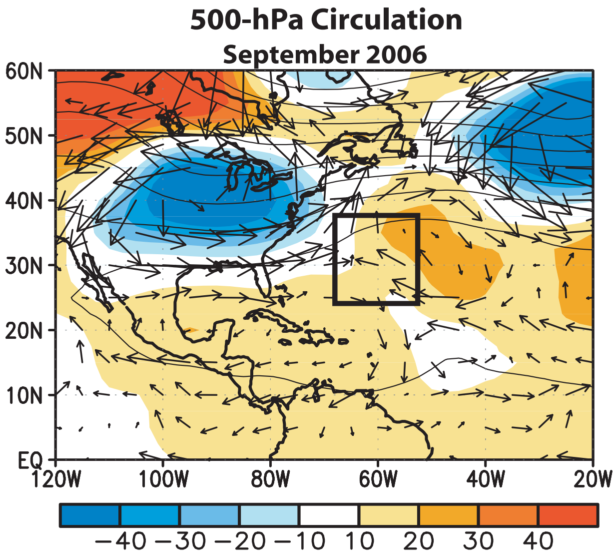

Fig. 12. September 2006: 500-hPa heights (contour interval is 60 m), height anomalies (shading), and vector wind anomalies. Black box shows where many hurricanes were steered during the month. Anomalies are departures from the 1971-2000 period monthly means.

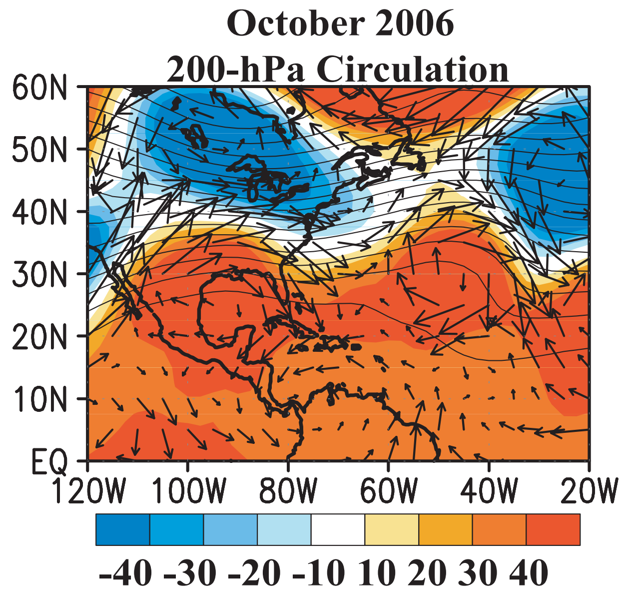

Fig. 13. October 2006: 200-hPa heights (contour interval is 60 m), height anomalies (shading), and vector wind anomalies. Anomalies are departures from the 1971-2000 period monthly means.

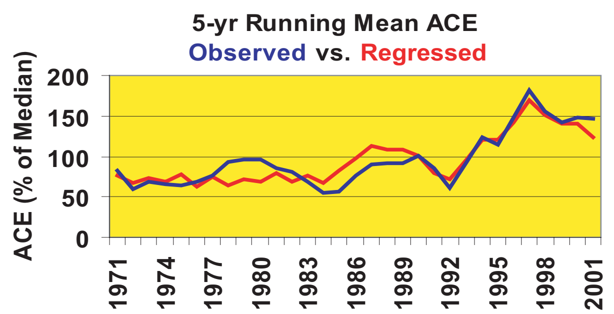

Fig. 14. Time series of the 5-yr running mean ACE index (blue curve) and the regressed seasonal ACE index associated with the tropical multi-decadal signal (red), from Bell and Chelliah (2006). The tropical multi-decadal signal accounts for 82% of the low frequency variance in the ACE index. The transition from the inactive hurricane era to the active hurricane era is captured by a phase change in the tropical multi-decadal signal.

also accentuated the sinking motion over Caribbean Sea (Fig. 13).

Only three Atlantic tropical storms, Alberto, Beryl, and Ernesto, struck the continental U.S. during 2006. Also, this was the first year since 2001 that no hurricanes struck the continental United States. This is a sharp drop in strikes compared to the prior four years (2002-2005), when an average of seven tropical storms and three hurricanes per season struck the continental United States. In September, (four of the five 2006 hurricanes formed in September) a deep trough near the U.S. east coast was critical in steering hurricanes out to sea long before they reached the coast (Fig. 12). The overall suppression of activity over the western part of the Atlantic Basin, due in part to El Niño, also contributed to fewer U. S. strikes.

c. Ongoing active Atlantic hurricane era

Despite the reduced 2006 activity, key oceanic and atmospheric features continued to reflect the ongoing active Atlantic hurricane era. A main contributing factor to this active era is the tropical multi-decadal signal, which reflects the leading modes of tropical convective rainfall variability occurring on multi-decadal time scales (Bell and Chelliah 2006). A regression analysis shows that the tropical multi-decadal signal captures 82% of the variance in the 5-yr running

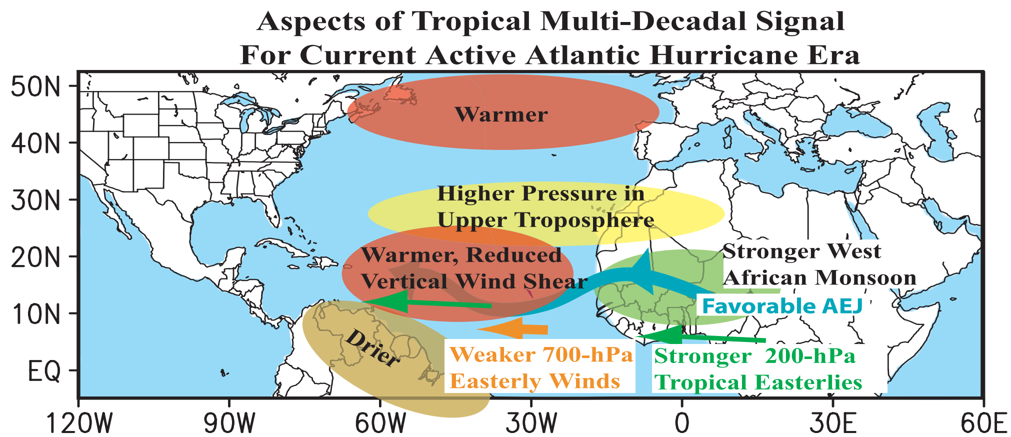

Fig. 15. Schematic showing regional conditions associated with the tropical multi-decadal signal during the current active hurricane era, based on Bell and Chelliah (2006).

mean ACE index since 1970 (Fig. 14). The tropical multi-decadal signal also captures the dramatic increase in ACE beginning in 1995, indicating that the transition from the inactive era to the active era is strongly associated with a phase change in that signal.

One key aspect of the tropical multi-decadal signal associated with the current active hurricane era is an east-west oscillation in anomalous tropical convection between the West African monsoon region and the Amazon Basin, signaling an enhanced West African monsoon system (see also Landsea and Gray 1992) and suppressed convection in the Amazon Basin (Fig. 15). This feature was pronounced during 2006, as seen in the pattern of 200-hPa velocity potential anomalies (Fig. 7a). A second prominent aspect of the tropical multi-decadal signal is a continuation of above average SSTs in the North Atlantic, consistent with the warm phase of the Atlantic multi-decadal mode (Goldenberg et al. 2001). Some of this anomalous warmth has also been linked to an increase in global temperatures over the last 100 years (Santer et al. 2006) not related to the tropical multi-decadal signal.

As shown by Bell and Chelliah (2006), the tropical multi-decadal signal is associated with an inter-related set of atmospheric anomalies known to favor active hurricane seasons. All of these

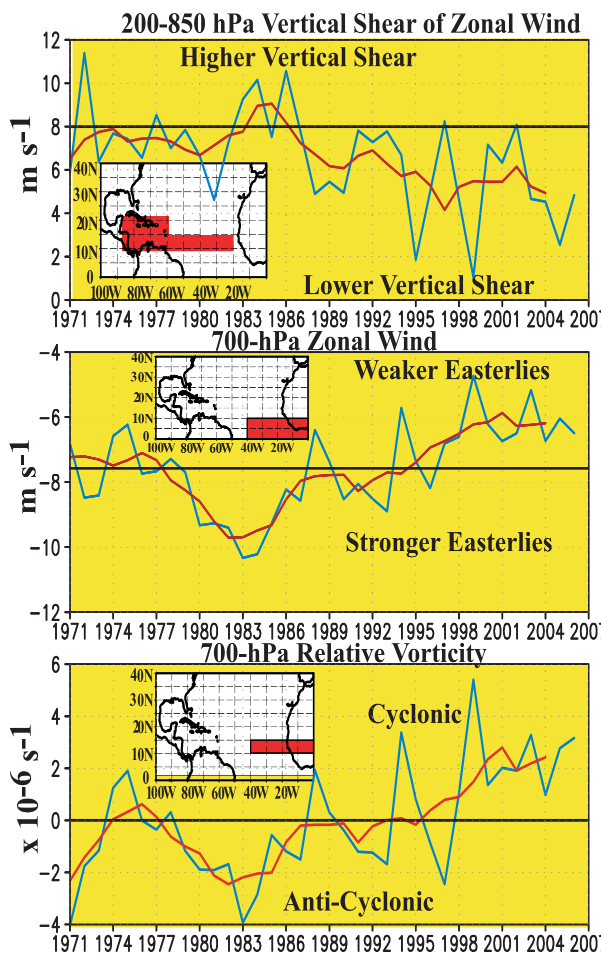

Fig. 16. August-October seasonal time series showing area-averaged values for key regions: (a) magnitude of the 200-850 hPa vertical shear of the zonal wind (m s^{-1}), (b) 700-hPa zonal wind (m s^{-1}) and (c) 700-Pa relative vorticity (x 10^{-6} s^{-1}). Blue curve shows unsmoothed three-month values, and red curve shows a 5-pt running mean of the time series. Averaging regions are shown in the insets.

anomalies were again in place during 2006, including (1) enhanced upper tropospheric (200-hPa) ridges in both hemispheres over the Atlantic Ocean (Fig. 7b), (2) an enhanced tropical easterly jet and a westward expansion of the area of anomalous easterly winds at 200-hPa, and (3) reduced tropical easterlies at 700-hPa across the central and eastern Atlantic (Fig. 16b).

These conditions lead to reduced wind shear across the tropical Atlantic (Fig. 16a, also Fig. 8a), increased cyclonic relative vorticity across the eastern MDR (Fig. 16c), and a more favorable configuration of the 700-hPa African easterly jet (AEJ). As a result, African easterly waves can more easily strengthen over the eastern tropical Atlantic, and then transform into hurricanes and major hurricanes as they move progressively westward into an extensive area of low wind shear and warmer SSTs.

In light of these conditions, there is no indication that the current active hurricane era has ended. Instead, the El Niño-related reduction in activity likely represents a short-term break (similar to the1997 and 2002 El Niño years) from an ongoing string of active hurricane seasons that began in 1995.

3. NOAA's Seasonal Outlooks

NOAA's seasonal Atlantic hurricane outlooks issued in both May and early August over-predicted the 2006 Atlantic hurricane activity. The May outlook called for a very active season with 13-16 named storms, 8-10 hurricanes, 4-6 major hurricanes, and an ACE value of 135%-205% of the median. The August outlook called for less activity, with 12-15 named storms, 7-9 hurricanes, 3-4 major hurricanes, and an ACE value of 110%-170% of the median. For these forecasts, the probabilities of an above-normal season were placed at 80% and 75%, respectively.

These over-predictions largely reflected a failure to forecast the rapid development of El Niño that occurred during August and September. This marks the first time since inception in August 1998 that NOAA's August outlook over-forecasted the seasonal ACE value, and the second time that NOAA's May outlook over-forecasted the ACE value. The other instance was also related to a rapidly developing El Niño in 2002.

4. Summary

The near-normal 2006 Atlantic hurricane season was consistent historically with moderate El Niño conditions occurring during an active hurricane era. The El Niño developed rapidly during August and early September, and strengthened to moderate intensity during October-November. NOAA's over-predictions of the seasonal activity largely reflected the failure to forecast the rapidly developing El Niño.

Since 1995 only three seasons have not been in the above-normal range (1997, 2002, and 2006), and all three were associated with El Niño. During 2006 El Niño's main impacts included anomalous upper-level convergence and sinking motion across the Caribbean Sea. It is not clear why this signal was manifested mainly in the upper-level convergence and vertical motion fields, as opposed to the 200-850 hPa vertical wind shear, as is typical for most episodes.

Anomalous mid-latitude and tropical circulations also contributed to the decreased activity in the central MDR in August, and to the reduced activity over the Caribbean Sea in October. A combination of El Niño and the anomalous mid-latitude circulation resulted in the 3rd earliest end to TC activity since the satellite era began.

The 2006 season saw no landfalling hurricanes in the continental United States. A deep trough over the eastern U.S. in September helped to steer hurricanes far out to sea. The overall suppression of activity over the western part of the Atlantic Basin, due in part to El Niño, also contributed to fewer U. S. strikes.

Despite the reduced activity, many of the ongoing atmospheric and oceanic conditions that have favored very active hurricane seasons since 1995 were again in place during 2006. In fact, tropical Atlantic sea-surface temperatures were the second warmest on record during the peak months of the season. The reduced activity, in spite of this anomalous warmth, is consistent with previous findings indicating that local atmospheric circulation anomalies, rather than local SST anomalies, are the dominant contributor to seasonal fluctuations in Atlantic hurricane activity (Shapiro and Goldenberg 1998, Bell and Chelliah 2006).

The analysis provides no indication that the current active hurricane era has ended. Instead, it indicates that the El Niño-related reduction in activity merely represents a short-term break (similar to the1997 and 2002 El Niño years) from an ongoing string of active hurricane seasons that began in 1995.

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