The 2003 North Atlantic Hurricane Season
A Climate Perspective

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1. Overview

The North Atlantic hurricane season officially runs from June-November. An average season produces 10 tropical storms (TS), 6 hurricanes (H), and 2 major hurricanes (MH) [defined as maximum sustained wind speeds at or above 100 kts, and measured by categories 3-5 on the Saffir-Simpson scale (Simpson 1974)]. In 2003 the Atlantic basin was extremely active, with 16 tropical storms, 7 hurricanes (H), and 3 major hurricanes (MH) (Fig. 1, section 2).

Five of these Atlantic storms made landfall in the United States, one as a tropical depression (Henri), two as tropical storms (Bill and Grace), and two as hurricanes (Claudette and Isabel). A sixth system, Hurricane Erika, made landfall in northeastern Mexico and brought tropical storm force winds and precipitation to southern Texas (section 3). Mexico also experienced tropical storm conditions from Claudette and Larry, and TS Odette affected Hispañola. Also, Nova Scotia and Bermuda experienced devastating impacts from Hurricanes Juan and Fabian, respectively.

Most of the activity during above-normal Atlantic hurricane seasons occurs during August- October, primarily in response to systems developing from African easterly wave disturbances. During 2003 ten tropical storms, of which four became hurricanes, formed between mid-August and mid-October. Three of these systems became major hurricanes. Above-normal hurricane seasons also feature a high concentration of activity in the Main Development Region (MDR) (Goldenberg and Shapiro 1996), which consists of the tropical Atlantic and Caribbean Sea between 9°-21.5°N (see inset Fig. 3). During 2003 eight tropical storms formed in the MDR. Four of these systems became hurricanes, with three becoming major hurricanes (Fig. 1).

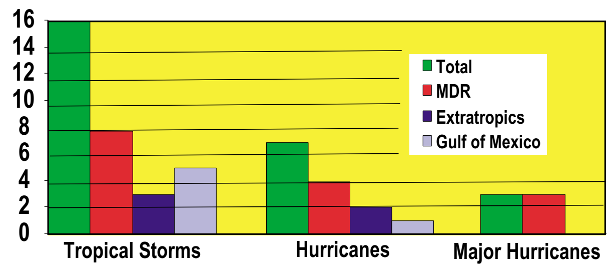

Fig. 1. 2003 Atlantic hurricane season total (green) tropical storms, hurricanes, and major hurricanes. Totals associated with tropical storms forming in the Main Development Region (MDR) (red), the Gulf of Mexico (grey), and the extratropics (blue) are also shown.

Another notable aspect of the season was the formation of five tropical storms over the Gulf of Mexico, which ties the season high observed in 1957. On average 1-2 tropical storms form in this region during a given season. Also, three tropical storms formed outside of the normal (June – November) hurricane season. Tropical Storm Ana formed on 22 April, and TS Odette and TS Peter formed on 4 Dec. and 9 Dec., respectively. This is the first season since 1887 that two tropical storms have formed in December.

Important aspects of the atmospheric circulation during the peak of the 2003 season (Fig. 2, section 4) are attributed to the ongoing active Atlantic multi-decadal signal (Chelliah and Bell 2004), including an amplified subtropical ridge, reduced vertical wind shear in the MDR resulting from upper-level easterly wind anomalies (green arrows) and lower-level westerly anomalies (light blue arrows), an exceptionally favorable African Easterly Jet (AEJ, dark blue arrow), an active West African monsoon system, and above-average sea surface temperatures in the MDR. During August the exceptionally conducive nature of the total signal is also related to a pre-existing mid-latitude circulation pattern known as the positive phase of the East Atlantic teleconnection pattern, and during September-October it is related to an anomalous atmospheric warming across the entire tropical Atlantic in association with a broader warming of the global tropical atmosphere.

2. Seasonal Activity

The National Oceanic and Atmospheric Administration (NOAA) quantifies "total seasonal activity" with the Accumulated Cyclone Energy (ACE) index, which accounts for the combined strength and duration of tropical storms and hurricanes during a given season (Bell et al. 2000). The ACE index is a wind energy index calculated by summing the squares of the estimated 6-hourly maximum sustained wind speed in knots (V_{max}^2) for all periods while the system is either a tropical storm or hurricane (blue bars, Fig. 3). The total ACE index for the 2003 season is 174.75 x 10^4 kt^2, or 200% of the 1951-2000 median value (87.5 x 10^4 kt^2).

NOAA classifies an above-normal Atlantic hurricane season based on two criteria. The seasonal ACE value must exceed 105 x 10^4 kt^2 (120% of the median), and at least two of the following three

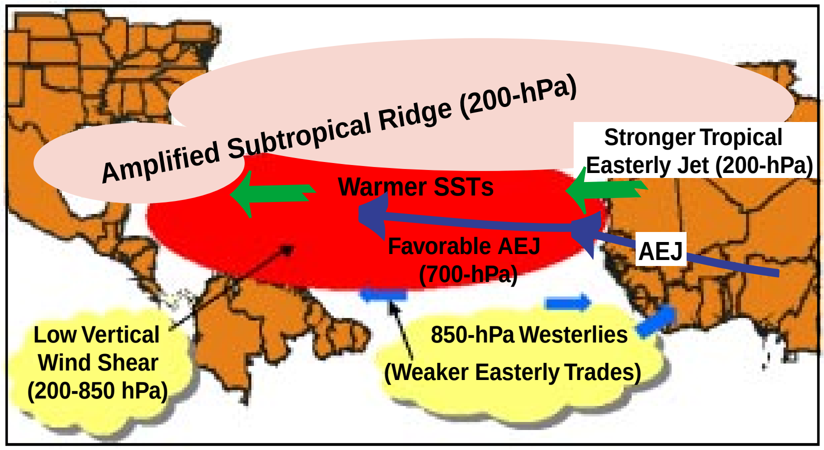

Fig. 2. Schematic representation of conditions during the peak (August-October) of the above-normal 2003 Atlantic hurricane season.

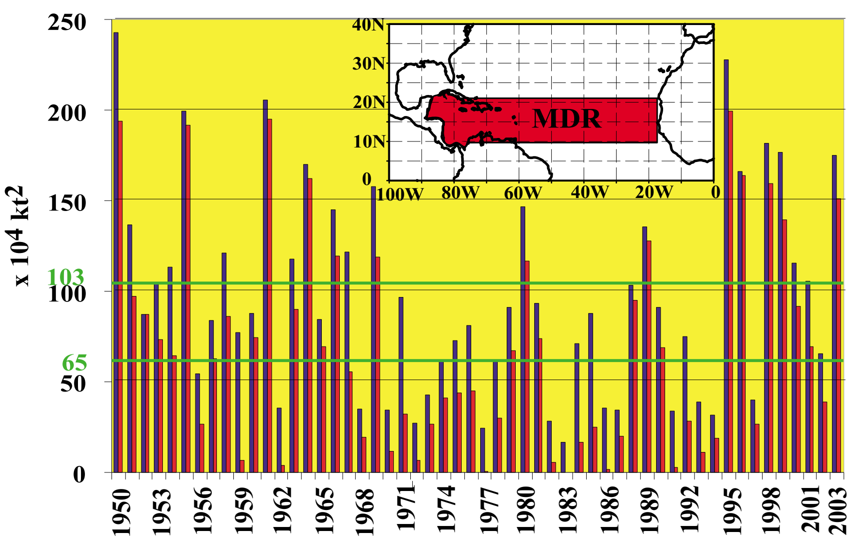

Fig. 3. Seasonal values of the Accumulated Cyclone Energy (ACE) index for the entire Atlantic Basin (blue) and for the Main Development Region (MDR, red). The MDR consists of the tropical Atlantic to 21.5°N and the Caribbean Sea (see inset). The ACE index for the MDR is based on systems that first became tropical storms in that region. NOAA defines near-normal seasons as having a total ACE value in the range 65-103 x 10^4 kt^2 (green lines).

must be above average: numbers of tropical storms, hurricanes and major hurricanes. The 2003 Atlantic hurricane season satisfies both criteria, thus marking a continuation of generally above-normal activity that began in 1995.

The eight tropical systems first named in the MDR accounted for most (86.6%) of the total ACE value during 2003 (red bars), with the three major hurricanes (Fabian, Isabel, and Kate) accounting for 74% of the total. Isabel produced one of the largest observed ACE values (63.3 x 10^4 kt^2) of any Atlantic tropical storm on record (Fig. 4), lasting 8 days as a major hurricane and 1.75 days at category-5 status (wind speeds at or above 140 kts). Fabian and Kate contributed an additional 43.2 x 10^4 kt^2 and 21.9 x 10^4 kt^2 to the ACE index, respectively, lasting 7.25 days and 1.5 days as major hurricanes, respectively. The combined duration of these three storms at major hurricane status is 16.75 days, which is fourth largest in the record behind 1961 (24.5 MH days), 1950 (18.5 MH days), and 1955 (17.25 MH days).

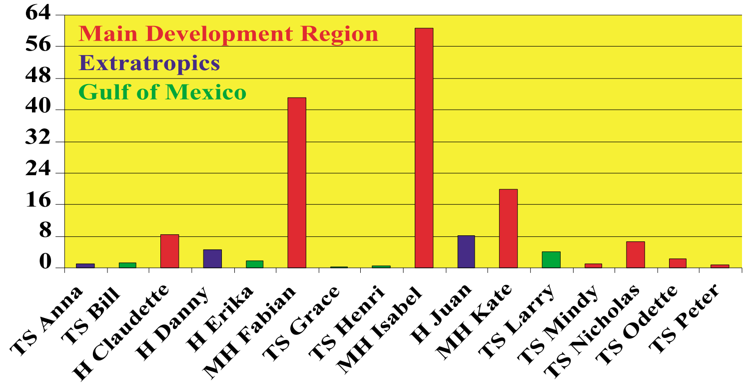

Fig. 4. The Accumulated Cyclone Energy (ACE) value for each of the sixteen Atlantic tropical storms during 2003. The ACE value is determined by summing the squares of the maximum sustained 6-hourly wind speeds while the system is either a tropical storm or hurricane.

The ACE index (Fig. 3) shows large multi-decadal fluctuations in total seasonal activity, characterized by above-normal activity during 1950-1969 and 1995-2003, and below-normal activity during 1970-1994 (see also Goldenberg et al 2001, Bell 2003). During 1995-2003 Atlantic hurricane seasons have averaged 13 TS, 7.6 H, and 3.6 MH. These numbers are larger than any consecutive nine-year period in the reliable record dating back to 1944. However, because of continuous improvements in the observational network, including satellite technology, aircraft measurements, and Doppler radar, it is likely that more systems are identified in the later part of the record than during the above-normal decades of the 1950s-1960s (Goldenberg et al. 2001). During the below-normal period, seasons averaged only 9 TS, 5 H, and 1.5 MH per season. This multi-decadal variability primarily reflects changes in activity originating in the MDR (Landsea and Gray 1992, Landsea 1993, Landsea et al. 1999), with the 1995-2003 mean MDR-based ACE index of 114 x 10^4 kt^2 nearly triple the 1970-1994 average of 41 x 10^4 kt^2.

3. Rainfall from landfalling U.S. tropical systems

Five named Atlantic storms made landfall in the United States during 2003, with a sixth system (H Erika) making landfall in northern Mexico, bringing tropical-storm force winds and rain to southern Texas. This compares with seven landfalling U.S. systems during 2002, when six hit as tropical storms and one hit as a hurricane (Bell 2003). For the period 2002-2003 twelve named storms have made landfall in the U.S, with nine (four in 2003 and five in 2002) striking the Gulf Coast.

During 2003 the first of these Gulf Coast systems (TS Bill) produced more than 150 mm of rain across eastern Louisiana, Mississippi, and western Alabama during 30 June- 1 July (Fig. 5a). Hurricane Claudette then crossed eastern Texas on 15-16 July, generally producing totals of 75-100 mm (Fig. 5b). One month later Hurricane Erika made landfall in northeastern Mexico on 16-17 August, and brought tropical storm force winds to extreme southern Texas. Erika produced 75-100 mm of rain in northeastern Mexico and a range of 25-75 mm in southern Texas (Fig. 5c). TS Grace brought 75-100 mm of rain to southeastern Texas on 31 August (Fig. 5d). This system was followed by TS Henri, which generally brought 100-125 mm of rain to west-central Florida on 6 September (Fig. 5e).

The sixth Atlantic system to make U.S. landfall was Hurricane Isabel, which came onshore along the North Carolina coast as a category-2 hurricane on 18 September. Rainfall totals associated with Isabel averaged 100-200 mm across eastern North Carolina and Virginia, and 50-100 mm across West Virginia and eastern Ohio (Fig. 5f). This storm was directly responsible for 16 fatalities and produced massive power outages in the Mid-Atlantic region, with total damages estimated by the National Hurricane Center at approximately US$3.4 billion.

The six named storms made landfall between 30 June and 9 October. During this period precipitation totals exceeded 500 mm along the Gulf Coast from eastern Texas to southern Florida, and across North Carolina and Virginia (Fig. 6a). These amounts are more than twice the long-term average in southern Texas, 100%-150% of normal along the Gulf Coast, and 150%-200% of normal in the Mid-Atlantic States (Fig. 6b). This excess precipitation is attributed largely to the land falling tropical systems (Fig. 6c), which generally accounted for 25%-40% of the total seasonal rainfall in these areas (Fig. 6d).

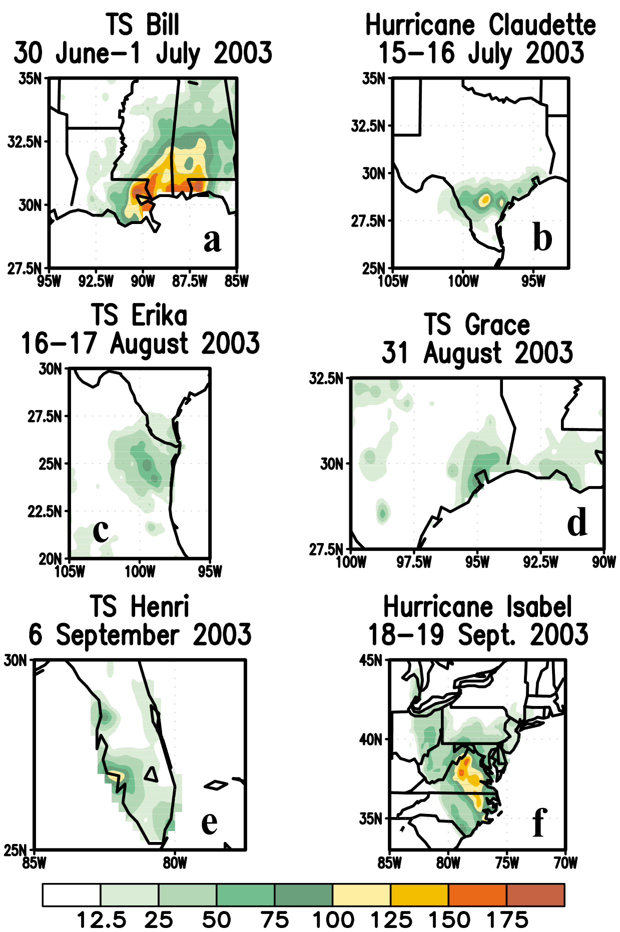

Fig. 5. Total rainfall (mm) over land associated with the six U.S. landfalling named storms during 2003: a) TS Bill during 30 June-1 July, b) Hurricane Claudette during 15-16 July, c) H Erika during 16-17 August, d) TS Grace on 31 August, e) TS Henri on 6 September, and f) H Isabel during 18-19 September.

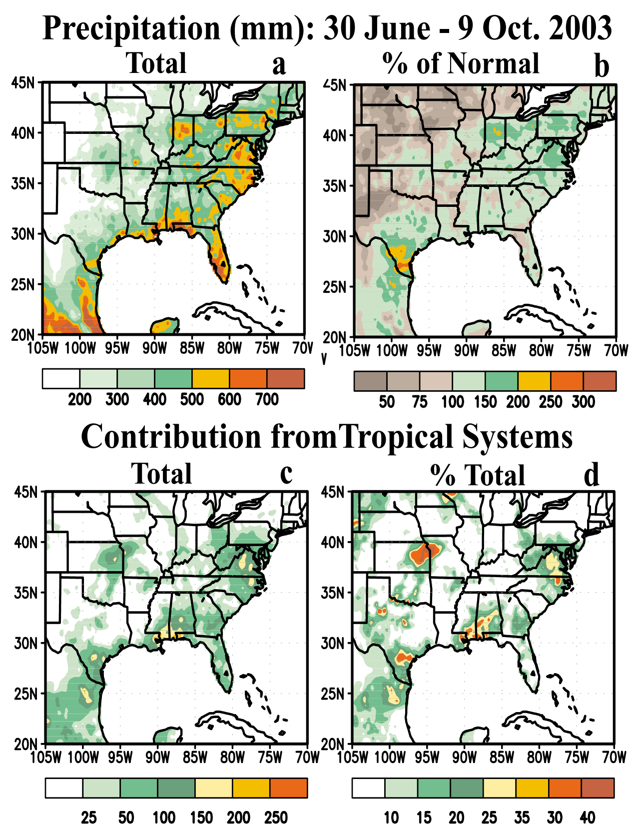

Fig. 6. 30 June-9 October 2003 precipitation: (a) total (mm) and (b) percent of the 1971-2000 normal. c) Total rainfall and (d) percent of the total associated with the six landfalling storms (Fig. 5).

4. Environmental Conditions

a. 200-hPa and 850-hPa circulation and vertical wind shear

During Aug.-Oct. 2003 the mean 200-hPa subtropical ridge axis was stronger and shifted north of normal from the Gulf of Mexico to northern Senegal (Fig. 2). South of the ridge axis upper level easterly wind anomalies covered the entire MDR in association with an enhanced Tropical Easterly Jet (green arrows). The ongoing multi-decadal signal can account for the amplified subtropical ridge and enhanced tropical easterly jet over the eastern North Atlantic and Africa (Chelliah and Bell 2004). Also, these features are not related to the ENSO-neutral conditions observed during the peak of the season.

During August the extensive area of positive 200-hPa height anomalies across the tropical North Atlantic is also partly related to a continuation of the positive phase of the East Atlantic teleconnection pattern (Fig. 7). This pattern has strong links to the both the subtropics and extratropics, and during April-August was associated with a marked amplification of the 200-hPa subtropical ridge across the North Atlantic (Fig. 8). During September and October the amplified subtropical ridge is partly related to an anomalous warming throughout the tropical Atlantic (red, Fig. 9), which occurred in association with a warming of the global tropics (green).

At 850-hPa westerly zonal wind anomalies across the North Atlantic and western Africa during Aug.-Oct. 2003 (Fig. 10a) reflected weaker than average tropical easterlies. This anomaly pattern was already evident during the preceding four months (Fig. 10b), indicating it did not result from the increased hurricane activity (see also Goldenberg and Shapiro 1996). In both periods these westerly anomalies contributed to anomalous cyclonic relative vorticity at 850-hPa across the heart of the MDR.

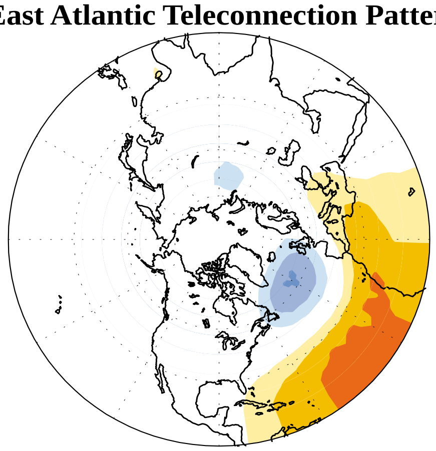

Fig. 7. The positive phase of the East Atlantic teleconnection pattern as indicated by 500-hPa height anomalies. Positive anomalies are shaded orange, negative anomalies are shaded blue.

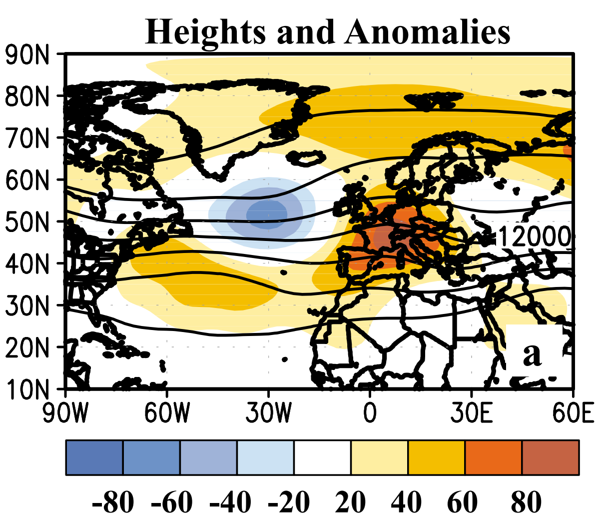

Fig. 8. April-August 2003: 200-hPa heights (m, contours) and anomalies (shading). Anomalies are departures from the 1971-2000 base period monthly means.

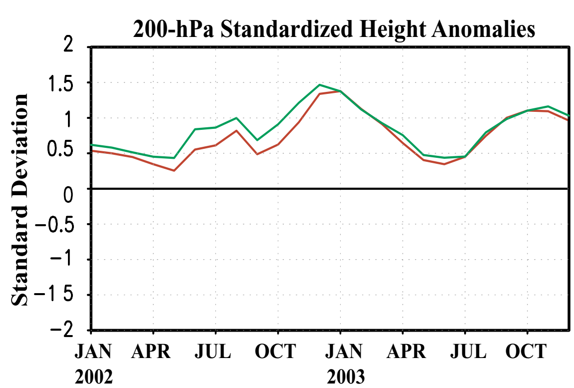

Fig. 9. Standardized values of the three-month running mean area-averaged 200-hPa height anomalies calculated for the entire global Tropics (20°N-20°S) (green curve) and for the region centered on the tropical Atlantic (120°W-40°E, 20°N-20°S) (red curve). Anomalies are departures from the 1971-2000 base period monthly means.

The combination of upper- and lower-level zonal wind anomalies resulted in easterly vertical wind shear anomalies between 200-850 hPa from the eastern tropical Pacific to western Africa (Fig. 11a). The result was lower total vertical wind shear over the heart of the MDR (Fig. 11b), and higher total shear over both tropical western Africa and portions of the eastern tropical Pacific. This three-celled anomaly pattern is typical of other above-normal Atlantic hurricane seasons. It is also consistent with the enhanced 2003 West African monsoon system, and with a below average 2003 East Pacific hurricane season that featured a record low of zero major hurricanes.

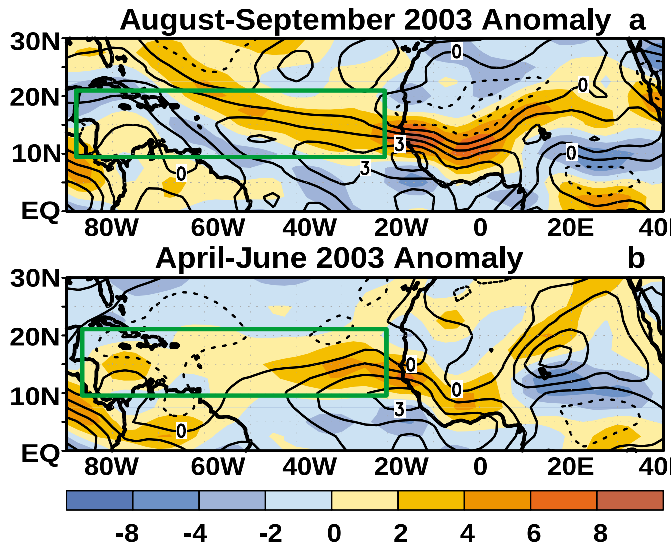

Fig. 10. Anomalous 850-hPa zonal winds (contours, interval is 1.0 m s^{-1}) and relative vorticity (shading, x 10^{-6} s^{-1}) during (a) August-September 2003, and (b) April-July 2003. Solid (dashed) contours indicate westerly (easterly) wind anomalies. Cyclonic (anticyclonic) relative vorticity anomalies are shaded orange (blue). Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

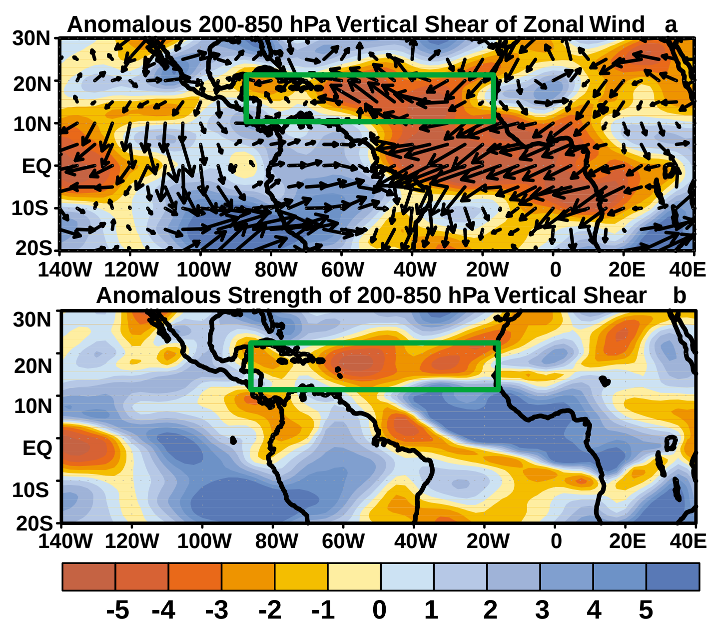

Fig. 11. August-September 2003 (a) anomalous 200-850 hPa vertical shear of zonal wind (shaded, ms^{-1}) and anomalous vertical shear vector, and (b) anomalous strength of the total 200-850 hPa vertical shear. In (a) red indicates anomalously easterly shear and blue indicates anomalously westerly shear. In (b) red indicates lower total shear and blue indicates higher total shear. Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

b. 700-hPa African Easterly Jet, Convective Available Potential Energy (CAPE), and SSTs

During August-October tropical cyclogenesis in the MDR tends to be associated with amplifying African easterly wave disturbances (Reed et al. 1977) moving within the region of high cyclonic relative vorticity along the equatorward flank of the 700-hPa African Easterly Jet (AEJ). During 2003 the AEJ was well defined (contours, Fig. 12a) with high values of cyclonic relative vorticity extending along its entire equatorward flank (shading). The AEJ was also shifted to almost 20°N over the central MDR, roughly 5° of latitude farther north than its climatological mean position (Bell and co-authors, 2000, their Fig. 31). This AEJ structure is consistent with the weaker-than-average tropical easterlies and enhanced 850-hPa cyclonic relative vorticity previously noted across the heart of the MDR (Fig. 10a).

The AEJ also featured a tongue of high potential vorticity (PV) air extending across the eastern half of the MDR and western tropical Africa (Fig.12b). A pronounced reversal in the north-south component of the PV gradient is seen in these areas, which satisfies the necessary condition for linear baroclinic instability. This structure suggests that the AEJ was very favorable for supplying energy to the developing African Easterly disturbances.

An enhanced cross-equatorial flow of deep tropical moisture was also evident at low levels, which contributed to high values of Convective Available Potential Energy (CAPE) extending well into the central MDR along the equatorward flank of the AEJ (Fig. 13a). These high CAPE values were also associated with near-record warm SSTs (0.5°-1°C above average) throughout the MDR (Fig. 13b). Area-averaged SSTs in the MDR were two standard deviations above normal during August-October 2003, which is comparable to the record warmth seen during the extremely active 1998 season (Fig. 13c).

These results indicate that the African easterly wave disturbances during the peak of the 2003 season were embedded within a linearly unstable mean current, and experienced an extended region of increased cyclonic vorticity as they propagated westward over very warm SSTs into the low-shear, high CAPE environment in the heart of the MDR. These conditions are exceptionally conducive to tropical cyclogenesis, as has also been described for the above normal 1998-2000 Atlantic hurricane seasons by Bell et al. (1999, 2000) and Lawrimore et al. (2001).

These very prominent circulation anomalies have prevailed throughout the above normal period 1995-2003, with the exception of the two El Niño years (1997, 2002) (Fig. 14). In contrast, the below-normal seasons during the 1980's featured a combination of anomalous westerly (i.e. increased) vertical wind shear over the central tropical North Atlantic (Fig. 14a, see also Goldenberg et al. 2001),

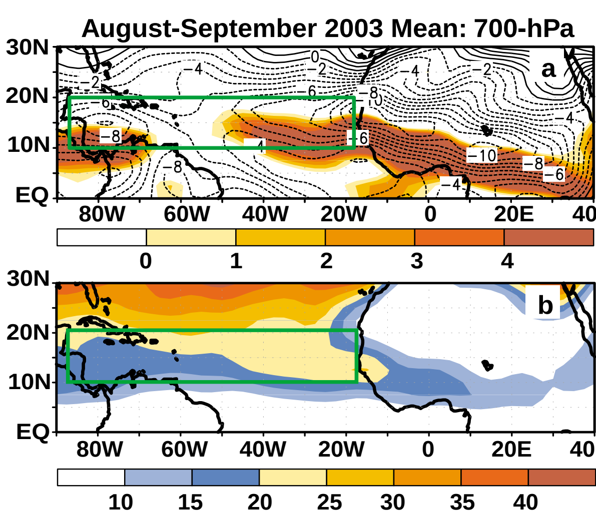

Fig. 12. August-September 2003 mean 700-hPa (a) zonal winds (contours, interval is 1.0 m s^{-1}) and relative vorticity (shading, x 10^{-6} s^{-1}) and (b) potential vorticity (x 10^{-7} K (s $hPa)^{-1}$). In (a) only cyclonic vorticity values are shaded. Green box denotes the MDR.

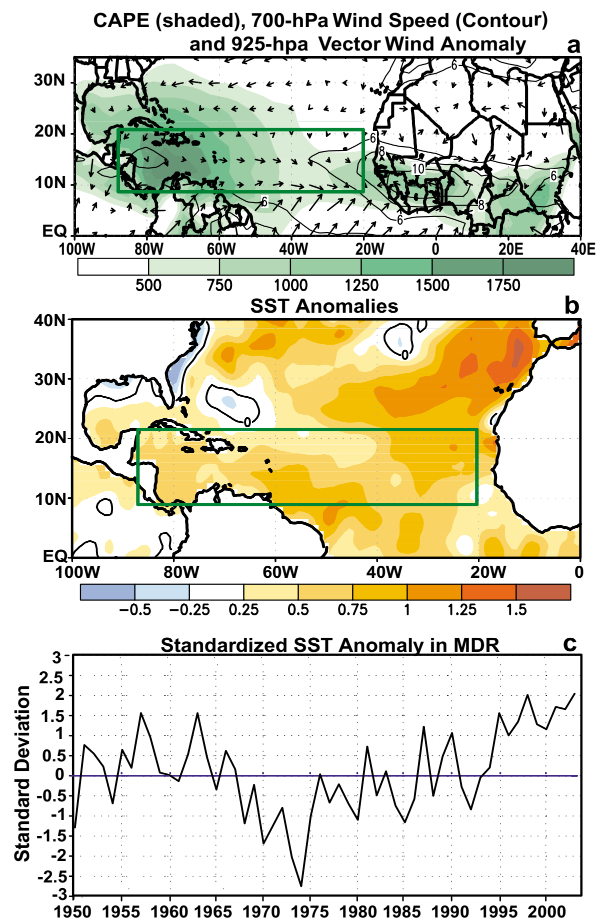

Fig. 13. August-October 2003 (a) convective Available Potential Energy (CAPE) (shaded, J kg^{-1}), 700-hPa wind speeds (contours, interval is 2.0 m s^{-1}), and anomalous 925-hPa wind vector, (b) Anomalous sea surface temperature (SST, °C). (c) Standardized, area-averaged SST anomalies in the Main Development Region (MDR, 90°W-20°W and 9°N-21.5°N) for consecutive August-October periods from 1950-2003. Green box in panels (a) and (b) shows the MDR. Anomalies in (a) and (b) are departures from the 1971-2000 base period means. SST anomalies in (c) are departures from the 1951-2000 base period means.

enhanced tropical easterly trade winds between 5°-10°N (Fig. 14b), and anomalous anticyclonic relative vorticity along the equatorward flank of the mean African Easterly Jet (Fig. 14c). This combination of conditions is not conducive to Atlantic hurricane formation.

These low-frequency fluctuations in key circulation anomalies over the tropical North Atlantic are consistent with the strong relationship between multi-decadal variations in seasonal Atlantic Basin activity and the West African monsoon system (Hastenrath 1990, Landsea and Gray 1992, and Goldenberg and Shapiro 1996). They are also consistent with the observed transition to the warm phase of the Atlantic multi-decadal mode during the early/ mid-1990s (Landsea et al. 1999, Mestas-Nuñez and Enfield 1999). Chelliah and Bell (2004) have shown that these multi-decadal fluctuations are associated with SST and convective rainfall anomalies spanning the global Tropics. The associated atmospheric circulation anomalies are also tropics-wide, and are important to seasonal Atlantic hurricane activity because they include key circulation features in the MDR (Fig. 14).

The atmospheric conditions favoring the overall higher levels of activity seen during 1995-2003 are expected to continue for perhaps another decade or so (Goldenberg et al. 2001). This means that we can continue to expect above-average numbers of hurricanes and major hurricanes forming in the MDR. Since these systems generally move westward across the tropical Atlantic, they often pose a threat to the United States and the region around the Caribbean Sea.

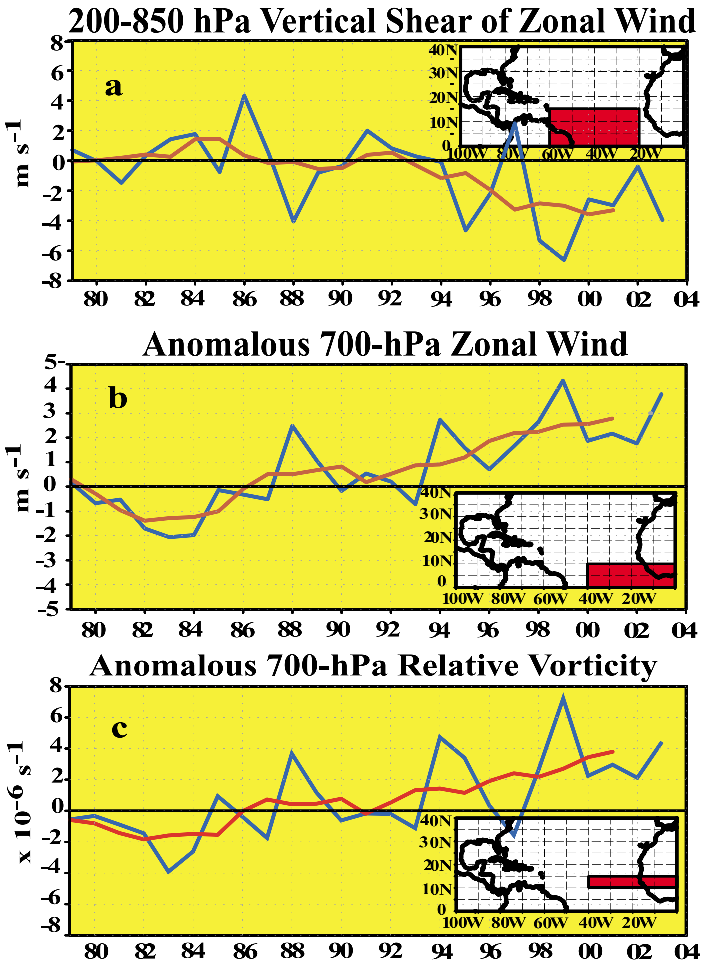

Fig. 14. Area-averaged anomaly time series' for each August-October period between 1979-2003: (a) 200-850-hPa vertical shear of the zonal wind (m s^{-1}), b) 700-hPa zonal wind (m s^{-1}), and (c) 700-Pa relative vorticity (x 10^{-6} s^{-1}). Blue curve shows un-smoothed two-month anomalies, and red curve shows a 5-pt running mean smoother applied to the time series. Averaging regions are shown in the insets. Anomalies are departures from the 1979-1995 base period monthly means.

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