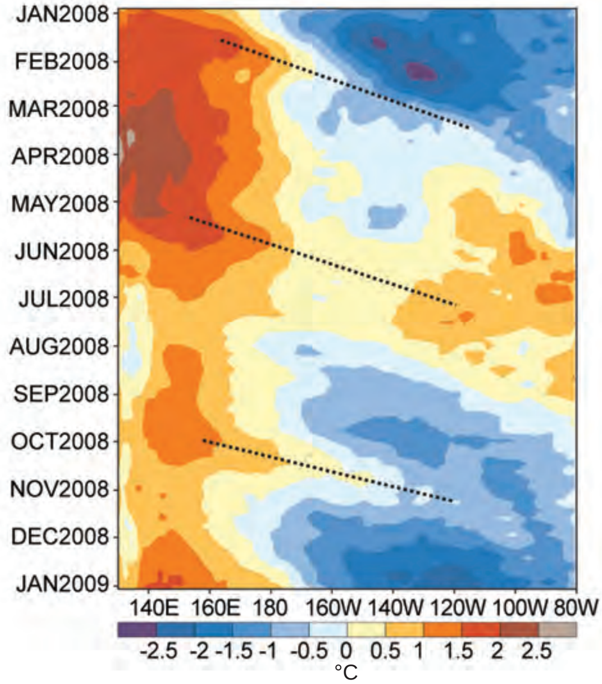

Fig. 4.7. Time–longitude section of the upper ocean (0–300 m) heat content anomaly (5°N–5°S) for 2008. Blue (yellow/red) shading indicates below- (above) average heat content. The downwelling phases (solid lines) of oceanic Kelvin waves are indicated. Anomalies are departures from the 1982–2004 base period pentad means.

sociated with La Niña. A similar warming due to the Kelvin wave triggered in May led to positive heat content anomalies across much of the Pacific basin during June and July, and to the end of La Niña (Fig. 4.3c).

A third equatorial Kelvin wave was triggered by the MJO in late September, again in response to the propagation of suppressed convection from the Indian Ocean to the western Pacific. This wave counteracted the anomalous cooling that was becoming reestablished across the central and east-central equatorial Pacific, and likely delayed the reemergence of La Niña until later in the year. The timing of La Niña's reemergence was also likely related to the opposite phase of the MJO in November, which featured significantly enhanced convection and stronger low-level easterlies over the western Pacific Ocean.

d. Tropical cyclones

1) Overview—H. J. Diamond

The global tallying of total storm numbers is always challenging and involves more than simply adding up basin totals, as there are a number of storms that cross basin boundaries. Averaged across all basins, the 2008 TC season (2007–08 in the Southern Hemisphere) saw a near-normal (1981–2000 base) number of tropical or NSs (≥ 34 kt) and a below-average number of HTCs (≥ 64 kt) and major HTCs (≥ 96 kt) than average. Globally, 96 NSs developed during 2008 (1 below average), and 46 became HTCs (9 below average). Of these, 20 (compared with 26 in 2006 and 18 in 2007) attained major/intense status (global average is 25.4).

The 2008 season was significantly above average in two basins (North Atlantic and south Indian); near to slightly above average in the NIO, and near to below average in the remaining basins (eastern North Pacific, northwest Pacific, southwest Pacific, and Australian region). The North Atlantic season was also active in terms of landfalling storms. The island of Hispaniola was affected by several storms (two direct hits); Cuba experienced two landfalls by major hurricanes; the continental United States experienced a total of six landfalling storms (including three hurricanes); and one hurricane made a very rare landfall in Nova Scotia, Canada. The NIO season was punctuated by a severe Category-5 storm (Cyclone Nargis), which was responsible for over 145,000 deaths and $10 billion (USD) in damages in Myanmar; Nargis is also ranked as the seventh-strongest storm ever in that basin. TC activity in the western North Pacific basin was also shifted farther westward and northward than normal and was unusually tranquil (see sidebar "Unusually Quiet West Pacific Typhoon Season Ends with a Dolphin Kick").

2) Atlantic basin—G. D. Bell, E. Blake, S. B. Goldenberg, T. Kimberlain, C. W. Landsea, R. Pasch, and J. Schemm

(i) Seasonal activity

The 2008 Atlantic hurricane season produced 16 NSs, of which 8 became Hs and 5 became MHs (J. Beven and D. Brown 2009, unpublished manuscipt). The 1950–2000 averages are 11 NSs, 6 Hs, and 2 MHs. For 2008 the ACE (Bell et al. 2000) was 167% of the median (Fig. 4.8).This value is the 14th most active since 1950 and is well into the above-normal range (see www.cpc.noaa.gov/products/outlooks/background_information.shtml), consistent with the ongoing active Atlantic hurricane era that began in 1995 (Goldenberg et al. 2001). It is the only season on record in which an MH existed in every month from July through November.

Consistent with other active seasons, 11 NSs formed in the MDR (Goldenberg and Shapiro 1996) during 2008 (green box, Fig. 4.9a). These systems accounted for seven Hs, all five MHs, and 88% of the ACE value. The season was also active in terms of landfalling NSs. The nations in and surrounding

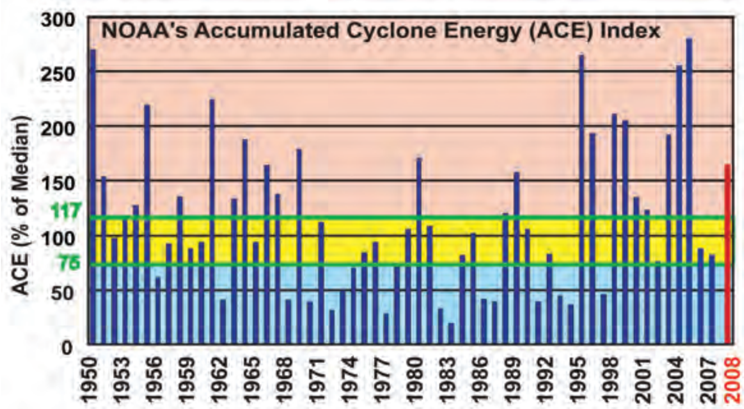

Fig. 4.8. ACE values expressed as percent of the 1950–2000 median value (87.5 × 10^4 kt^2). ACE is a wind energy index that measures the combined strength and duration of the NSs. ACE is calculated by summing the squares of the 6-hourly maximum sustained surface wind speed in knots (Vmax2) for all periods while the storm has at least TS strength. Pink, yellow, and blue shades correspond to NOAA's classifications for above-, near-, and below-normal seasons, respectively.

the Caribbean Sea were severely impacted by four TSs and four Hs. Cuba experienced three hurricane landfalls (including two MHs, Gustav and Ike), while Hispaniola was affected by several NSs including direct strikes by TS Fay and H Hanna. The continental United States was struck by three TSs and three Hs, with all but one TS making landfall along the Gulf Coast. Elsewhere, H Kyle made landfall in Nova Scotia, Canada.

(ii) SSTs

For the ASO climatological peak months of the season, SSTs were generally 0.5°–1.0°C above average in the MDR (Fig. 4.9a). The area-averaged SST anomaly in the MDR was 0.60°C, the fifth warmest since 1950 (Fig. 4.9b).

This warmth partly reflects the warm phase of the AMO (Enfield and Mestas-Nuñez 1999), which accompanied the 1995 transition to the active Atlantic phase of the tropical multidecadal signal (Goldenberg et al. 2001; Bell and Chelliah 2006). It also reflects reduced mixing and reduced evaporation from the ocean surface in response to weaker northeasterly trade winds (anomalous southwesterly flow) across the southern half of the MDR (Fig. 4.10a).

(iii) Atmospheric circulation

An interrelated set of atmospheric anomalies typical of recent active hurricane seasons (Landsea et al. 1998; Bell et al. 1999, 2000, 2004, 2006; Goldenberg et al. 2001; Bell and Chelliah 2006; Kossin and Vimont 2007) set the stage for the active 2008 hurricane season. These conditions are also known to greatly increase the probability of hurricane landfalls, as was seen in 2008.

During ASO 2008, weaker trade winds and high values of CAPE covered the southern half of the MDR (Fig. 4.10a), and sea level pressure was below average across the MDR (blue shading, Fig. 4.10b). These conditions were associated with a more northward position of the Atlantic ITCZ (section 4e2) and with an enhanced West African monsoon system.

The low-level westerly anomalies extended past 700 hPa, the approximate level of the African Easterly Jet, and were associated with a 5° northward shift of the AEJ core (black arrow) compared to climatology. As a result, the bulk of the African easterly wave energy (Reed et al. 1977) was often centered within the MDR. The AEJ also featured increased cyclonic shear along its equatorward flank, which dynamically favors stronger easterly waves and provides an inherent cyclonic rotation to their embedded convective cells.

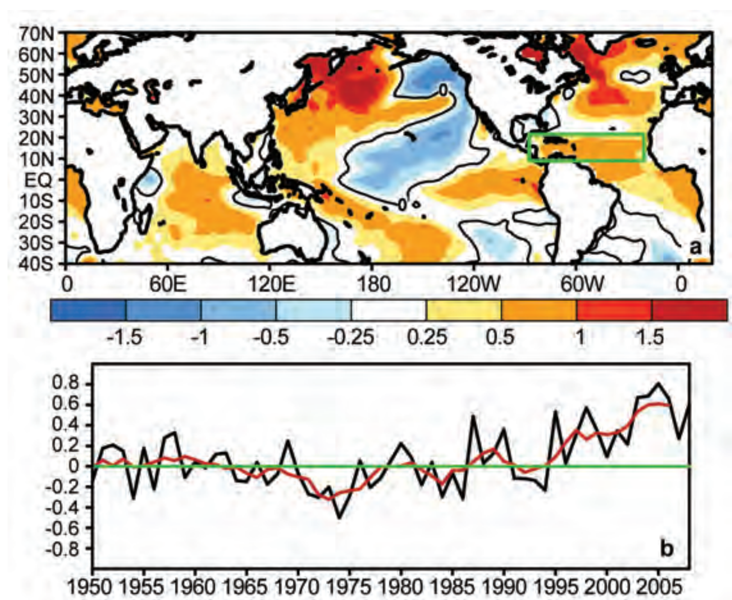

Fig. 4.9 (a) SST anomalies (°C) during Aug–Oct 2008. (b) Consecutive Aug–Oct area-averaged SST anomalies in the MDR. Red line shows the corresponding 5-yr running mean. Green box in (a) denotes the MDR. Anomalies are departures from the 1971–2000 monthly means.

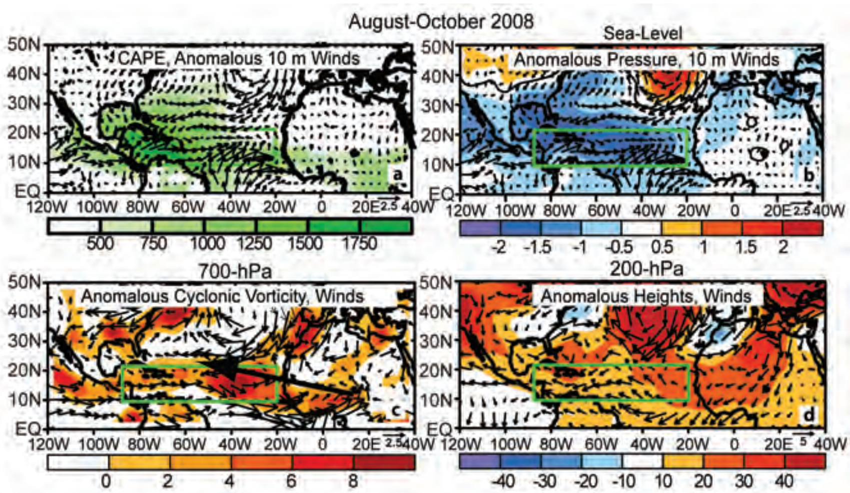

Fig. 4.10. Aug–Oct 2008: (a) total CAPE (J kg^{-1}) and anomalous vector winds (m s^{-1}) at 10 m; (b) anomalous sea level pressure (shading, hPa) and vector winds at 10 m; (c) 700-hPa anomalous cyclonic relative vorticity (shading) and vector winds, with thick arrow indicating the observed AEJ core; (d) 200-hPa anomalous heights and vector winds. Green boxes denote the MDR. Anomalies are departures from the 1971–2000 monthly means.

At 200 hPa, the wind and height anomalies reflected an enhanced upper-level ridge and a stronger, more westward extension of the tropical easterly jet (Fig. 4.10d). The result was weak (less than 8 m s^{-1}) vertical wind shear between 200 and 850 hPa across much of the MDR (shading, Fig. 4.11a), with the most anomalously weak shear spanning the central tropical Atlantic Ocean and Caribbean Sea (Fig. 4.11b).

This combination of conditions meant that many TSs developed from amplifying African easterly waves in an environment of below-average pressure and increased cyclonic shear. Those waves were also embedded within an extended region of weak vertical wind shear, which enabled further intensification as they moved westward over progressively warmer SSTs.

Two prominent climate phenomena can account for the interrelated set of anomalies associated with the 2008 Atlantic hurricane season. These are the ongoing active Atlantic phase of the tropical multidecadal signal and lingering La Niña signals.

(iv) Conditions associated with the ongoing active Atlantic hurricane era

2008 marks the 10th above-normal Atlantic hurricane season since the current high-activity era began in 1995. During 1995–2008 only the strong El Niño year of 1997 had below-normal activity. The increased activity since 1995 contrasts with the preceding low-activity era 1971–94, when half of the seasons were below normal and only three were above normal.

The transition to the current active era was associated with a phase change in the tropical multidecadal signal, which reflects the leading modes of tropical convective rainfall variability occurring on multidecadal time scales (Bell and Chelliah 2006; Bell et al. 2007). This signal highlights the convectively driven nature of the atmospheric anomalies across the central and eastern MDR, and links them to an east–west oscillation in anomalous convection between western Africa (Landsea and Gray 1992; Goldenberg and Shapiro 1996) and the Amazon basin. As seen in 2008, the combination of an enhanced West African monsoon and suppressed convection in the Amazon basin (Fig. 4.12a) is consistent with the ongoing high-activity era (Fig. 4.12b), as is the anomalous low-level inflow into the West African monsoon region

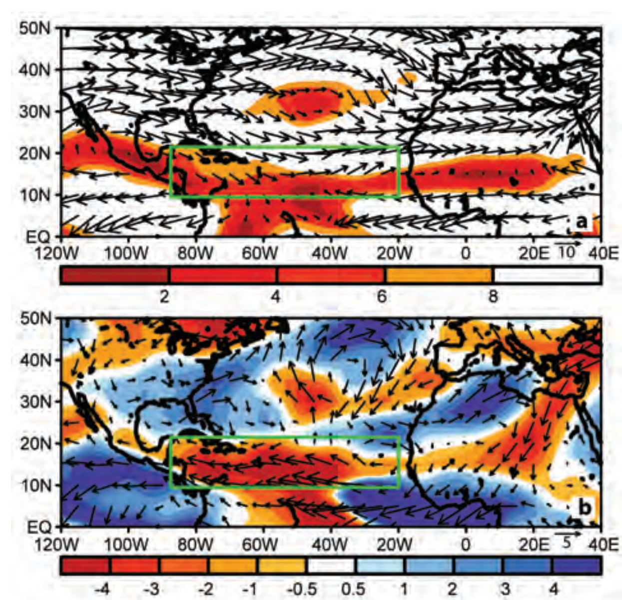

Fig. 4.11. Aug–Oct 2008: 200–850-hPa vertical wind shear magnitude (m s^{-1}) and vectors (a) total and (b) anomalies. In (a), shading indicates values below 8 m s^{-1}. In (b), red (blue) shading indicates below-(above) average magnitude of the vertical shear. Green boxes denote the MDR. Anomalies are departures from the 1971–2000 monthly means.

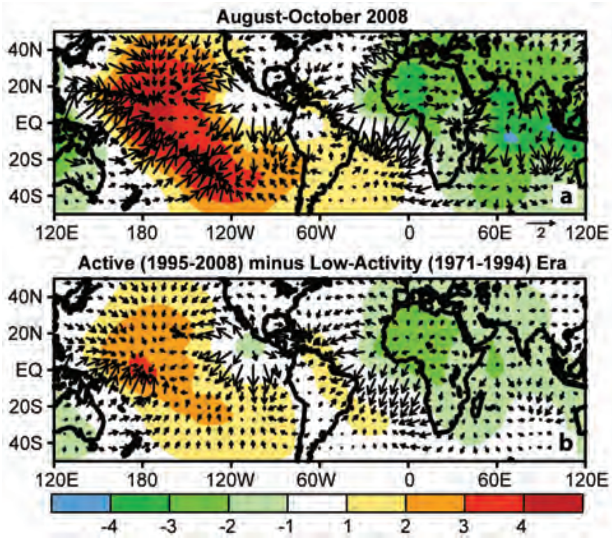

Fig. 4.12. 200-hPa velocity potential (shading) and divergent wind vectors (m s^{-1}): (a) Aug–Oct 2008 anomalies and (b) high-activity (1995–2008) period means minus low-activity (1971–94) period means. Anomalies are departures from the 1971–2000 monthly means.

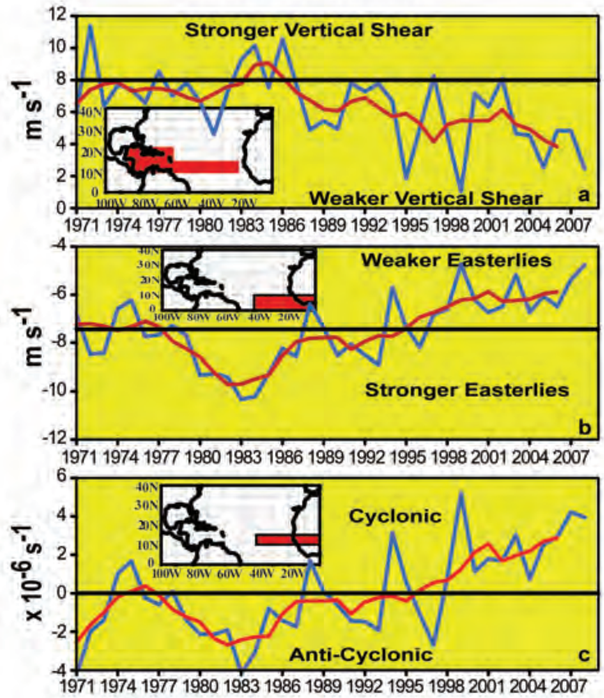

Fig. 4.13. Time series showing consecutive Aug–Oct values of area-averaged (a) 200–850-hPa vertical shear of the zonal wind (m s^{-1}), (b) 700-hPa zonal wind (m s^{-1}), and (c) 700-Pa relative vorticity (× 10^{-6} s^{-1}). Blue curves show unsmoothed values, and red curves show a 5-pt running mean of the time series. Averaging regions are shown in the insets.

(Fig. 4.11a) and enhanced upper-level outflow from that region (Figs. 4.10d, 4.12a).

Consistent with these conditions are dramatic differences in the vertical wind shear (Fig. 4.13a), 700-hPa zonal winds (Fig. 4.13b), and 700-hPa relative vorticity (Fig. 4.13c), within the MDR between the high-activity and low-activity era.

An enhanced West African monsoon system has major impacts on the 200-hPa Northern Hemispheric circulation, as seen in 2008 by the pronounced inter-hemispheric symmetry of streamfunction anomalies across the eastern subtropical Atlantic Ocean and Africa (Fig. 4.14a). This pattern reflects enhanced upper-level ridges in the subtropics of both hemispheres and a stronger tropical easterly jet, both of which have prevailed throughout this high-activity era (Fig. 4.14b) (Bell and Chelliah 2006).

(v) La Niña

La Niña acts to reduce the vertical wind shear in the western MDR, thus favoring increased Atlantic hurricane activity (Gray 1984). During 2008, SSTs in the Niño-3.4 region returned to normal in June (Fig. 4.1). However, tropical convection remained suppressed near the date line throughout ASO (e.g., Fig. 4.4c), which favored cyclonic anomalies at 200 hPa over the western subtropical Pacific and anticyclonic anomalies over the eastern subtropical Pacific and Caribbean Sea (Fig. 4.14a). The associated anomalous easterly winds extended from the eastern Pacific to the tropical Atlantic, and contributed to reduced vertical wind shear in the western MDR. Historically, the presence of these conditions during a high-activity era greatly increases the probability of an above-normal Atlantic hurricane season.

During 2008, the window of opportunity for TC formation widened, as the above circulation anomalies (Figs. 4.12–4.14) were present before the peak of the season. For example, a large area of anomalous upper-level divergence and enhanced convection (indicated by the core of negative velocity potential anomalies; Fig. 4.15a) was already present during April–June over the eastern tropical Atlantic Ocean and West Africa (Fig. 4.15a). Impacts from this anomalous convection can be seen in the pattern of 200-hPa streamfunction anomalies (Fig. 4.15b), which shows amplified ridges in the subtropics of both hemispheres flanking the region of enhanced convection. As shown by Bell et al. (2009), the associated upper-level easterly anomalies and reduced vertical wind shear contributed to the development of two TCs (including long-lived MH Bertha) within the MDR during July, a month when conditions are normally unfavorable for low-latitude TC formation (DeMaria et al. 2001).