STATE OF THE CLIMATE IN 2003

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ABSTRACT—D. H. Levinson[14] and A.M. Waple[14] (Eds).

The earth's climate was influenced by a moderate El Niño in the tropical Pacific Ocean at the beginning of 2003. This ENSO warm event developed during October–November of 2002, and eventually dissipated during March–April 2003, giving way to near-neutral ENSO conditions for the remainder of the year. Despite the cessation of El Niño during the boreal spring, the ENSO warm event affected regional precipitation anomalies over a broad area of the Pacific basin, including wet anomalies along the west coast of South America, and dry anomalies in eastern Australia, the southwest Pacific, and Hawaii.

The global mean surface temperature in 2003 was within the highest three annual values observed during the period of regular instrumental records (beginning in approximately 1880), but below the 1998 record-high value. Global surface temperatures in 2003 were 0.46°C (0.83°F) above the 1961–90 mean, according to one U.K. record, which ranked as third highest in this archive. In the U.S. temperature archive, the 2003 anomaly was also 0.46°C (0.83°F), equivalent to the 2002 value, which ranked second over the period of record. Similar to the surface temperature anomalies, satellite retrievals of global midtropospheric temperatures ranked 2003 as third warmest relative to the 1979–98 mean value.

The hurricane season was extremely active in the Atlantic basin, with a total of 16 tropical storms, seven hurricanes, and three major hurricanes in 2003. Five of these tropical cyclones made landfall in the United States, three made landfall in northeastern Mexico, and a tropical storm affected Hispañola. In addition, Nova Scotia and Bermuda experienced devastating impacts from hurricanes in 2003. Another notable aspect of the season in the Atlantic was the formation of five tropical storms over the Gulf of Mexico, which tied the season high observed in 1957. In addition, three tropical storms formed outside of the normal (June–November) hurricane season in 2003—one in April and two in December—which made this the first season since 1887 that two tropical storms have formed during December in the Atlantic basin. Also of note was the below-normal activity in the eastern North Pacific basin. There were no major hurricanes in this basin during the 2003 season, which made this the first year since 1977 with no category 3–5 storms. Despite the below-normal activity, four tropical cyclones made landfall on the Pacific coast of Mexico, two as hurricanes and two as tropical storms, which was twice the long-term mean.

The summer of 2003 was one of the warmest on record across parts of Europe, where a heat wave affected most of Central and Western Europe. Two distinct periods of exceptional heat occurred during the season—the first in June and the second during the latter half of July and the first half of August. The July–August heat wave was the more serious of the two, since it coincided with the normal peak in summer temperatures and was accompanied by an almost complete absence of rainfall. The high temperatures and dry conditions exacerbated forest fires that burned across southern France and Portugal in July and August. The record heat wave spread across most of Western Europe in August, and it was likely the warmest summer since 1540 in parts of Central Europe. In France, 11,000 heat-related deaths were reported between late July and mid-August. In Germany, both June and August were the warmest such months since at least the beginning of the twentieth century. The summer was also the hottest in Germany since 1901, and, with the exception of some stations in northern and northwestern Germany, it was the hottest summer since the beginning of recorded measurements.

Other climatic events of note during 2003 included 1) record wet conditions across parts of the southeast, mid-Atlantic, and eastern coast of the United States; 2) record cold temperatures and anomalous June snowfalls in European Russia; 3) 546 tornadoes during May 2003 in the United States, which was an all-time record of reported tornadoes for any month; 4) continuing drought conditions across the western United States, with some areas experiencing their fourth and fifth years of significant precipitation deficits; 5) severe bushfires in eastern Australia in January, the worst wildfire season on record in British Columbia during August, as well as severe wildfires across southern California in October; 6) above-average rainfall across West Africa and the Sahel, which had its second wettest rainy season since 1990; 7) a return to normal rainfall across the Indian subcontinent during the summer monsoon; and 8) a near-record extent of the Antarctic ozone hole, which was 28.2 million km² at its maximum in September 2003.

central extratropical Pacific were evident along the poleward flanks of the anomalous subtropical ridges in both hemispheres (Fig. 4.5a). These anomalies reflected an eastward extension of the midlatitude jet streams in both hemispheres, and an eastward shift in the areas of strong upper-level diffluence that defined the jet exit regions.

These El Niño conditions dissipated during MAM 2003 as anomalous cross-equatorial flow at 850-hPa developed across the Pacific (Fig. 4.4b), and resulted in enhanced oceanic upwelling and a rapid cooling of ocean temperatures across the eastern Pacific.

b. Tropical Storms

1) Atlantic Hurricane Season—G. D. Bell,[5] S. Goldenberg,[16] C. Landsea,[16] E. Blake,[7] R. Pasch,[7] M. Chelliah,[5] and K. Mo[5]

(i) Overview

The North Atlantic hurricane season officially runs from June through November. An average season produces 10 tropical storms (TSs), six hurricanes (Hs), and two major hurricanes [MHs; 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 TSs, seven hurricanes Hs, and three MHs.

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, H Erika, made landfall in northeastern Mexico, and brought tropical storm–force winds and precipitation to southern Texas. Mexico also experienced tropical storm conditions from Claudette and Larry, and TS Odette affected Hispañola. In addition, Nova Scotia and Bermuda experienced devastating impacts from hurricanes Juan and Fabian, respectively.

Most of the activity during Atlantic hurricane seasons occurs during August–October, primarily in response to systems developing from African easterly wave disturbances. During the above-normal 2003 season, 10 tropical storms, of which 4 became hurricanes, developed 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 beween 9° and 21.5°N (see map inset in Fig. 4.6). Eight tropical storms formed in the MDR during 2003; four of these systems became hurricanes, with three becoming major hurricanes.

Another notable aspect of the season was the formation of five tropical storms over the Gulf of Mexico, which tied the season high observed in 1957. On average, one to two tropical storms form in this region during a given season. Also, three tropical storms formed outside of the normal (June–November) hurricane season in 2003. Tropical Storm Ana formed on 22 April, and TS Odette and TS Peter formed on 4 and 9 December, respectively. This was 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. 4.7) can be attributed to the ongoing active Atlantic multidecadal signal (Chelliah and Bell 2004), including 1) an amplified subtropical ridge, 2) reduced vertical wind shear in the MDR resulting from upper-level easterly wind anomalies (green arrows) and lower-level westerly anomalies (light blue arrows), 3) an exceptionally favorable African easterly jet (AEJ; dark blue arrow), 4) an active West African monsoon system, and 5) above-average SSTs in the MDR. During August the exceptionally conducive nature of the total signal was also related to a pre-existing midlatitude circulation pattern known as the positive phase of the East Atlantic teleconnection pattern, and during September–October it was related to an anomalous atmospheric warming across the entire tropical Atlantic in association with a broader warming of the global tropical atmosphere.

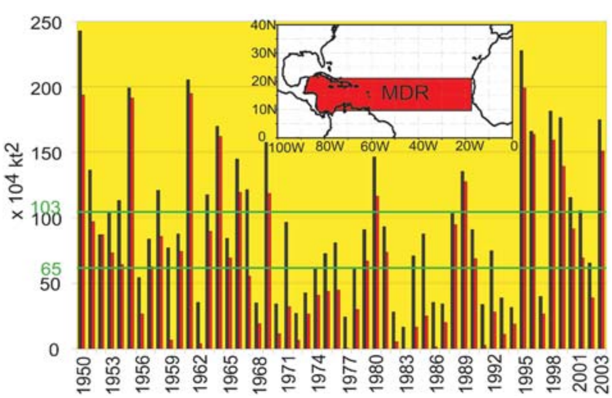

Fig. 4.6. Seasonal values of the ACE index for the entire Atlantic basin (blue) and for the MDR (red). The MDR consists of the tropical Atlantic to 21.5°N and the Caribbean Sea (see inset). The ACE index for the MDR is based on systems that first became tropical storms in that region. NOAA defines near-normal seasons as having a total ACE value in the range of 65–103 × 10^4 kt^2 (green lines).

(ii) Seasonal activity

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 ($V\text{max}^2$) for all periods while the system is either a tropical storm or hurricane (Fig. 4.6, blue bars). The total ACE index for the 2003 season was 174.75×10^4 kt^2, or 200% of the 1951–2000 median value (87.5×10^4 kt^2).

NOAA classifies an above-normal Atlantic hurricane season based on two criteria. The seasonal ACE value must exceed 105×10^4 kt^2 (120% of the median), and at least two of the following three must be above average: the number of tropical storms, hurricanes, and major hurricanes. The 2003 Atlantic hurricane season satisfied 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 (Fig. 4.6, 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 (63.3×10^4 kt^2) of any Atlantic hurricane on record, 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 43.2×10^4 kt^2 and 21.9×10^4 kt^2 to the ACE index, lasting 7.25 days and 1.5 days as major hurricanes, respectively. The combined duration of these three storms at major hurricane status was 16.75 days, which is fourth largest on record behind 1961 (24.5 MH days), 1950 (18.5 MH days), and 1955 (17.25 MH days).

The ACE index has shown large multidecadal fluctuations in total seasonal activity, characterized by above-normal activity during 1950–69 and 1995–2003, and below-normal activity during 1970–94 (Goldenberg et al. 2001; Bell 2003). During 1995–2003, Atlantic hurricane seasons have averaged 13.6 TSs, 7.7 Hs, and 3.6 MHs. The average numbers of tropical storms and hurricanes were larger than any consecutive 9-yr 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 were identified in the latter part of the record than during the above-normal decades of the 1950s and 1960s (Goldenberg et al. 2001). During the below-normal period, Atlantic hurricane seasons averaged only 9 TSs, 5 Hs, and 1.5 MHs. This multidecadal 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 114×10^4 kt^2 nearly triple the 1970–94 average of 41×10^4 kt^2.

(iii) 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 and 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 2002–03, 12 named storms have made landfall in the United States, with 9 (4 in 2003 and 5 in 2002) striking the Gulf Coast.

The storm-total precipitation associated with the Gulf Coast landfalling tropical storms and hurricanes during 2003 is shown in Fig. 4.8. The first of these systems (TS Bill) produced more than 150 mm of rain across eastern Louisiana, Mississippi, and western Alabama during 30 June–1 July. Hurricane Claudette then crossed eastern Texas on 15–16 July, generally producing totals of 75–100 mm. 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. Tropical Storm Grace brought 75–100 mm of rain to southeastern Texas on 31 August. This system was followed by TS Henri, which generally brought 100–125 mm of rain to west-central Florida on 6 September.

The sixth Atlantic system to make U.S. landfall was Hurricane Isabel, which came onshore along the Outer Banks of 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. 4.8f). This storm was directly responsible for 17 fatalities and produced mas-

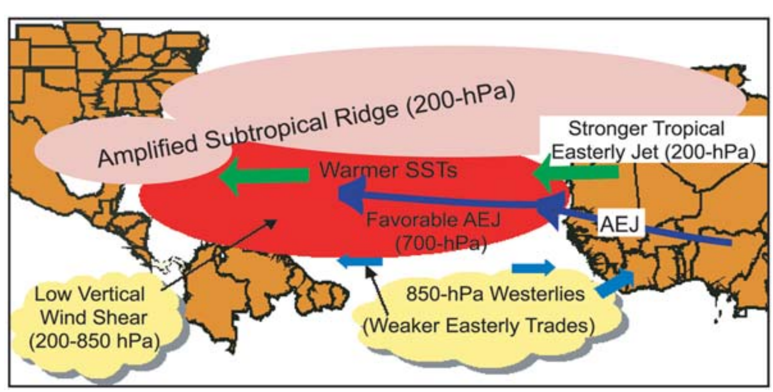

FIG. 4.7. Schematic representation of conditions during the peak (Aug–Oct) of the above-normal 2003 Atlantic hurricane season.

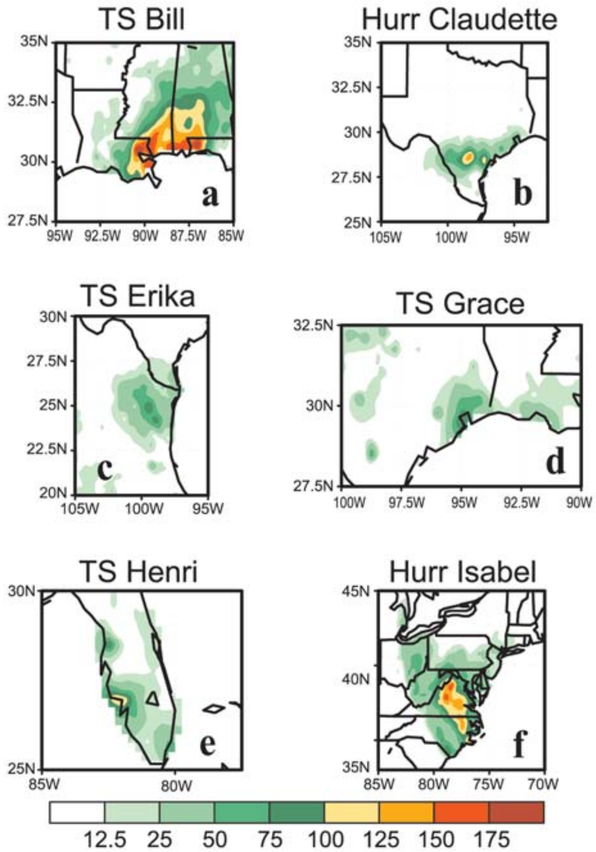

Fig. 4.8. Total rainfall (mm) over land associated with the six U.S. landfalling named storms during 2003: (a) TS Bill during 30 Jun–1 Jul, (b) H Claudette during 15–16 Jul, (c) H Erika during 16–17 Aug, (d) TS Grace on 31 Aug, (e) TS Henri on 6 Sep, and (f) H Isabel during 18–19 Sep.

sive power outages in the mid-Atlantic region, with total damages estimated by NOAA's National Hurricane Center at U.S. $3.4 billion.

(iv) Environmental conditions influencing the 2003 Atlantic hurricane season

(a) 200- and 850-hPa circulation and vertical wind shear

During August–October 2003, the mean 200-hPa subtropical ridge axis was stronger and farther north of its normal position from the Gulf of Mexico to northern Senegal (Fig. 4.7). South of the ridge axis, upper-level easterly wind anomalies covered the entire MDR in association with an enhanced tropical easterly jet (Fig. 4.7, green arrows). The ongoing multidecadal signal can account for the amplified subtropical ridge and enhanced tropical easterly jet over the eastern North Atlantic and Africa (Chelliah and Bell 2004). These features were 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 was also partly related to a continuation of the positive phase of the eastern Atlantic teleconnection pattern (see Fig. 6.21). This pattern has strong links to 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 (see Fig. 6.20). During September and October, the amplified subtropical ridge was partly related to an anomalous warming throughout the tropical Atlantic (red in Fig. 4.9), which occurred in association with a warming of the global Tropics (Fig. 4.9, green).

At 850-hPa, westerly zonal wind anomalies across the North Atlantic and western Africa during August–October 2003 (Fig. 4.10a) reflected weaker-than-average tropical easterlies. This anomaly pattern was already evident during the preceding 4 months (Fig. 4.10b), indicating it did not result from the increased hurricane activity (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.

The combination of upper- and lower-level zonal wind anomalies resulted in easterly vertical wind shear anomalies between 200 and 850 hPa from the eastern tropical Pacific to western Africa (Fig. 4.11a). The anomalous easterly shear resulted in lower total vertical shear over the heart of the MDR, and higher total shear over both tropical western Africa and portions of the eastern tropical Pacific (Fig. 4.11b). This three-celled anomaly pattern was typical of other above-normal Atlantic hurricane seasons. It was also consistent with the enhanced 2003 West African monsoon system (see section 6eii), and with a below average 2003

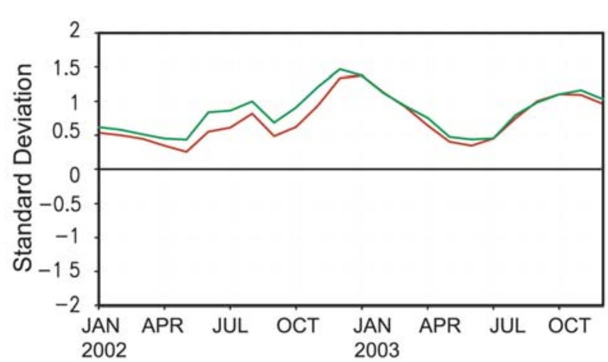

Fig. 4.9. Standardized values of the 3-month running mean area-averaged 200-hPa height anomalies calculated for the entire global Tropics (20°N–20°S) (green curve) and for the region centered on the tropical Atlantic (120°W–40°E, 20°N–20°S) (red curve). Anomalies are departures from the 1971–2000 base period monthly means.

eastern North Pacific hurricane season that featured a record low of no major hurricanes [see section 4bII(ii)].

(b) 700-hPa African easterly jet, convective available potential energy, and SSTs

During August–October, tropical cyclogenesis in the MDR is typically 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 AEJ. The AEJ was well defined during 2003, (Fig. 4.12a, contours), 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 et al. 2000, see their Fig. 31). This structure was consistent with the weaker-than-average tropical easterlies and enhanced 850-hPa cyclonic relative vorticity previously noted across the heart of the MDR (Fig. 4.10a).

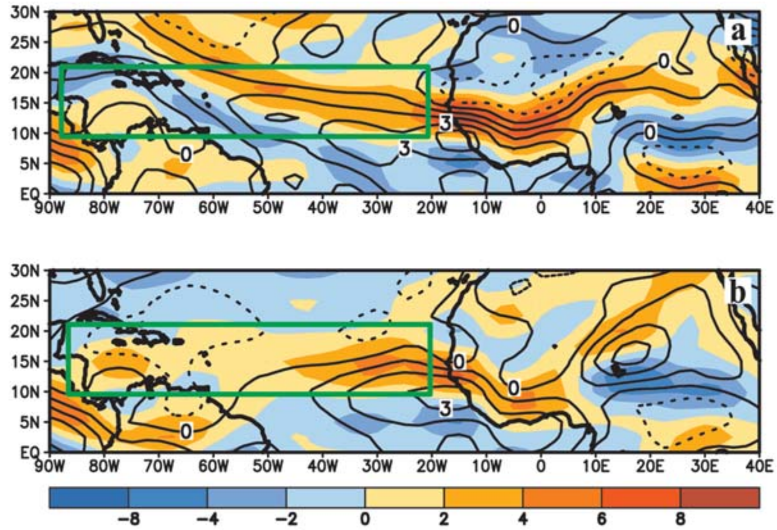

Fig. 4.10. Anomalous 850-hPa zonal winds (contours, interval is 1.0 m s^{-1}) and relative vorticity (shading, x 10^{-6} s^{-1}) during (a) Aug–Sep 2003, and (b) Apr–Jul 2003. Solid (dashed) contours indicate westerly (easterly) wind anomalies. Cyclonic (anticyclonic) relative vorticity anomalies are shaded orange (blue). Green box denotes the MDR. Anomalies are departures from the 1971–2000 base period monthly means.

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. 4.13a). The high CAPE values were also associated with near-record warm SSTs (0.5°–1°C above average) throughout the MDR (Fig. 4.13b). Area-averaged SSTs in the

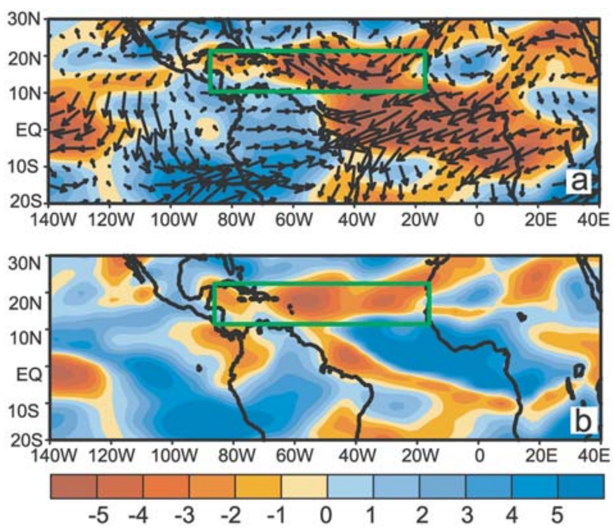

Fig. 4.11. Aug–Sep 2003 (a) anomalous 200–850-hPa vertical shear of zonal wind (shaded, m s^{-1}) and anomalous vertical shear vector, and (b) anomalous strength of the total 200–850-hPa vertical shear. In (a) red indicates anomalous easterly shear and blue indicates anomalous westerly shear. In (b) 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.

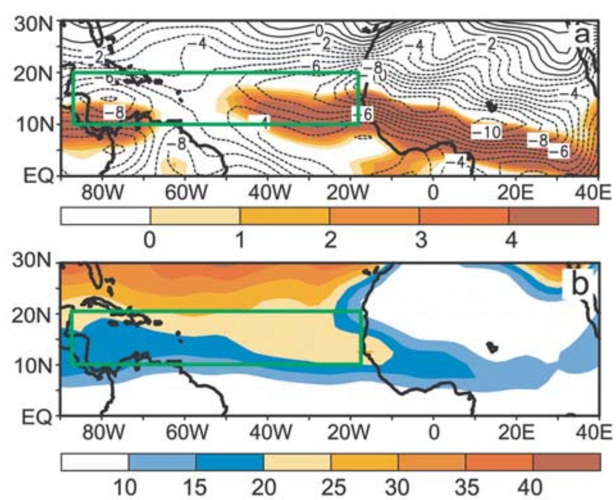

Fig. 4.12. Aug–Sep 2003 mean 700-hPa (a) zonal winds (contours, interval is 1.0 m s^{-1}) and relative vorticity (shading, × 10^{-6} s^{-1}), and (b) potential vorticity [× 10^{-7} K (s hPa)$^{-1}$]. In (a) only cyclonic vorticity values are shaded. Green box denotes the MDR.

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. 4.13c).

These results indicate that the tropical disturbances during the peak of the 2003 season experienced a linearly unstable mean current and 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 were 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 of 1995–2003, with the exception of the two El Niño years (1997, 2002) (Fig. 4.14).

These low-frequency fluctuations in key circulation anomalies over the tropical North Atlantic are consistent with the strong relationship between multidecadal variations in the seasonal Atlantic basin activity and the West African monsoon system (Hastenrath 1990; Landsea and Gray 1992; Goldenberg and Shapiro 1996). They are also consistent with the observed transition to the warm phase of the Atlantic multidecadal mode during the early and mid-1990s (Landsea et al. 1999; Mestas-Nuñez and Enfield 1999). Chelliah and Bell (2004) have shown that these multidecadal 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. 4.14).

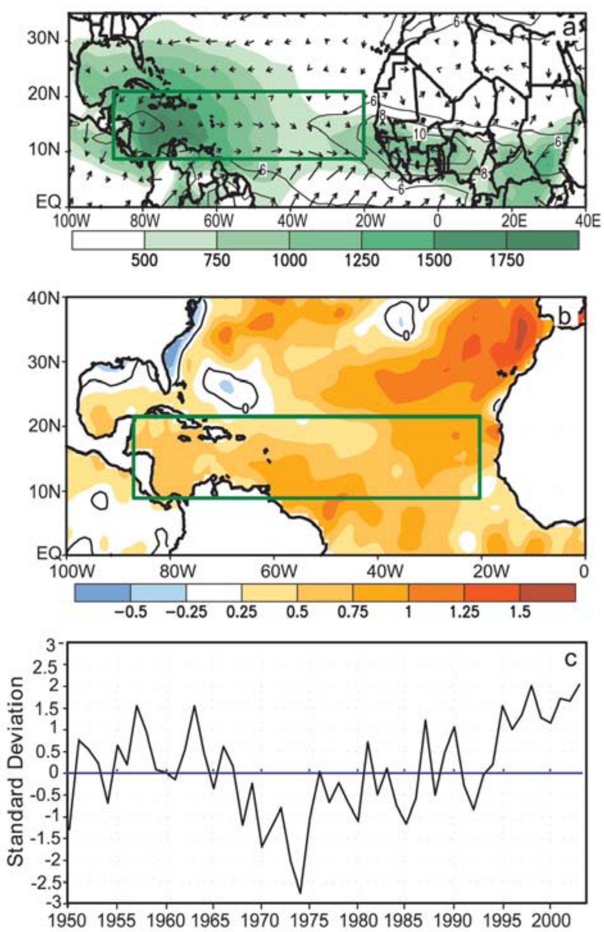

FIG. 4.13. Aug–Oct 2003 (a) CAPE (shaded, in J kg^{-1}), 700-hPa wind speeds (contours, interval is 2.0 m s^{-1}), and anomalous 925-hPa wind vector, and (b) anomalous SST (°C). (c) Standardized, area-averaged SST anomalies (°C) in the MDR (20°–90°W and 9°–21.5°N) for consecutive Aug–Oct periods from 1950 to 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.

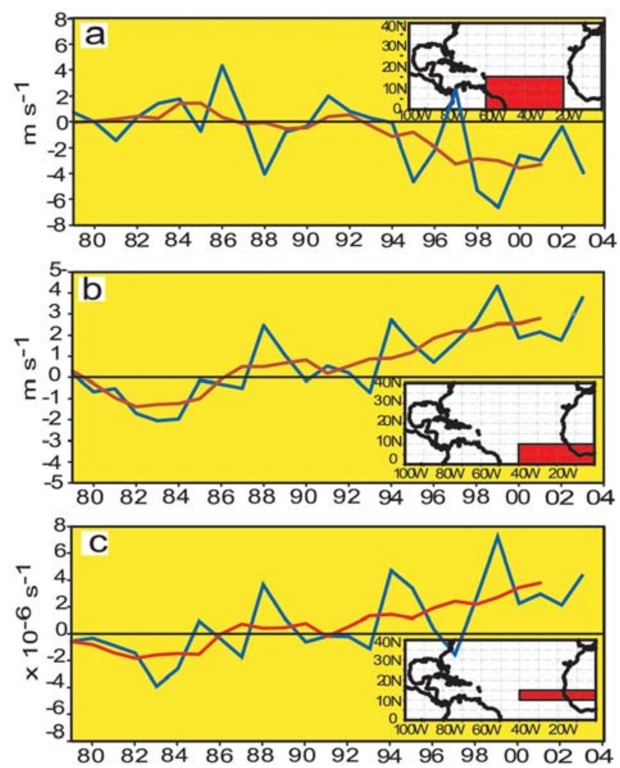

FIG. 4.14. Area-averaged anomaly time series for each Aug–Sep period between 1979 and 2003: (a) 200–850-hPa vertical shear of the zonal wind (m s^{-1}), b) 700-hPa zonal wind (m s^{-1}), and (c) 700-Pa relative vorticity (× 10^{-6} s^{-1}). Blue curve shows unsmoothed 2-month anomalies, and red curve shows a 5-pt running mean smoother applied to the time series. Averaging regions are shown in the insets. Anomalies are departures from the 1979–95 base period monthly means.

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