The 2002 North Atlantic Hurricane Season

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a. Overview

The 2002 Atlantic hurricane season featured twelve named storms, four hurricanes, and two major hurricanes. This is one-half the average seasonal number of hurricanes measured since a marked upturn in hurricane activity began in 1995 (Goldenberg et al. 2001). The climatological peak in Atlantic hurricane activity occurs between mid-August and mid-October from an increased number of hurricanes and major hurricanes forming in the Main Development Region [MDR, defined as the tropical North Atlantic south of 21°N and the Caribbean Sea]. During 2002 nine of the twelve named storms and all four hurricanes formed during this 2-month period, but only three of these systems formed in the MDR.

The 2002 seasonal activity reflected the competing influences of three leading climate factors: El Niño, the active multi-decadal signal, and the Madden-Julian Oscillation (MJO). The decreased activity in the MDR was related to El Niño (section d1). However, key aspects of the atmospheric circulation over the tropical Atlantic continued to reflect the ongoing active multi-decadal signal, which moderated the "apparent" El Nino signal in portions of the MDR (section d2). A "window of opportunity" for hurricane activity in late September and early October developed in response to the westerly phase of the MJO, which temporarily offset the high vertical wind shear associated with El Niño during a period when conditions are climatologically most conducive to hurricane development (section e).

b. Seasonal Activity

The National Oceanic and Atmospheric Administration (NOAA) defines the total seasonal activity based on the combined strength, duration, and number of named storms and hurricanes (Bell et al. 2000). One measure of this seasonal activity is the Accumulated Cyclone Energy (ACE) index (Fig. 1), which 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. For the 2002 season the total ACE index was 62.5 x 10^5 kt^2 (Fig. 1), or 73% of the long-term median value. NOAA defines near-normal seasons as having a total ACE value in the range of 65-103 x 10^5 kt^2. Therefore the 2002 season activity falls into the below-normal range.

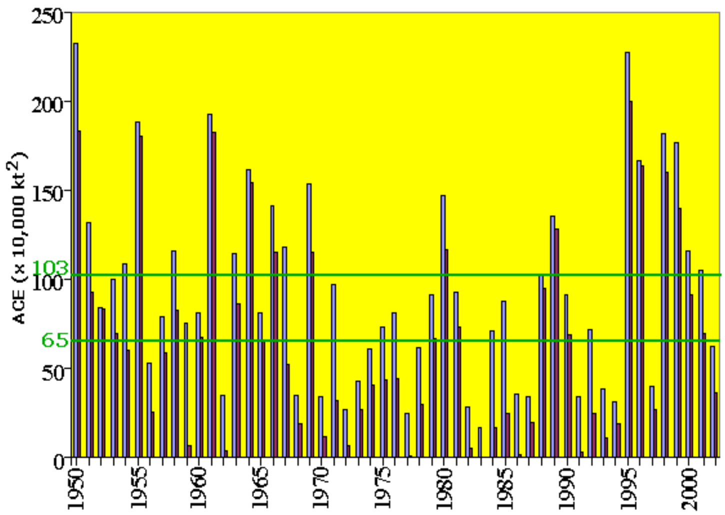

Fig. 1. Seasonal values of the Accumulated Cyclone Energy (ACE) index for the total Atlantic Basin (blue) and the Main Development Region (MDR) (red). The ACE index for the MDR is based only on systems that first become named storms within the MDR, which includes the tropical North Atlantic south of 21°N and the Caribbean Sea. NOAA defines near-normal seasons as having a total ACE value in the range of 65-103 x 10^5 kt^2 (green lines).

Almost 75% of the total 2002 seasonal activity was associated with three hurricanes that formed during a brief 6-day window of 18-23 September (Fig. 2). Two of these systems became hurricanes over the Caribbean Sea (Isidore and Lili) and eventually became major hurricanes, while the third (Kyle) persisted over the extratropical North Atlantic for 20 days between 23 September and 12 October.

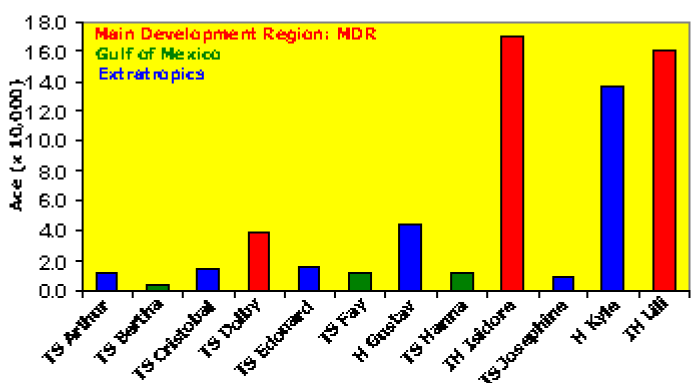

Fig. 2. The Accumulated Cyclone Energy (ACE) index calculated for each of the twelve Atlantic tropical storms during 2002, determined by summing the squares of the estimated 6-hourly maximum sustained wind speed in knots ($Vmax^2$) for all periods while the particular system is either a tropical storm or hurricane.

Three tropical storms, two of which became hurricanes (Isidore and Lili), formed in the MDR during 2002. This is only one-third the average number of hurricanes forming in the MDR since the 1995 upturn in hurricane activity, and is consistent with the El Niño- related suppression of hurricane formation in this region. These three named storms accounted for 37.1 x 10^5 kt^2 (or 59.4%) of the seasonal ACE value, which amounts to 55% of the 1950-2001 period mean for the region (Fig. 1). This deficit in activity within the MDR accounts for 90% of the 2002 seasonal ACE anomaly of –31.5 x 10^5 kt^2.

Six tropical storms, two of which became hurricanes (Gustav and Kyle), formed over the extratropical North Atlantic during 2002, and accounted for 22.7 x 10^5 kt^2 (or 36.3%) of the seasonal ACE value. Long-lived Hurricane Kyle contributed to more than one-half of this regional total. Three tropical storms also formed over the Gulf of Mexico during the season, but accounted for only 2.7 x 10^5 kt^2 (or 4.3%) of the seasonal ACE value.

c. Landfalling U.S. tropical storms and hurricanes

Seven named storms made landfall in the United States during the 2002 hurricane season, six as tropical storms and one as a hurricane (Lili). Five of these systems made landfall along the Gulf Coast. The first of these Gulf Coast systems was TS Bertha (Fig. 3a), which produced local precipitation amounts of 25-50 mm in southern Mississippi and Alabama. The second was TS Fay and its remnant low-

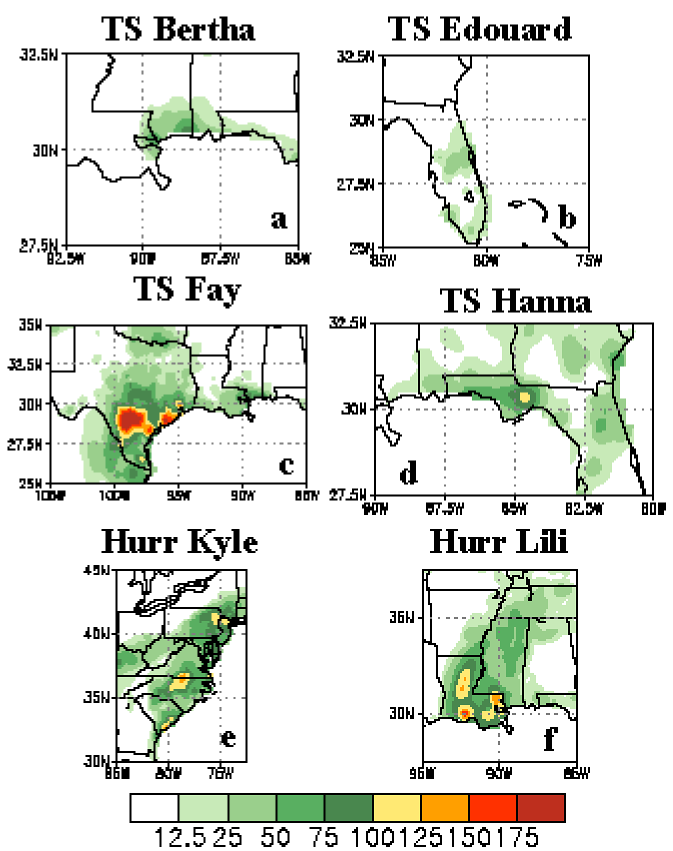

Fig. 3. Total rainfall (mm) associated with (a) TS Bertha during 4-5 Aug. 2002, (b) TS Edouard during 4-5 Sep., (c) TS Fay during 6-10 Sep., (d) TS Hanna during 13-14 Sep., (e) Hurricane Kyle during 11-12 Oct., and (f) Hurricane Lili during 2-5 Oct. 2002.

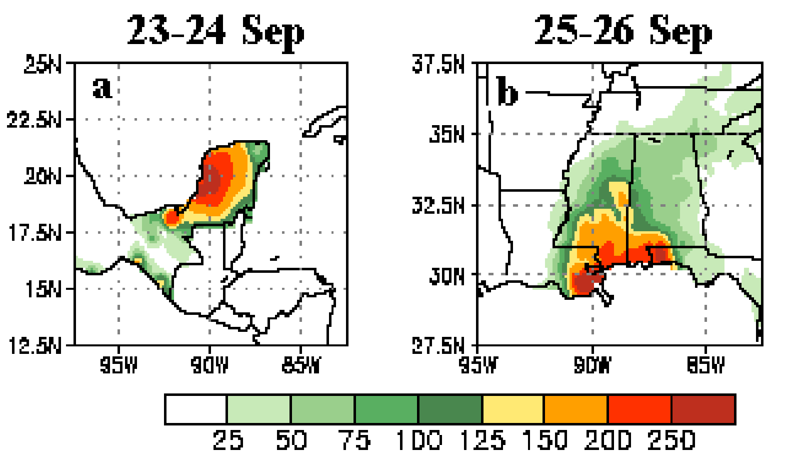

Fig. 4. Total rainfall (mm) associated with Hurricane Isidore during (a) 23-24 Sep. and (b) 25-26 Sep. 2002.

pressure center during 6-10 Sep. (Fig. 3b), which produced on average more than 175 mm of rain over southeastern Texas. The third was TS Hanna, which brought 75-125 mm of precipitation to the Florida Panhandle (Fig. 3d). In late September Hurricane Isidore brought extremely heavy rains (200-300 mm) to the Yucatan Peninsula (Fig. 4a) prior to making landfall along the Gulf Coast as a tropical storm. In the United States rainfall from TS Isidore during 25-26 September exceeded 200 mm from eastern Louisiana to the western Florida Panhandle, and also extended northward across Mississippi and Alabama (Fig. 4b). Hurricane Lili then followed with 100-150 mm of precipitation between 2-5 October across central and eastern Louisiana (Fig. 3f).

Tropical Storm Edouard was the only system to directly hit Florida during the 2002 season. Edouard came onshore along the northeastern coast on 4 September before moving across the state and dissipating over the Gulf of Mexico (Fig. 3b). The final named storm to impact the United States

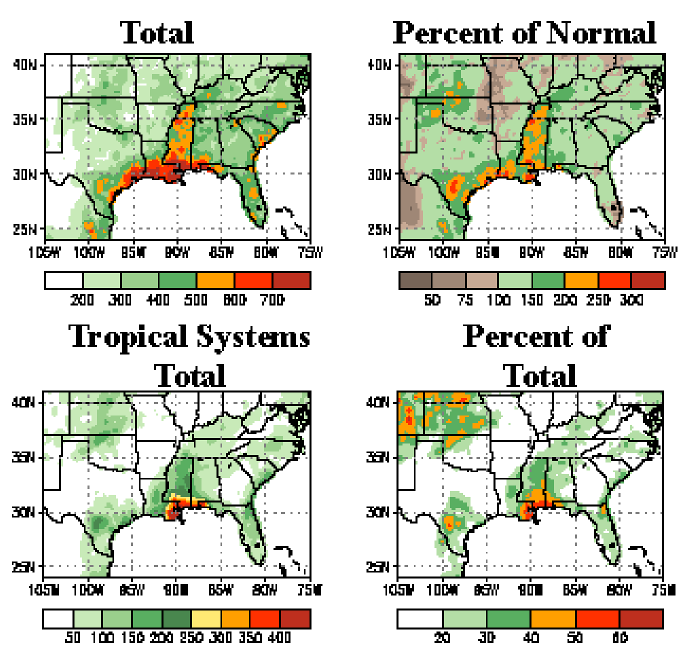

Fig. 5. August-October 2002 precipitation (a) total (mm) and (b) percent of normal. (c) Total rainfall (mm) and (d) percent of the total ASO rainfall associated with the seven landfalling tropical systems shown in Figs. 2 and 3. Normals in panel (b) are based on the 1971-2000 base period daily means.

during the season was Hurricane Kyle, which moved along the South Carolina and North Carolina coasts on 11-12 October after being downgraded to a tropical storm.

August-October 2002 rainfall totals exceeded 600 mm along the Gulf Coast from eastern Texas to western Florida, and reached 500 mm across most of Mississippi extending northward into western Tennessee (Fig. 5a). These amounts are more than twice the long-term average (Fig. 5b) and are attributed to the landfalling tropical systems (Fig. 5c), which generally accounted for 40%-50% of the seasonal total in these areas (Fig. 5d).

New Orleans, LA. is situated within the seasonal rainfall maximum, and experienced heavy rains from four named storms (Fig. 6b). A time series of daily rainfall totals at New Orleans indicates approximately 35 mm of rain from both Bertha and Fay, and nearly 300 mm from Isidore, which completely eliminated the precipitation deficits that had accumulated during the preceding 3 ½ months (Fig. 6a). Hurricane Lili then produced an additional 80 mm of rain, resulting in a total station accumulation from these four storms of almost 450 mm.

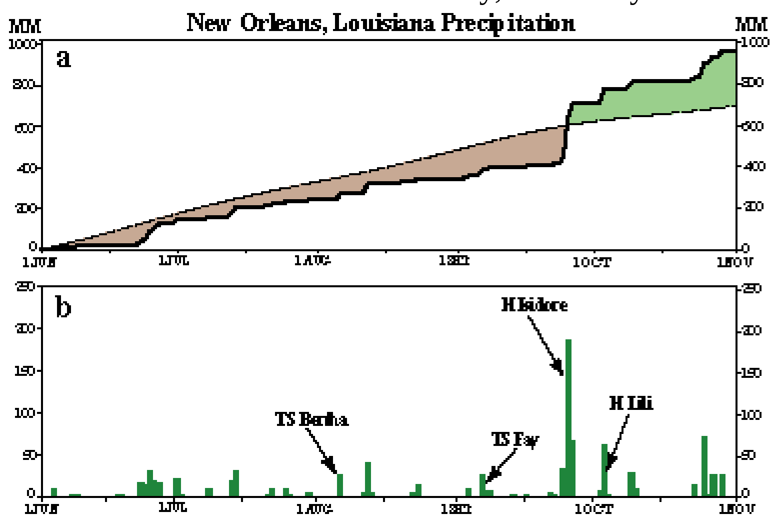

Fig. 6. (a) Accumulated precipitation (thick curve) and (b) daily rainfall totals (mm) at New Orleans, Louisiana during June-October 2002. Panel (a) also shows accumulation of climatological precipitation (thin line), and accumulated departures from normal (shading) beginning 1 June 2002. Green (brown) shading denoted an accumulated precipitation surplus (deficit).

d. Dominant climate factors influencing the 2002 Atlantic hurricane season

The Atlantic Basin seasonal activity during 2002 reflected the competing influences of three leading climate factors: El Niño, the active multi-decadal signal (section d2), and the Madden-Julian Oscillation (MJO, section e).

1. EL NIÑO

The ENSO (El Niño/ Southern Oscillation) cycle is a major factor influencing interannual variations in Atlantic hurricane activity (Gray 1984). During 2002 El Niño was the primary contributor to the seasonal downturn in activity by causing a sharp reduction in the number of hurricanes forming within the MDR during August-October. El Nino was also responsible for the shortened period of tropical activity, with no named storms forming after 23 September and no tropical storm or hurricane activity evident after 12 October.

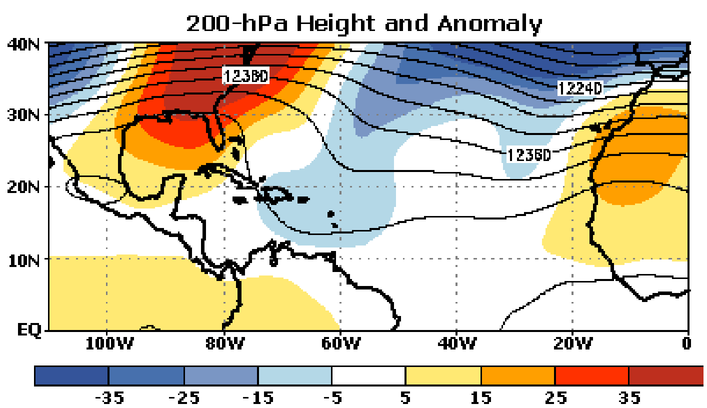

Fig. 7. August- October 2002 mean (contours) and anomalous (shaded) 200-hPa heights. Contour interval for heights is 30 m. Shading interval for anomalies is 10 m. Anomalies are departures from the 1971-2000 base daily means

The El Niño contributed to suppressed hurricane activity in the MDR in three characteristic and inter-related ways. First, it contributed to an enhanced tropical upper-level trough (TUTT) across the North Atlantic and to an overall weaker than average subtropical ridge across the heart of the MDR (Fig. 7). Second, it was associated with enhanced westerly winds at 200-hPa in the Tropics extending from the Pacific Ocean eastward across the MDR (vectors, Fig. 8). Third, these winds resulted in anomalous westerly vertical wind shear across the eastern tropical North Pacific, northern South America, and most of the MDR (blue shading Fig. 8). The resulting increase in the magnitude of the vertical wind shear within the MDR suppressed Atlantic hurricane

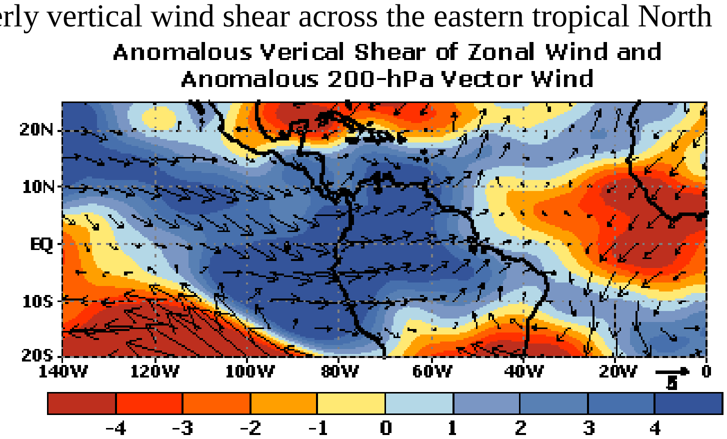

Fig. 8. August-October 2002 anomalous 200-850 hPa vertical shear of zonal wind (shaded) and 200-hPa vector wind. Shading interval for vertical shear is 1.0 m s^{-1}. Anomalies are departures from the 1971-2000 base daily means.

formation similar to that discussed by Goldenberg and Shapiro (1986).

2. THE ACTIVE MULTI-DECADAL SIGNAL

Large multi-decadal variations in seasonal Atlantic Basin activity are evident in the ACE index time series (Fig. 1, also Landsea 1993, Landsea et al 1999). Above-normal activity occurred during 1950-1969 and 1995-2002, while below-average activity occurred during 1970-1994. For the 1995-2002 period the average seasonal ACE index and the average seasonal number of hurricanes and major hurricanes (Goldenberg et al. 2001) were larger than any consecutive eight-year period in the record.

These fluctuations in activity have been linked to multi-decadal variations in several key atmospheric circulation features within the MDR, including the vertical wind shear (Fig. 9a,

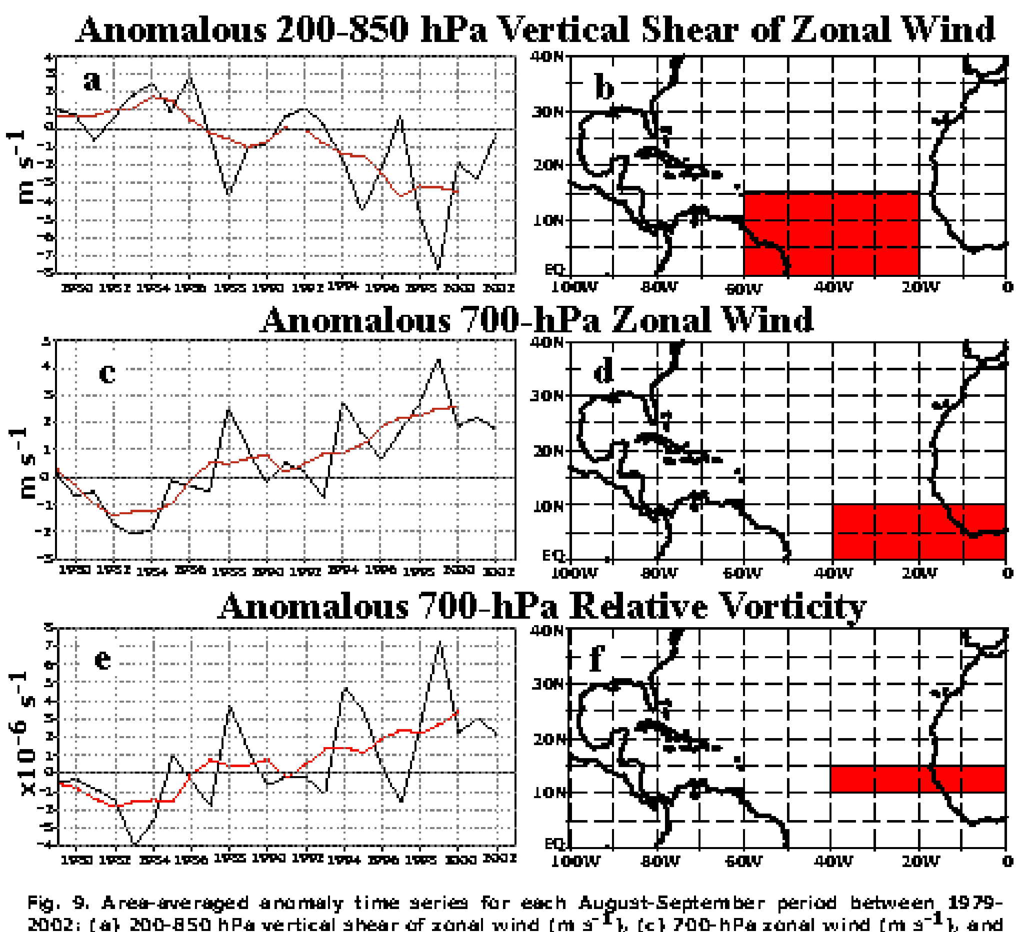

Fig. 9. Area-averaged anomaly time series for each August-September period between 1979-2002: (a) 200-850 hPa vertical shear of zonal wind (m s^{-1}), (c) 700-hPa zonal wind (m s^{-1}), and (e) 700-hPa relative vorticity (x 10^{-6} s^{-1}). In each panel the black curve shows the unsmoothed 2-month anomalies and the red curve shows a 5-point running mean smoother applied to the August-September 2-month anomalies. Averaging regions are highlighted in red in panels (b, d, f), respectively. Anomalies are departures from the 1979-95 base period monthly means.

Goldenberg et al. 2001), the tropical easterly trade winds (Fig. 9b), and the structure of the African Easterly Jet (Fig. 9c). For the first half of the 1980s anomalous westerly (i.e. increased) vertical wind shear is evident over the central tropical North Atlantic (Figs. 9a, b), the tropical easterly trade winds are stronger than average between 5°-10°N (Figs. 9c, d), and anomalous anticyclonic relative vorticity occupies the tropical eastern North Atlantic along the equatorward flank of the mean African Easterly Jet (Figs. 9e, f). This combination of conditions is known to be unfavorable for Atlantic hurricane formation.

Since the mid-1990s the circulation has featured more easterly (i.e. lower) vertical wind shear over the central tropical Atlantic, along with weaker tropical easterly trade winds and anomalous cyclonic relative vorticity along the equatorward flank of the African easterly jet. This combination of conditions is known to favor tropical cyclone formation from African easterly wave disturbances during the climatological peak in the season, and has prevailed during the past four above-normal hurricane seasons (Bell et al. 2000, Lawrimore et al. 2002). The continuing presence of these active-decade circulation features during August-October 2002 (Figs. 8, 10) suggests a moderating influence of the El Niño signal by the multi-decadal

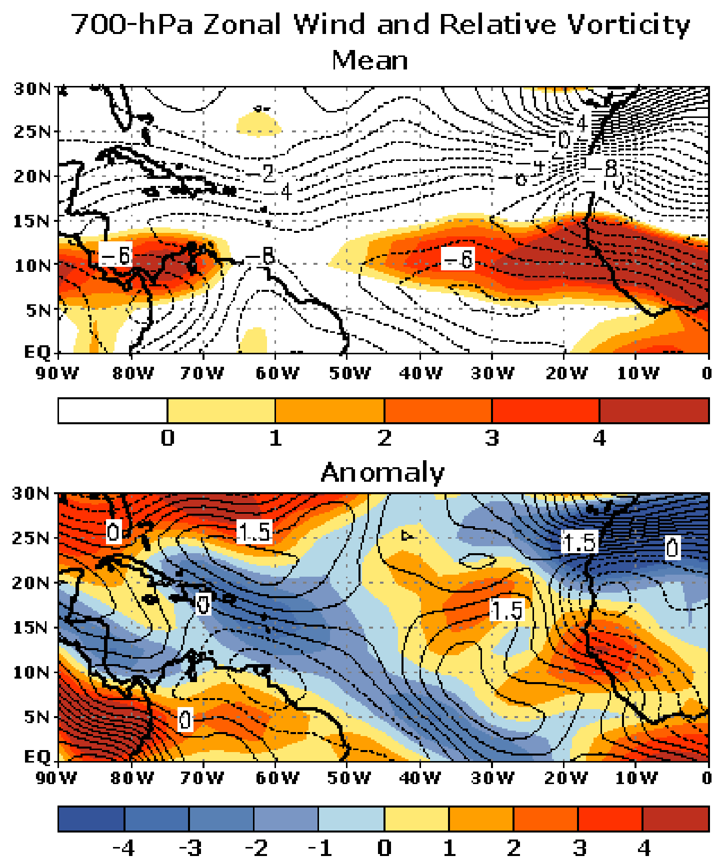

Fig. 10. August- September 2002 (a) mean and (b) anomalous 700-hPa zonal wind (contours) and relative vorticity (shading). Contour interval for zonal wind is 2 m s^{-1} and for anomalies is 0.5 m s^{-1}. Shading interval for relative vorticity and anomalies is $1x10^{-6}$ s^{-1}, with cyclonic relative vorticity shaded red in both panels. In (a) anti-cyclonic relative vorticity is unshaded.

signal.

This multi-decadal variability has been related to three climate factors: 1) the Atlantic multi-decadal mode (Mestas-Nuñez and Enfield 1999, Goldenberg et al. 2001), 2) the leading unrotated multi-decadal EOF global sea-surface temperature (SST) anomalies (e.g., Mo et al. 2001), and 3) West African monsoon variability (Hastenrath 1990; Landsea and Gray 1992; Goldenberg and Shapiro 1996).

More recently Chelliah and Bell (2003) showed that the leading tropical multi-decadal atmospheric mode in the NCEP-NCAR reanalysis system (Kalnay et al. 1996) not only accounts for the multi-decadal variations seen in Fig. 9, but also captures low-frequency fluctuations in the above three climate factors themselves. This tropical multi-decadal mode is related to coherent fluctuations in convective activity occurring throughout the global Tropics between the 1950s-1960s and the 1980s-1990s, including the West African monsoon region, the central equatorial Pacific, and tropical South America.

e. Intraseasonal hurricane variability associated with the Madden-Julian Oscillation (MJO)

Anomalous intraseasonal variability in hurricane activity has been linked to the Madden-Julian Oscillation (MJO), which influences both the rotational and divergent components of the wind in the MDR (Maloney and Hartmann 2000, Mo 2000). The easterly and westerly phases of the MJO derive their names from the sign of the low-level zonal wind anomalies over the eastern tropical Pacific. The easterly phase is associated with enhanced convection over the central tropical Pacific, and with negative (i.e., cyclonic) 200-hPa streamfunction anomalies, westerly 200-hPa zonal wind anomalies, and increased (i.e., anomalous westerly) vertical wind shear in the MDR. These conditions are "El Niño-like" and act to inhibit Atlantic hurricane formation in the MDR (Mo 2000). Opposite circulation anomalies during the westerly MJO phase are "La

Niña-like", and are associated with increased hurricane activity in the MDR. Maloney and Hartmann (2000) suggest a nearly 4-fold increase in hurricane activity within the MDR during the westerly phase of the MJO compared to the easterly phase.

Time-longitude sections of 200-hPa velocity potential anomalies between 5°N-5°S (Fig. 11a) and 10°N-20°N (Fig. 11b) are used to identify both the El Niño-related and MJO-related variability during the 2002 hurricane season. The El Niño- related anomalous upper-level divergence and enhanced convective activity over the central equatorial Pacific are associated with negative velocity potential anomalies beginning early July 2002. Over the western tropical North Atlantic and Caribbean Sea, positive velocity potential anomalies during much of the season are associated with anomalous upper-level convergence and descending motion/ suppressed convective activity. These conditions were most pronounced during the first halves of

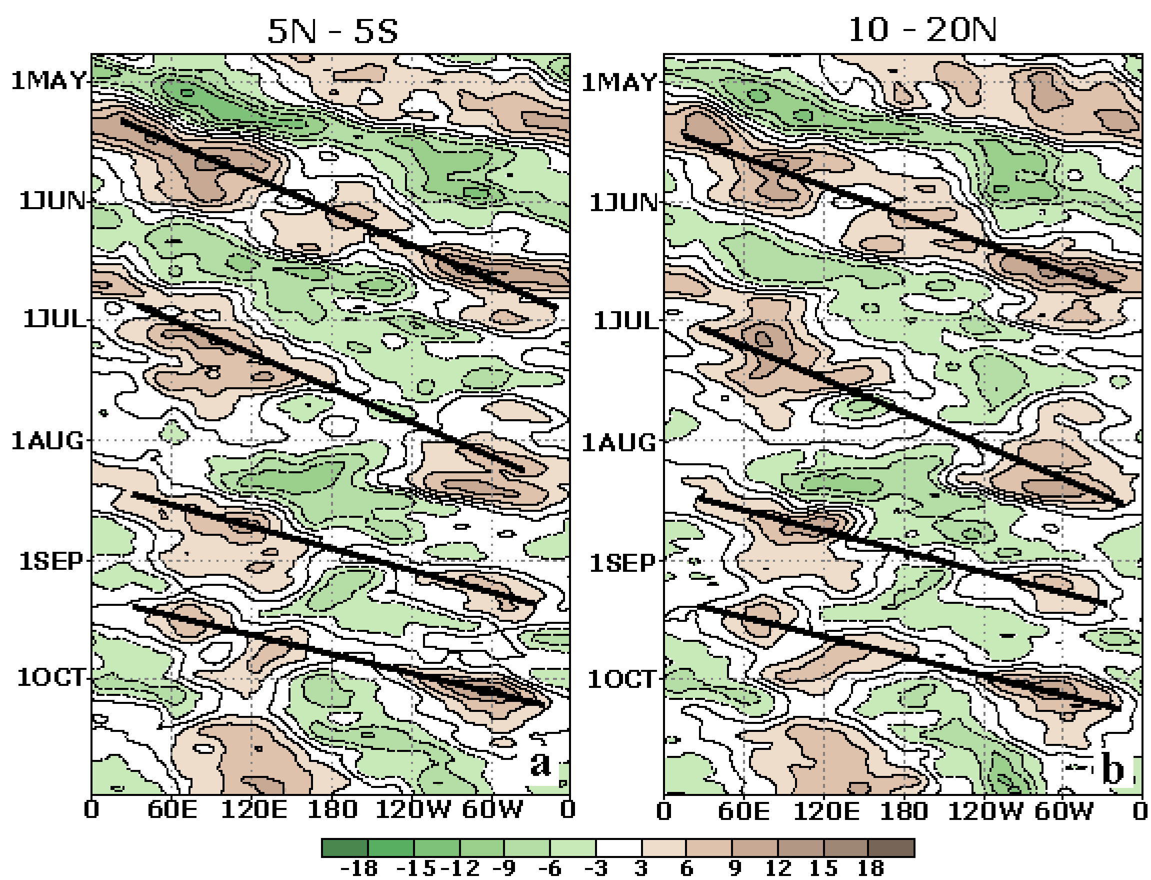

Fig. 11. Time-longitude sections of 5-day running mean 200-hPa velocity potential anomalies averaged over the latitude bands (a) 5°N-5°S and (b) 10°-20°N. Contour interval is 3×10^6 m^2 s^{-1}. Anomalies are departures from the 1979-95 base period daily means.

August and September and most of October, in association with the combination of El Niño and the easterly MJO phase. Over the western MDR and Gulf of Mexico, the cyclonic streamfunction anomalies (Fig. 12), the upper-level trough (Fig. 13a), and the westerly (i.e., higher) vertical wind shear, are also stronger during these periods relative to the background El Niño signal.

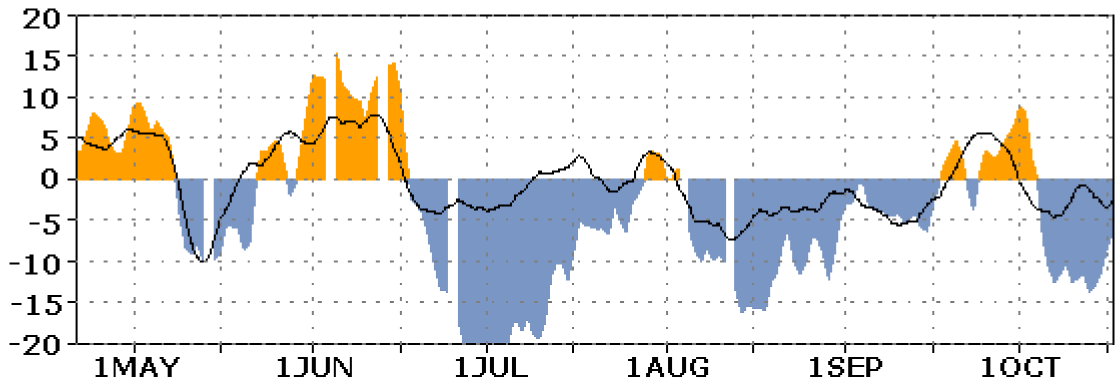

Fig. 12. Daily time series during 22 April-16 October 2002 of area-averaged anomalous 200-hPa velocity potential (solid curve) and streamfunction (shading). Velocity potential anomalies are calculated for the central tropical Pacific region bounded by (160°E-170°W) (10-20°N). Streamfunction anomalies are calculated for the Gulf of Mexico and Caribbean Sea bounded by (100°W-60°W) (10 -30°N). Anomalies are departures from the 1979-95 base period daily means.

In contrast, the westerly MJO phase during both late July and late September is associated with a temporary disappearance of the El Niño- related enhanced convection from the central equatorial Pacific, and with a shift of the negative velocity potential anomalies and associated anomalous ascending motion to the eastern tropical Pacific and MDR. Anticyclonic streamfunction anomalies (Fig. 12) and an amplified subtropical ridge are also evident during both periods over the Caribbean Sea and Gulf of Mexico. Importantly, the stronger MJO in late September contributed to larger anomalies at a time when conditions are normally most conducive to hurricane development (Fig. 13b).

Consistent with these conditions a broad area of anomalous easterly (i.e., lower) vertical shear is evident over most of the MDR and across the western extratropical North Atlantic during late September. Two major hurricanes, long-lived hurricane Kyle, and almost seventy-

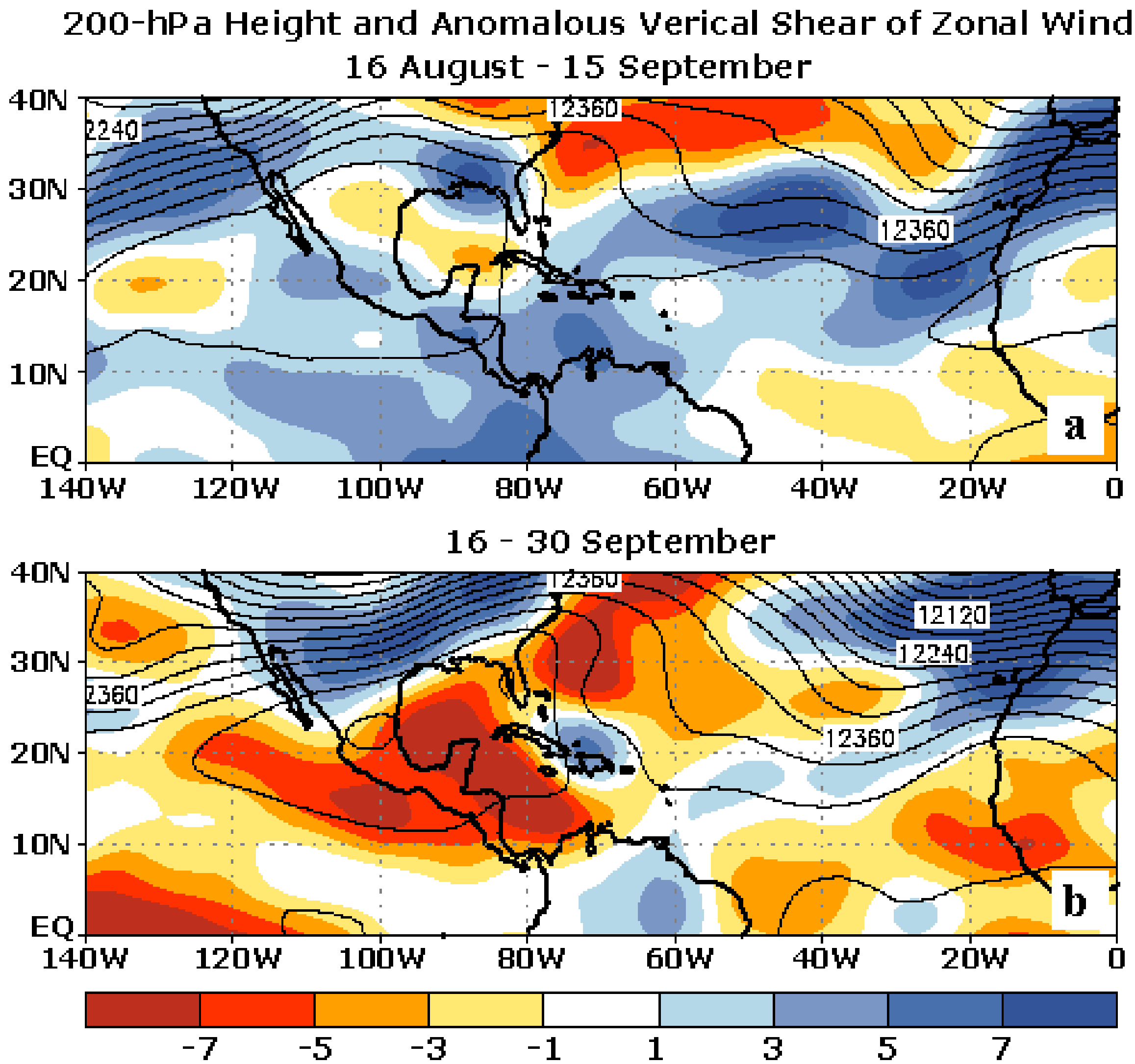

Fig. 13. Mean 200-hPa heights (contours) overlaid with anomalous 200-850 hPa vertical shear of zonal wind (shading) during (a) 16 August - 15 September 2002 and (b) 16-30 September 2002. Contour interval for heights is 30 m. Shading interval for anomalous vertical shear is 2.0 m s^{-1}, with easterly shear anomalies shaded red and westerly shear anomalies shaded blue. Anomalies are departures from the 1979-95 base period daily means.

five per cent of the total seasonal activity, occurred in this period. Lawrimore et al. (2002) also note several periods of substantially increased activity during the 2001 Atlantic hurricane season in association with the westerly phase of the MJO.

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