The 2009 North Atlantic Hurricane Season
A Climate Perspective

Gerald Bell[1], Eric Blake[2], Todd Kimberlain[2], Jon Gottschalck[1],
Chris Landsea[2], Richard Pasch[2], Jae Schemm[1], Stanley Goldenberg[3]

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

Contents:

1. 2009 Seasonal Activity

The 2009 Atlantic hurricane season produced nine named storms, of which three became hurricanes and two became major hurricanes (Fig. 1). The 1950-2000 averages are eleven named storms, six hurricanes, and two major hurricanes. The reduced activity during 2009 reflected fewer, shorter-lived, and generally weaker named storms when compared to most seasons since the current high activity era for Atlantic hurricanes began in 1995 (Goldenberg et al. 2001). As a result, the Accumulated Cyclone Energy (ACE) index (Bell et al. 2000) for 2009 was 60% of the median (Fig. 2), approximately one-third of the seasonal average (165% of the median) since 1995. Based on NOAA's classification (cpc.ncep.noaa.gov/products/outlooks/background_information.shtml), this

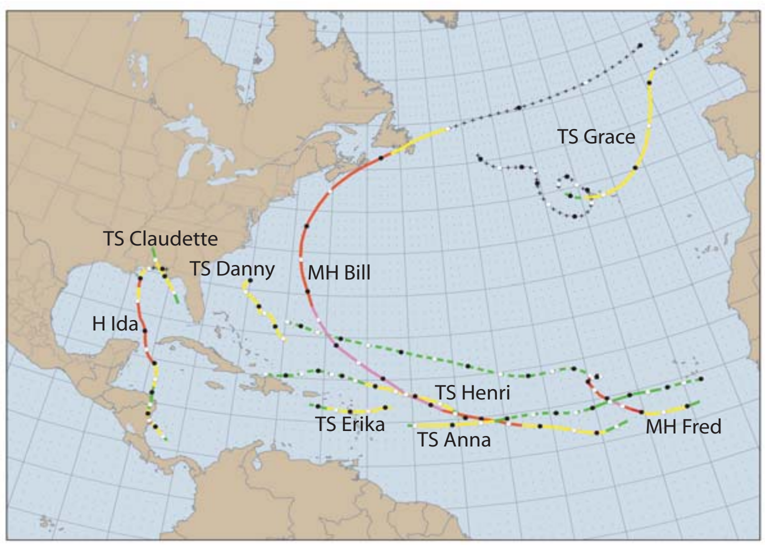

Fig. 1. Tracks of Atlantic named storms during 2009. Shading corresponds to strength of maximum sustained surface wind speeds, with green indicating tropical depression intensity (< 39 mph), yellow indicating tropical storm (TS) intensity (39-73 mph), red indicating hurricane (H, cat. 1-2) intensity, and magenta indicating major hurricane (MH, cat. 3-5) intensity).

makes 2009 only the second (along with 1997) below normal Atlantic hurricane season since 1995.

NOAA's predicted ranges of activity for 2009 verified well. The pre-season outlook issued 21 May 2009 (cpc.ncep.noaa.gov/products/outlooks/hurricane2009/May/hurricane.shtml) called for 9-14 named storms, 4-7 hurricanes, 1-3 major hurricanes, and an ACE range of 65%-130% of the median (Red bar, Fig. 2). The updated NOAA outlook issued 6 August 2009 (cpc.ncep.noaa.gov/products/outlooks/hurricane2009/August/hurricane.shtml) called for less activity due to the development of El Niño, with ranges of 7-11 named storms, 3-6 hurricanes, 1-2 major hurricanes, and an ACE range of 60%-110% of the median.

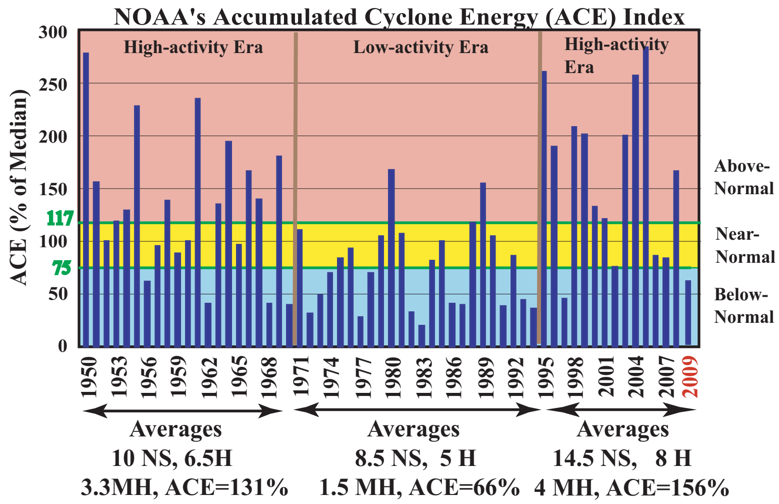

Fig. 2. NOAA's Accumulated Cyclone Energy (ACE) index expressed as percent of the 1950-2000 median value (87.5 x 10^4 kt^2). ACE is a wind energy index that measures the combined strength and duration of the named storms. ACE is calculated by summing the squares of the 6-hourly maximum sustained wind speed (measured in knots) for all periods while the named storm has at least tropical storm strength. Pink, yellow, and blue shadings correspond to NOAA's classifications for above-, near- and below-normal seasons, respectively. Red bars indicate NOAA's official 2009 outlooks for ACE, which were issued on 21 May and 6 August 2009.

One tropical storm (Claudette in the Florida Panhandle) during 2009 made landfall in the United States, and Ida brought tropical storm force winds to the northern Gulf Coast before becoming extratropical prior to making landfall. Only one named storm (Ida) formed in the Caribbean Sea, making landfall as a hurricane in Nicaragua before weakening to a tropical depression while crossing southeastern Honduras. Tropical storm Erika passed through the northern Caribbean Islands while weakening, and Hurricane Bill brushed Nova Scotia and Newfoundland.

This represents a sharp decrease in the number of landfalling named storms compared to 2008 (cpc.ncep.noaa.gov/products/expert_assessment/hurrsummary_2008.pdf, also Bell et al. 2009), when the nations in and surrounding the Caribbean Sea were severely impacted by four tropical storms and four hurricanes, and the continental United States was struck by three tropical storms and three hurricanes. NOAA's seasonal hurricane outlooks currently do not predict hurricane landfalls, and do not indicate whether a particular region is more likely to

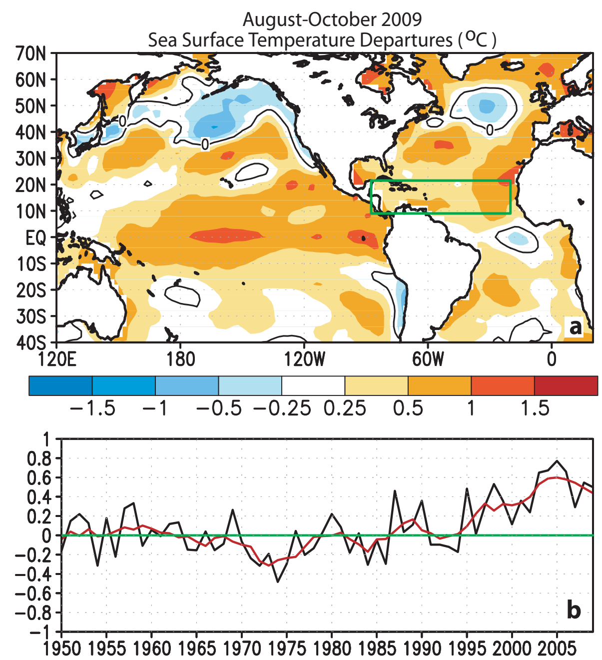

Fig. 3. (a) Sea surface temperature (SST) departures (°C) during Aug-Oct 2009. (b) Consecutive Aug-Oct area-averaged SST anomalies in the Main Development Region [MDR, denoted by green box in (a)]. Red line in (b) shows the corresponding 5-yr running mean. Departures are with respect to the 1971-2000 period monthly means.

be struck during the season.

2. Sea surface temperatures (SSTs)

The Caribbean Sea and tropical Atlantic Ocean (between 9.5°N and 21.5°N) are referred to collectively as the Main Development Region (MDR, green box in Fig. 3a). For the August-October (ASO) peak months of the season, SSTs were above average throughout the MDR during 2009, with the largest departures (+0.5°C to +1.0°C) found across the south-central and eastern MDR. The area-averaged SST anomaly for the entire MDR during ASO 2009 was +0.50°C, which is tied for seventh warmest since 1950 (Fig. 3b).

This warmth reflects three main factors: 1) the warm phase of the Atlantic Multi-decadal Oscillation (AMO) (Enfield and Mestas-Nuñez 1999), which accompanied the 1995 transition to the active Atlantic phase of the tropical multi-decadal signal (Goldenberg et al. 2001, Bell and Chelliah 2006), 2) reduced mixing and reduced evaporation from the ocean surface in association with weaker northeasterly trade winds (anomalous southwesterly flow) across most of the tropical Atlantic portion of the MDR (Fig. 4a), and 3) long-term trend (Santer et al. 2006).

The reduction in Atlantic hurricane activity during 2009, despite this anomalous warmth, is consistent with previous findings indicating that local atmospheric circulation anomalies, rather than local SST anomalies, are the dominant contributor to seasonal fluctuations in Atlantic hurricane activity (Shapiro and Goldenberg 1998, Bell and Chelliah 2006, Bell et al. 2006).

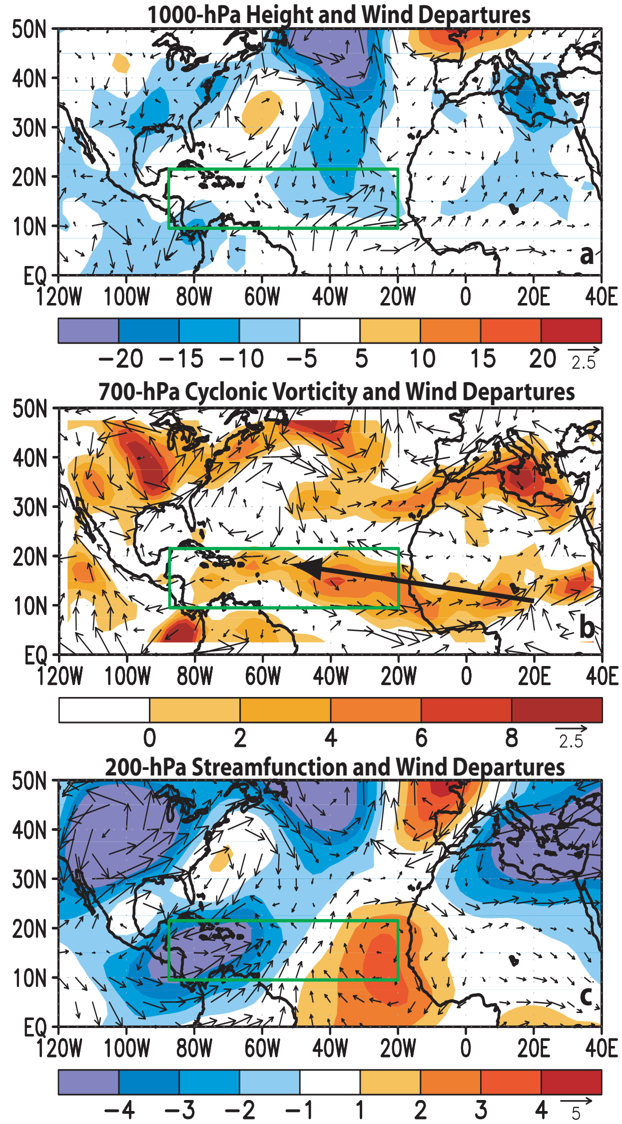

Fig. 4. Aug-Oct 2009 departures from normal: (a) 1000-hPa height (shading) and vector wind (m s^{-1}), (b) 700-hPa cyclonic relative vorticity (shading) and vector wind, with thick solid line indicating the axis of the African easterly jet, and (c) 200-hPa streamfunction and vector wind. Green boxes denote the MDR. Vector scales are to right of color bars. Departures are with respect to the 1971-2000 period

3. Atmospheric circulation

The below-normal hurricane activity during 2009 reflected circulation features that were associated with competing climate factors. Consistent with the anomalously warm SSTs in the MDR, several circulation features have been in place since 1995 and were again conducive to tropical cyclone development during 2009.

These conditions include weaker tropical easterly winds (westerly wind departures) and below-average air pressure at sea level over large portions of the MDR (blue shading, Fig. 4a). The westerly wind departures extended above the 700-hPa level, the approximate level of the African Easterly Jet (AEJ, Fig. 4b), and were associated with a 5° lat. 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 well within the MDR.

As also seen since 1995, the AEJ during 2009 featured enhanced cyclonic shear along its equatorward flank (red shading), which dynamically favors stronger easterly waves and provides a cyclonic rotation to their embedded convective cells. Aiding the development of these waves was an enhanced ridge at 200-hPa over the eastern MDR (red shading, Fig. 4c). As a result, a majority (seven of nine) of named storms during the season formed within the MDR. This activity is not typical of most below normal seasons, which often feature little to no tropical cyclone activity in the MDR (Shapiro and Goldenberg 1998, Bell and Chelliah 2006).

Offsetting the above conducive conditions during ASO 2009 was an enhanced and persistent Tropical Upper-Tropospheric Trough (TUTT) over the mid-Atlantic Ocean and Caribbean Sea (blue shading, Fig. 4c). This trough produced exceptionally strong vertical wind shear across much of the MDR (blue shading, Fig. 5) along with anomalous upper-level convergence (Fig. 6) and reduced rising motion over the Caribbean Sea.

A vertical profile of zonal winds averaged over the Caribbean Sea (black curve, Fig. 7a) shows that the increased vertical wind shear during ASO 2009 resulted from a combination of stronger westerly winds above 300-hPa compared to climatology (purple line with X's), and stronger-than-average easterly winds below 700-hPa. These conditions are typical of El Niño (Gray 1984, Knaff 1997, Goldenberg and Shapiro 1996, Bell and Chelliah 2006), and were also observed during the recent El Niño years of 1997 (red curve) and 2002 (green curve).

A similar plot of vertical motion (black curve, Fig. 7b) shows only weak ascent throughout the troposphere over the Caribbean Sea during ASO 2009, with the normal peak in ascending motion between 500-250-hPa being notably absent. Rising motion was also suppressed over the Caribbean Sea during the recent El Niño years of 1997 (red), 2002 (green), and 2006 (blue) (Bell et al. 2007).

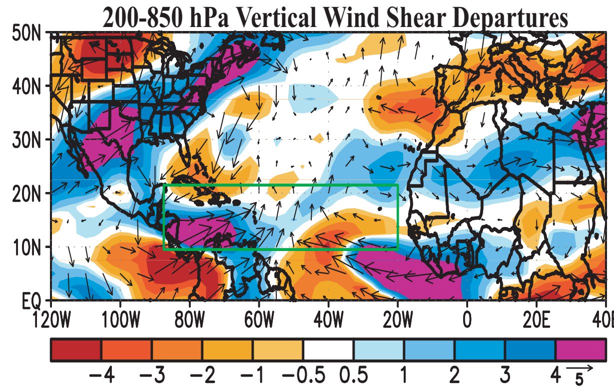

Fig. 5. Aug-Oct 2009: Departures from normal of 200-850 hPa vertical wind shear magnitude (m s^{-1}) and vectors. Green box denotes the MDR. Vector scale is to right of color bar. Departures are with respect to the 1971-2000 period monthly means.

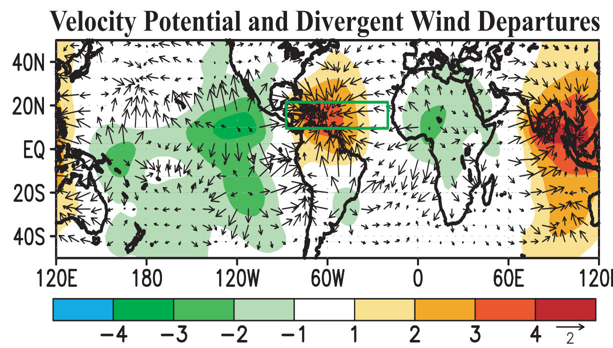

Fig. 6. Aug-Oct 2009: Departures from normal of 200-hPa velocity potential (shading) and divergent wind vectors (m s^{-1}): Vector scale is to right of color bar. Departures are with respect to the 1971-2000 period monthly means.

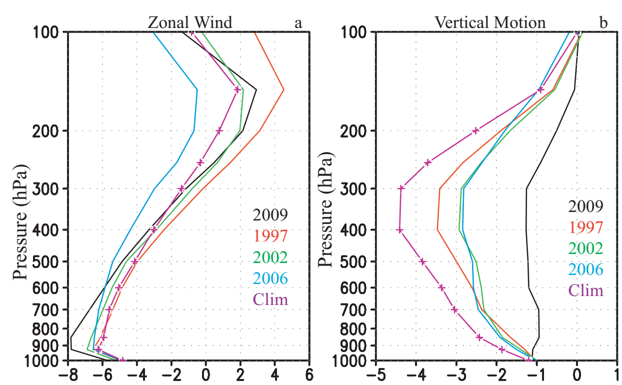

Fig. 7. Area-averaged conditions in the MDR during Aug.-Oct. for recent El Niño years: (a) total zonal wind (m s^{-1}), with negative (positive) values indicating easterly (westerly) winds and (b) vertical motion (x 10^{-2} hPa s^{-1}), with negative (positive) values indicating rising (sinking) motion. Years are color-coded as indicated on plot.

4. Links to global climate patterns

The regional atmospheric conditions and seasonal Atlantic hurricane activity during 2009 largely reflected two competing climate factors: the ongoing active Atlantic phase of the tropical multi-decadal signal and El Niño. Some intra-seasonal variability in Atlantic hurricane activity was also evident, and can be linked partly to the Madden-Julian Oscillation (MJO).

(a) Ongoing high activity era in the tropical Atlantic

During the current high-activity era for Atlantic hurricanes which began in 1995, two-thirds (10 of 15) of Atlantic hurricane seasons have been above normal, and only two have been below normal (Fig. 2). This elevated activity contrasts with the preceding low-activity era 1971-94, during which one-half of the seasons were below normal and only three were above normal. During 1995-present, four of the five seasons that are not classified as above normal (1997, 2002, 2006, and 2009) are linked to El Niño.

The transition to the current high activity era was associated with a phase change in the tropical multi-decadal signal, which reflects the leading modes of tropical convective rainfall variability and Atlantic SSTs occurring on multi-decadal time scales (Bell and Chelliah 2006, Bell et al. 2007, also cpc.ncep.noaa.gov/products/expert_assessment/hurrsummary_2006.pdf). 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.

The combination of an enhanced West African monsoon and suppressed convection in the Amazon Basin was seen again during ASO 2009 (Fig. 6a), and is known to be associated with an inter-related set of atmospheric conditions typical of active hurricane seasons (Landsea et al. 1998, Bell et al. 1999, 2000, 2004, 2006, 2009; Goldenberg et al. 2001, Bell and Chelliah 2006, Kossin and Vimont 2007). These conditions include enhanced low-level inflow into the West African monsoon region (Fig. 4a) and enhanced upper-level divergent outflow from that region (Fig. 6). They also include stronger upper-level ridges over both the eastern MDR and across the subtropical South Atlantic as seen in 2009 (Fig. 8), along with a stronger tropical easterly jet at 200-hPa (Bell and Chelliah 2006, Bell et al. 2009).

Accompanying these conditions, the vertical wind shear (Fig. 9a) and 700-hPa zonal winds (Fig. 9b) have been much weaker since 1995 in critical parts of the MDR compared to the preceding low activity era, and the 700-hPa relative vorticity has been cyclonic rather than anticyclonic across the southern MDR (Fig. 9c). These latter two features were again present during ASO 2009, and are consistent with the more conducive AEJ described above.

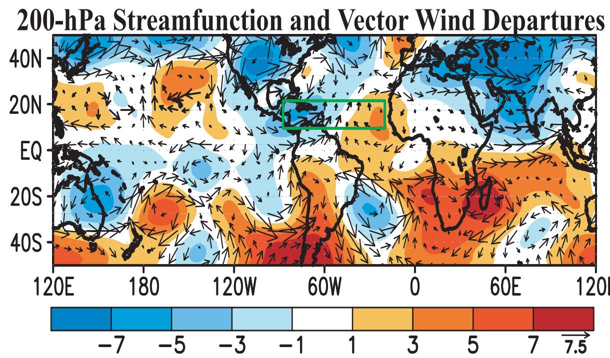

Fig. 8. Aug-Oct 2009: Departures from normal of 200-hPa streamfunction (shading) and wind vectors (m s^{-1}) Anomalous ridges are indicated by positive values (red) in the NH and negative values (blue) in the SH. Anomalous troughs are indicated by negative values in the NH and positive values in the SH. Vector scale is to right of color bar. Anomalies are departures from the 1971-2000 period monthly means.

As discussed by Bell and Chelliah (2006) and Bell et al. (2009), the above combination of conditions means that tropical storms can develop within the MDR from amplifying African easterly waves moving within the region of below-average pressure and increased cyclonic shear along the equatorward flank of the AEJ. In the absence of El Niño, these waves are also embedded within an extended re-

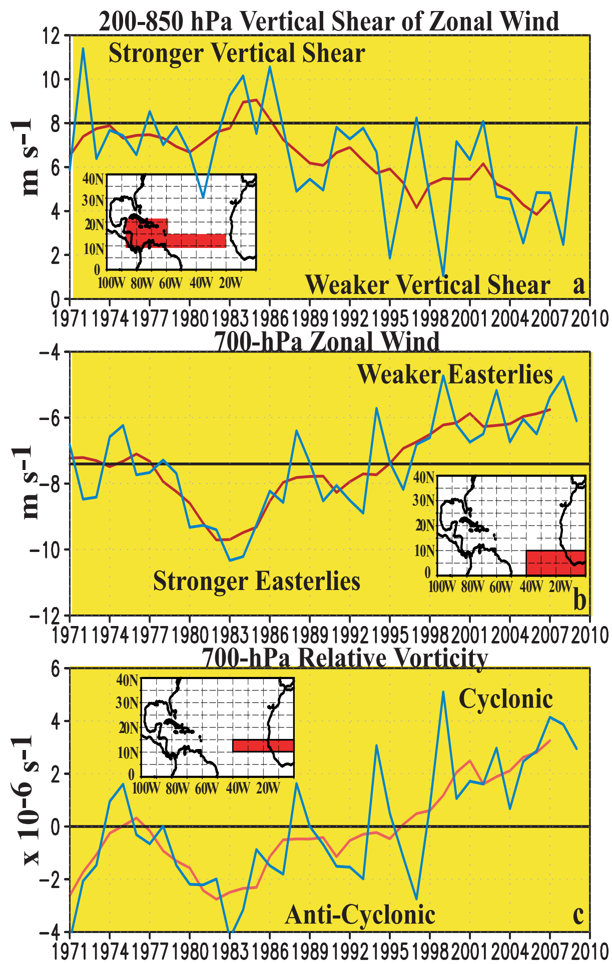

Fig. 9. Time series showing consecutive Aug-Oct values of area-averaged (a) 200-850 hPa vertical shear of the zonal wind (m s^{-1}), (b) 700-hPa zonal wind (m s-1) and (c) 700-Pa relative vorticity (x 10^{-6} s^{-1}). Blue curve shows unsmoothed values, and red curve shows a 5-pt running mean of the time series. Averaging regions are shown in the insets.

gion of weak vertical wind shear, which often enables further significant intensification as they move westward over progressively warmer SSTs.

(b) El Niño

El Niño typically produces stronger westerly winds at 200-hPa over the Caribbean Sea, which increases the vertical wind shear and suppresses Atlantic hurricane activity (Gray 1984, Goldenberg and Shapiro 1996, Bell and Chelliah 2006). El Niño developed during June 2009, and quickly affected the upper-level atmospheric winds in the subtropics of both hemispheres (cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_jul2009/ensodisc.pdf).

During ASO 2009, the 200-hPa velocity potential and divergent wind anomalies across the tropical Pacific Ocean (Fig. 6) were consistent with El Niño (Fig. 3), as was an overall zonal wave-1 pattern of 200-hPa streamfunction anomalies in the subtropics of both hemispheres (Fig. 8). This pattern reflected enhanced subtropical ridges over the Pacific Ocean in both hemispheres, and weaker than average subtropical ridges throughout the remainder of the global subtropics.

Over the Caribbean Sea, regional aspects of this El Niño signal included the enhanced TUTT at 200-hPa, increased vertical wind shear, and reduced rising motion, all of which overwhelmed the ongoing multi-decadal signal and suppressed the 2009 Atlantic hurricane season. These conditions are opposite to those observed during 2008, when the combination of the high activity era and La Niña contributed to an above normal Atlantic hurricane season (cpc.ncep.noaa.gov/products/expert_assessment/hurrsummary_2008.pdf, also Bell et al. 2009).

c) Intra-seasonal variability in Atlantic hurricane activity

Atlantic hurricane activity was sporadic during 2009. For example, six named storms including both major hurricanes formed during 11 Aug. - 9 Sep., and the third hurricane of the season did not form until early November. Only two tropical storms developed during most of September and October.

The Madden-Julian Oscillation (MJO) (Madden and Julian 1971, 1972, 1994) is a major source of intra-seasonal variability in Atlantic hurricane activity (Maloney and Hartmann 2000, MO 2000). As discussed by Gottschalck and Bell (2009), “the MJO is a leading climate mode of tropical convective variability that occurs on intra-seasonal timescales. The convective anomalies associated with the MJO often have the same spatial scale as El Niño and La Niña (i.e. ENSO), but differ in that they exhibit a distinct eastward propagation and generally traverse the globe in 30-60 days.

The MJO can strongly affect the tropical and extratropical atmospheric circulation patterns, and sometimes produces ENSO-like anomalies (Mo and Kousky 1993; Kousky and Kayano 1994, Kayano and Kousky 1999). The MJO is often quite variable in a given year, with periods of moderate-to-strong activity sometimes followed by little or no activity."

The MJO is seen by continuous propagation of 200-hPa velocity potential anomalies around the globe. A time-longitude section of this parameter shows two distinct periods with MJO activity during the 2009 Atlantic hurricane season (Fig. 10). From late July to mid-August 2009, several forms of intra-seasonal variability [including the MJO and a faster propagating atmospheric Kelvin wave (Wheeler and Kiladis, 1999; Wheeler and Weickmann, 2001)], contributed to an eastward shift of positive velocity potential anomalies and anomalous upper-level convergence from Indonesia to the central Pacific Ocean near the date line (top dashed blue circle in Fig. 10).

This shift created a somewhat more conducive pattern of vertical wind shear leading to increased Atlantic tropical storm and hurricane activity (Fig. 11a), and is consistent with past studies showing that conditions are more favorable for tropical development in the Atlantic basin when upper-level convergence prevails over the western Pacific Ocean to near the Date Line, and upper-level divergence dominates the western hemisphere (Maloney and Hartmann 2000, Mo 2000).

A similar pattern of velocity potential anomalies during late October and early November (lower blue circle, Fig. 10) was more clearly linked to strong MJO activity, which also offset the El Niño signal and allowed for a rare late-season hurricane (Ida) to form in the Caribbean Sea. Ida was the only Caribbean hurricane of the season.

Opposite patterns of anomalous velocity potential were evident near the date line during both July and September (red boxes, Fig. 10). During September, these conditions were associated with El Niño, and contributed to a significant increase in vertical wind shear over the Atlantic basin (Fig. 4.11b)

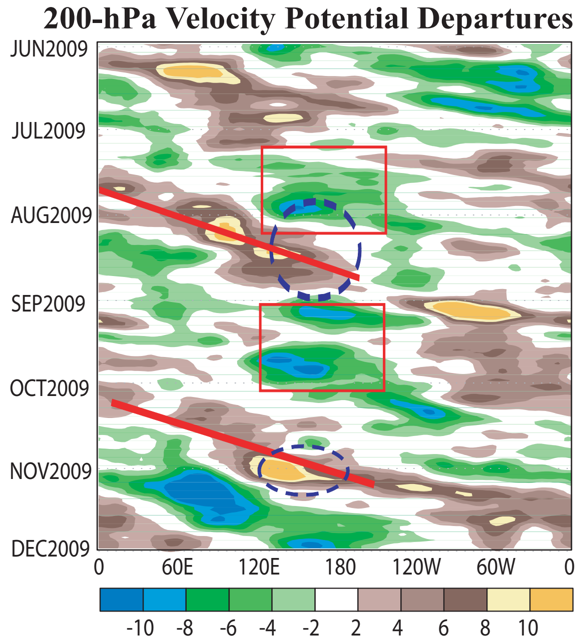

Fig. 10. Time-longitude section showing departures of 200-hPa velocity potential averaged between 5°N-5°S. For each day, the average departure for the previous 120 days is removed prior to plotting. Green (brown) shading highlights likely areas of anomalous divergence and rising motion (convergence and sinking motion). Red lines highlight the main MJO episodes. Anomalies are departures from the 1971-2000 base period daily means.

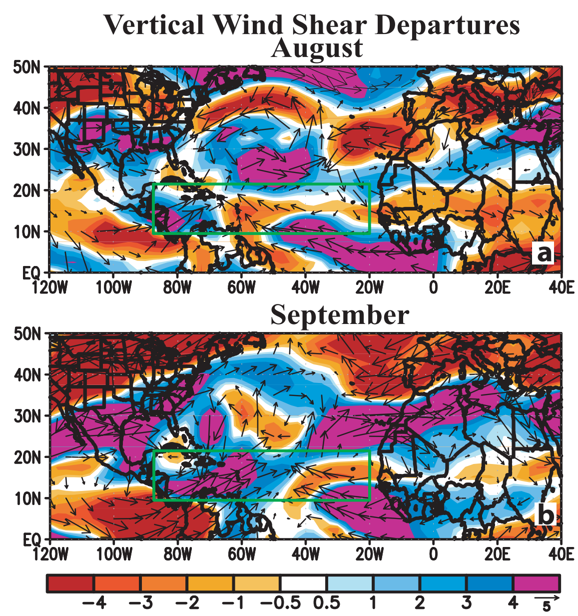

Fig. 11. Departures from normal of 200-850 hPa vertical wind shear magnitude (m s^{-1}) and vectors during (a) August 2009 and (b) September 2009. Green box denotes the MDR. Vector scale is to right of color bar. Anomalies are departures from the 1971-2000 period monthly means.

which suppressed Atlantic hurricane activity.

5. Summary

The below-normal 2009 Atlantic hurricane season resulted largely from El Niño, which significantly impacted the atmospheric circulation across the MDR during the peak months (August-October) of the season. El Niño developed during June, and strengthened to moderate intensity during September-November. Only two tropical storms and one hurricane formed after 9 September.

Since 1995 only two seasons have been below-normal (1997 and 2009), and both were associated with El Niño. During 2009, El Niño's main impacts included 1) enhanced upper-level westerly winds and very strong vertical wind shear across the western MDR, and 2) anomalous upper-level convergence and markedly reduced rising motion over the Caribbean Sea.

For the continental United States, the 2009 season saw no landfalling hurricanes and only one landfalling tropical storm (Claudette in the Florida Panhandle). Only one named storm (Ida) formed in the Caribbean Sea, making landfall as a hurricane in Nicaragua. Tropical storm Erika passed through the northern Caribbean Islands while weakening. This represents a sharp decrease in the number of landfalling named storms compared to 2008, when the continental United States was struck by three tropical storms and three hurricanes, and the nations in and surrounding the Caribbean Sea were severely impacted by four tropical storms and four hurricanes.

This reduction in hurricane landfalls during 2009 is largely due to two factors, both of which are related to El Niño. First, an amplified TUTT over the central North Atlantic either destroyed named storms within the MDR or steered those storms well out to sea. Second, only one named storm (H Ida) formed over the Caribbean Sea, and no hurricanes propagated into that region.

Despite the reduced activity, many of the ongoing atmospheric and oceanic conditions that have favored very active hurricane seasons since 1995 were again in place during 2009. In fact, sea-surface temperatures in the MDR during Aug-Oct. were tied for the seventh warmest on record dating back to 1950. The reduced hurricane activity, in spite of this anomalous warmth, is consistent with previous findings indicating that local atmospheric circulation anomalies, rather than local SST anomalies, are the dominant contributor to seasonal fluctuations in Atlantic hurricane activity (Shapiro and Goldenberg 1998, Bell and Chelliah 2006).

The analysis provides no indication that the current high activity era for Atlantic hurricanes has ended. Instead, it indicates that the El Niño-related reduction in activity merely represents a short-term break (similar to the 1997, 2002, and 2006 El Niño years) from the otherwise significantly elevated levels of activity seen since 1995.

References

Bell, G. D., and co-authors, 1999: Climate Assessment for 1998. *Bull. Amer. Meteor. Soc*., **80**, S1-S48.

Bell, G. D., and co-authors, 2000: The 1999 North Atlantic Hurricane Season: A Climate Perspective. *State of the Climate in 1999*. *Bull. Amer. Meteor. Soc*., **86**, S1-S68.

Bell, G. D., and co-authors 2004: The 2003 North Atlantic Hurricane Season: A Climate Perspective. *State of the Climate in 2003*. A. M. Waple and J. H. Lawrimore, Eds. *Bull. Amer. Meteor. Soc*., **85**, S1-S68.

Bell, G. D., and co-authors 2006: The 2005 North Atlantic Hurricane Season: A Climate Perspective. *State of the Climate in 2005*. A. M. Waple and J. H. Lawrimore, Eds. *Bull. Amer. Meteor. Soc*., **86**, S1-S68.

Bell, G. D., and co-authors 2007: The 2006 North Atlantic Hurricane Season: A Climate Perspective. *State of the Climate in 2006*. A. M. Waple and J. H. Lawrimore, Eds. *Bull. Amer. Meteor. Soc*., **87**, S1-S68.

Bell, G. D., and co-authors 2009: The 2008 North Atlantic Hurricane Season: A Climate Perspective. *State of the Climate in 2008*. A. M. Waple and J. H. Lawrimore, Eds. *Bull. Amer. Meteor. Soc*., **87**, S1-S68.

Bell, G. D., and M. Chelliah, 2006: Leading tropical modes associated with interannual and multi-decadal fluctuations in North Atlantic hurricane activity. *J. Climate*, **19**, 590-612.

Enfield, D. B., and A. M. Mestas-Nuñez, 1999: Multi-scale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns. *J. Climate*, **12**, 2719-2733.

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.

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

Gottschalck, J, and G. D. Bell 2009: The MJO during 2008. *State of the Climate in 2008*. A. M. Waple and J. H. Lawrimore, Eds. *Bull. Amer. Meteor. Soc*., **87**, S1-S68.

Gottschalck, J, and G. D. Bell 2010: Tropical intra-seasonal variability during 2009. *State of the Climate in 2009*. A. M. Waple and J. H. Lawrimore, Eds. *Bull. Amer. Meteor. Soc*., **88**, S1-S68.

Gray, W. M., 1984: Atlantic seasonal hurricane frequency: Part I: El Niño and 30-mb quasi-bienniel oscillation influences. *Mon. Wea. Rev*., 112, 1649-1668.

Hendon, H., C. Zhang, J. Glick, 1999: Interannual variation of the Madden-Julian Oscillation during Austral Summer. *J. Climate*, **12**, 2538-2550.

Kayano, M. and V. Kousky, 1999: Intraseasonal (30-60 day) variability in the global tropics: principal modes and their evolution. *Tellus*, ***51***, 373-386.

Knaff, J.A., 1997: Implications of summertime sea level pressure anomalies in the tropical Atlantic Region. *J. Clim*., **10**, 789-804.

Kousky, V. and M. Kayano, 1994: Principal modes of outgoing longwave radiation and 250-mb circulation for the South American sector. *J. Climate*, **7**, 1131-1143.

Kossin, J. P., and D. J. Vimont, 2007: A more general framework for understanding Atlantic hurricane variability and trends. *Bull. Amer. Meteor. Soc.*, **88**, 1767-1781.

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., G. D. Bell, W. M. Gray, and S. B. Goldenberg, 1998: The extremely active 1995 Atlantic hurricane season: Environmental conditions and verification of seasonal forecasts. *Mon. Wea. Rev.*, **126**, pp. 1174-1193.

Madden R. and P. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific, *J. Atmos. Sci*., **28**, 702-708.

Madden R. and P. Julian, 1972: Description of global-scale circulation cells in the tropics with a 40-50 day period. *J. Atmos. Sci*., **29**, 1109-1123.

Madden R. and P. Julian, 1994: Observations of the 40-50 day tropical oscillation: A review. *Mon. Wea. Rev*., **122**, 814-837.

Maloney, E. D., and D. L. Hartmann, 2000: Modulation of eastern North Pacific hurricanes by the Madden-Julian Oscillation, *J. Clim*., 13, 1451–1460.

Mo, K. C., 2000: The association between intraseasonal oscillations and tropical storms in the Atlantic Basin. *Mon. Wea. Rev*., **128**, 4097-4107.

Mo, K. C., and V. E. Kousky 1993: Further analysis of the relationship between circulation anomaly patterns and tropical convection, *J. Geophys. Res.*, ***98*****(D3)**, 5103–5113.

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.

Santer, B. D., and co-authors, 2006: Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *PNAS*, **103,** 13905-13910.

Shapiro, L. J., and S. B. Goldenberg, 1998: Atlantic sea surface temperatures and tropical cyclone formation. *J. Climate*, **11**, 578-590.

Wheeler, M., and G.N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of clouds and temperature in the wave number-frequency domain. *J. Atmos. Sci.*, 56, 374-399.

Wheeler, M., and K. M. Weickmann, 2001: Real-time monitoring and prediction of modes of coherent synoptic to intraseasonal tropical variability. *Mon. Wea. Rev.*, 129, 2677-2694.

Zhang, C, 2005: Madden-Julian Oscillation. *Reviews of Geophysics*, **43**, 1-36.

Zhang, C. and J. Gottschalck, 2002: SST Anomalies of ENSO and the Madden Julian Oscillation in the equatorial Pacific. *J. Climate*, **15**, 2429-2445.