The 2003 North Atlantic Hurricane Season
A Climate Perspective

Gerald Bell[1], Stanley Goldenberg[2], Chris Landsea[2]
Eric Blake[3], Muthuvel Chelliah[1], Kingtse Mo[1],
Richard Pasch[3]

[1]Climate Prediction Center/NOAA/NWS/NCEP
[2]Hurricane Research Division/NOAA/OAR
[3]National Hurricane Center/NOAA/NWS/NCEP

1. Overview

The 2003 Atlantic hurricane season featured 16 tropical storms (TS), 7 hurricanes (H), and 3 major hurricanes (MH) (Fig. 1), indicated by categories 3-5 on the Saffir-Simpson scale (Simpson 1974). These numbers are higher than the 1951-2000 climatological seasonal averages of 9-10 tropical storms, 6 hurricanes, and 2 major hurricanes. A detailed analysis of the individual tropical storms and hurricanes during 2003 is provided by National Oceanic and Atmospheric Administration's (NOAA's) National Hurricane Center at:

http://www.nhc.noaa.gov/2003atlan.shtml

Most of the 2003 activity occurred between mid-August and mid-October, when ten tropical storms, four hurricanes, and all three major hurricanes formed. However, three tropical storms formed outside of the normal June-November hurricane season. The first system of the season system (TS Ana) formed on 22 April, and the last two (TS Odette and TS Peter) formed on 4 Dec. and 9 Dec., respectively. According to the National Hurricane Center (personal communication, Lixion Avila), this is the first time since 1887 that two tropical storms formed in December, although it is possible that undetected systems have occurred in December prior to the meteorological satellite era.

Regionally, four of the hurricanes and all of the major hurricanes during 2003 were associated with tropical storms that first developed in the Main Development Region (MDR; Goldenberg and Shapiro 1996) (red bars, Fig. 1). The MDR is shown for reference in Fig. 2. The concentration of activity in the MDR during mid-August through mid-October is typical of above-normal hurricane seasons (Landsea 1993, Goldenberg and Shapiro 1996).

Five tropical storms also formed over the Gulf of Mexico (grey bars, Fig. 1), tying the seasonal high observed in 1957. Climatologically, 1-2 tropical storms form in this region during a given season.

Six systems affected the United States during the season (section 3), which follows seven landfalling U.S. systems in 2002. In addition Nova Scotia and

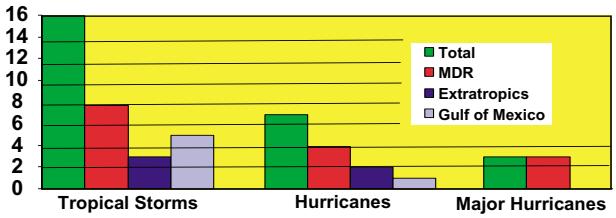

Fig. 1. 2003 Atlantic hurricane season total (green) tropical storms, hurricanes, and major hurricanes. Totals associated with tropical storms forming in the Main Development Region (MDR) (red), the Gulf of Mexico (grey), and the extratropics (blue) are also shown.

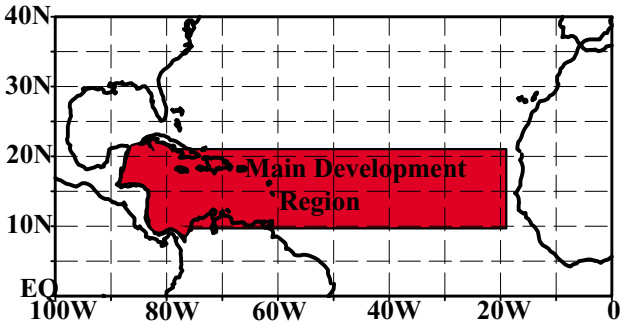

Fig. 2. The Main Development Region (MDR) consists of the tropical Atlantic to 21.5°N and the Caribbean Sea.

Bermuda experienced devastating hurricane impacts from H Juan and H Fabian, respectively. Mexico experienced tropical storm conditions from Claudette and Larry, while Hispanola was affected by TS Odette.

Atmospheric conditions during August-September 2003 were very conducive to an above-normal Atlantic hurricane season (Fig. 3). The ongoing active Atlantic multi-decadal signal can account for important aspects of this signal, including an amplified upper-level subtropical ridge, reduced vertical wind shear in the MDR resulting from upper-level easterly wind anomalies and lower-level westerly anomalies, an exceptionally favorable African Easterly Jet, and an active West African monsoon system. The presence of ENSO-neutral conditions throughout the season suggests that these conditions were independent of any significant ENSO influence.

However, neither the multi-decadal signal nor ENSO is believed to account for the exceptionally conducive nature of the total signal. This is particularly true in the northern and western MDR, and over the Gulf of Mexico where a very persistent upper-level ridge contributed to the formation of five tropical storms.

2. 2003 Seasonal Activity

One measure of the total seasonal activity is NOAA's Accumulated Cyclone Energy (ACE) index, which measures the combined strength and duration of tropical storms and hurricanes during a given season (Bell et al. 2000). The ACE index is essentially 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 (Fig. 4). The total ACE index for the 2003 season is 169.9 x 10^4 kt^2, or 197.5% of the long-term median value (86 x 10^4 kt^2).

NOAA defines an above-normal Atlantic hurricane season based on two criteria. First, the season must have a total ACE value exceeding 103 x 10^4 kt^2 (or 120% of the median). Second, at least two of the following three must be above average: numbers of tropical storms, hurricanes or major hurricanes. The 2003 Atlantic hurricane season satisfies both of these criteria.

A large percentage (86.6%) of the total ACE value during 2003 is associated with the hurricanes and major hurricanes that first became tropical storms in the MDR (Fig. 5). An additional 8.4% came from the three named storms (two became hurricanes: Danny and Juan) that formed north of the MDR (listed as "extratropics"), and 5% came from the

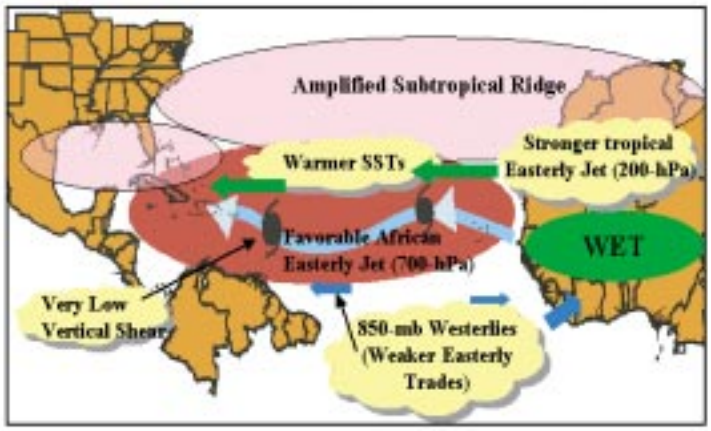

Fig. 3. Schematic representation of conditions conducive to the above-normal 2003 Atlantic Hurricane Season.

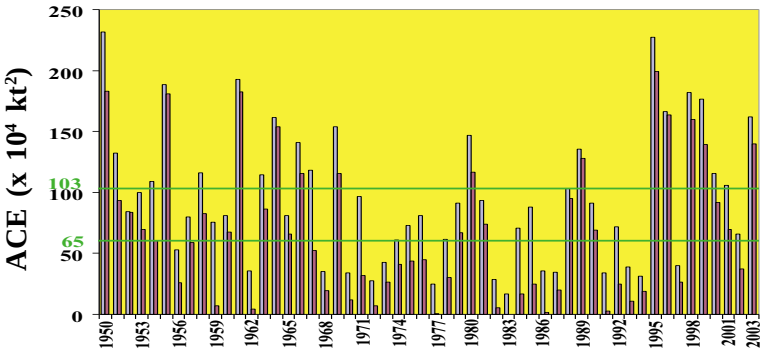

Fig. 4. Seasonal values of the Accumulated Cyclone Energy (ACE) index for the total Atlantic Basin (blue) and Main Development Region (MDR, red). The ACE index for the MDR is based on systems that first became tropical storms in the MDR. NOAA defines near-normal seasons as having a total ACE value betwen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

The large contribution to the seasonal ACE dex

The large contribution to the ACE index from systems first named in the MDR is typical of above-normal hurricane seasons, and reflects the high percentage of these storms that eventually become long-lived hurricanes and/or major hurricanes. During 2003 the three major hurricanes (Fabian, Isabel, and Kate) accounted for 74% of the total ACE index (Fig. 6).

Hurricane Isabel lasted from 6-19 September and was a major hurricane for 7.75 days. Isabel was also a category-5 hurricane (maximum sustained winds above 135 kts) for 3.25 days. Since the ACE index is based on the square of the wind speed, Isabel produced one of the largest ACE values (61.3 x 10^4 kt^2) of any storm in the record. Isabel finally made landfall in North Carolina on 18 September as a category-2 hurricane.

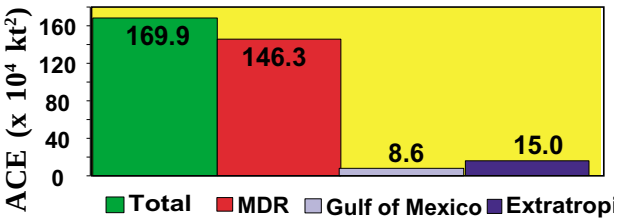

Fig. 5. 2003 seasonal values of the Accumulated Cyclone energy (ACE) index for the total Atlantic Basin (green), the Main Development Region (MDR, red), the Gulf of Mexico (grey), and the extratropics (blue). The regional ACE values are based on systems that first become tropical storms in the specified region.

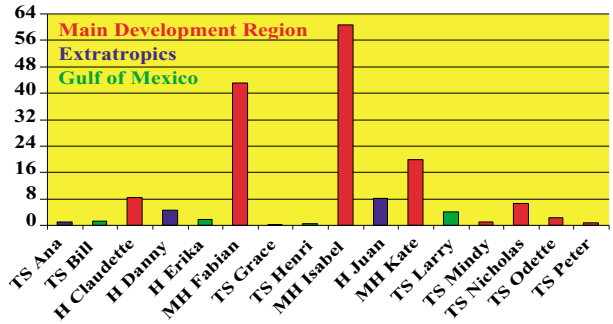

Fig. 6. The Accumulated Cyclone Energy (ACE) value for each of the sixteen Atlantic tropical storms during 2003. The ACE value is determined by summing the squares of the maximum sustained 6-hourly wind speeds while the system is either a tropical storm or hurricane.

The ACE index contribution from Hurricane Fabian was also substantial (43.2 x 10^4 kt^2). This storm lasted from 28 Aug- 8 Sep, and was a major hurricane for 7.25 days, reaching maximum sustained winds of 125 kts (145 mph). Hurricane Kate contributed an additional 21.9 x 10^4 kt^2 to the seasonal ACE index. Kate was a major hurricane for 1.5 days, and reached maximum sustained winds of 110 kts (125 mph).

The combined duration of these three systems at major hurricane status is 16.75 days, which is second only to the 20.75 total days observed in 1961. That season featured six major hurricanes lasting for an average of 3.5 days each at that strength.

3. Rainfall from landfalling U.S. tropical storms and hurricanes

Six named storms made landfall in the United States/ northern Mexico during the 2003 Atlantic hurricane season. One made landfall as a tropical depression (Henri), two hit as tropical storms (Bill and Grace) and three hit as hurricanes (Claudette, Erika, and Isabel). This compares to seven landfalling U.S. systems during 2002, when six hit as tropical storms and one hit as a hurricane (Lawrimore et al. 2003). For the 2002-2003 period thirteen named storms have made landfall in the U.S, with ten hitting the Gulf Coast (five in each season).

During 2003 the first of these Gulf Coast systems was TS Bill, which produced more than 150 mm of rain across eastern Louisiana, Mississippi, and western Alabama (Fig. 7a). The second was Hurricane Claudette, which went across eastern Texas during 15-16 July and produced totals of 75-100 mm (Fig. 7b). The third was Hurricane Erika during 16-17 August, which made landfall as a hurricane in northeastern Mexico and brought tropical storm force winds to extreme southern Texas. Erika produced 75-100 mm of rain in northeastern Mexico and 25-75 mm of rain in southern Texas (Fig. 7c). The fourth was TS Grace, which brought 75-100 mm of rain to southeastern Texas on 31 August (Fig. 7d). The fifth Gulf Coast system was TS Henri, which made landfall in west-central Florida as a tropical

depression and brought 100-125 mm of rain to the region (Fig. 7e).

The sixth landfalling system of the season was Hurricane Isabel, which came onshore along the North Carolina coast on 18 Sep as a category-2 hurricane. This system subsequently moved northward across western Pennsylvania on 19 September. Rainfall totals with Isabel ranged from 100-200 mm across eastern North Carolina and Virginia, and 50-100 mm across West Virginia and eastern Ohio (Fig. 7f). This storm caused 29 fatalities and produced massive power outages in the Mid-Atlantic region, with total damages estimated by the National Hurricane Center at 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. 8a). 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. 8b). This excess precipitation is attributed largely to the land falling tropical systems (Fig. 8c), which generally accounted for 25%-40% of the total seasonal rainfall in these areas (Fig. 8d).

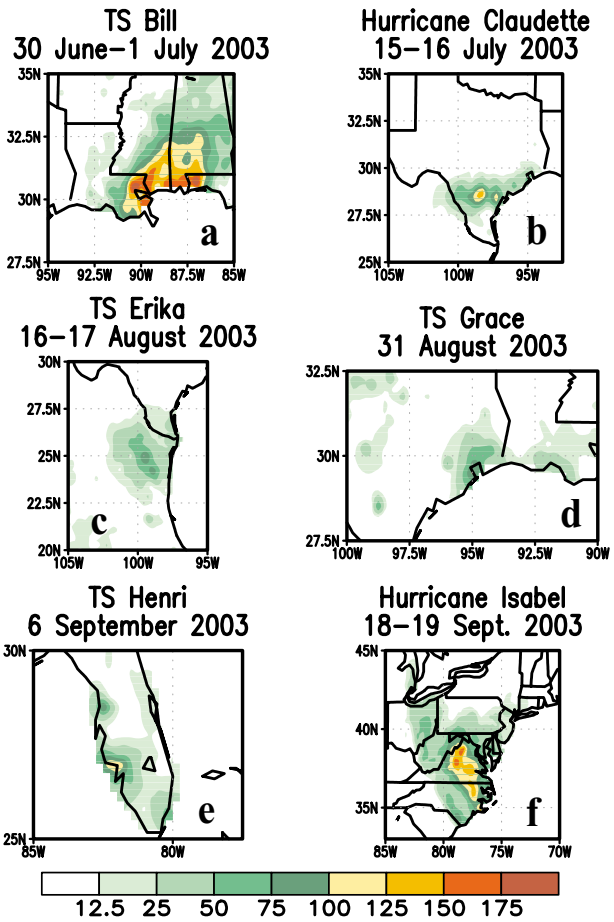

Fig. 7. Total rainfall (mm) over land associated with the six landfalling named storms during 2003: a) TS Bill during 30 June-1 July 2003, b) Hurricane Claudette during 15-16 July, c) H Erica during 16-17 August, d) TS Grace on 31 August, e) TS Henri on 6 September, and f) Hurricane Isabel during 18-19 September.

4. Atmospheric circulation

a. Vertical Wind Shear

The mean 200-hPa heights during Aug.-Sep. 2003 indicate an overall strengthening and northward shift of the subtropical ridge axis, which extends from the Gulf of Mexico to northern Senegal (Fig. 9). South of the ridge axis anomalous easterly flow at upper levels (not shown) covers the entire MDR and reflects an enhanced Tropical Easterly

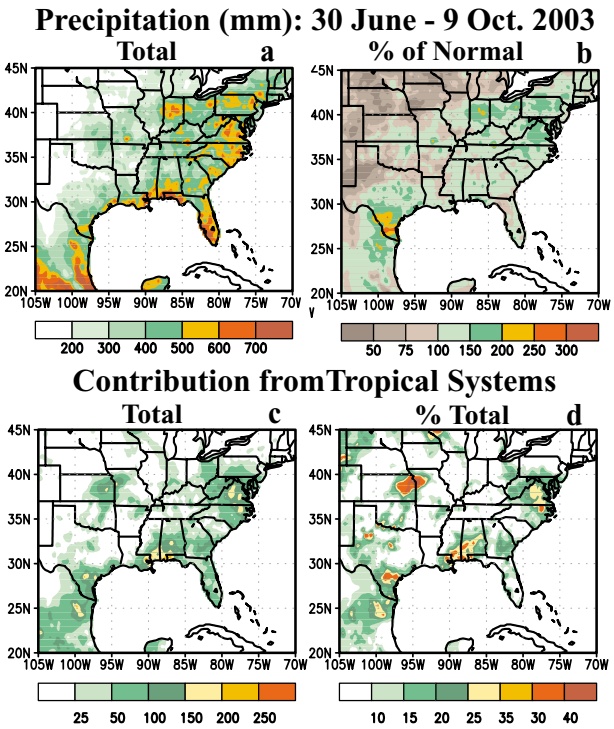

Fig. 8. 30 June-9 October 2003 precipitation (a) total (mm) and (b) percent of the 1971-2000 normal. c) Total rainfall and (d) percent of the total associated with the six landfalling storms (Fig. 7).

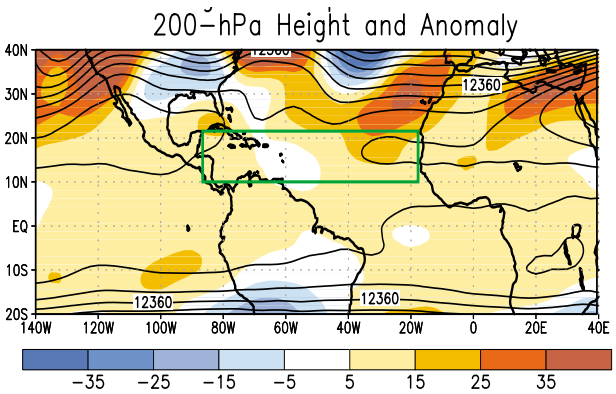

Fig. 9. August- September 2003 mean (contours) and anomalous (shaded) 200-hPa heights. Contour interval for heights is 30 m. Shading interval for anomalies is 10 m. Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

Jet.

Conversely, at lower levels the tropical easterlies (contours, Fig. 10a) were weaker than average across the North Atlantic and western Africa, as indicated by westerly zonal wind anomalies throughout the region (contours, Fig. 10b). These conditions were already in place during April-May (Fig. 10c) and June-July (Fig. 10d), well prior to the main hurricane activity.

The combination of upper- and lower- level zonal wind anomalies during Aug.-Sep. produced anomalously easterly vertical wind shear between 200-850 hPa from tropical western Africa to the eastern tropical Pacific (red, Fig. 11a). The result was lower total vertical wind shear over the heart of the MDR (red, Fig. 11b), and higher total vertical wind shear over both tropical western Africa and portions of the eastern tropical Pacific (blue).

This three-celled pattern of anomalous total shear is consistent with 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 with a record low of zero major hurricanes.

b. African Easterly Jet

During August-September, 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

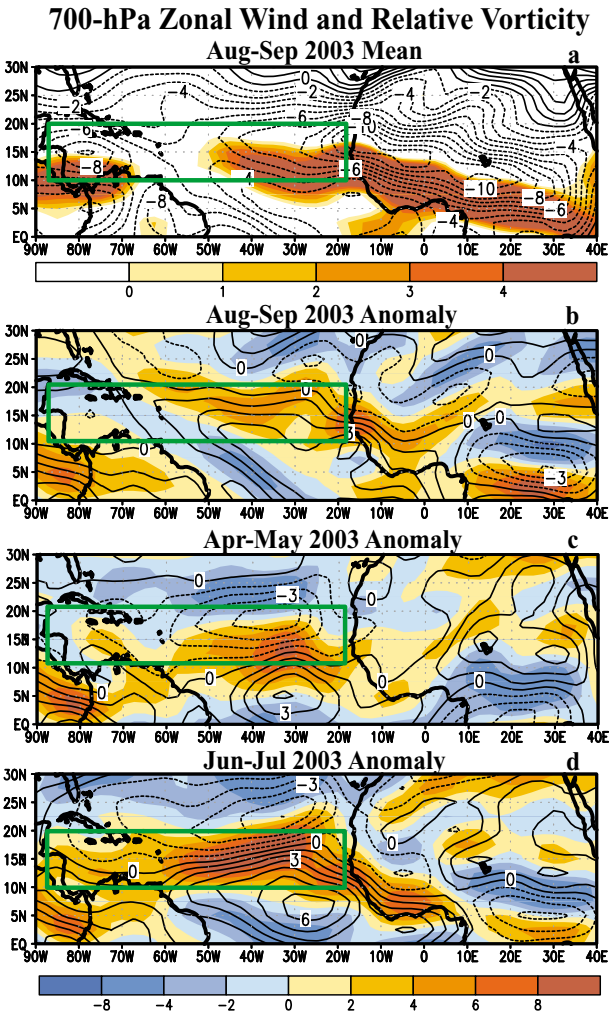

Fig. 10. 700-hPa zonal winds (contours, m s^{-1}) and relative vorticity (x 10^{-6} s^{-1}, shading) (a) total and (b) anomalies during August-September 2003, and anomalies during (c) April-May 2003 and (d) June-July 2003. In panel (a) only cyclonic vorticity values are shaded. Interval for wind speeds is 1.0 m s^{-1} in all panels. Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

relative vorticity along the equatorward flank of the 700-hPa African Easterly Jet (AEJ) (Fig. 10a).

During 2003 the low-level westerly wind anomalies (contours, Fig. 10b) across the tropical Atlantic are associated with a well-defined AEJ core extending farther west into the MDR than normal. Over the central MDR the jet axis is shifted northward to almost 20°N, and features an extended region of enhanced cyclonic relative vorticity along its equatorward flank. This circulation is accompanied

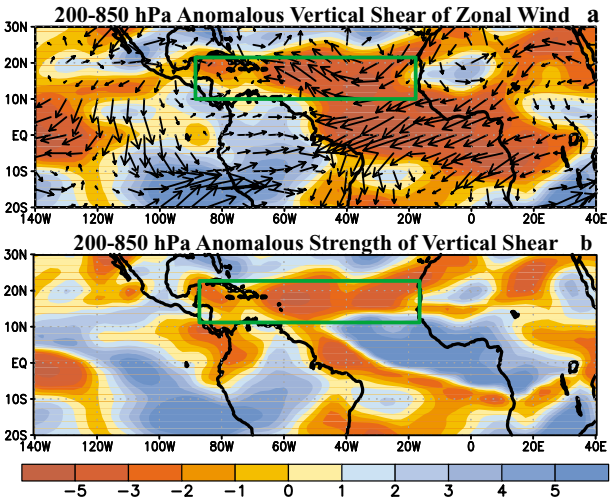

Fig. 11. August-September 2003 anomalous 200-850-hPa vertical wind shear: (a) anomalous vertical shear of zonal wind (shaded) and vertical shear vector, and (b) anomalous strength of the total vertical wind shear. Shading interval is 1.0 m s^{-1}. In (a) red indicates easterly shear and blue indicated 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.

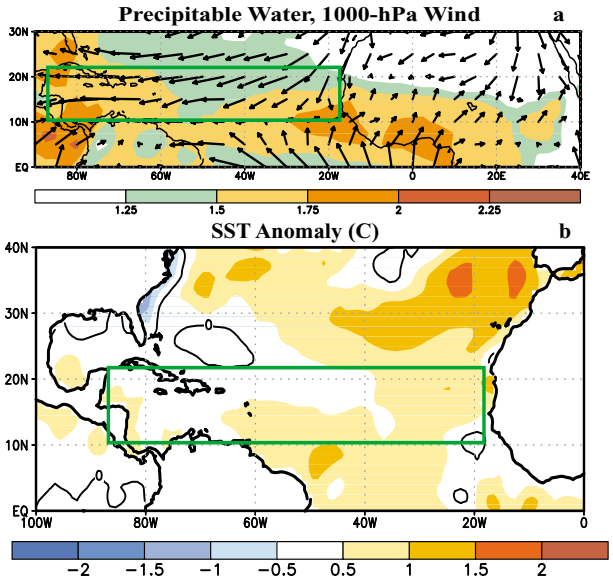

Fig. 12. August-September 2003 (a) total precipitable water (inches) and 1000-hpa vector winds, and (b) anomalous sea surface temperatures (°C). Green box denotes the MDR. Anomalies are departures from the 1971-2000 base period monthly means.

by a northward shift of the ITCZ to 10°N, and by an associated penetration of deep tropical moisture (Fig. 12a) over slightly warmer than average SSTs that covered the entire MDR (Fig. 12b).

These conditions indicate that disturbances developing in the MDR remained in an extended region of increased cyclonic vorticity, deep tropical moisture, and warmer SSTs while moving westward into the low-shear environment over the heart of the MDR. This interpretation is consistent with the atmospheric conditions described by Bell et al. (1999, 2000) for the above-normal 2000 and 2001 hurricane seasons.

Further examination of the AEJ during Aug.-Sep. 2003 indicates a tongue of high potential vorticity air extending across the eastern half of the MDR and western tropical Africa (Fig. 13a). A notable reversal in the potential vorticity gradient is also evident, as indicated by a northward increase in values over the southeastern portion of the MDR, and a northward decrease in values over the northeastern MDR.

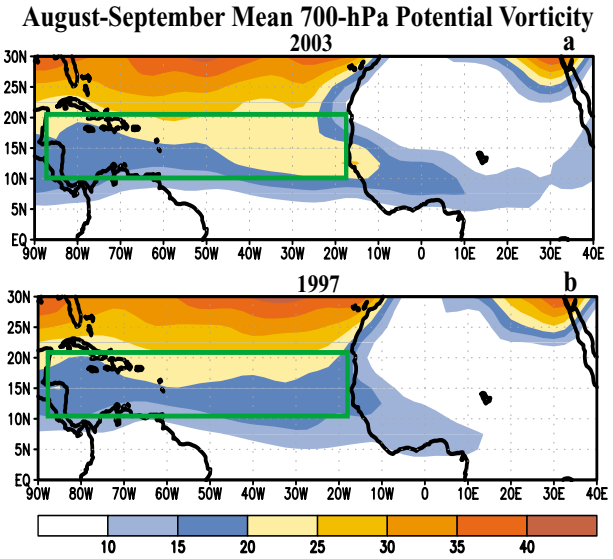

Fig. 13. August-September mean 700-hPa potential vorticity during (a) 2003 and (b) 1997. Shading interval is 5.0 x 10^{-7} K (s hPa)$^{-1}$. Green box denotes the MDR.

This reversal in the north-south component of the PV gradient satisfies the necessary condition for linear baroclinic instability, and suggests that the background flow in this region was very favorable for supplying energy to developing African Easterly disturbances. In contrast, during the inactive 1997

season lower PV values and no major reversal in the PV gradient are seen in the MDR (Fig. 13b).

5. The ongoing active Atlantic multi-decadal signal

a. Atmospheric Circulation

Large multi-decadal fluctuations in seasonal Atlantic Basin activity are evident in ACE index time series (Fig. 4), with above-normal activity during 1950-1969 and 1995-2003, and below-normal activity during 1970-1994 (see also Landsea and Gray 1992, Landsea et al. 1999, Goldenberg et al 2001, Lawrimore et al. 2002). The above normal 2003 season continues the marked increase in activity that began in 1995.

Multi-decadal fluctuations in seasonal activity have been linked to multi-decadal variations in several key atmospheric circulation features within the MDR, including the vertical wind shear (Fig. 14a, see also Goldenberg et al. 2001), the tropical easterly trade winds (Fig. 14c), and the cyclonic shear along the equatorward flank of the African Easterly Jet (Fig. 14e). For the first half of the 1980s anomalous westerly (i.e. increased) vertical wind shear is evident over the central tropical North Atlantic (Figs. 14a, b), the tropical easterly trade winds are stronger than average between 5°-10°N (Figs. 14c, d), and anomalous anticyclonic relative vorticity is seen along the equatorward flank of the mean African Easterly Jet (Figs. 14e, f). This combination of conditions is not conducive to Atlantic hurricane formation.

Since the mid-1990s the circulation has featured anomalous easterly (i.e. lower) vertical wind

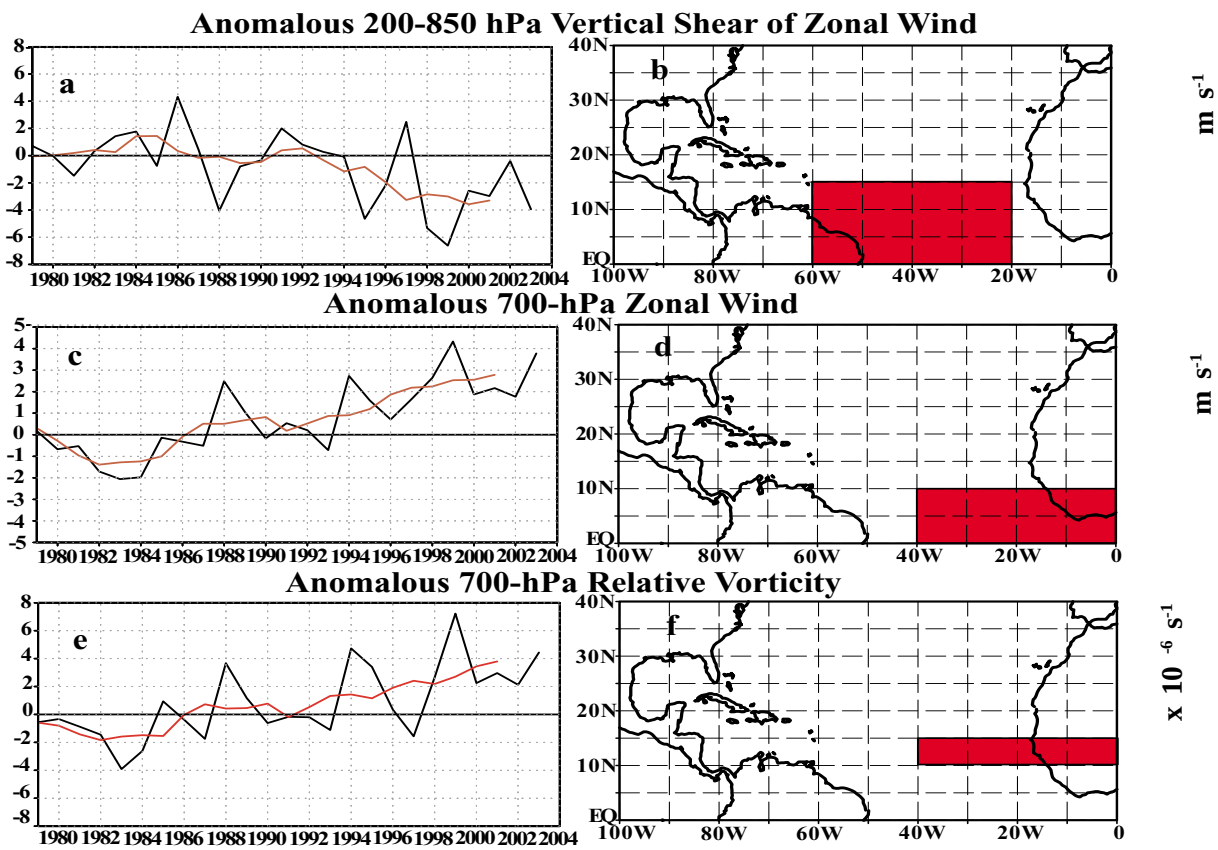

Fig. 14. Area-averaged anomaly time series' for each August-September period between 1979-2003: (a) 200-850-hPa vertical shear of the zonal wind (m s^{-1}) , c) 700-hPa zonal wind m s^{-1}), and 700-Pa relative vorticity (x 10^{-6} s^{-1}). Black curves show un-smoothed two-month anomalies, and red curve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

shear over the central tropical Atlantic (Goldenberg et al. 2001), along with weaker tropical easterly trade winds and anomalous cyclonic relative vorticity along the equatorward flank of the AEJ. As seen for the 2003 season this combination of conditions is conducive to tropical cyclone formation from African easterly wave disturbances during the climatological peak of the season.

Similar circulation anomalies have been associated with an enhanced West African monsoon system (Thaiw et al. 1988, Chelliah and Bell 2003), as was also seen during 2003. More generally these results are also 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 ongoing warm phase of the Atlantic multi-decadal mode (Landsea et al. 1999, Mestas-Nuñez and Enfield 1999).

b. Activity

During 1995-2003 Atlantic hurricane seasons have averaged 13 tropical storms, 7.6 hurricanes, and 3.6 major hurricanes. 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 (Goldenberg et al. 2001), it is possible that more systems are identified in the later part of the record than during the above-normal decades of the 1950s-1960s.] During the below-normal 1970-1994 period, seasons averaged only 9 tropical storms, 5 hurricanes and 1.5 major hurricanes.

The seasonal mean ACE index during 1995-2003 is 145 x 10^4 kt^2, more than double the 1970-1994 average of 65 x 10^4 kt^2. The mean contribution from systems first named in the MDR during 1995-2003 is 114 x 10^4 kt^2, almost triple the average contribution during 1970-1994 of 41 x 10^4 kt^2. The increased number of hurricanes and major hurricanes associated with the MDR during 1995-2003 (Fig. 15) account for almost 91% of the total difference in the ACE index between the two periods.

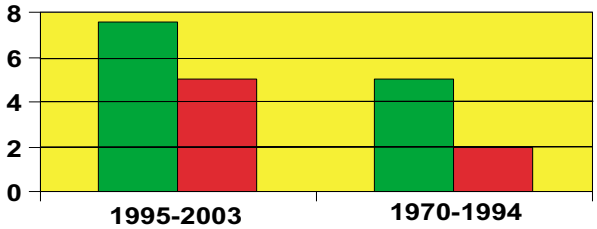

Fig. 15. 1995-2003 and 1970-1994 seasonal mean number of Atlantic hurricanes (green bars), and mean number of hurricanes that first become tropical storms in the MDR (red bars).

Seven of the nine seasons during 1995-2003 are classified as above normal according to NOAA's hurricane season classification. The remaining two seasons (1997 and 2002) were El Niño years, and were associated with below-normal and near-normal levels of activity, respectively. In contrast, NOAA identifies only three above-normal seasons (1980, 1988, 1989) during the entire period 1970-1994.

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.

References

Bell, G. D., and Co-authors, 2000: Climate Assessment for 1999. *Bull. Amer. Meteor*. Soc., **81**, S1-S50.

Bell, G. D., and Co-authors, 2001: Climate Assessment for 2000. *Bull. Amer. Meteor*. Soc., **82**, S1-S52.

Chelliah, M., and G. D. Bell, 2003: Tropical multi-decadal and interannual climate variations in the NCEP/ NCAR Reanalysis. Accepted for Publication *J. Climate*, July 2003.

Goldenberg, S. B., and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricanes. *J. Climate*, **9**, 1169-1187.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, **293**, 474-479.

Hastenrath, S., 1990: Decadal-scale changes of the circulation in the tropical Atlantic sector associated with Sahel drought. Int. *J. Climatol*., 10, 459-472.

Landsea, C. W. and W. M. Gray, 1992: The strong association between Western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Climate*, 5, 435-453.

Landsea, C. W., 1993: The climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev*., **121**, 1703-1713.

Landsea, C. W., R. A. Pielke, A. M. Mestas-Nuñez, and J. A. Knaff, 1999: Atlantic Basin hurricanes: Indices of climate changes. *Climate Change*, **42**, 89-129.

Lawrimore, J., and Co-authors, 2002: Climate Assessment for 2001. *Bull. Amer. Meteor*. Soc., **82**, S1-S55.

Lawrimore, J., and Co-authors, 2003: Climate Assessment for 2002. *Bull. Amer. Meteor*. Soc., **83**, S1-S55.

Mestas-Nuñez, A. M., and D. B. Enfield, 1999: Rotated global modes of non-ENSO sea surface temperature variability. *J. Climate*, 12, 2734-2746.

Reed, R. J., D. C. Norquist, and E. E. Recker, 1977: The structure and properties of African wave disturbances as observed during Phase III of GATE. *Mon. Wea. Rev*., 105, 317-333.

Simpson, R. H., 1974: The hurricane disaster potential scale. *Weatherwise*, **27**, 169-186.