The 2008 North Atlantic Hurricane Season
A Climate Perspective

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1. 2008 Seasonal Activity

The 2008 Atlantic hurricane season produced 16 named storms (NS), of which eight became hurricanes (H) and five became major hurricanes (MH) (Fig. 1). The 1950-2000 averages are 11 NS, six H, and two MH.

For 2008, the Accumulated Cyclone Energy (ACE) index (Bell et al. 2000), a measure of the season's overall activity, was 167% of the median (Fig. 2). This value is the 14th most active since 1950, and indicates an above-normal season consistent with the ongoing active Atlantic hurricane era that began in 1995 (Goldenberg et al. 2001).

The 2008 activity fell within NOAA's predicted ranges. (www.cpc.ncep.noaa.gov/products/outlooks/hurricane-archive.shtml). NOAA's pre-season outlook issued May 22nd called for a 60%-70% chance of each of the following: 12-

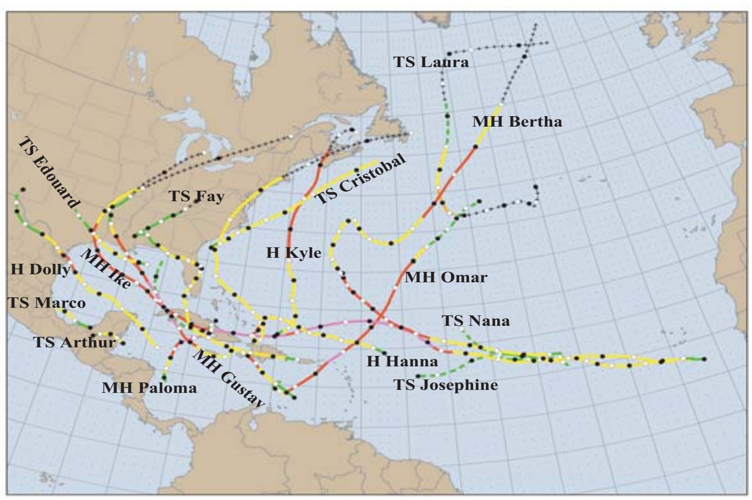

Fig. 1. Atlantic tropical storm and hurricane tracks during 2008. Shading indicates storm strength, with green indicating tropical depression, yellow indicating tropical storm (TS), red indicating hurricane (H, Cat. 1-2) and purple indicating major hurricane (MH, Cat. 3-5).

16 NS, 6-9 H, 2-5 MH, and an ACE range of 100%-210% of the median (red bars, Fig. 2). The updated outlook issued August 7th called for slightly more activity, with a 67% chance of each of the following: 14-18 NS, 7-10 H, 3-6 MH, and an ACE range of 140%-230% of the median. NOAA also increased the probability of an above-normal season from 65% in May to 85% in August.

During 2008, 11 named storms formed in the Main Development Region [MDR, green box in Fig. 3a], which spans the tropical Atlantic Ocean and Caribbean Sea between 9.5°N-21.5°N and 20.0°W-87.5°W (Goldenberg and Shapiro 1996). These systems accounted for seven hurricanes, all five major hurricanes, and 88% of the ACE value. This activity is consistent with other very active seasons, which only occur when conditions are extremely conducive in the MDR (Bell and Chelliah 2006).

The 2008 season was also active in terms of landfalling named storms. The nations in and surrounding the Caribbean Sea were severely impacted by four tropical storms (TS) and four hurricanes. Cuba experienced three hurricane landfalls (including MHs Gustav and Ike), while Hispaniola was affected by several storms including direct strikes by TS Fay and H Hanna. The continental United States was struck by three tropical storms and three hurricanes, with all but one TS making landfall along the Gulf Coast. One additional hurricane (Kyle) made a rare landfall in Nova Scotia.

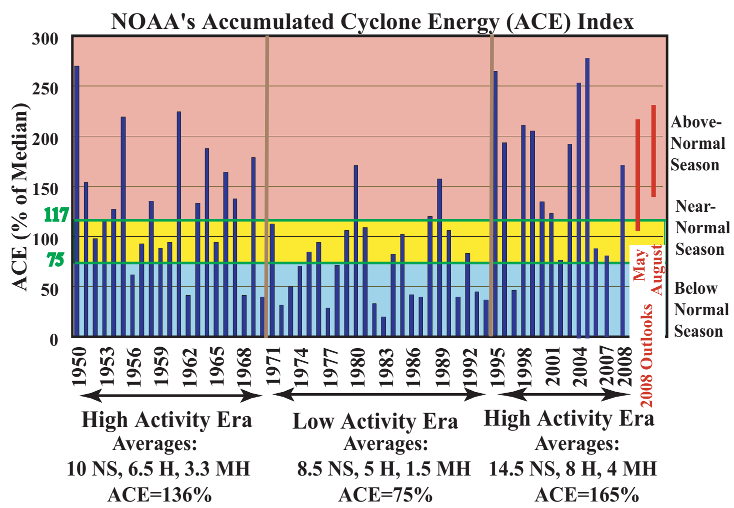

Fig. 2. NOAA's ACE index expressed as percent of the 1950-2000 median value (87.5 x 10^4 kt^2). ACE is a wind energy index that measures the combined strength and duration of the named storms. ACE is calculated by summing the squares of the 6-hourly maximum sustained surface wind speed in knots ($Vmax^2$) for all periods while the named storm has at least TS strength. Pink, yellow, and blue shadings correspond to NOAA's classifications for above-, near, and below-normal seasons, respectively. Red bars at right show NOAA's 2008 seasonal ACE forecasts issued in May and updated in August. Brown bars delineate the high-activity and low-activity eras, with averages at bottom corresponding to the specified era.

2. Sea surface temperatures (SSTs)

For the August-October (ASO) climatological peak months of the hurricane season, sea surface temperatures (SSTs) were above average in the MDR during 2008, with the largest departures (approaching 1.0 C) found east of the Caribbean Islands (Fig. 3a). The area-averaged SST anomaly in the MDR was 0.6 C, which is the fifth warmest

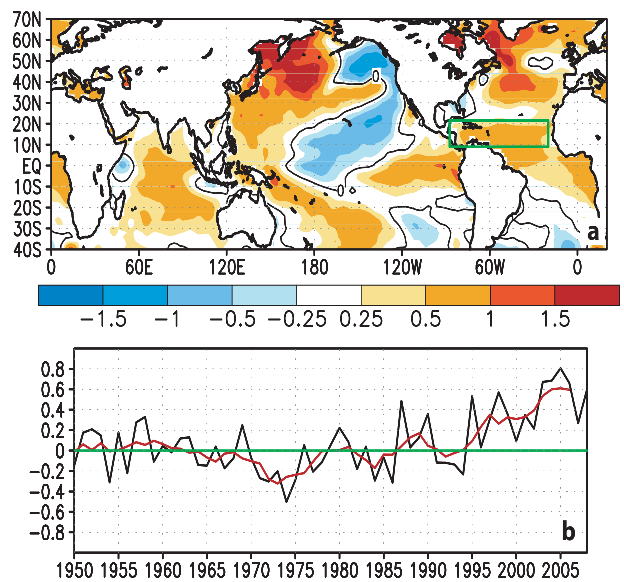

Fig. 3 (a) SST anomalies (°C) during Aug-Oct 2008. (b) Consecutive Aug-Oct area-averaged SST anomalies in the MDR. Red line shows the corresponding 5-yr running mean. Green box in (a) denotes the MDR. Anomalies are departures from the 1971-2000 period monthly means.

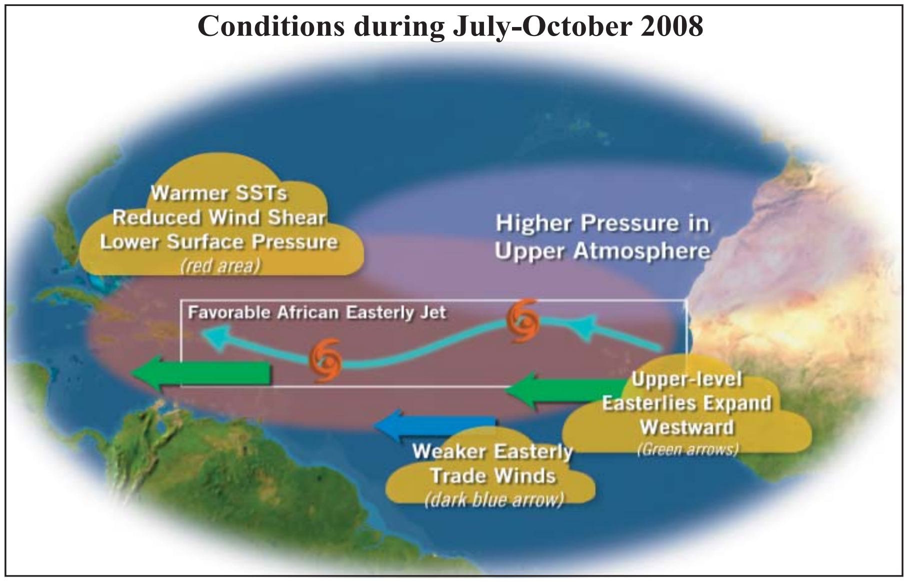

Fig. 4. Schematic showing regional conditions associated with the above-normal 2008 Atlantic hurricane season. These conditions largely reflect the ongoing active Atlantic hurricane era and lingering La Niña signals.

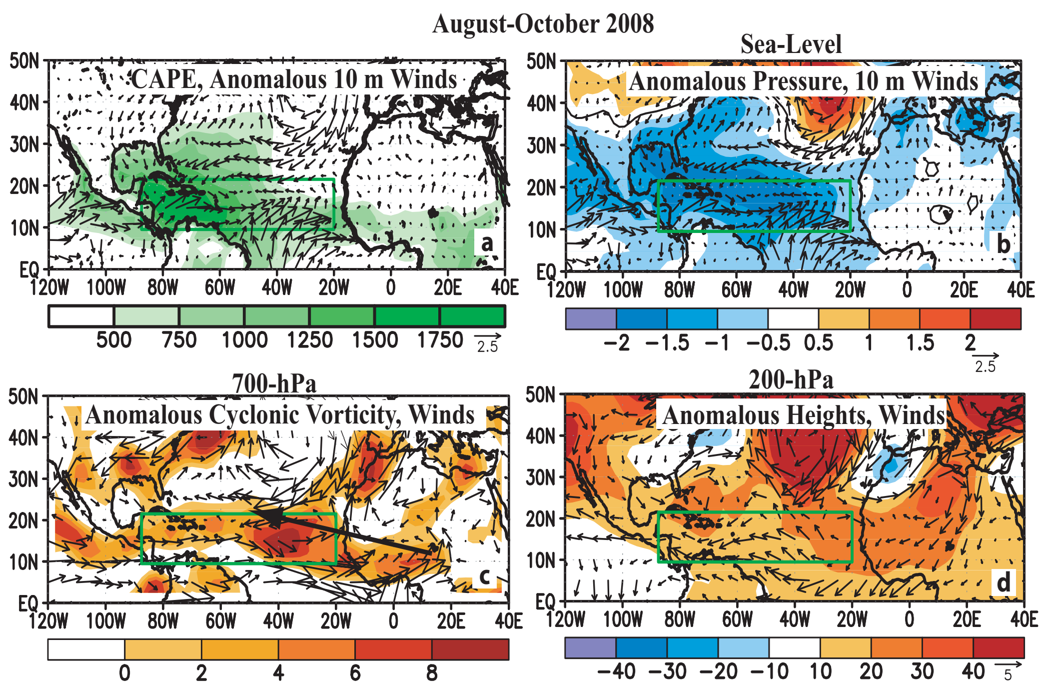

Fig. 5. Aug-Oct 2008: (a) Total CAPE (J kg^{-1}) and anomalous vector winds (m s^{-1}) at 10 m. (b) Anomalous sea-level pressure (shading, hPa) and vector winds at 10 m. (c) 700-hPa anomalous cyclonic relative vorticity (shading) and vector winds, with thick solid line indicating the observed AEJ core. (d) 200-hPa anomalous heights and vector winds. Green boxes denote the MDR. Anomalies are departures from the 1971-2000 monthly means.

since 1950 (Fig. 3b).

This warmth likely reflected two main factors. The first is the warm phase of the Atlantic Multi-decadal Oscillation (AMO) (Enfield and Mestas-Nuñez 1999) that began in association with the 1995 transition to the active Atlantic phase of the tropical multi-decadal signal (Goldenberg et al. 2001, Bell and Chelliah 2006). The second is reduced mixing and reduced evaporation from the ocean surface in response to weaker northeasterly trade winds (Fig. 4), as indicated by anomalous southwesterly flow across the southern half of the MDR (Fig. 5a).

3. Atmospheric circulation

An inter-related set of atmospheric anomalies typical of recent active hurricane seasons (Landsea et al. 1998, Bell et al. 1999, 2000, 2004, 2006a; Goldenberg et al. 2001, Bell and Chelliah 2006, Kossin and Vimont 2007) set the stage for the active 2008 hurricane season (Figs. 4, 5). These conditions are also known to greatly increase the probability of hurricane landfalls in the United States and in the region around the Caribbean Sea, as was seen in 2008.

During ASO 2008, weaker trade winds and high values of Convective Available Potential Energy (CAPE) covered the southern half of the MDR (Fig. 5a), and sea-level pressure was below average throughout the MDR (blue shading, Fig. 5b). These conditions were associated with a more northward position of the Atlantic ITCZ and with an enhanced west African monsoon system.

The low-level westerly wind anomalies extended up past 700-hPa, the approximate level of the African Easterly Jet (AEJ, Fig. 5c), and were associated with a 5 deg. latitude northward shift of the AEJ core (thick black arrow) compared to climatology. This shift meant that the bulk of the African easterly wave energy, which is closely linked to the AEJ (Reed et al. 1977), was often centered well within the MDR. The AEJ also featured increased cyclonic shear along its equatorward flank, which is not only more dynamically conducive to the strengthening of African easterly waves, but also provides an inherent cyclonic rotation to their embedded convective cells.

At 200-hPa, the wind and height anomalies reflected an enhanced upper-level ridge and a stronger and more westward extension of the tropical easterly jet within the MDR (Fig. 5d). The resulting combination of low-level southwesterly anomalies and upper-level easterly anomalies resulted in weak (less than 8 m s^{-1}) vertical wind shear between 200-hPa and 850-hPa across much of the MDR (shading, Fig. 6a), with the most anomalously weak shear spanning the central tropical Atlantic Ocean and Caribbean Sea (Fig. 6b).

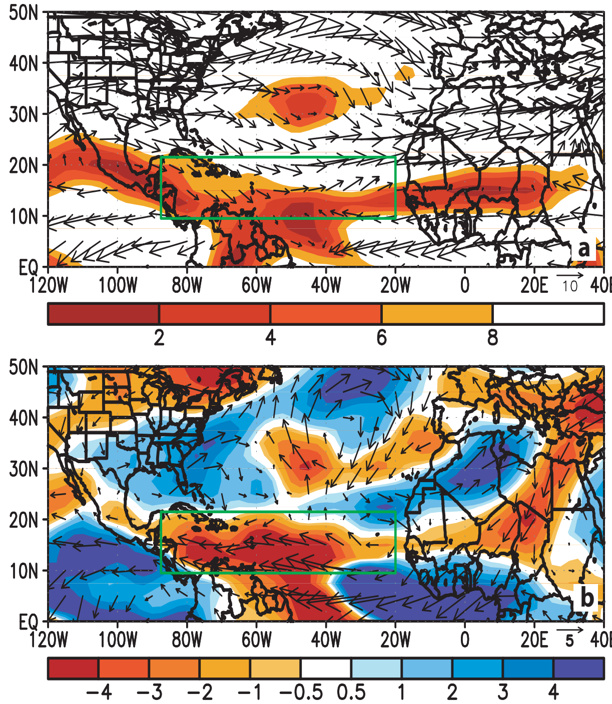

Fig. 6 Aug-Oct 2008: 200-850 hPa vertical wind shear magnitude (m s^{-1}) and vectors (a) total and (b) anomalies. In (a), shading indicates values below 8 ms^{-1}. In (b), red (blue) shading indicates below- (above-) average magnitude of the vertical shear. Green box denotes the MDR. Anomalies are departures from the 1971-2000 monthly means.

This combination of conditions meant that tropical storms and hurricanes often developed from amplifying African easterly waves moving within the region of below-average pressure and increased cyclonic shear along the equatorward flank of the AEJ. These waves were also embedded within an extended region of weak vertical wind shear, which enabled further intensification as they moved westward over the progressively warmer SST environment of the central and western MDR.

4. Dominant climate patterns

A combination of two prominent climate factors can account for the inter-related set of anomalies associated with the 2008 Atlantic hurricane season. These are the ongoing active Atlantic phase of the tropical multi-decadal signal and lingering La Niña signals.

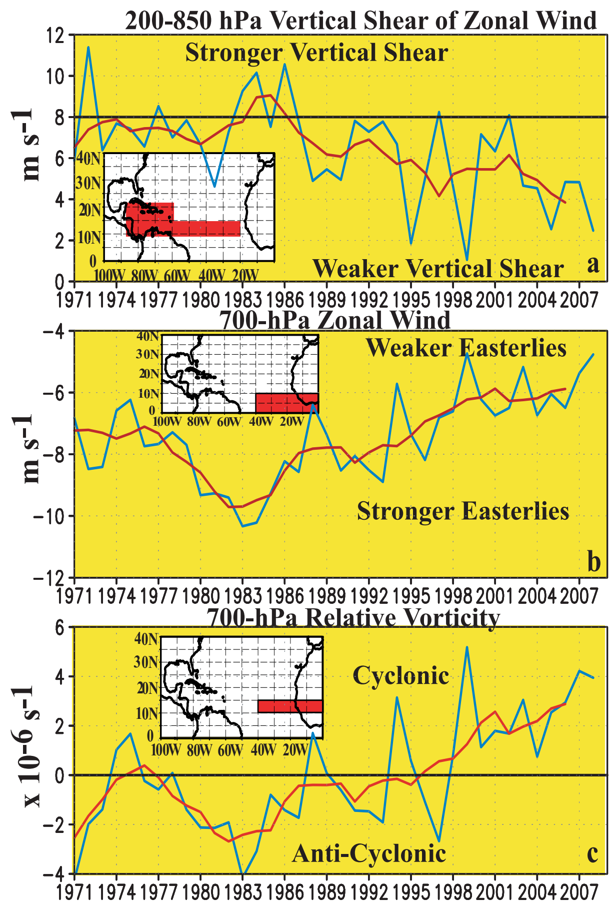

Fig. 7. Time series showing consecutive Aug-Oct values of area-averaged (a) 200-850 hPa vertical shear of the zonal wind (m s^{-1}), (b) 700-hPa zonal wind (m s^{-1}) and (c) 700-Pa relative vorticity (x 10^{-6} s^{-1}). Blue curve shows unsmoothed values, and red curve shows a 5-pt running mean of the time series. Averaging regions are shown in the insets. Black horizontal line in (a) shows 8 m s^{-1} threshold for vertical wind shear, and in (c) shows zero relative vorticity.

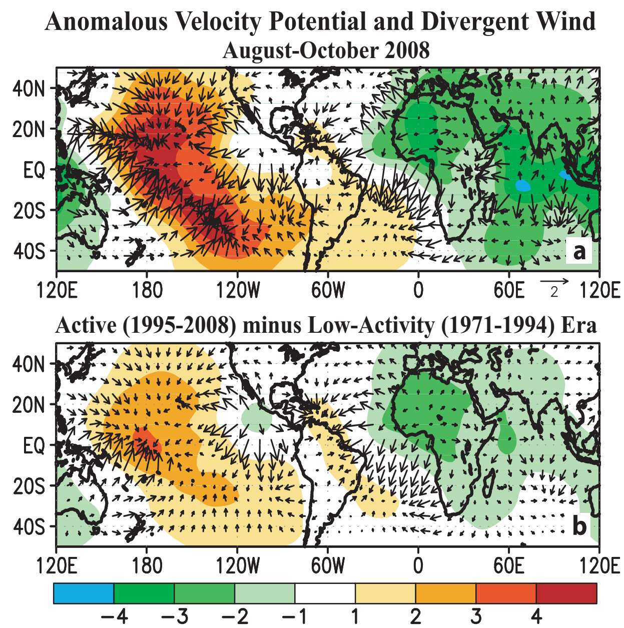

Fig. 8. 200-hPa velocity potential (shading) and divergent wind vectors (m s^{-1}): (a) Aug-Oct 2008 anomalies and (b) high-activity (1995-2008) period means minus low-activity (1971-1994) period means. Anomalies are departures from the 1971-2000 monthly means.

(a) The ongoing active Atlantic hurricane era

2008 marks the tenth above-normal Atlantic hurricane season since the current high-activity era began in 1995. During 1995-2008 only the very strong El Niño year of 1997 was below normal (Fig. 2). This increased activity since 1995 contrasts with the preceding low-activity era 1971-94, when one-half of the seasons were below normal and only three were above normal.

Bell and Chelliah (2006) showed that a main contributing factor to the current active Atlantic hurricane era is the tropical multi-decadal signal, which reflects the leading modes of tropical convective rainfall variability occurring on multi-decadal time scales. A phase change in the tropical multi-decadal signal is thought to be primarily responsible for the transition into the current high-activity era (Bell and Chelliah 2006, Bell et al. 2007). Indices that track aspects of this multi-decadal signal within the MDR highlight the dramatic differences in the vertical wind shear (Fig. 7a), 700-hPa zonal winds (Fig. 7b), and 700-hPa relative vorticity (Fig. 7c), between these high-activity and low-activity eras.

The multi-decadal signal highlights the convectively-driven nature of the atmospheric anomalies across the central and eastern MDR (Fig. 8), linking them to an east-west oscillation in anomalous convection between the west African monsoon region (Landsea and Gray 1992; Goldenberg and Shapiro 1996) and the Amazon Basin. As seen in 2008, the combination of an enhanced west African monsoon and suppressed convection in the Amazon Basin (Fig. 8a) is consistent with the ongoing active hurricane era (Fig. 8b). The stronger low-level inflow into the west African monsoon region (Fig. 5a) and stronger upper-level outflow from that region (Figs. 5d, 8a), are also consistent with these results.

An enhanced west African monsoon system has major impacts on the 200-hPa circulation even well away from the monsoon region (Bell and Chelliah 2006), as indicated in 2008 by the pronounced inter-hemispheric symmetry of streamfunction anomalies across the eastern subtropical Atlantic Ocean and Africa (Fig. 9a). This pattern reflects enhanced upper-level ridges in the subtropics of both hemispheres and a stronger tropical easterly jet, both of which are consistent with the ongoing high-activity era (Fig. 9b).

(b) La Niña

NOAA's Climate Prediction Center noted in their monthly ENSO advisory issued July 10th 2008 (www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_jul2008) that the 2007-08 La Niña episode dissipated during June, when SSTs returned to near average across the east-central equatorial Pacific (Fig. 10a). Despite this evo-

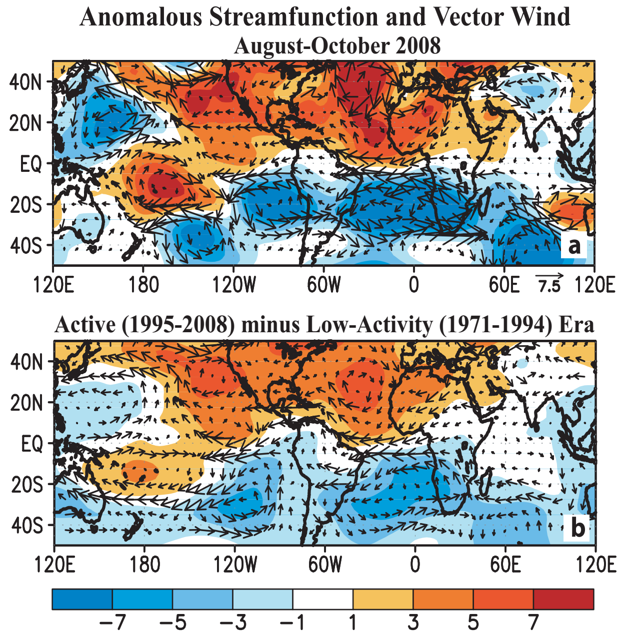

Fig. 9. 200-hPa streamfunction (shading) and total wind vectors (m s^{-1}): (a) Aug-Oct 2008 anomalies and (b) high-activity (1995-2008) period means minus low-activity (1971-1994) period means. Anomalous ridges are indicated by positive values (red) in the NH and negative values (blue) in the SH. Anomalous troughs are indicated by negative values in the NH and positive values in the SH. Anomalies are departures from the 1971-2000 monthly means.

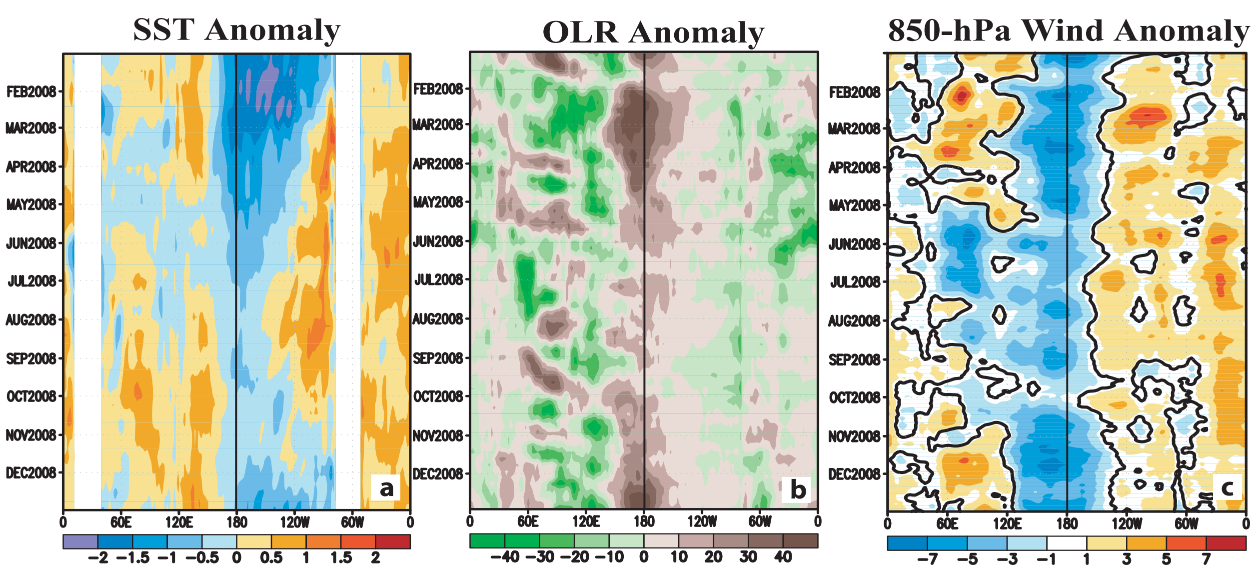

Fig. 10. Equatorial time longitude sections of anomalies averaged between 5N-5S: (a) weekly sea surface temperatures (C), (b) Outgoing Longwave Radiation (OLR, W m^{-2}), and (c) 850-hPa zonal winds (m s^{-1}). In (b) brown shading shows suppressed convection and green shading shows enhanced convection. In (c) blue shading shows easterly anomalies and orange shading shows westerly anomalies. Anomalies are departures from the (a) 1971-2000 weekly SST means, (b) 1979-2000 pentad OLR means , and (c) 1971-2000 pentad zonal wind means. A 3-pt running mean is applied to the data in all plots.

lution, two prominent La Niña signals lingered during the Atlantic hurricane season. These signals included suppressed equatorial convection near the date line (brown shading, Fig. 10b), and anomalous low-level easterly winds across the central and western equatorial Pacific (blue shading, Fig. 10c). As seen during 2008, this anomalous convection favors increased Atlantic hurricane activity (Gray 1984, Bell and Chelliah 2006) primarily by contributing to easterly 200-hPa wind anomalies and reduced vertical wind shear in the western MDR.

The pattern of 200-hPa streamfunction anomalies establishes the link between these conditions in the western MDR and the suppressed convection near the date line. In particular, the large-scale pattern of cyclonic anomalies over the western subtropical Pacific Ocean in both hemispheres and anticyclonic anomalies over the eastern subtropical Pacific Ocean and Caribbean Sea (Fig. 9a) is consistent with suppressed convection near the date line. Associated with this circulation, the tropical easterly wind anomalies at 200-hPa extended from the eastern Pacific to the tropical Atlantic, contributing to reduced vertical wind shear in the western MDR.

Historically these conditions, when combined with the active Atlantic phase of the tropical multi-decadal signal as was seen in 2008, greatly increase the probability of an above-normal Atlantic hurricane season (Bell and Chelliah 2006, Bell et al. 2006b).

c. July 2008 hurricane activity in the MDR

During July, the stability and moisture patterns are normally unfavorable to low-latitude tropical storm formation in the MDR (DeMaria et al. 2001). However, during July 2008 two named storms (including long-lived MH Bertha) formed in the MDR.

Two main reasons for this increased early-season activity are evident. First, the tropics-wide 200-hPa circulation anomalies described above were in place even well before the peak ASO months of the season (Fig. 11), which increased the window of opportunity for tropical cyclone formation especially during July. Second, the regional circulation anomalies during July (Fig. 12) very similar to those observed during the peak of the season (compare to Fig. 5). Bell et al. (2006) also noted similar early-season conditions during the active month of July 2005.

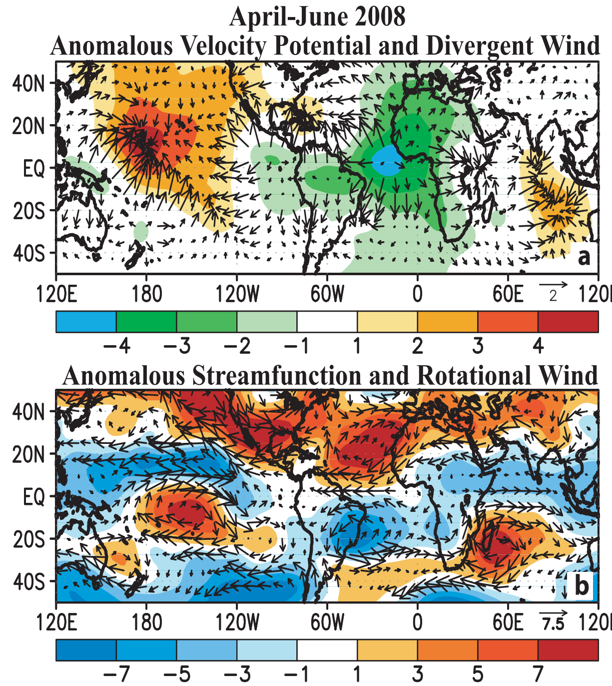

Fig. 11. Apr-Jun 2008 anomalies at 200-hPa: (a) velocity potential (shading) and divergent wind vectors (m s^{-1}), and (b) streamfunction and total wind vectors (m s^{-1}). In (b) anomalous ridges are indicated by positive values (red) in the NH and negative values (blue) in the SH. Anomalous troughs are indicated by negative values in the NH and positive values in the SH. Anomalies are departures from the 1971-2000 monthly means.

DeMaria et al. (2001) showed that favorable thermodynamics are often critical for early-season activity in the MDR. During July 2008, these favorable thermodynamic conditions occurred in combination with the above inter-related set of atmospheric anomalies that are known to produce increased activity in the MDR.

5. Summary

2008 marks the tenth above-normal Atlantic hurricane season since the current high-activity era began in 1995. During 1995-2008, seasons have averaged 8 H and 4 MH, with an ACE value of

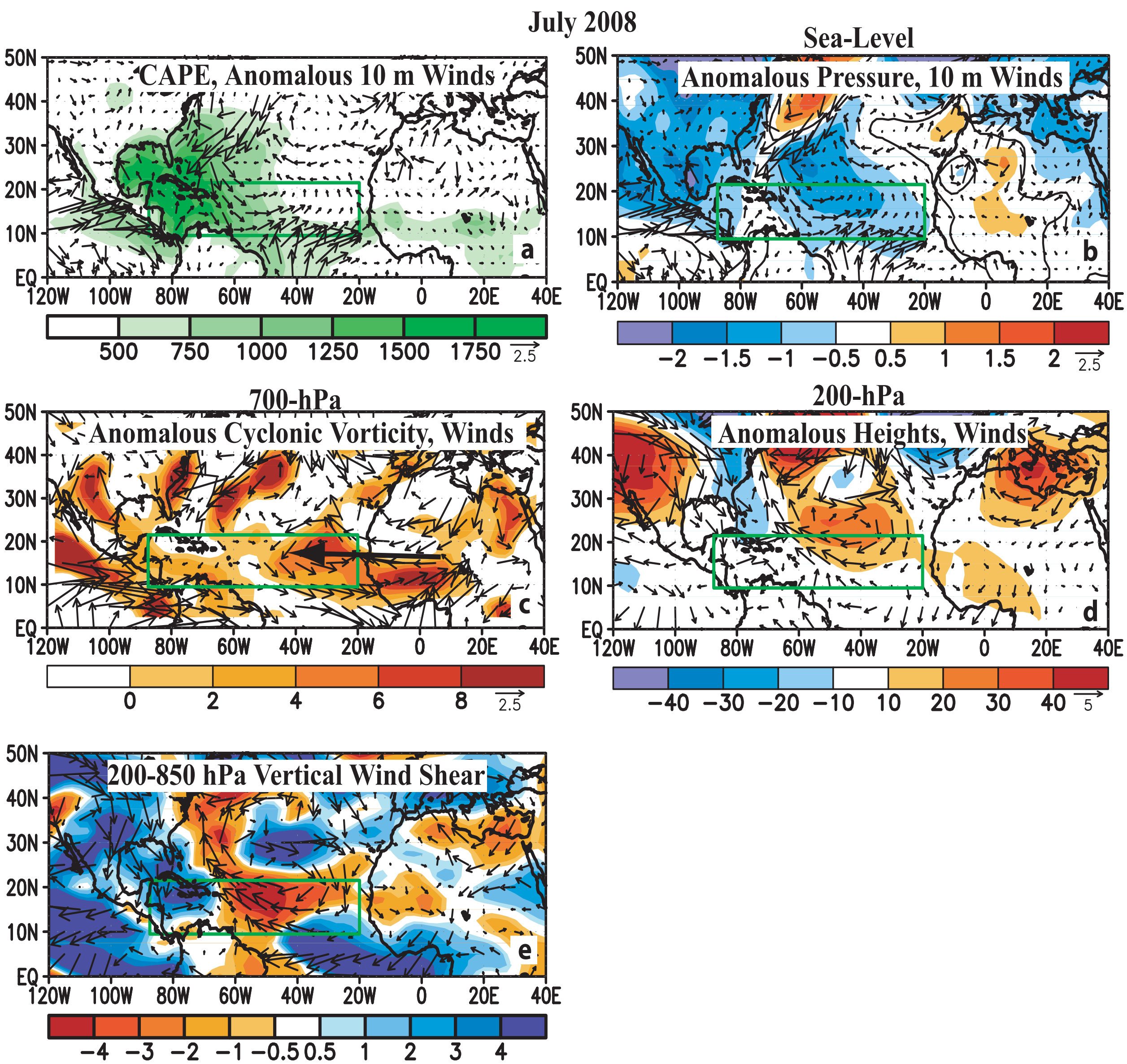

Fig. 12. July 2008: (a) Total CAPE (J kg^{-1}) and anomalous vector winds (m s^{-1}) at 10 m. (b) Anomalous sea-level pressure (shading, hPa) and vector winds at10 m. (c) 700-hPa anomalous cyclonic relative vorticity (shading) and vector winds, with thick solid line indicating the observed AEJ core. (d) 200-hPa anomalous heights and vector winds. (e) 200-850 hPa vertical wind shear magnitude (m s^{-1}) and vectors. In (e), red (blue) shading indicates below- (above-) average magnitude of the vertical shear. Green boxes denote the MDR. Anomalies are departures from the 1971-2000 monthly means.

165% of the median. This activity is similar to the previous high-activity era 1950-1970, when seasons averaged 6.5 H and 3.3 MH, with an ACE value of 136% of the median. These numbers are much higher than those observed during the low-activity era 1971-1994, when seasons averaged 5 H and 1.5MH, with an ACE value of only 75% of the median.

The above normal 2008 Atlantic hurricane activity reflected an inter-related set of atmospheric and oceanic anomalies in the MDR that is known to produce very active seasons. These conditions have been in place since 1995, and are generally similar to those observed during the 1950s-1960s.

Within the MDR, key inter-related anomalies during ASO 2008 included weaker easterly trade winds, lower surface pressure, stronger tropical easterlies and an enhanced ridge at 200-hPa, reduced vertical wind shear, a very conducive structure and position of the 700-hPa African Easterly Jet, deep tropical moisture, and warmer SSTs. This combination not only produces more hurricane activity in the MDR, but also greatly increases the probability of hurricane landfalls in the United States and in the region around the Caribbean Sea, as was seen in 2008.

These conditions can be largely accounted for by the combination of the ongoing active Atlantic phase of the tropical multi-decadal signal and lingering La Niña impacts. For example, key atmospheric anomalies known to be associated with the current active hurricane era were in place as predicted. A nearly identical set of conditions has been described by these same authors for every Atlantic hurricane season since 1998 (Bell et al. 1999-2008). Additionally, although La Niña dissipated in June its related pattern of suppressed equatorial convection lingered throughout ASO, thereby helping to expand the region of reduced vertical wind shear associated with the multi-decadal signal. NOAA's prediction for an above-normal season reflected an accurate forecast of these climate conditions.

Also during 2008, two named storms (including one MH) formed in the MDR during July. This early-season activity reflected exceptionally conducive wind patterns and thermodynamic conditions that are more typical of the peak months of the season. These conditions are also consistent with the above climate factors, which increased the window of opportunity for tropical cyclone formation in the MDR.

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