The 2011 North Atlantic Hurricane Season
A Climate Perspective

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1. 2011 Seasonal Activity

The 2011 Atlantic hurricane season produced 19 tropical storms (TS), of which seven became hurricanes (H) and four became major hurricanes (MH, with maximum sustained surface wind speeds exceeding 111 mph or 178 km h^{-1}) (Fig. 1). The 1981-2010 seasonal averages are twelve tropical storms, six hurricanes, and three major hurricanes. August-October (ASO) are typically the peak months of the season, and all but five tropical storms during 2011 formed in ASO.

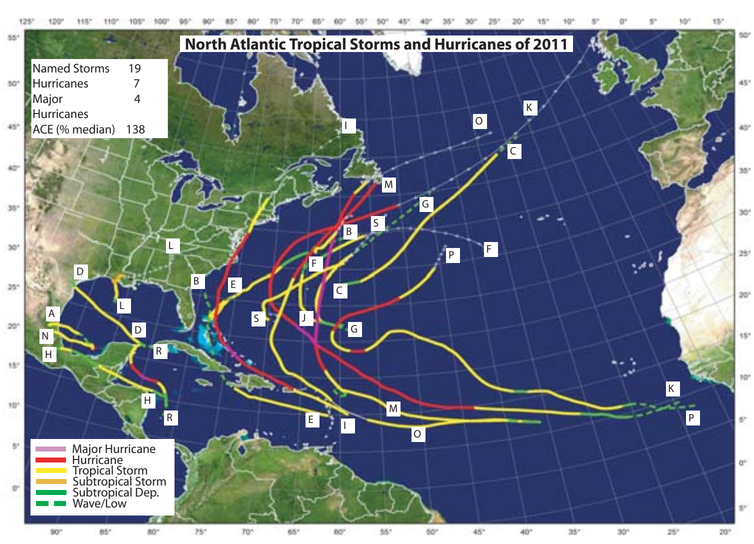


Fig. 1. Tracks of Atlantic named storms during 2011. Storm intensity is color-coded as indicated at bottom left. Letters correspond to the first initial of the storm name.

The 2011 seasonal Accumulated Cyclone Energy (ACE) value (Bell et al. 2000) was 127.1 x 10^4 kt^2, which corresponds to 138% of the 1981-2010 median (Fig. 2). ACE is used by NOAA to classify the overall hurricane strength. Based on the 2011 ACE value, combined with above-average numbers of TS, H, and MH, NOAA classifies the 2011 season as above normal. This is the 12th above-normal season since the current high activity era for Atlantic hurricanes began in 1995 (Goldenberg et al. 2001), and the 14th busiest season since 1966. NOAA's seasonal hurricane outlooks, issued by the Climate Prediction Center (CPC) in late May and early August, indicated a high likelihood of an above-normal 2011 season (Fig. 3).

2. Storm Tracks

The Atlantic storm tracks during 2011 were generally divided into three clusters. One cluster comprised six storms that formed over the central and eastern tropical Atlantic, which is the eastern half of the Main Development Region (MDR) (green boxed region, Fig. 4). The MDR encompasses the tropical Atlantic Ocean and Caribbean Sea between 9.5°N and 21.5°N; Goldenberg et al. 2001). Five of these storms eventually became hurricanes (three became MHs) and three made landfall. Maria and Ophelia made landfall in Newfoundland with tropical storm strength, and Irene made landfall as a hurricane along the U.S. Atlantic coast.

The second cluster of storm tracks reflected six systems (four TSs and two Hs, with one becoming MH Rina) that formed over the western Caribbean Sea and Bay of

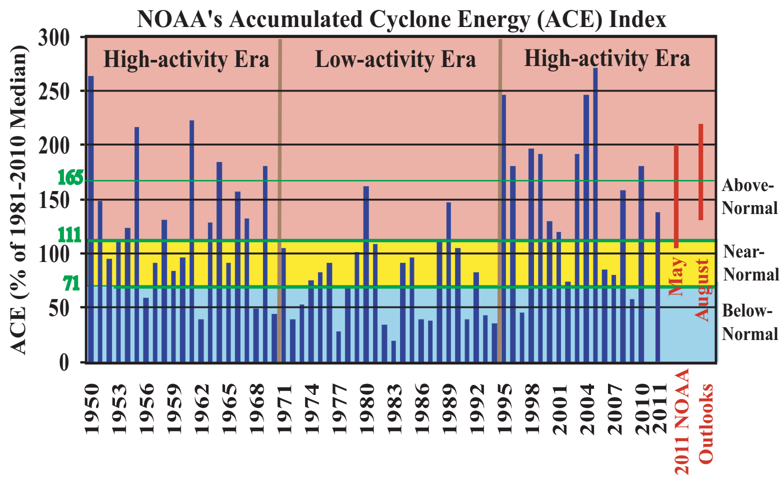
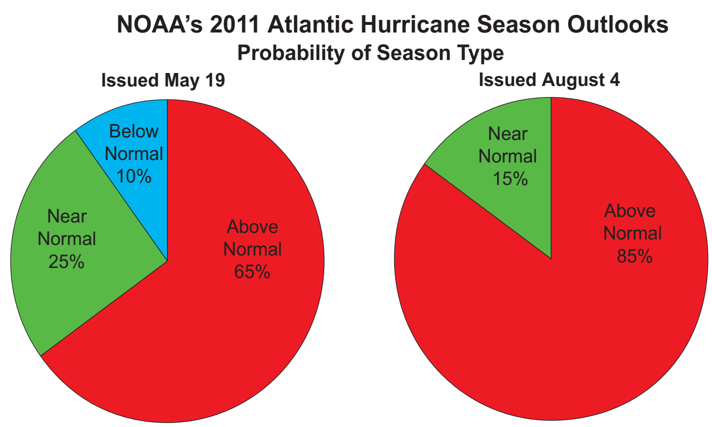


Fig. 2. NOAA's Accumulated Cyclone Energy (ACE) index expressed as percent of the 1981-2010 median value. ACE is calculated by summing the squares of the 6-hourly maximum sustained wind speed (knots) for all periods while the storm has at least tropical storm strength. Red bars show NOAA's predicted ACE ranges in their May and August seasonal hurricane outlooks. Pink, yellow, and blue shadings correspond to NOAA's classifications for above-, near-, and below-normal seasons, respectively. The 165% threshold for a hyperactive season is indicated. Vertical brown lines separate high- and low-activity eras.



Activity

Observed	
Named Storms	19
Hurricanes	7
Major Hurricanes	4
ACE (% median)	138

Predicted: 70% Probability For Each Range

Issued May 19	
Named Storms	12-18
Hurricanes	6-10
Major Hurricanes	3-6
ACE (% median)	105-200

Issued August 4	
Named Storms	14-19
Hurricanes	7-10
Major Hurricanes	3-5
ACE (% median)	135-210

Fig. 3. NOAA's 2011 Atlantic hurricane season outlooks issued on 19 May and updated on 4 August. The observed seasonal activity is also indicated.

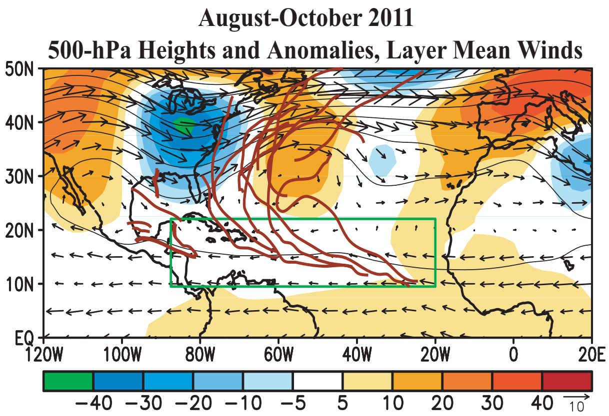


Fig. 4. ASO 2011: 500-hPa heights (contours, m) and anomalies (shading), and layer mean wind vectors (ms^{-1}) between 600 hPa – 300 hPa. Atlantic named storm tracks are shown in brown. Green box denotes the MDR. Vector scale is below right of color bar. Anomalies are with respect to the 1981-2010 period monthly means.

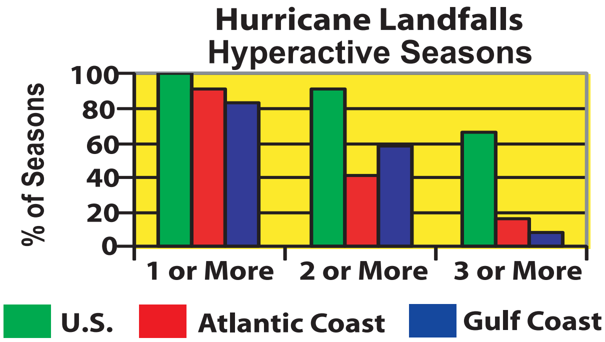


Fig. 5. Seasonal frequency (during 1950-2009) of Atlantic basin hurricanes making landfall in the United States during hyperactive seasons. Green bars show landfalls for the entire U.S., red bars show landfalls along the U.S. Atlantic Coast, and blue bars show landfalls along the U.S. Gulf Coast. Landfalls are based on the HURDAT data produced by the National Hurricane Center and compiled by Blake et al. (2011).

Campeche, regions that often see increased activity during La Niña (e.g. 1989, 1996, and 2010). Five of these systems made landfall as tropical storms, with only Don weakening to a tropical depression before moving over southeastern Texas. Arlene and Nate struck Mexico, Harvey made landfall in Belize and Mexico, Lee came ashore in south-central Louisiana, and Rina struck the Yucatan Peninsula.

The third cluster of tracks consisted of seven tropical storms that formed north of the MDR over the subtropical North Atlantic, and remained at sea throughout their life cycle (although Jose and Sean did pass close to Bermuda.). This is one of the largest number of baroclinically-initiated (i.e., not from tropical waves) tropical storms since the satellite era began. On average, 3-4 named storms form over the subtropical North Atlantic per season, and roughly two become hurricanes.

3. U.S. Hurricane landfalls during 2009-2011

Irene was the first United States hurricane landfall since 2008. This storm initially made landfall in North Carolina (after striking the Bahamas as a MH), and then made a second landfall as a tropical storm in New Jersey, subsequently causing major flooding in the Northeast. Irene is the most significant hurricane to strike the northeastern U.S. since Hurricane Bob in 1991.

An analysis of the low U.S. hurricane landfall count during 2009-2011 (i.e., only one landfall in three seasons) was performed. The lack of landfalls during the below-normal 2009 season (Bell et al. 2010), and the occurrence of one landfall during the above-normal 2011 season, are consistent with past seasons of similar strength, although at the lower end of the distribution (Blake et al. 2011). However, the lack of hurricane landfalls during the hyperactive 2010 season (ACE > 165% of the median) is quite anomalous (Bell et al. 2011), as all hyperactive seasons had previously featured at least one U.S. landfall, 92% had at least two landfalls, and 67% had at least three landfalls (Fig. 5).

Two main atmospheric factors known to limit U.S. hurricane landfalls were present during both 2010 and 2011. These include: 1) a persistent mid-level trough and strong southwesterly flow over the western North Atlantic (Fig. 4), which steered all but one approaching hurricane

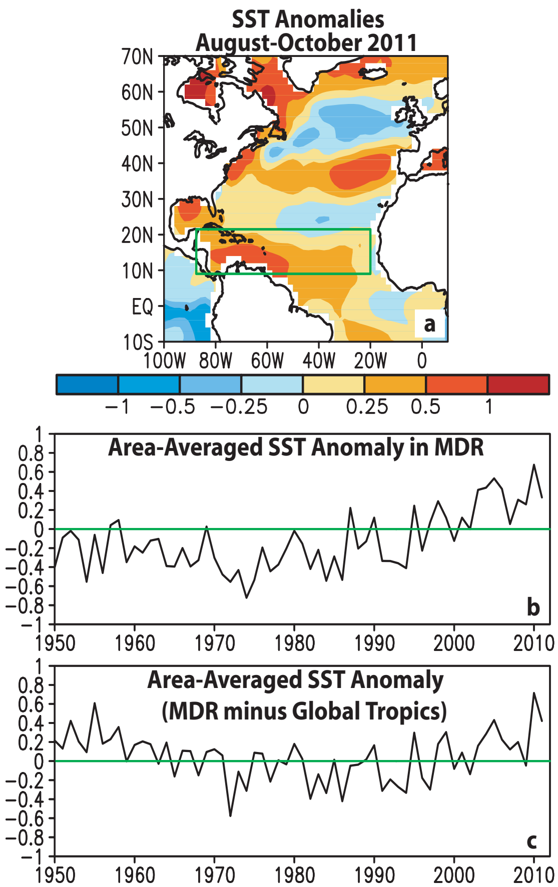


Fig. 6. (a) ASO 2011 sea surface temperature (SST) anomalies (°C). (b) Time series of consecutive ASO area-averaged SST anomalies (°C) in the MDR [green box in (a)]. (c) Time series showing the difference between ASO area-averaged SST anomalies (°C) in the MDR and those for the entire global tropics (30°N-30°S). Anomalies are departures from the ERSST-v3b (Smith et al. 2008) 1981-2010 period monthly means.

(Irene) away from the U.S. Atlantic coast, and 2) the absence of hurricanes either forming or propagating over the central and northern Gulf of Mexico. Historically 50% of above-normal seasons have previously featured at least one hurricane formation in these regions. Also, such seasons often feature hurricanes that move into the central Gulf from the Caribbean Sea, yet none took such a track during either 2010 or 2011.

4. Atlantic sea surface temperatures

Sea surface temperatures (SSTs) in the MDR were above average during August-October 2011, with the largest departures (between +0.5°C and +1.0°C) observed in the Caribbean Sea and western tropical North Atlantic (Fig. 6a). The mean SST departure within the MDR was +0.33°C (Fig. 6b), which is also +0.44°C warmer than the average departure for the entire global tropics (Fig. 6c). These conditions were partly responsible for the above-normal Atlantic hurricane season.

This anomalous warmth is related to weaker-than-average easterly trade winds (i.e. westerly anomalies) across the tropical Atlantic (see section 5). This combination of weaker trade winds and anomalously warm SSTs in the MDR (both of which typically become established prior to the start of the season) has generally prevailed since 1995, in association with the warm phase of the Atlantic Multi-decadal Oscillation (AMO, Enfield and Mestas-Nuñez 1999) and the active Atlantic phase of the tropical multi-decadal signal (see section 6a).

5. Atmospheric circulation

The atmospheric circulation during ASO 2011 (Fig. 7) featured an inter-related set of conditions known to be exceptionally conducive for tropical cyclone formation and intensification within the

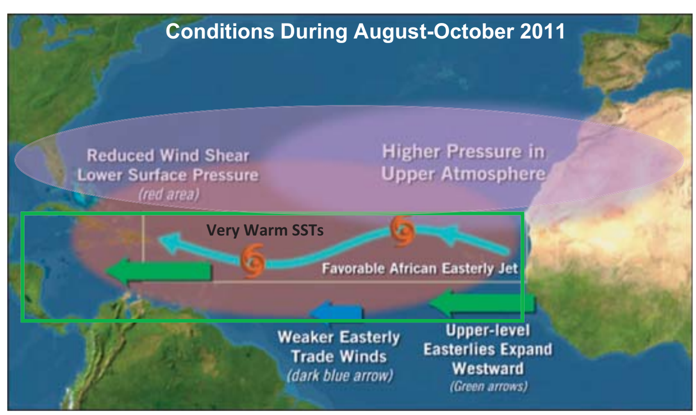


Fig. 7. Conditions over the Atlantic basin during ASO 2011. Green box denotes the Main Development Region (MDR).

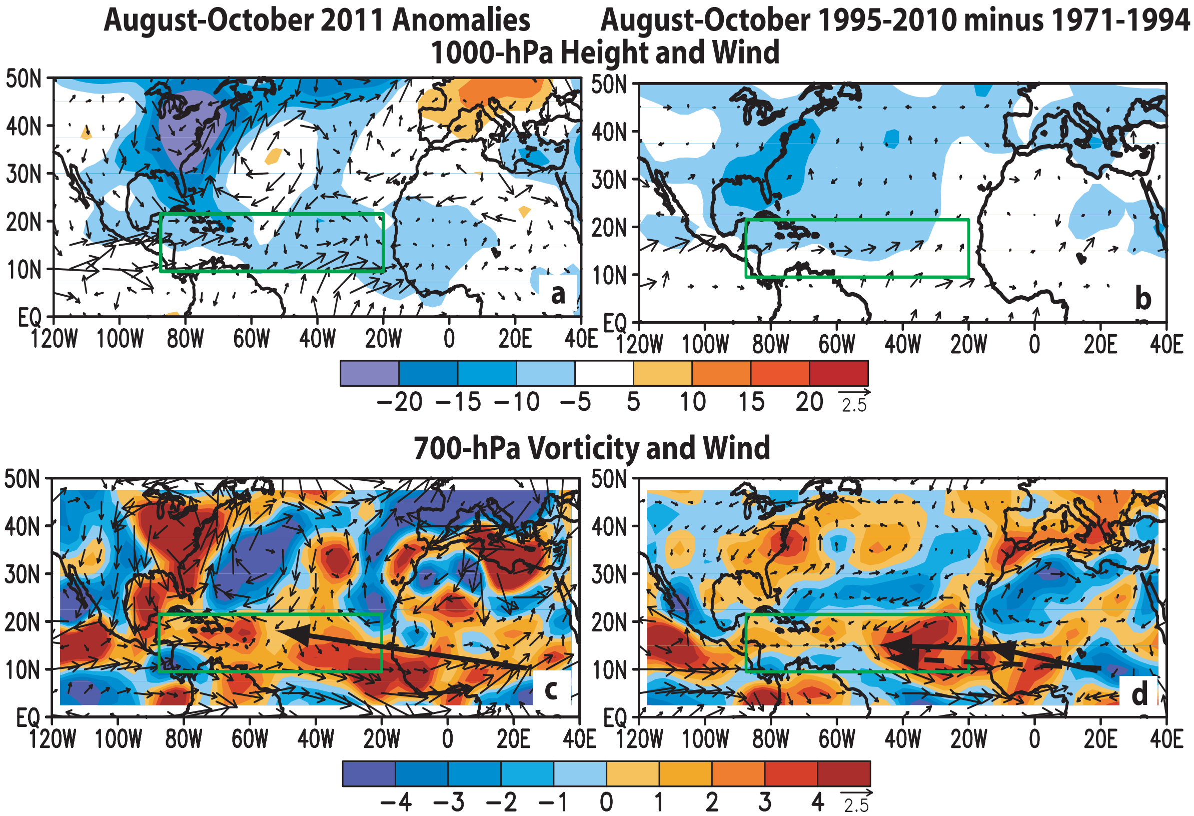


Fig. 8. (Left) ASO 2011 anomalies and (Right) difference between the 1995-2010 and 1971-1994 ASO means. Panels (a, b) show 1000-hPa heights (shading, m) and wind vectors (m s^{-1}). Panels (c, d) show 700-hPa relative vorticity (shading, x 10^{-6} s^{-1}) and wind vectors. In (c) thick arrow shows the axis of the African easterly jet (AEJ). In (d) thick solid (dashed) arrow indicates the mean position of the AEJ during 1995-2010 (1971-1994). Vector scales are below right of color bars. Green boxes denote the MDR. Anomalies are with respect to the 1981-2010 period monthly means.

MDR (Landsea et al. 1998, Bell et al. 1999, 2000, 2004, 2006, 2009, 2011; Goldenberg et al. 2001, Bell and Chelliah 2006, Kossin and Vimont 2007). Ten tropical storms formed in the MDR this year, eventually producing six out of the seven hurricanes, all major hurricanes, and 88% of the seasonal ACE value.

In the lower atmosphere, ASO conditions within the MDR included weaker trade winds, a deep layer of anomalous cross-equatorial flow, and below-average heights/ sea-level pressure (blue shading, Fig. 8a). Across the Atlantic basin and sub-Saharan Africa, the low-level westerly anomalies extended above 700-hPa, the approximate level of the African Easterly Jet (AEJ, Fig. 8c), and were associated with an 2.5°-5° latitude northward shift of the AEJ core (black arrow).

As a result, the bulk of the African easterly wave energy (Reed et al. 1977) was often centered well within the MDR. The AEJ also featured increased cyclonic shear along its equatorward flank (red shading), which dynamically favors stronger easterly waves. These conditions have generally prevailed since 1995, and are opposite to those seen during the low activity era of 1971-1994 (Figs. 8b, d).

Also during ASO 2011, anomalous easterly flow at 200-hPa extended from the Gulf of Guinea to the eastern North Pacific (Fig. 9a), although this flow was less extensive than seen in

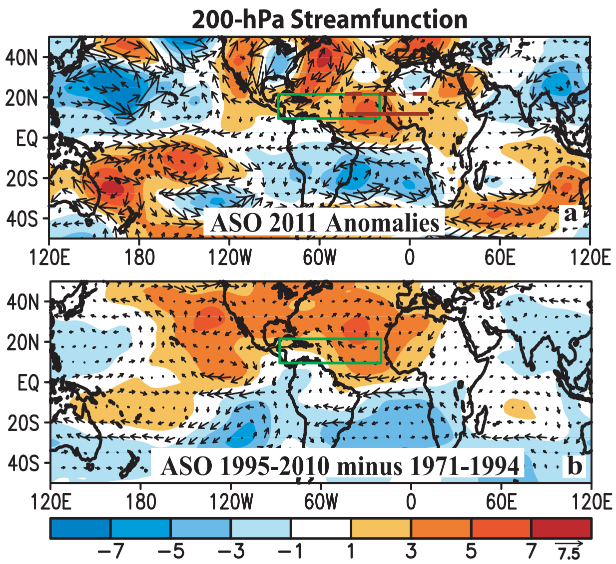


Fig. 9. 200-hPa streamfunction (shading, x 10^6 m^2 s^{-1}) and wind vectors (m s^{-1}): (a) Anomalies during ASO 2011 and (b) difference between 1995-2010 and 1971-1994 ASO means. In (a), brown solid (dashed) line over the eastern MDR shows location of mean ridge axis during ASO 2011 (ASO 1995-2010). 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. Green boxes denote the MDR. Vector scale is below right of color bar. Anomalies are with respect to the 1981-2010 period monthly means.

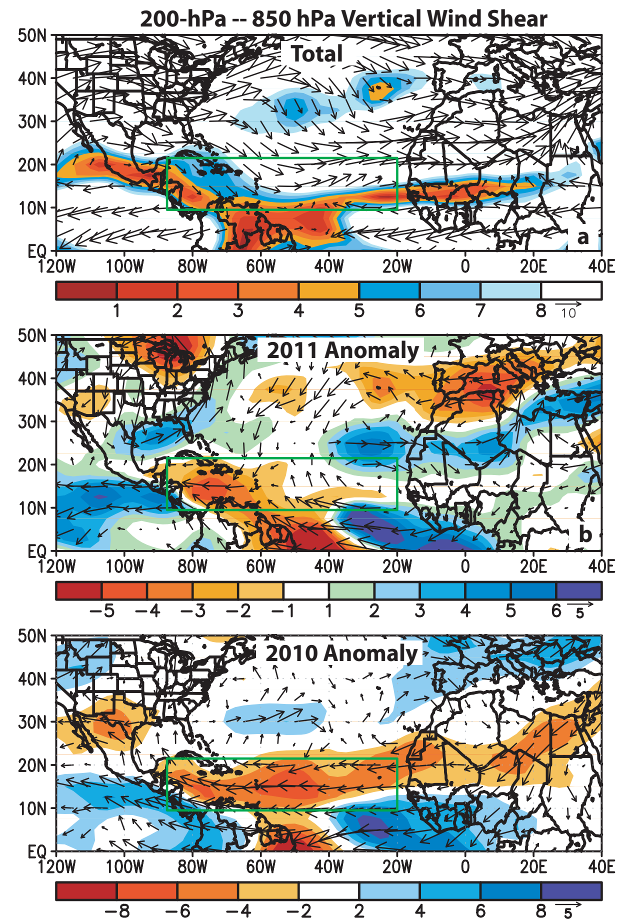


Fig. 10. ASO 2011 vertical wind shear magnitudes and vectors (m s^{-1}): (a) total and (b) anomalies. Panel (c) shows corresponding shear anomalies for ASO 2010. Green boxes denote the MDR. Vector scales are below right of color bars. Anomalies are with respect to the 1981-2010 period monthly means.

2010. This pattern reflected a stronger and more westward extension of the tropical easterly jet, and occurred in association with enhanced upper-level ridges that spanned the entire subtropical Atlantic in both hemispheres. This inter-hemispheric symmetry is another prominent feature of the current high activity era (Fig 9b).

The above circulation anomalies resulted in weaker vertical wind shear (less than 8 ms^{-1}) across the southern and western MDR (Fig. 10), with the most anomalously weak shear located over the central tropical Atlantic and Caribbean Sea (Fig. 10b). However, the area of anomalously weak shear was far less extensive than in 2010 (Fig. 10c).

These conditions were part of the larger-scale pattern that included increased shear over both the eastern equatorial Atlantic and the eastern tropical North Pacific (blue shading, Fig. 10b), and are typical of other above-normal seasons since 1995 (Bell and Chelliah 2006, Bell et al. 2011). There was also an area of weaker-than-average shear over the northwestern Atlantic near Bermuda during ASO 2011, which could have helped promote the high number of tropical storms that formed in the subtropics.

These circulation anomalies were accompanied by a stronger Atlantic ITCZ (Inter-tropical Convergence Zone) and enhanced convection across the MDR (Fig. 11). They were also associated with an enhanced West African Monsoon system, as indicated by enhanced convection

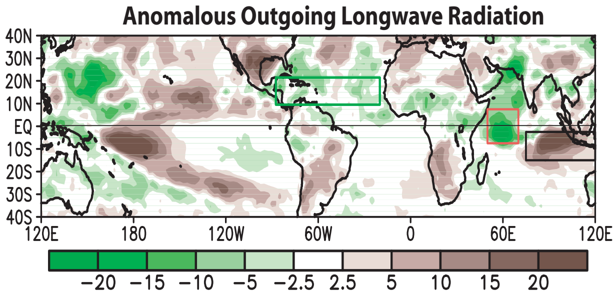


Fig. 11. ASO 2011 anomalous Outgoing Longwave Radiation (OLR, W m^{-2}). Red (black) box denotes the western (eastern) portion of the Indian Ocean dipole (IOD). Green box denotes the MDR. Anomalies are with respect to the 1981-2010 period monthly means.

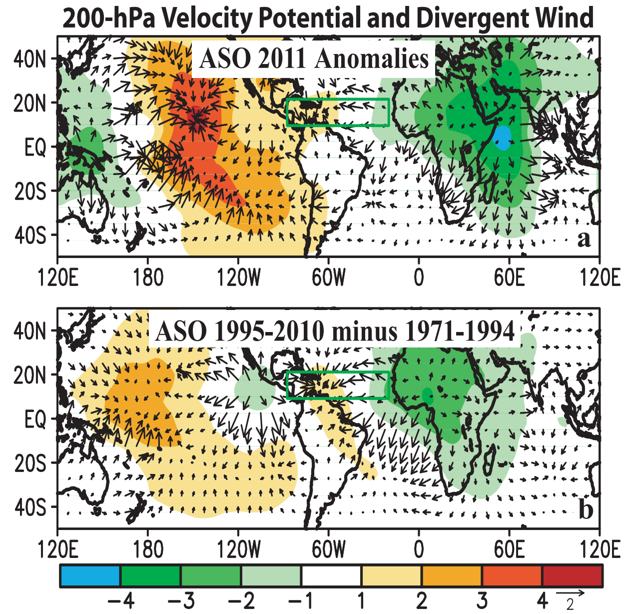


Fig. 12. 200-hPa velocity potential (shaded, x 10^6 m^2 s^{-1}) and divergent wind vectors (m s^{-1}): (a) ASO 2011 anomalies, and (b) difference between the 1995-2010 and 1971-1994 ASO means. Green boxes denote the MDR. Vector scale is below right of color bar. Departures are with respect to the 1981-2010 period monthly means.

across the African Sahel and Sudan regions and by a large area of negative velocity potential anomalies over northern Africa (Fig. 12a). Similar anomaly patterns have been present throughout current high activity era (Fig. 12b).

For the Atlantic basin, the above conditions meant that many tropical storms formed within the MDR, primarily from easterly waves moving westward from Africa. These systems entered an extensive area of below-average pressure, deep tropical moisture, increased low-level convergence, and increased cyclonic shear south of the AEJ core— conditions known to be conducive for tropical cyclone formation. Many of these systems then generally strengthened while propagating westward within the extended region of weak vertical wind shear and anomalously warm SSTs.

6. Links to global climate patterns

Four climate factors influenced the 2011 Atlantic hurricane season. Three of these contributed to the conducive conditions within the MDR, including the active-Atlantic phase of the tropical multi-decadal signal (section 6a), La Niña (section 6b), and anomalously warm SSTs in the MDR (section 4). A fourth climate factor, the Indian Ocean dipole (IOD), may have acted to limit the overall 2011 seasonal activity (section 6c).

a. The Tropical Multi-Decadal Signal

Since 1995, more than 70% (12 of 17) of Atlantic hurricane seasons have been above normal, and only two have been below normal (Fig. 1). This elevated level of activity contrasts strongly with the 1971-94 low-activity era, when one-half of seasons were below normal and only three were above normal.

The sharp transition to the current high activity era reflected a phase change in the tropical multi-decadal signal. This signal includes 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). It directly links atmospheric variability across the central and eastern MDR to multi-decadal fluctuations in the strength of the west African monsoon system (Landsea and Gray 1992, Landsea et al. 1998, Bell et al. 1999, 2000, 2004, 2006, 2009; Goldenberg and Shapiro 1996, Goldenberg et al.

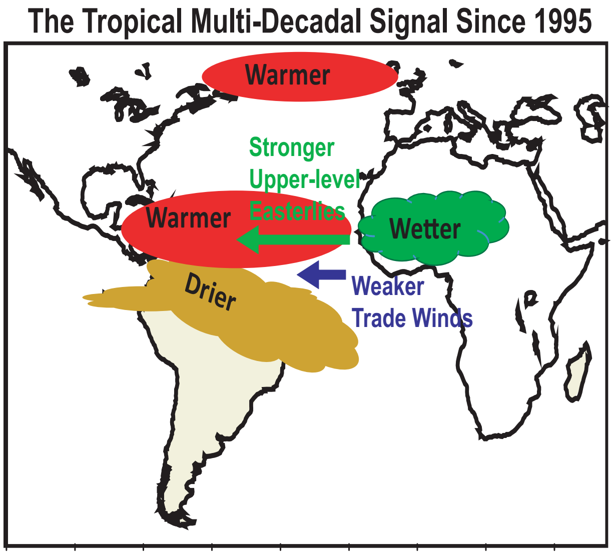


Fig. 13. Schematic depiction of the tropical multi-decadal signal during 1995-2011, adapted from Bell and Chelliah (2006).

2001, Bell and Chelliah 2006, Kossin and Vimont 2007).

Between 1994 and 1995, the ocean-atmosphere system switched to the active-Atlantic phase of the tropical multi-decadal signal (Fig. 13), which features an enhanced west African monsoon system and above-average SSTs in the MDR (i.e. the warm phase of the AMO) (Fig. 6). As a result, the atmospheric circulation within the MDR became much more conducive to Atlantic hurricane activity, as also indicated by the transition to weaker vertical wind shear (Fig. 14a), weaker 700-hPa zonal winds (Fig. 14b), and cyclonic (rather than anticyclonic) relative vorticity at 700-hPa across the southern MDR (Fig. 14c).

As discussed in sections 4 and 5, all of the key inter-related features of the active Atlantic phase of the tropical multi-decadal signal were again present during 2011 (Figs. 6-14). Therefore, there is no apparent weakening of the conditions that have prevailed since 1995.

b. La Niña

The El Niño/ Southern Oscillation (ENSO) affects Atlantic hurricane activity through

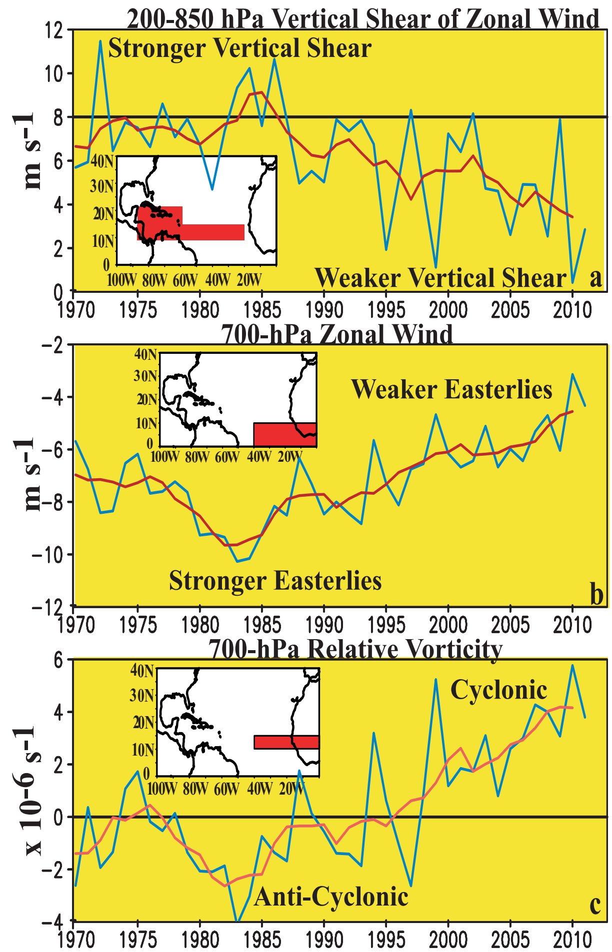


Fig. 14. Time series showing consecutive ASO values of area-averaged (a) 200-850 hPa vertical shear of the zonal wind (m s^{-1}), (b) 700-hPa zonal wind (m s^{-1}) and (c) 700-Pa relative vorticity (x 10^{-6} s^{-1}). Blue curve shows unsmoothed values, and red curve shows a 5-pt running mean of the time series. Averaging regions are shown in the insets.

a combination of vertical shear and atmospheric stability variations (Gray 1984, Tang and Neelin 2004, Goldenberg and Shapiro 1996). Opposite phases of ENSO are called El Niño and La Niña. La Niña typically enhances the seasonal activity while El Niño suppresses it. According to the CPC, La Niña developed during August 2011 and then continued as a weak event through the remainder of the hurricane season (Fig. 15). This evolution reflected the re-emergence of La Niña conditions from earlier in the year (January-May).

Across the tropical Pacific Ocean, the 200-hPa velocity potential and divergent wind

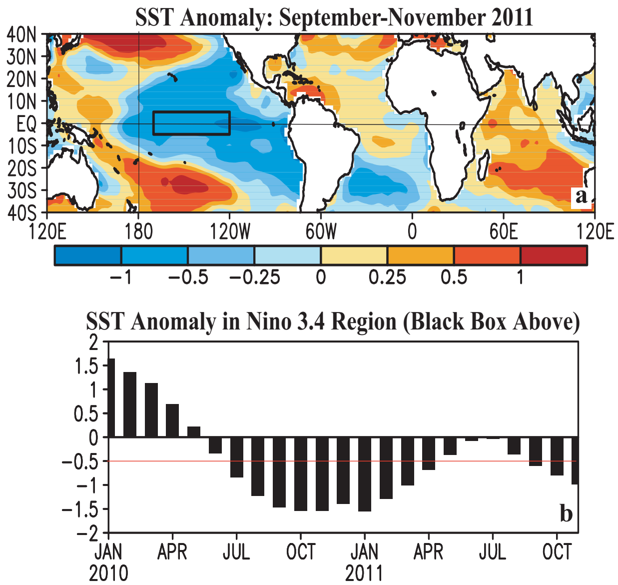


Fig. 15. (a) Sep.-Nov. 2011 sea surface temperature (SST) anomalies (°C). (b) Time series of monthly area-averaged SST anomalies in the Niño 3.4 region [black box in (a)], with red line indicating the threshold for a La Niña. Anomalies are departures from the ERSST-V3b (Smith et al. 2008) 1981-2010 period monthly means.

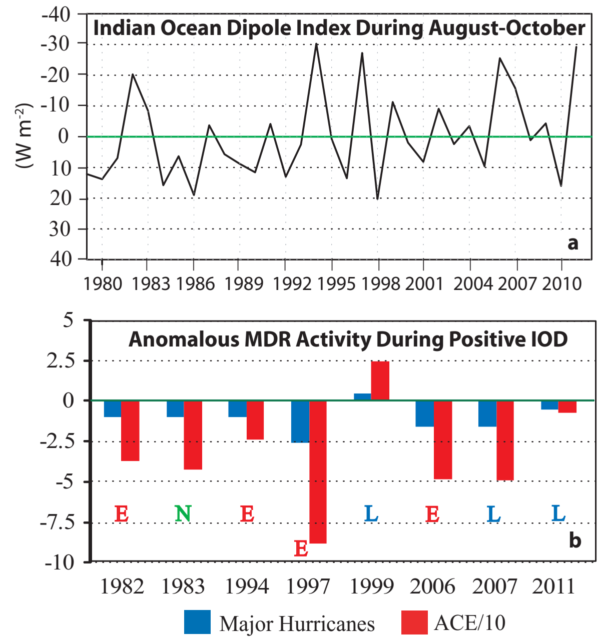


Fig. 16. (Top) ASO time series of the Indian Ocean Dipole (IOD), calculated as the difference in area-averaged OLR anomalies ($W\ m^{-2}$) between the western and eastern Indian Ocean (western minus eastern, boxes shown in Fig. 11). Anomalies are with respect to the 1981-2010 period monthly means. (Bottom) Anomalous Atlantic major hurricane (blue) and ACE/10 (i.e., x 10^3 kt^2) activity associated with storms first named in the MDR when there was a strong positive IOD during ASO. Anomalies for years during 1979-1994 (low-activity era) and 1995-2011 (high-activity era) are based on the respective period means. Corresponding El Niño (red E), La Niña (blue L), and ENSO-Neutral (green N) periods are indicated.

anomalies during ASO 2011 were consistent with La Niña (Fig. 12a), as was the overall zonal wave-1 pattern of 200-hPa streamfunction anomalies in the subtropics of both hemispheres (Fig. 9a) (Bell and Chelliah 2006). This pattern reinforced the circulation features associated with the active Atlantic phase of the tropical multi-decadal signal, and contributed to 1) an enhanced subtropical ridge extending across the entire MDR, and 2) decreased vertical wind shear in the western MDR.

c. Indian Ocean Dipole (IOD)

The Indian Ocean Dipole (IOD) reflects opposite patterns of anomalous tropical convection between the western and eastern Indian Ocean (Saji et al. 1999, Saji and Yamagata 2003a, b). A strong positive phase of the IOD was present during ASO 2011 (Fig. 16a), as indicated by enhanced convection over the western equatorial Indian Ocean and suppressed convection over the eastern tropical Indian Ocean (Fig. 11, red and black boxes, respectively).

Historically, there have been eight significant positive IOD events since reliable global OLR data became available in 1979. While these events have occurred during all phases of ENSO, they are typically associated with reduced Atlantic hurricane activity (Fig. 16b). The positive IOD event in 2011may have been one reason why the overall Atlantic activity was lower (i.e., at the low end of the NOAA seasonal Outlook issued in August) than what might have been expected given the combination of conducive climate factors described above.

The observations suggest that the IOD may have acted to limit the 2011 Atlantic hurricane activity by weakening both the west African monsoon circulation and the La Niña-related convection patterns. There are three indications of a weaker west African monsoon system compared to the 1995-2010 mean. First, the anomalous upper-level divergent circulation over northern Africa was weaker and less focused, and the anomalies were actually less than those over the western equatorial Indian Ocean (Fig. 12a).

Second, the position of the 200-hPa subtropical ridge axis over the eastern MDR was located approximately 10° latitude farther south than the 1995-2010 mean (red lines, Fig. 9a). A similar southward shift of the ridge axis was seen during the 2007 Atlantic hurricane season, which also featured a strong positive IOD (Bell et al. 2008). Third, the anomalous southerly flow in the lower atmosphere was confined to the southern MDR and Gulf of Guinea region, rather than extending well into the central MDR and the African Sahel region (Fig. 8a).

The positive IOD also appears to have affected the La Niña-related convection patterns. One component of La Niña is an extensive area of enhanced convection across Indonesia and the eastern Indian Ocean. However, convection was suppressed over the eastern Indian Ocean during ASO 2011 in association with the positive IOD (Fig. 11), meaning that the La Niña forcing of the atmospheric circulation was weaker than if no IOD signal had been present. A similar observation was made by Bell et al. (2008) for the 2007 Atlantic hurricane season.

7. Summary

The above-normal 2011 Atlantic hurricane season resulted from an inter-related set of atmospheric and oceanic anomalies that have been present since the onset of the current high activity era in 1995. The observations provide no indication that the current high activity era for Atlantic hurricanes has ended. Also, there is no indication of a weakening or disappearance of the conditions responsible for this Atlantic high activity era.

The atmospheric and oceanic conditions during the 2011 season showed strong links to a combination of three climate factors: the tropical multi-decadal signal, La Niña, and anomalously warm SSTs across the tropical Atlantic Ocean and Caribbean Sea.

NOAA's seasonal hurricane outlooks indicated a high likelihood of an above-normal season. Correct predictions of the atmospheric and oceanic anomalies, and of the associated climate factors, meant that nearly all of NOAA's predicted ranges of activity verified.

For the continental United States, the 2011 season saw one landfalling hurricane (Irene), which caused tremendous flooding in the northeastern United States. Irene is the first hurricane to strike the U.S. since 2008. Two main factors are identified as limiting the number of U.S. hurricane landfalls this year and also during the hyperactive 2010 season. First, an amplified mid-level trough over the eastern U.S. in both years steered away all but one approaching hurricane. Second, there were no landfalls along the Gulf coast in either year, which reflected the complete absence of hurricanes either forming or tracking over the central and northern Gulf of Mexico.

During 2011 the major climate factors conducive to an above-normal season included 1) the tropical multi-decadal signal, which is associated with many key circulation features seen in nearly every season since the current high activity era began in 1995, 2) La Niña, which contributed to reduced vertical wind shear in the central and western MDR, and 3) anomalously warm SSTs in the MDR.

The totality of these conditions meant that tropical storms developed primarily from amplifying African easterly waves moving within the region of below-average pressure and increased cyclonic shear along the equatorward flank of the AEJ. These waves were also embedded within an extended region of weak vertical wind shear and deep tropical moisture, which enabled further intensification as they moved westward over progressively warmer SSTs.

This overall scenario for storm formation and amplification has been in place since 1995.

However, a fourth climate factor, called the positive phase of the Indian Ocean dipole (IOD), was also present during ASO 2011, and may have acted to limit the overall Atlantic hurricane activity in two ways: 1) by causing the west African monsoon circulation to be weaker and less focused compared to past above-normal seasons since 1995, and 2) by disrupting the La Niña-related pattern of enhanced convection over the eastern Indian Ocean and Indonesia. As a result, the overall atmospheric conditions appear to have been less conducive to Atlantic hurricane activity than if no IOD signal had been present.

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