The 2005 North Atlantic Hurricane Season
A Climate Perspective

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1. Overview

The 2005 Atlantic hurricane season broke many tropical cyclone records. The season featured a record 27 tropical storms (TS), a record 15 hurricanes (H), a record four category-5 hurricanes, a record estimated Accumulated Cyclone Energy (ACE) index (Bell et al. 2000) of 285% of the median (Fig. 1), and an ACE contribution of 131% of the median from named storms forming outside the Main Development region [MDR, consisting of the tropical Atlantic and Caribbean Sea south of 21.5°N]. The season also featured a record fifteen landfalling named storms in the Atlantic Basin, a record four landfalling U.S. major hurricanes [MH, defined as categories 3-5 on the Saffir-Simpson scale, Simpson (1974)], a record seven named storms during June-July, and a record 10 named storms forming after 1 October. The seven major hurricanes during the season is one shy of the record set in 1950.

Two tropical storms, two hurricanes, and four major hurricanes struck the United States during 2005. The combined rainfall totals from these eight systems shows that very heavy rains extending well inland from the coast (Fig. 2). The largest totals exceeded 400 mm (16 inches) in a swath extending from southeastern

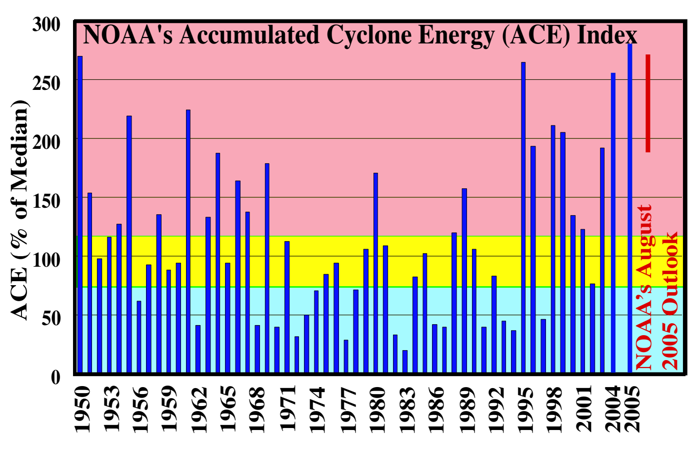

Fig. 1. NOAA's Accumulated Cyclone Energy (ACE) index expressed as percent of the 1951-2000 median value. NOAA definitions of season types are indicated by the background shading, with pink, yellow, and blue indicating above-, near-, and below-normal seasons, respectively.

Louisiana/ southwestern Mississippi to northern Mississippi. This swath was associated with Hurricane Katrina, which struck the central Gulf Coast in late August. Katrina, one of the worst natural disasters to ever strike the United States, made the 2005 season the costliest in the nation's history. Elsewhere, three tropical storms and three hurricanes struck Mexico, one tropical storm made landfall in the Dominican Republic, and one hurricane struck Nicaragua.

The National Oceanic and Atmospheric Administration's (NOAA) seasonal Atlantic hurricane outlook issued in May 2005 indicated a high (70%) likelihood the season would be above normal. The updated outlook issued in early August indicated a 95%-100% chance of an above-normal season, with the possibility of near-record activity. That outlook called for 18-21 named storms (previous record was 21), 9-11 hurricanes (previous record was 12), and 5-7 major hurricanes (record is 8). It also called for an ACE index in the range of 180%-270% of the median (previous record was 277% in 1950).

Many of the regional conditions during 2005 were consistent with other very active hurricane seasons (Fig. 3). However, both the amplitude and spatial extent of these anomalies were generally larger than seen in other active seasons. These conditions are attributed to four main factors: 1) the ongoing tropical multi-decadal signal, 2) long periods of anomalous upper-level convergence and suppressed convection over the central tropical Pacific reminiscent of La Niña conditions, 3) record warm sea-surface temperatures across the MDR, and (4) exceptionally conducive upper-level and lower-level wind and

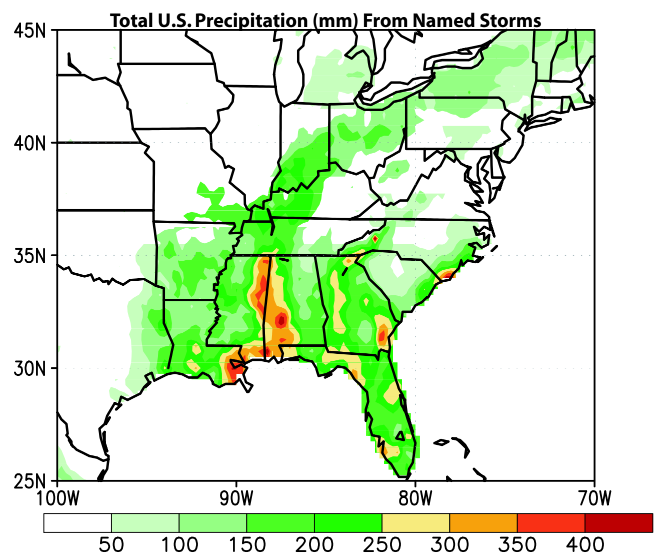

Fig. 2. Total rainfall (mm) during June-November 2005 from the eight named storms that struck the United States.

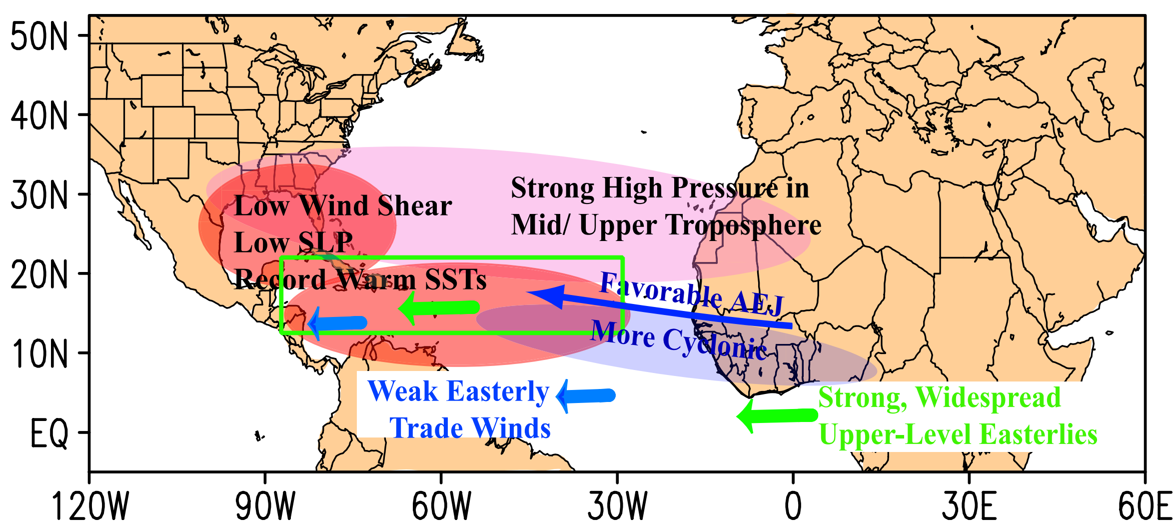

Fig. 3. Schematic representation of conditions during the peak (July-October) months of the 2005 Atlantic hurricane season. Green box denotes the Main Development Region (MDR), bounded by 90°W-20°W and 9.5°N-21.5°N.

air pressure patterns over the western Atlantic and Gulf of Mexico.

2. 2005 Season Activity

NOAA's ACE index measures seasonal activity based on the combined strength and duration of the named storms (Bell et al. 2000). This wind energy index is calculated by summing the squares of the 6-hourly maximum sustained wind speed in knots (V_{max}^2) for all periods while the system is a tropical storm or hurricane (Fig. 1).

The record 2005 ACE value [249 x 10^4 kt^2 or 285% of the 1951-2000 median] marks a continuation of the active hurricane era that began in 1995. During the last eleven years, seasons have averaged 14.7 TS, 8.4 H, and 4.1 MH, and NOAA classifies every season as above normal except for the two El Niño years of 1997 and 2002.

The historical time series of the ACE index shows large multi-decadal fluctuations in seasonal activity (Goldenberg et al 2001, Bell and Chelliah 2006), with the previous active era occurring during the 1950s-1960s [Longer records show the increased activity started in the 1930s.], followed by an inactive era during 1971-1994. Seasons during this inactive era averaged only 9 TS, 5 H, and 1.5 MH, and only three seasons were classified as above-normal (1980, 1988, 1989). These large differences between the active and inactive eras result almost entirely from differences in the number of named storms forming in the MDR and eventually becoming hurricanes and major hurricanes (Landsea 1993, Goldenberg et al. 2001).

During 2005 eleven named storms formed in the MDR, resulting in eight hurricanes and five major hurricanes. These numbers are larger than the above-normal season averages for the MDR of 5.8 TS, 4.3 H, and 3 MH and well above the 1951-2000 MDR averages of 4.6 TS, 3.2 H, and 1.9 MH.

A record sixteen named storms also formed outside the MDR during 2005, resulting in six hurricanes and two major hurricanes. The ACE contribution from these 16 systems (130.5% of the me-

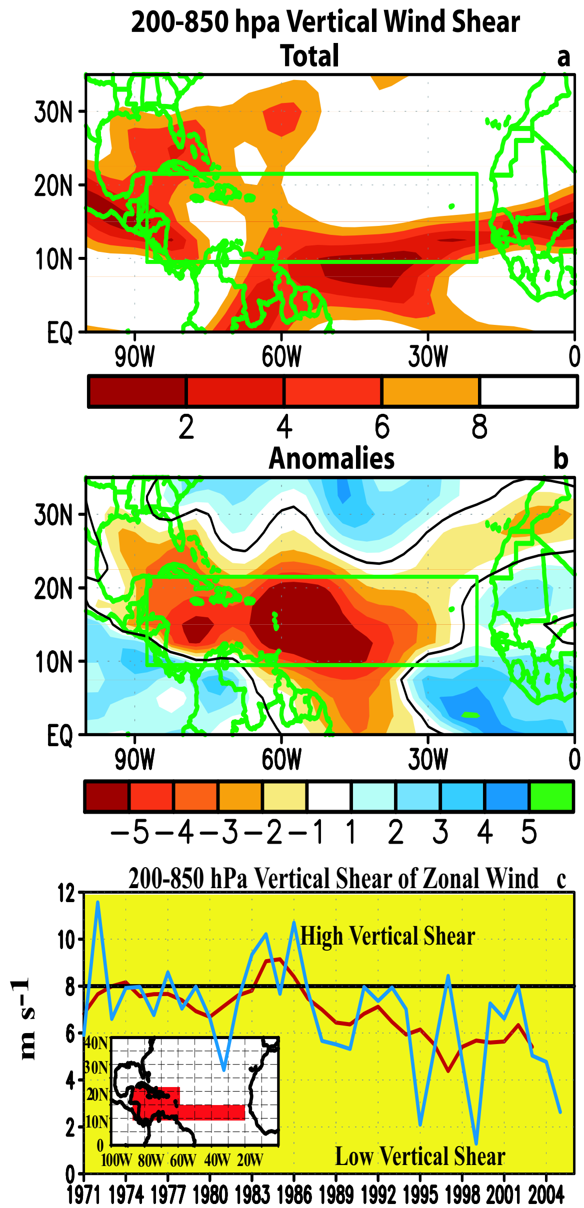

Fig. 4. 200-850 hPa vertical shear magnitude (a) total (m s^{-1}) and (b) anomalies during June-October 2005. In (a) only values less than 8 m s^{-1} are shaded. In (b) red shading indicates weaker-than-average vertical shear. Green box denotes the MDR. Anomalies in (b) are departures from the 1971-2000 base period monthly means.

Panel (c) shows a time series of August-October area-averaged 200-850-hPa vertical shear of the zonal wind (m s^{-1}) across the MDR (inset). Blue curve shows unsmoothed three-month values, and red curve shows a 5-pt running mean applied to the time series.

dian) far exceeded the previous season high of 80.8% set in 1959. During 2005, these non-MDR systems accounted for 45.6% of the total ACE value, far above the average contribution during above-normal seasons of only 14.5% of the total.

3. Atmospheric and Oceanic Conditions

The tropical multi-decadal signal incorporates the leading modes of tropical convective rainfall variability occurring on multi-decadal time scales. Three important aspects of this signal, which have contributed to the increased hurricane activity since 1995, are 1) a stronger West African monsoon system, 2) suppressed convection in the Amazon Basin, and 3) the warm phase of the Atlantic Multi-decadal Oscillation (Goldenberg et al. 2001, Bell and Chelliah 2006). This signal is very important for Atlantic hurricanes because it affects the entire set of conditions that controls hurricane formation in the MDR for decades at a time. During 2005, the multi-decadal signal again set the backdrop for many of the observed atmospheric and oceanic anomalies.

For example, the season featured an extensive area of low vertical wind shear (less than the 8 m s^{-1} threshold for tropical cyclone formation) throughout the MDR and Gulf of Mexico (Fig. 4a), with the largest anomalies over the central tropical Atlantic and Caribbean Sea (Fig. 4b). Since 1995 the August-October area-averaged vertical shear in the heart of this low-shear area has averaged approximately 5-6 m s^{-1}, with values dropping to as low as 2 m s^{-1} during individual years such as 1995, 1999, and 2005 (Fig. 4c).

During 2005, the low vertical shear resulted in part from a stronger-than-average tropical easterly jet and an expanded area of upper-level easterly winds across the western MDR, both of which are related to an enhanced subtropical ridge at 200-hPa (red shading, Fig. 5). The 200-hPa streamfunction field shows these conditions were part of a larger-scale pattern, characterized by anticyclonic anomalies (red in NH, blue in SH) and enhanced subtropical ridges in both hemispheres from the eastern Pacific to Africa, and by cyclonic anomalies in both hemispheres over the central subtropical Pacific.

This pattern, with its pronounced inter-hemispheric symmetry, is a classic signature of very active Atlantic hurricane seasons (Bell and Chelliah 2006). It signifies a response to anomalous tropical convection related to the combination of the ongoing tropical multi-decadal signal and suppressed convection over the central tropical Pacific.

The anomalous convection over the central tropical Pacific is examined through the 200-hPa ve-

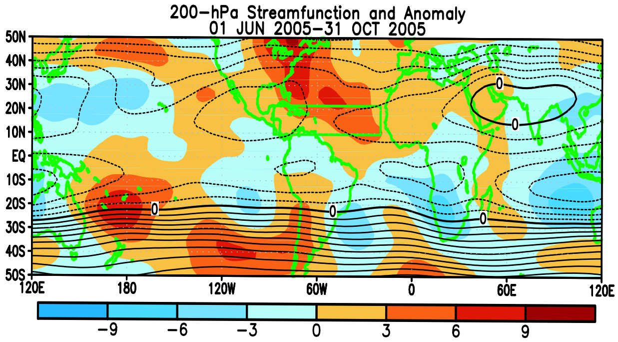

Fig. 5. 200-hpa streamfunction (a) mean (contours, interval is 10 x 10^6 $m^2 s^{-1}$) and anomalies (shading) during June – October 2005. Anticyclonic anomalies are indicated by positive values in the NH and negative values in the SH. Cyclonic anomalies are indicated by negative values in the NH and positive values in the SH. Anomalies are departures from the 1971-2000 base period monthly means. Green box denotes the MDR.

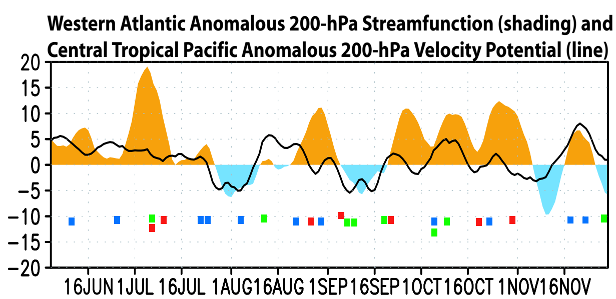

Fig. 6. Five-day running mean time series showing area-averaged anomalies of 200-hPa velocity potential (line) and 200-hPa streamfunction (shading) during 10 June – 30 November 2005. Velocity potential anomalies are calculated for the central tropical Pacific region bounded by (160°E-170°W) (10°-20°N). Streamfunction anomalies are calculated for the Gulf of Mexico and Caribbean Sea bounded by 100°W-60°W and 10°N-30°N. Small boxes below the time series' indicate when TS-only systems formed (blue), cat. 1-2 hurricanes formed (green), and major hurricanes formed (red). Anomalies are departures from the 1971-2000 base period daily means.

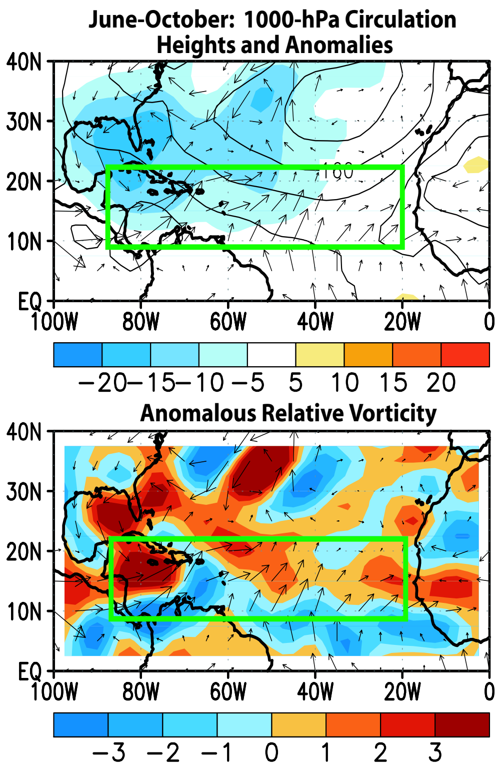

Fig. 7. 1000-hPa circulation during June-October 2005: (a) Heights (contours, interval is 20 m) and anomalies (shaded), and (b) anomalous relative vorticity (x 10^{-6} s^{-1}). The anomalous 1000-hPa vector winds are displayed in both panels. In bottom panel, red (blue) shading indicates anomalous cyclonic (anticyclonic) relative vorticity. Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

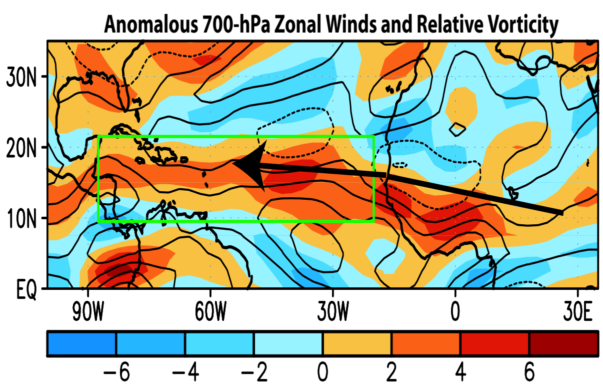

Fig. 8. 700-hPa anomalous zonal winds (contour interval is 1.0 m s^{-1}) and relative vorticity (shading, x 10^{-6} s^{-1}) during June-October 2005. Solid (dashed) contours indicate westerly (easterly) winds. Yellow-red (blue) shading indicates anomalous cyclonic (anticyclonic) relative vorticity. Arrow shows mean position of the African Easterly jet axis during August-September. Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

locity potential (line, Fig. 6). Long periods of anomalous upper-level convergence and suppressed convection were evident during the season (positive values), with shorter-period fluctuations sometimes related to the MJO also evident. It is well known that suppressed convection over the central tropical Pacific acts to enhance the 200-hPa subtropical ridge over the western North Atlantic, as seen during 2005 (orange shading, see also Mo 2000), which in turn acts to focus tropical cyclone activity. For example, 10 of the 11 tropical storms during June-November that did not become hurricanes formed when convection was suppressed near the date line, along with 10 of 15 hurricanes and all seven major hurricanes. All seven early-season named storms and two mid-November named storms also occurred under these conditions. In contrast, a break in activity during the first half of August coincided with enhnaced convection and anomalous upper-level divergence near the date line.

The low vertical shear during 2005 was also related to westerly wind anomalies in the lower troposphere, in association with a markedly reduced strength of the tropical easterly trade winds from the eastern Pacific to Africa (Fig. 7a). In combination with the anomalous upper-level easterlies, this wind distribution is consistent with the baroclinic response of the atmospheric circulation to anomalous tropical convection associated with the tropical multi-decadal signal (Bell and Chelliah 2006). The weaker easterly trade winds also resulted from exceptionally low sea-level pressure (SLP) and 1000-hPa heights in response to a weakening and northeastward shift of the Bermuda High.

These conditions were accompanied by an anomalous cross-equatorial flow of deep tropical moisture into the heart of the MDR, which certainly favored tropical storm formation. They were also associated with anomalous cyclonic vorticity across the northern half of the MDR, western North Atlantic and Gulf of Mexico (red shading, Fig. 7b). This pattern of weaker easterlies and anomalous cyclonic vorticity extended up to 700-hPa along the equatorward flank of the African Easterly Jet (AEJ) (Fig. 8). This pattern is also consistent with the ongoing tropical multi-decadal signal, as indicated by time series' of area-averaged anomalies calculated for core loading regions of that signal (Figs. 9a, b). Conversely, during the inactive hurricane era 1971-1994, stronger easterly trade winds (Fig. 9a) and reduced cyclonic vorticity (Fig. 9b) south of the AEJ axis, combined with higher vertical shear (Fig. 4c), were not conducive to hurricane formation in the MDR.

The favorable lower-level conditions during 2005 were also associated with record warm SSTs across the tropical Atlantic, Caribbean Sea, and Gulf of Mexico (Fig. 10a), with area-averaged SSTs reaching an 1870-2005 high of 28.7°C in the region where tropical cyclone activity tended to be focused (Fig. 10b).

The above conditions meant that African easterly waves were embedded within an extended region of anomalous cyclonic vorticity south of the AEJ axis as they moved westward over very warm SSTs into the low-shear, low SLP, high vorticity, environment of the central and western MDR. This combination has favored very active hurricane seasons since 1995 (Bell et al. 1999, 2000, 2004, Lawrimore et al. 2001).

In mid-May, NOAA correctly predicted these conditions to be in place during the peak of the season. However, their early-season strength was not well predicted. In early August, NOAA's updated outlook again pointed to these conditions and indicated they could possibly bring a near-record season.

4. Systems Forming Near The Gulf of Mexico

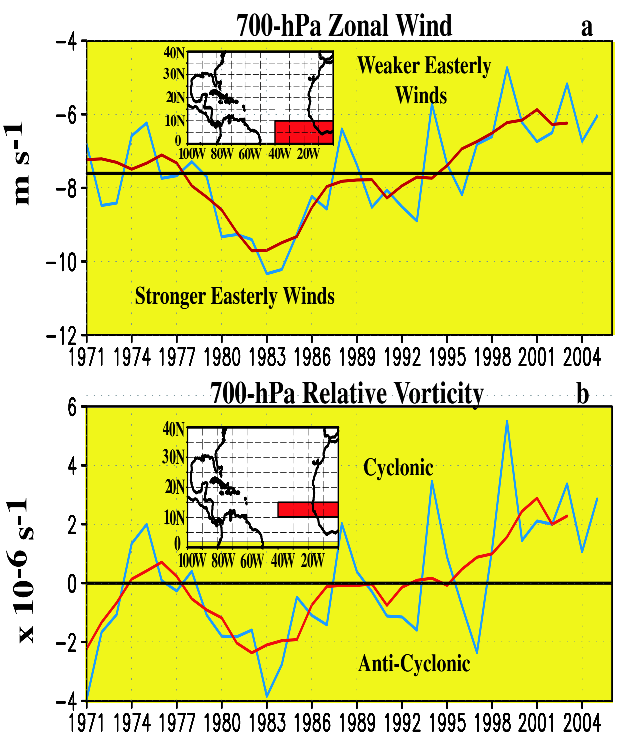

Fig. 9. August-October time series showing area-averaged values of (a) 700-hPa zonal wind (m s^{-1}) and (b) 700-Pa relative vorticity (x 10^{-6} s^{-1}). Blue curve shows unsmoothed three-month values, and red curve shows a 5-pt running mean of the time series. Averaging regions are shown in the insets.

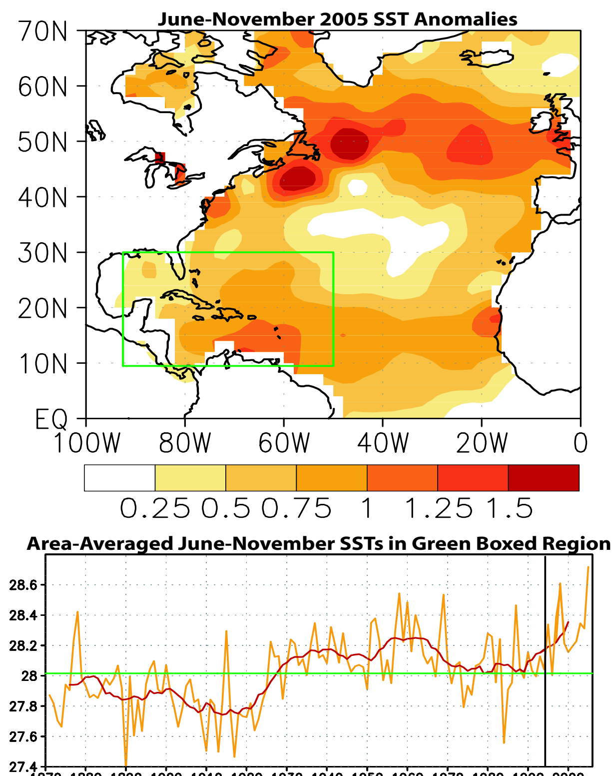

Fig. 10. Seasonal June-November (a) sea-surface temperature (SST) anomalies (°C) during 2005 and (b) time series of area-averaged SSTs for the green boxed region shown in (a). Red line in (b) shows the corresponding 11-yr running mean.

While the combination of the ongoing multi-decadal signal and suppressed convection near the date line set up the overall environment for a very active season, these factors cannot account for periods during 2005 when the atmospheric anomalies were exceptionally strong. They also cannot entirely account for so many named storms developing in and around the Gulf of Mexico, and for a record eleven passing through the Gulf.

Three additional factors likely contributed to this distribution of activity. The first was a persistent ridge of high pressure in the middle and upper atmosphere over the southeastern U.S. and Gulf regions. This feature has links to the large-scale anomalous extratropical circulation (Fig. 5). This amplified ridge contributed to the low vertical shear, as was seen in early July (Fig. 6) when it contributed to a sharp drop in vertical shear across the southern and western MDR. Three hurricanes formed in the MDR during this period, with two becoming major hurricanes.

The second additional contributor was a northeastward shift and strengthening of the ITCZ over the eastern North Pacific (Fig. 11). Associated with this pattern, an extensive area of low SLP further strengthened the low-level cyclonic circulation over the Gulf of Mexico.

The third factor, above-average SSTs in an already very warm Gulf of Mexico and Caribbean Sea, made the low-level environment even more conducive to tropical cyclogenesis and major hurricane formation. In effect, the environment in these regions for much of the season typified the central MDR of an active season.

South of the upper-level ridge over the eastern U.S., the broad easterly flow helped to steer many of the developing named storms into the Gulf of Mexico, all of which eventually made landfall. A similar persistent upper-level ridge also contributed to many landfalling U.S. hurricanes during 2004 (Bell et al. 2005).

The failure of many tropical storms to develop until they reached the western part of the basin is partly related to a pronounced eastward shift of the mean upper-level trough to the extreme eastern North Atlantic (Fig. 5). This shift occurred in association with the persistent ridge farther west, and resulted in periods of increased vertical shear which acted to suppress tropical wave development in the eastern MDR.

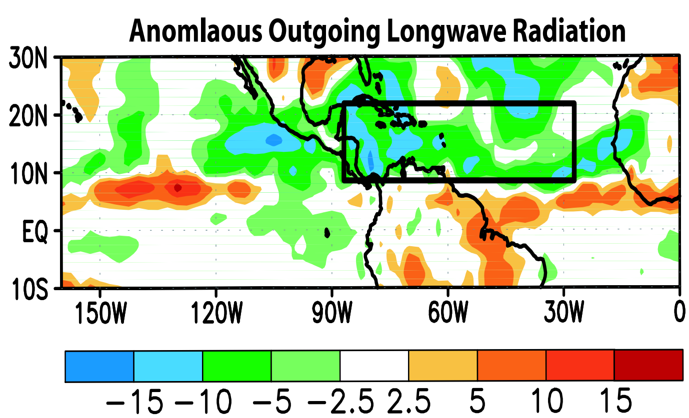

Fig. 11. June-October anomalous Outgoing Longwave Radiation (OLR, units are W m^{-2}). Green shading indicates areas of anomalously cold cloud tops normally associated with above-average tropical convection. Red shading indicates below-average tropical convection. Black box denotes the MDR. Anomalies are departures from the 1979-2000 base period monthly means.

4. Summary

The record 2005 Atlantic hurricane season resulted from exceptionally favorable conditions in both the upper-and lower atmosphere, combined with record warm SSTs. Four large-scale factors appear to account for these conditions. The first is the ongoing active Atlantic phase of the tropical multi-decadal signal, which has favored very active seasons since 1995 (Bell and Chelliah 2006). This signal accounts for the coherent patterns of atmospheric and oceanic anomalies across the MDR throughout the season. The second main factor is prolonged periods of suppressed tropical convection near the date line, which produced a La Nina-like response in the atmospheric circulation over the western Atlantic.

Historically, this combination of the ongoing multi-decadal signal and suppressed convection near the date line has produced very active hurricane seasons.

The third main factor is exceptionally conducive upper-level and lower-level wind and air pressure patterns over the western Atlantic and Gulf of Mexico. These patterns were associated with the suppressed tropical convection near the date line, and also with a northeastward displacement of the eastern Pacific ITCZ and a persistent mid-latitude circulation regime. This same mid-latitude regime was associated with an eastward shift of the mean upper-level trough over the North Atlantic to well east of its climatological position, which contributed to increased vertical shear and reduced TC formation in the eastern MDR.

The fourth main factor is record SSTs across the tropical Atlantic. SSTs have been at record or near-record levels in both the tropical latitudes and high latitudes of the North Atlantic for the last two years. During the 2005 season, the anomalous SSTs were maintained in part by a marked weakening of the tropical easterly trade winds, which was accompanied by 1) a reduced northeasterly flow of dry subsiding air around the east side of an exceptionally weak Bermuda High, and 2) an increased flow of moist, equatorial air into the MDR.

Although the record 2005 activity resulted from a combination of factors, the underlying active Atlantic phase of the multi-decadal signal continued to be very pronounced through the season. Because the mean conditions in the MDR exhibit such strong multi-decadal variability, it is reasonable to expect generally high levels of Atlantic hurricane activity for the next 10 to 20 years or perhaps longer (Goldenberg et al. 2001). This has implications for the coastal U.S. and Caribbean Sea regions, both of which experience an average of 2-3 hurricane landfalls during above-normal seasons. It also has implications for areas well inland from initial strike areas, as inland flooding is a leading cause of death from hurricanes in the United States.

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