The 2004 North Atlantic Hurricane Season
A Climate Perspective

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1. Overview

The 2004 Atlantic hurricane season had well above-normal activity, with 15 named storms, 9 hurricanes (H), and 6 major hurricanes [MH, defined as categories 3-5 on the Saffir-Simpson scale, Simpson (1974)]. Nine of these systems struck the continental United States, three as tropical storms (Bonnie, Hermine, and Matthew) and six as hurricanes (Alex, Charley, Frances, Gaston, Ivan, and Jeanne). Three of the hurricanes (Charley, Ivan, and Jeanne) hit as major hurricanes.

Five named storms hit Florida, one as a tropi-

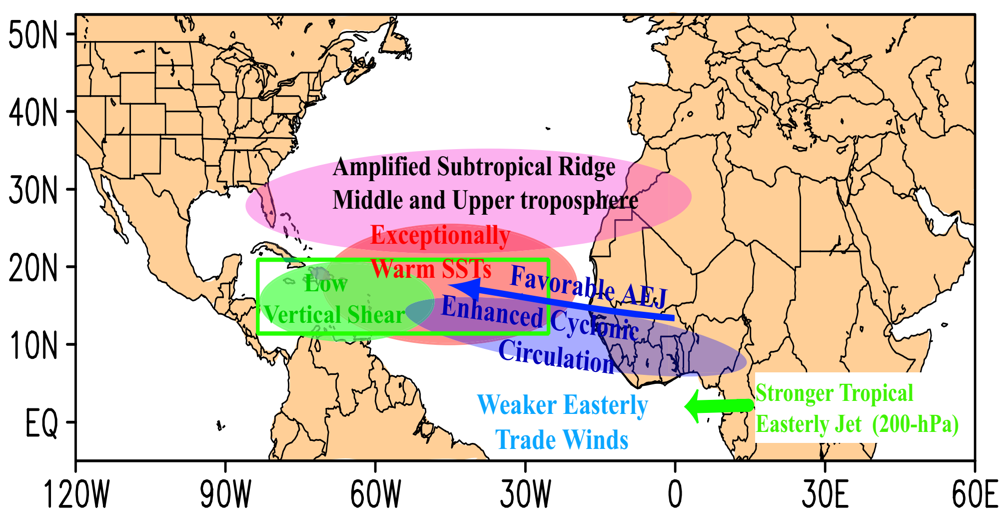

Fig. 1. Schematic representation of conditions during the peak (August-September) months of the above-normal 2004 Atlantic hurricane season. The green box denotes the Main Development Region (MDR), bounded by 90°W-20°W and 9°N-21.5°N.

cal storm (Bonnie) and four as hurricanes (Charley, Frances, Ivan, and Jeanne). This ties the record with Texas (in 1886) for the most hurricanes to hit one state in a single season. Also, all three landfalling major hurricanes struck Florida, which is the most ever recorded for that state in a single season since accurate state records began in 1900. Total rainfall associated with the U.S. landfalling storms reached 500 mm or more across Florida, Georgia, and the western Carolinas, and accounted for 60%-80% of the total August-September rainfall in these regions.

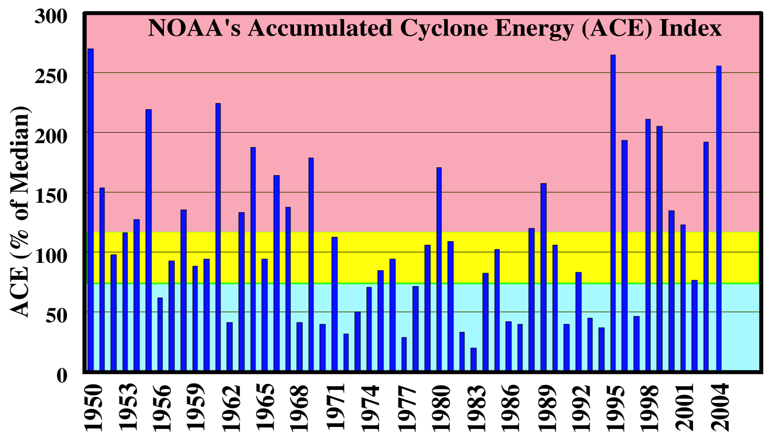

Fig. 2. Atlantic hurricane seasonal values of NOAA's Accumulated Cyclone Energy (ACE) index expressed as percent of the 1951-2000 median value. NOAA definitions of season types are indicated by the background shading, with pink, yellow, and blue indicating above-, near-, and below-normal seasons, respectively.

Over the central and eastern tropical Atlantic, most aspects of the atmospheric circulation and sea-surface temperatures departures during the peak August-September months of the 2004 season (Fig. 1, section 4) can be attributed to the ongoing active Atlantic multidecadal signal (section 5). Over the subtropical North Atlantic an amplified subtropical ridge resulted in very low vertical wind shear across the Caribbean Sea, and in an exceptionally focused easterly steering current confined almost entirely to the deep Tropics. These conditions caused many hurricanes to track further south and west than normal, ultimately making landfall in Florida and the Gulf Coast region of the United States.

Although weak El Niño conditions appeared by mid-August, the enhanced tropical convection typically associated with El Niño never became established. Consequently, the typical downstream atmospheric teleconnections, which would have had a suppressing influence on seasonal hurricane activity by increasing the vertical wind shear over the Caribbean Sea and western tropical Atlantic, did not develop.

2. 2004 Seasonal Activity

An accepted measure of seasonal activity is the National Oceanic and Atmospheric Administration's (NOAA's) Accumulated Cyclone Energy (ACE) index (Bell et al. 2004), which accounts for the combined strength and duration of tropical storms and hurricanes during a given season. This wind energy index is calculated by summing the squares of the 6-hourly maximum sustained surface wind speed in knots ($Vmax^2$) for all periods while the system is either a tropical storm or hurricane. The total ACE value for the 2004 season was August-September 257% of the 1951-2000 median (Fig. 2). This is the third largest seasonal value in the 1950-2004 record, exceeded only by 1950 and 1995.

During above-normal hurricane seasons a large fraction of the total ACE value results from tropical storms that form in the Main Development Region [MDR, which consists of the tropical Atlantic and Caribbean Sea south of 21.5°N (green box in Fig. 1)], and later become hurricanes and major hurricanes (Goldenberg and Shapiro 1996). During 2004 nine tropical storms formed in the MDR, with seven subsequently becoming hurricanes. These numbers are larger than the average of 5.6 TS that form in the MDR during above-normal seasons, and result in an average of 4.3 hurricanes. They are considerably larger than the long-term seasonal average of 4.6 TS that form in the MDR and result in only 3.2 hurricanes.

During 2004 the systems first named in the MDR accounted for 91% of the seasonal ACE value. MH Ivan, the strongest of the 2004 hurricanes, eventually made landfall in Alabama and produced the largest storm total ACE value (70.4 x 104 kt2) in the reliable record.

The historical time series of the ACE index reflects large multi-decadal fluctuations in seasonal activity, with 1995 marking the onset of the current period of above-normal activity (Goldenberg et al 2001). During the 10-yr period 1995-2004, seasons have averaged 13.6 TS, 7.8 H, 3.8 MH, with every season having above-normal activity except for the two El Niño years of 1997 and 2002. In contrast, seasons during the below normal 24-yr period 1971-1994 averaged only 8.6 TS, 5 H, and 1.5 MH, and only three seasons were above normal (1980, 1988, 1989). These dramatic differences between above- and below-normal hurricane decades result from multi-decadal fluctuations in the number of tropical storms that form in the MDR and eventually become hurricanes (Landsea and Gray 1992, Landsea 1993, Landsea et al. 1999).

3. Landfalling U.S. tropical systems and associated rainfall

During 2004, three of the systems that struck the United States hit as tropical storms (Bonnie, Hermine, and Matthew), three struck as a category 1-2 hurricanes (Alex, Gaston and Frances), and three hit as major hurricanes (Charley, Ivan, and Jeanne). The first eight strikes, including all five Florida strikes, occurred during August and September. For this two-month period rainfall from Florida to Pennsylvania was 200% or more above average (Fig. 3a), mainly due to the landfalling storms. The total rainfall associated with these systems reached 500 mm or more across Florida, Georgia, and the western Carolinas (Fig. 3b), and accounted for 60%-80% of the two-month total in these regions (Fig. 3c).

Rainfall totals for each of the nine named storms that struck the U.S. are summarized in Fig. hurr3. Three hurricanes with long tracks over the eastern United States produced the largest totals. The first of these was H Frances during 5-9 Sep., which

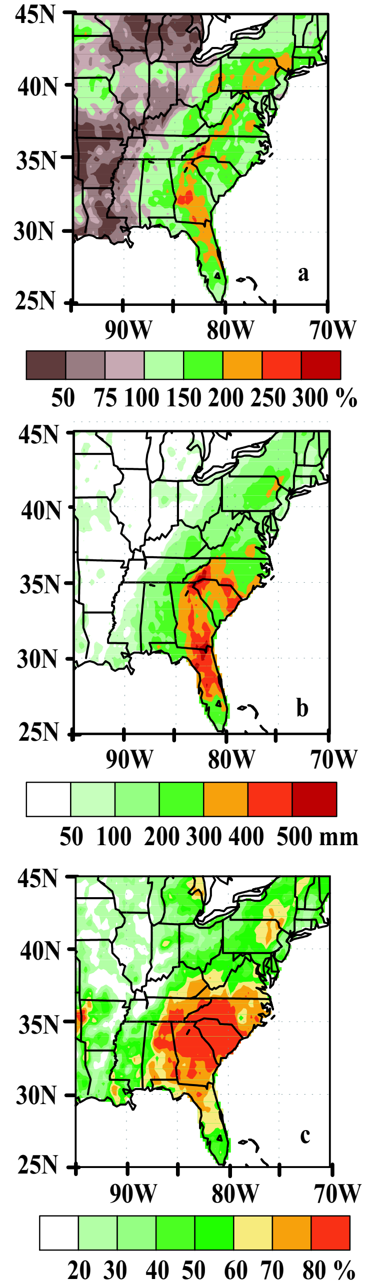

Fig. 3. (a) Percent of normal August-September 2004 precipitation, (b) total rainfall (mm) during the periods in which the eight tropical systems that struck the U.S. during August-September were producing precipitation in U.S., and (c) percent of the total August-September rainfall associated with these eight tropical systems. In (a) normals are calculated from the 1971-2000 base period means.

brought more than 175 mm of rain to Florida, Georgia, and the western Carolina's (Fig. 4f). The second was MH Ivan during16-18 Sep., which produced more than 150 mm from Alabama to Pennsylvania (Fig. 4g). Ivan eventually tracked back into the Gulf of Mexico, where it regained tropical storm status before making a second landfall on 23 Sep. in southeastern Texas. The third was MH Jeanne during 25-28 Sep., which produced 100+ mm totals from Florida to the western Carolinas (Fig. 4h).

All but one of the nine named storms (Alex) that struck the United States during 2004 officially made landfall, which is defined as the circulation center crossing the coastline. Since 2002 the United States has experienced 19 landfalling named storms, with seven occurring in 2002 and four in 2003. Eleven of these 19 systems hit as tropical storms and eight hit as hurricanes. The Gulf Coast region from the southern tip of Texas to the southern tip of Florida has been struck by twelve of these named storms (5 in 2002, 3 in 2003, and 4 in 2004), with 8 hitting as tropical storms and four hitting as hurricanes.

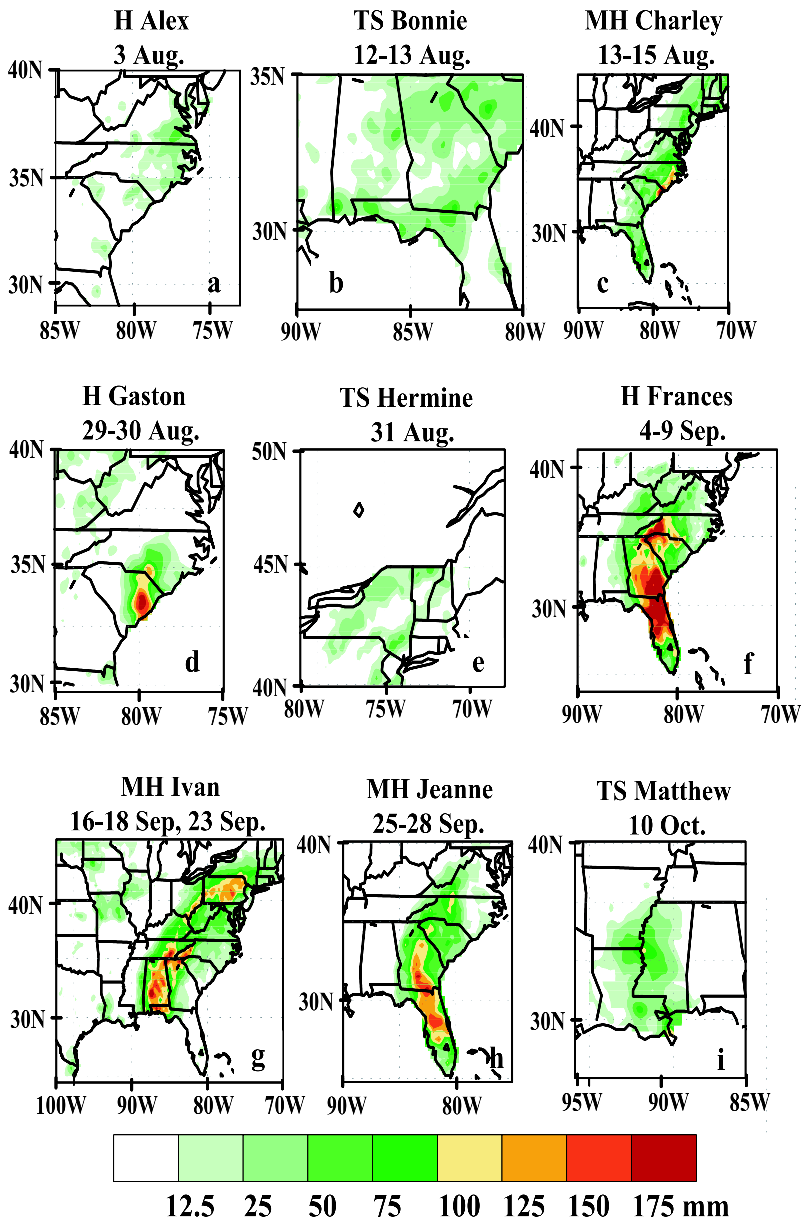

Fig. 4. Storm total rainfall amounts (mm) in the U.S. for the nine tropical systems that struck the country during 2004.

4. Atmospheric and oceanic conditions

Most of the 2004 seasonal activity occurred during August and September. The mean atmospheric and oceanic conditions across the tropical Atlantic during these two months were characteristic of most above-normal seasons (Fig. 1). At middle and upper levels the subtropical ridge was stronger than average from the Gulf of Mexico to northern Senegal (Fig. 5a), with large anticyclonic circulation anomalies also extending northward along the east coast of the United States. South of the mean ridge axis, anomalous upper-level easterly flow covered the entire MDR in association with an enhanced Tropical Easterly Jet. Over the eastern North Atlantic and western Africa, these conditions are consistent with the ongoing active Atlantic multi-decadal signal (section 5).

However, over the western subtropical North Atlantic and eastern United States these conditions

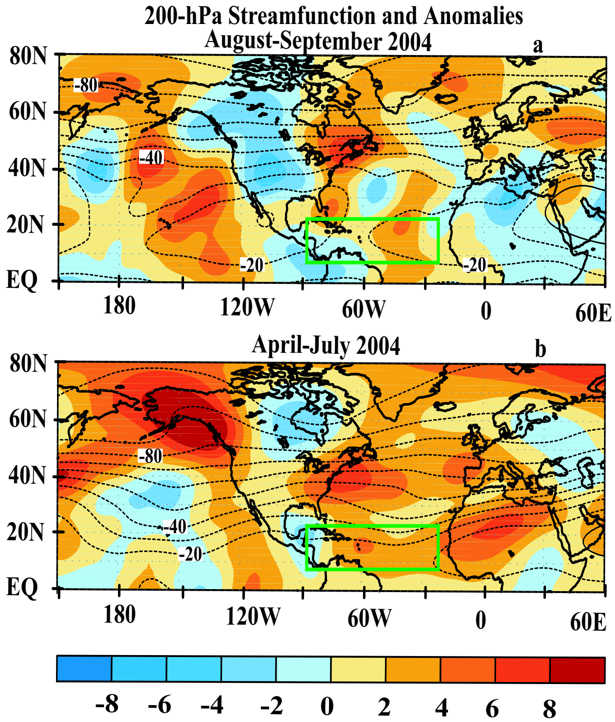

Fig. 5. 200-hpa streamfunction (contours, x 10^6 m^2 s^{-1}) and anomalies (shading) during (a) August-September, and (b) April-July, 2004. Anticyclonic (cyclonic) anomalies are indicated by positive (negative) values. Anomalies are departures from the 1971-2000 base period monthly means. Green box denotes the MDR.

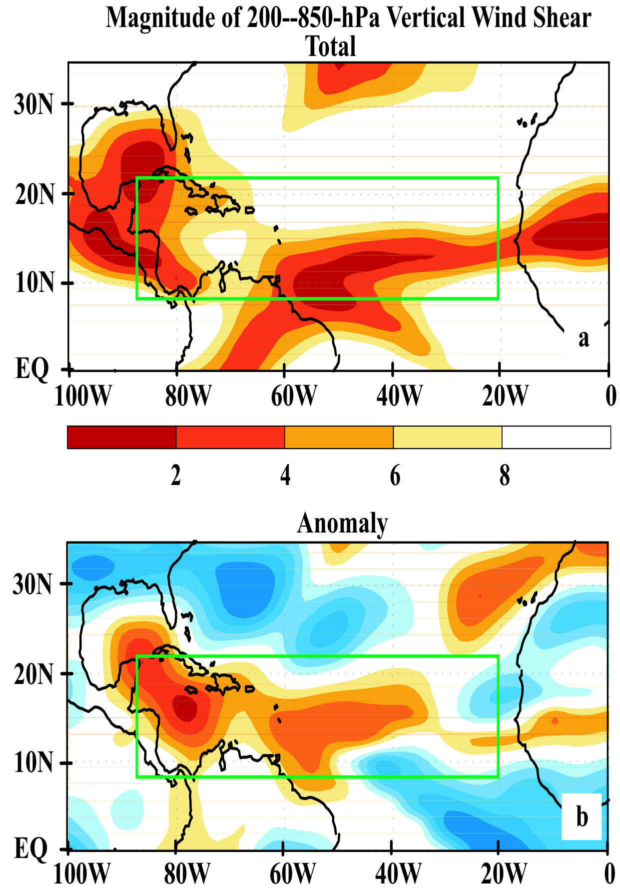

Fig. 6. August-September 2004: 200-850 hPa vertical wind shear magnitude (a) total (m s^{-1}) and (b) anomalies. In (a) only vertical shear magnitudes less than |8 m s^{-1}| are shaded. In (b) yellow-red and blue shading indicates below-average and above-average shear magnitudes, respectively. Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

were linked to large-scale, extratropical circulation anomalies that extended throughout North America. As discussed by Bell and Kousky (2004), these extratropical anomalies first developed during April. They then dominated the mean April-July circulation (Figs. 5b), contributing to extremely warm and dry conditions in Alaska, to an exceptionally cool summer across the eastern half of the U.S., and to a below-average strength of the Southwest U.S. monsoon system.

The pronounced westward extent of the enhanced subtropical ridge and anomalous upper-level easterlies contributed to below-average vertical wind shear across the MDR during August-September (Fig. 6), which allowed for intense and long-lived hurricanes. The mean steering current during September 2004, characterized by a 500-hPa ridge along the U.S. east coast (Fig. 7a), caused hurricanes to track further west than normal, eventually making landfall in Florida and the Gulf Coast region. Several of these systems were then steered over the eastern United States, producing heavy rains and flooding along their paths. These conditions are in marked contrast to the climatological mean (Fig. 7b), which features a broad trough across the eastern U.S. that acts to divert hurricanes out to sea often well prior to reaching the U.S. east coast.

In the lower atmosphere the 700-hPa African Easterly Jet (AEJ) was well-defined, with its associated region of strong cyclonic vorticity extending farther west than normal into the central MDR (Fig. 8a). The AEJ also featured a tongue of high potential vorticity (PV) air extending across western tropical Africa and the eastern MDR (Fig. 8b). A pro-

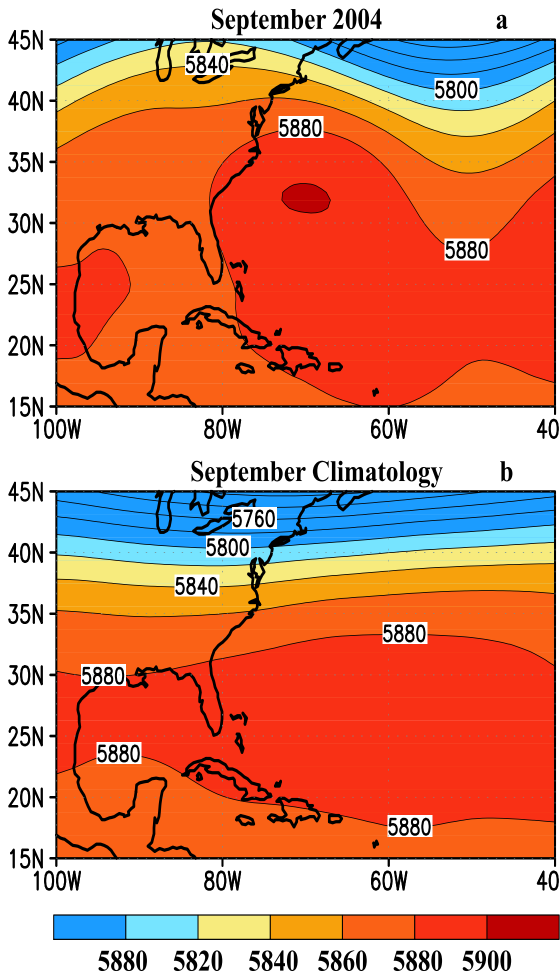

Fig. 7. September mean 500-hPa heights (m) during (a) 2004 and (b) the 1971-2000 climatological mean.

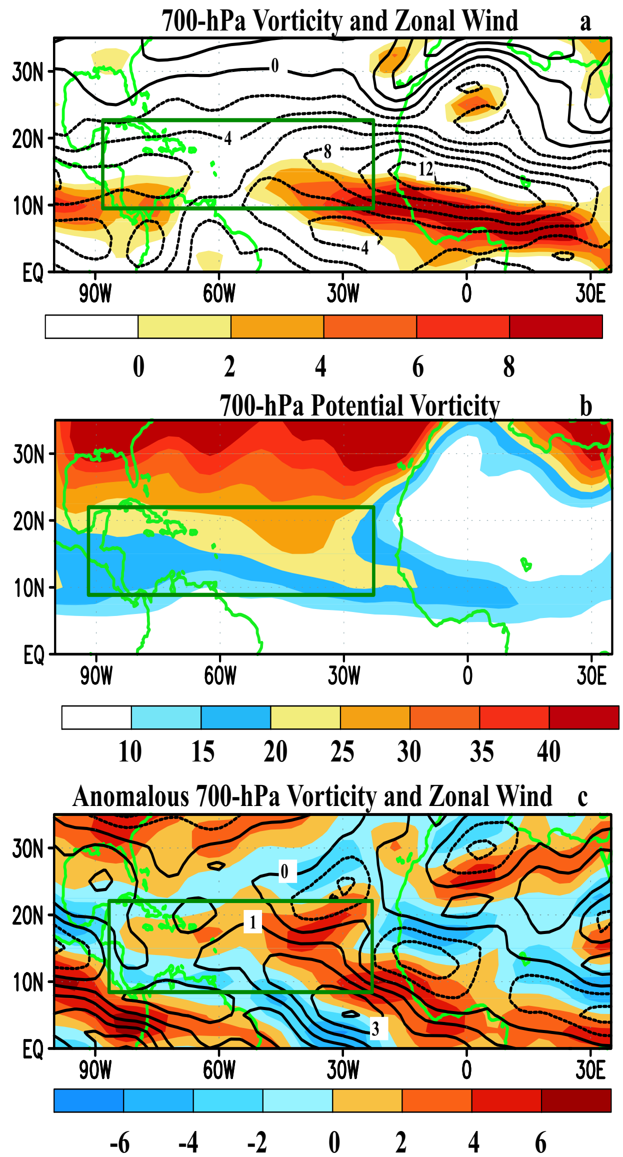

Fig. 8. August-September 2004: 700-hPa (a) zonal winds (contours) and relative vorticity (only cyclonic values shaded), (b) potential vorticity (x 10^{-7} K (s hPa)$^{-1}$), and (c) anomalous zonal winds (contours) and relative vorticity (shading). In (a) and (c) contour interval for zonal winds and anomalies is 1.0 m s^{-1}, and for vorticity and anomalies is 1 x 10^{-6} s^{-1}. In (c) cyclonic anomalies are shaded red and anticyclonic anomalies are shaded blue. Anomalies are departures from the 1971-2000 base period monthly means. Green box in all panels denotes the MDR.

nounced reversal in the north-south component of the PV gradient in these areas indicates that the mean flow satisfied the necessary condition for linear baroclinic instability. Therefore, the AEJ was very favorable for supplying energy to the developing African easterly disturbances during the period. These conditions were consistent with a below-average strength of the tropical easterly trade winds, as indicated by westerly anomalies from the eastern Pacific to western Africa (Fig. 8c).

The 2004 hurricane season also featured exceptionally warm (0.5°-1.25°C above average) sea-surface temperatures (SSTs) in the central MDR (Fig. 9a). For the entire MDR, area-averaged SSTs during August-September were almost two standard deviations above normal, which is the second warmest value since 1950 (Fig. 9b).

The above conditions indicate that the African easterly wave disturbances during the peak of the season were embedded within a linearly unstable mean current at 700-hPa, and experienced an ex-

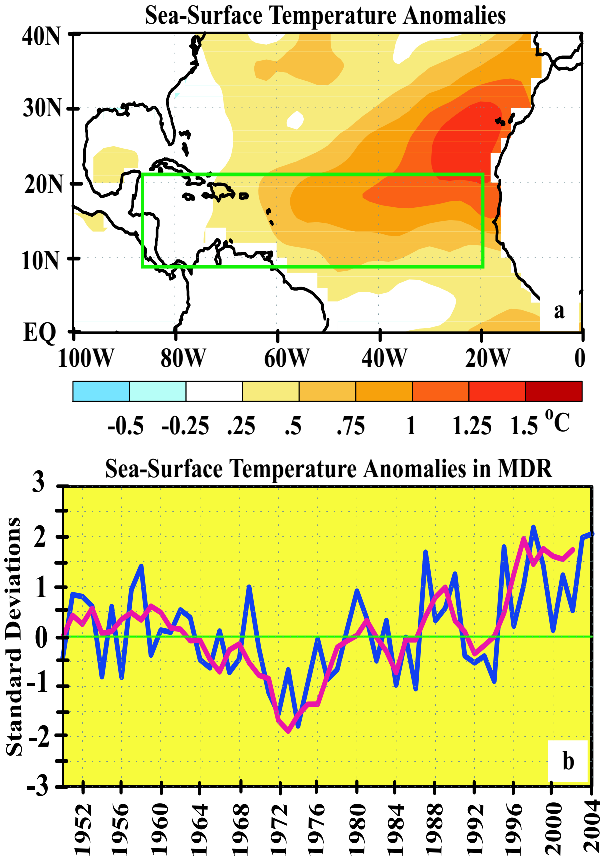

Fig. 9. August-September: (a) anomalous sea surface temperatures (SST, °C) during 2004, and (b) standardized, area-averaged SST anomalies (blue) in the MDR from 1950-2004. In (b) the standardized 5-yr running mean of August-September anomalies is shown red. The analysis is based on the extended reconstructed SST dataset of Smith and Reynolds (2004). Anomalies are departures from the 1971-2000 base period monthly means.

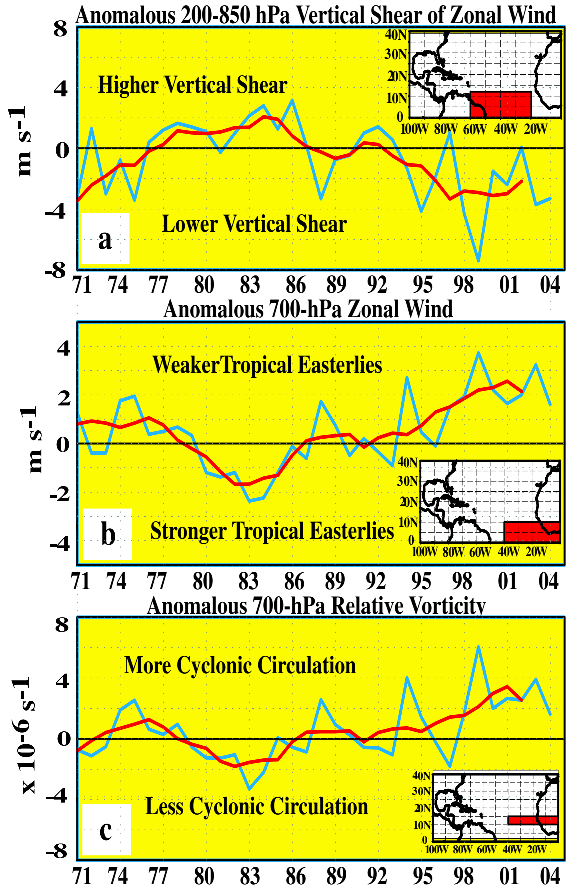

Fig. 10. August-October area-averaged anomaly time series during 1971-2004: (a) 200-850-hPa vertical shear of the zonal wind (m s^{-1}), (b) 700-hPa zonal wind (m s^{-1}), and (c) 700-Pa relative vorticity (x 10^{-6} s^{-1}). Blue curve shows unsmoothed three-month anomalies, and red curve shows a 5-pt running mean of the time series. Averaging regions are shown in the insets. Anomalies are departures from the 1971-2000 base period monthly means.

tended region of increased cyclonic vorticity along the equatorward flank of the AEJ as they moved westward over very warm SSTs into the low-shear environment of the central and western MDR. This combination of conditions is known to favor very active hurricane seasons and is also a key component of the active Atlantic multi-decadal signal (e. g., Bell et al. 2004).

5. The active Atlantic multi-decadal signal

The 2004 hurricane season represents yet another in a series of above-normal seasons that began in 1995 (Fig. 2), in response to favorable atmospheric and oceanic conditions in the MDR during August-October. These conditions include the combination of lower vertical wind shear in the MDR (Fig. 10a, see also Goldenberg et al. 2001), weaker easterly trade winds (Fig. 10b), and increased cyclonic vorticity at 700-hPa along the equatorward flank of the mean African Easterly Jet (Fig. 10c). Conversely, the combination of high vertical wind shear, strong easterly trade winds, and less cyclonic vorticity at 700-hPa, as observed during 1971-1994, is not conducive to Atlantic hurricane formation in the MDR.

Multi-decadal atmospheric fluctuations in the MDR are linked to several inter-related climate phenomena, including the Atlantic multi-decadal mode (Landsea et al. 1999, Mestas-Nuñez and Enfield 1999), the West African monsoon system (Hastenrath 1990, Landsea and Gray 1992, and Goldenberg and Shapiro 1996), and the leading EOF of tropical multi-decadal variability (Chelliah and Bell 2004).

For example, the increased activity since 1995 occurred in conjunction with a transition to the warm phase of the Atlantic multi-decadal mode, which is associated with increased SSTs in the MDR (Fig. 9b, Goldenberg et al. 2001). The increased activity also occurred in association with an overall stronger West African monsoon system and a weaker Amazonian rainfall system, as indicated by a comparison of the 200-hPa velocity potential and divergent wind anomalies during 1995-2004 with those seen during 1971-1994 (Fig. 11a, Chelliah and Bell 2004).

Accompanying the fluctuations in these two convective rainfall regimes, the mean upper-level flow during 1995-2004 has featured a stronger anticyclonic circulation across Africa and the Atlantic Ocean in the subtropics of both hemispheres (Fig. 11b), along with upper-level easterly wind anomalies from Africa to the Caribbean Sea. These conditions are known to be associated with above-normal hurricane seasons.

Because the above climate phenomena significantly influence August-October mean conditions in the MDR and have such strong temporal variability on multi-decadal time scales, it is reasonable to expect the generally elevated levels of Atlantic hurricane activity to continue for the next 10 to 20 years or even longer (Goldenberg et al. 2001). This has implications for the coastal U.S. and the Caribbean Sea region, both of which experience an average of 2-3 hurricane landfalls during above-normal seasons. In contrast, the U.S. experiences an average of only one hurricane landfall during below-normal seasons, while the Caribbean Sea region averages one hurricane landfall every three below-normal seasons.

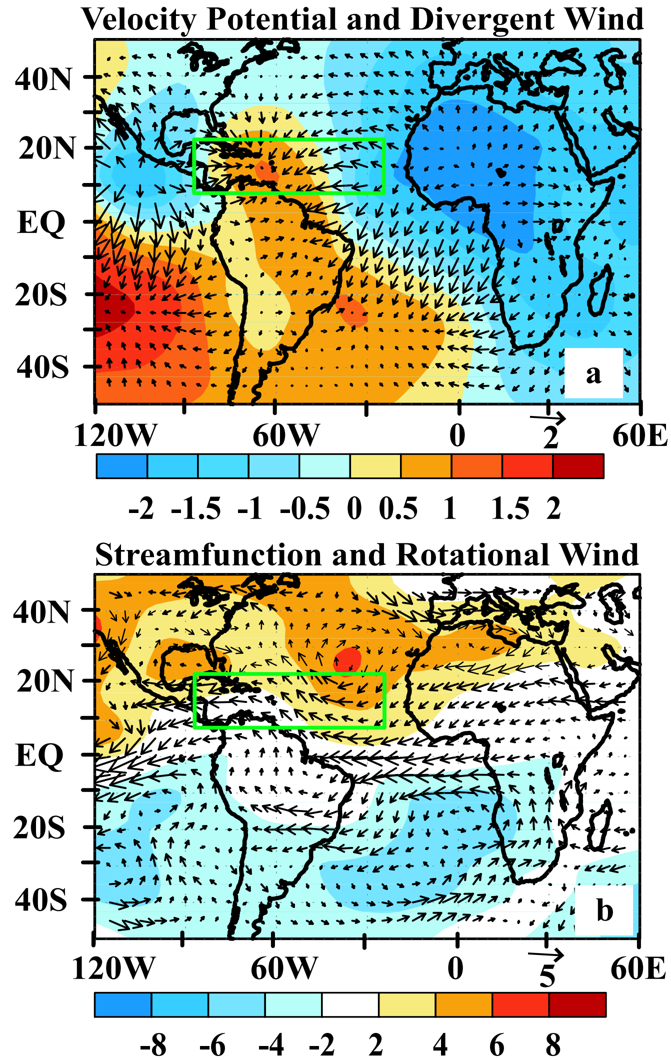

Fig. 11. Difference in the mean 200-hPa circulation between September 1995-2004 and August-September 1970-1994 (1995-2004 minus 1971-1994): (a) velocity potential (shading) and divergent wind vectors and (b) 200-hPa streamfunction (shading) and rotational component of the vector wind. Anticyclonic streamfunction anomalies are indicated by positive (negative) values in the Northern Hemisphere (Southern Hemisphere). Units for velocity potential and streamfunction are 1 x 10^{-6} $m^2 s^{-1}$. Vector scale (m s^{-1}) is shown below each panel. Green box denotes the MDR.

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