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Contrasting the 2007 and 2005 Hurricane Seasons: Evidence of Possible Impacts of Saharan Dry Air and Dust on Tropical Cyclone Activity in the Atlantic Basin

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Contrasting the 2007 and 2005 hurricane seasons: Evidence of possible impacts of Saharan dry air and dust on tropical cyclone activity in the Atlantic basin

Donglian Sun,[1,2] K. M. Lau,[3] and Menas Kafatos[2]

[1] In this study, we provide preliminary evidence of possible modulation by Saharan dust of hurricane genesis and intensification, by contrasting the 2007 and 2005 hurricane seasons. It is found that dust aerosol loadings over the Atlantic Ocean are much higher in 2007 than in 2005. The temperature difference between 2007 and 2005 shows warming in the low-middle troposphere (900–700 hPa) in the dusty region in the eastern North Atlantic, and cooling in the Main Development Region (MDR). The humidity (wind) differences between 2007 and 2005 indicate significant drying (subsidence) in the Western North Atlantic (WNA) in 2007. The drier air in the WNA in 2007 is found to be associated with the further westward transport of the Saharan air layer (SAL). To quantify wind pattern favorable for transport of SAL over the WNA, we define a zonal wind stretch index which shows significant long-term correlation with the mid-level humidity in the WNA. Analyses of the stretch index and related environmental controls suggest that the westward expansion of the Saharan dry air and dust layer can be an important factor in contributing to the difference between the relatively quiescent hurricane season in 2007 and the very active season of 2005. **Citation:** Sun, D., K. M. Lau, and M. Kafatos (2008), Contrasting the 2007 and 2005 hurricane seasons: Evidence of possible impacts of Saharan dry air and dust on tropical cyclone activity in the Atlantic basin, *Geophys. Res. Lett.*, *35*, L15405, doi:10.1029/2008GL034529.

1. Introduction

[2] Based on the expected lack of an El Niño event, the continuation of above average Sea Surface Temperature (SST) in the Atlantic Main Development Region (MDR), and weak wind shear, many forecasters predicted a much above-normal hurricane season for 2007 (P. J. Klotzbach and W. M. Gray, Summary of 2007 Atlantic tropical cyclone activity and verification of authors' seasonal and monthly forecasts, 2007, available at http://typhoon. atmos.colostate.edu/forecasts/2007/nov2007/nov2007.pdf). However, the hurricane activities in the Atlantic basin were near normal in 2007.

[3] *Lau and Kim* [2007a, 2007b] compared the difference between the 2006 and 2005 hurricane seasons, and found the cooling effect of Saharan dust on Atlantic Sea SST may be an important factor, which might have foiled the 2006 hurricane forecasts. Dust aerosols generally originate over desert regions such as the Sahara, while atmospheric transport allows dust to spread far away from its source regions [*Prospero and Carlson*, 1981; *Prospero and Nees*, 1986; *Prospero and Lamb*, 2003; *Kaufman et al.*, 2005].Radiative forcing [e.g., *Carlson and Benjamin*, 1980; *d'Almeida*, 1987; *Li et al.*, 1996, 2003; *Miller and Tegen*, 1998; *Weaver et al.*, 2002; *Christopher and Jones*, 2007] is recognized as the most important physical aspect of African dust. African dust outbreaks are associated with an elevated layer of hot and dry air outbreaks [e.g., *Prospero and Carlson*, 1981]. Dry air has impacts on tropical cloud and precipitation directly through thermal structure and indirectly through dry air entrainment [e.g., *Mapes and Zuidema*, 1996; *Tompkins*, 2001]. Dry air outbreaks have been shown to affect the formation and intensification of tropical cyclones [*Dunion and Velden*, 2004]. However, it still remains uncertain how hurricanes are linked to the dust, dry air, and their associated wind fields.

[4] Previous studies show that rainfall in the Sahel is highly anti-correlated with African dust [*Prospero and Lamb*, 2003], while negative Sahelian rainfall anomalies or Sahel drought were associated with suppressed Atlantic basin Tropical Cyclone (TC) activity [*Goldenberg and Shapiro*, 1996]. *Goldenberg and Shapiro* [1996] explained that drought induced the increase of vertical wind shear and therefore inhibited TC development. *Wong and Dessler* [2005] found that dust is associated with warm and dry Saharan Air layer (SAL), which reduces occurrence of deep convection by increasing stability and therefore inhibiting TC formation.

[5] Since rainfall in the Sahel is found to be highly anti-correlated with African dust [*Prospero and Lamb*, 2003], a hypothesis has been advanced that the Atlantic basin TC activity is anti-correlated with African dust outbreaks [*Evan et al.*, 2006].

[6] Recently, *Wu et al.* [2006] analyzed the effects of SAL on Hurricane Isabel in 2003 by incorporating the Atmospheric Infrared Sounder (AIRS on Aqua satellite) measurements into the MM5 model. They found that the SAL may have delayed the formation of Hurricane Isabel and inhibited the development of another tropical disturbance that was following it. *Dunion and Velden* [2004] suggested the dry SAL can suppress Atlantic tropical cyclone activity by increasing the vertical wind shear and stabilizing the environment at low levels. *Dunion and*

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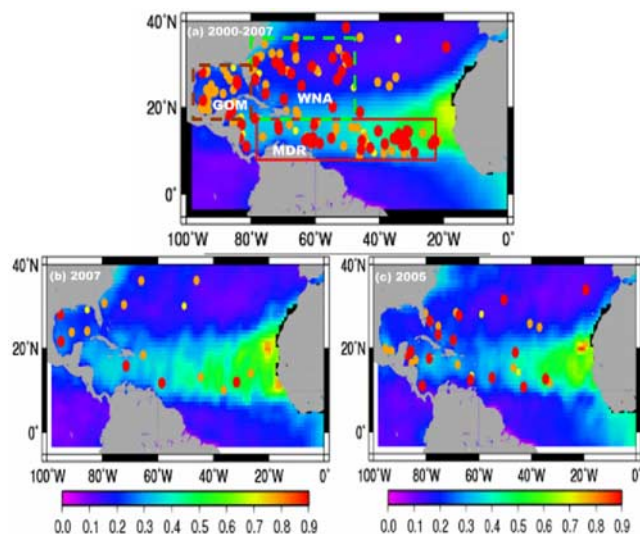
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Figure 1. The initial locations of tropical depressions (yellow circles), tropical storms (orange circles), and hurricanes (red circles) in the Atlantic basin overlapped with the June−July (JJ) mean dust aerosol optical depth from the MODIS for the period from (a) 2000 to 2007, (b) 2007, and (c) 2005. The color bar in Figure 1a is the same as in Figures 1b and 1c.

Velden [2004] suggested that convectively driven downdrafts caused by the SAL's dry air can also be an important inhibiting factor for TCs.

[7] Besides the dust effect on SST, we are investigating several other factors here, such as the advection of dry air from the Western African source region by the dust-carrying winds, and vertical moisture structure.

2.　Data Used

[8] The data we used are described here, including where they can be obtained from.

[9] 1. MODIS (Moderate Resolution Imaging Spectroradiometer) Terra Level-3 daytime aerosol optical depth (AOD) at 0.55 μm and fine mode fraction, obtained from the NASA GSFC DISC GIOVANNI system [*Acker and Leptoukh*, 2007].

[10] 2. The extended reconstructed sea surface temperature (ERSST) (1854−2007) [*Smith et al.*, 2008]. TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) SST and 10 m wind (http://www.ssmi.com).

[11] 3. AIRS daytime vertical temperature and moisture profiles, from the NASA GSFC DISC GIOVANNI tool [*Acker and Leptoukh*, 2007].

[12] 4. Tropical cyclone data, obtained from the National Hurricane Center (NHC) Hurricane Best Track Files (HURDAT) [*Jarvinen et al.*, 1984].

[13] 5. Monthly mean wind, temperature, and humidity profile data, from the NCEP reanalysis from 1948 to present [*Kalnay et al.*, 1996].

3.　Distribution of the Tropical Cyclogenesis Locations in the Atlantic Basin

[14] Based on the MODIS daytime AOD data, we extracted the dust AOD from the total aerosols by using

the methodology proposed by *Kaufman et al.* [2005]. The TCs are often found to develop outside the borders of heavy dust region (dust AOD > 0.3), including the Main Development Region (MDR) (10°−20°N, 80°−20°W), which is to the south of the dusty region. This is because the dust and dry SAL associated with heavy dust enhances convection along its southern neighboring region, in the vicinity of the Intertropical convergence zone (ITCZ) ahead of the trough with Saharan air to the north [*Chen*, 1985]. In addition to the MDR, TCs are also found to form over the Western Atlantic Region (WAR: 20−35°N, 98−50°W), which is to the west of the dusty region, and includes the U.S. East coast or Western North Atlantic (WNA: 20−35°N, 80−50°W), and the Gulf of Mexico (GOM: 20−30°N, 100−80°W). Note that Figure 1 shows only the initial locations (cyclogenesis) of TCs, and the large number of locations indicates that the WNA is also a development region as well as the MDR. In 2005, most TCs developed over the WNA (Figure 1), including the two most destructive hurricanes Katrina and Rita, while the decrease of TCs over the WNA in 2007 is very clear in Figure 1.

4.　Contrasts Between the 2007 and 2005 Hurricane Seasons

[15] As compared to 2005, dust aerosols in 2007 increased over the eastern Atlantic and MDR (Table 1). Coincident with dust increase, there was SST cooling in these regions (Table 1). Nevertheless, SST changes may also be affected by other factors, such as surface winds [*Sun et al.*, 2004], clouds, and the depth of ocean mixed layer, etc. *Lau and Kim* [2007b] showed that about 30% SST cooling in the month of June 2006 compared to the same month in 2005 can be attributed to the radiative cooling effect of dust aerosols. The 2007 SST conditions were very similar to 2006. The difference in Relative Humidity (RH) at low-middle level (e.g., 700 hPa) shows significant drying in the western region, including the southern region of WNA, but no significant change in the GOM (see Figure S1[1]). This provides evidence that the GOM receives relatively less dust loading than the MDR and is not likely affected by dust aerosols, while the MDR and southern region of WNA can be partially affected by dust aerosols.

[16] The SST's for both MDR and WNA in 2007 were lower than in 2005 but still above average values (Table 1). *Evans* [1993] indicated that SST alone is an inadequate factor, while *Emanuel et al.* [2004] demonstrated that the TC intensity changes are very sensitive to humidity in the lower troposphere. *Hoyos et al.* [2006] showed that the 850 hPa specific humidity (the ratio of water vapor to air) over 5−25°N, and 90°W−20°E, may be linked to the frequency of intense hurricanes (category 4 and 5). *Wu* [2007] indicated that the 850 hPa humidity averaged over 10−20°N, 30−80°W, which is similar to the MDR, is correlated with the mean peak hurricane intensity.

[17] As shown in the SAL conceptual model, the dry SAL is usually associated with African heavy dust outbreaks [*Karyampudi et al.*, 1999]. The transport of dust and

Table 1. JJ Mean SST, RH$_{700}$, and U$_{stretch}$

	Dust AOD in MDR	Dust AOD in WNA	MDR SST (°C)	WNA SST (°C)	WNA RH$_{700}$ (%)	U$_{stretch}$ (m/s)
2007	0.41	0.21	27.01	27.07	38.58	−1.51
2006	0.42	0.20	27.23	26.92	37.79	−1.54
2005	0.36	0.18	27.91	27.40	43.67	1.00
Long-term mean	0.38 (2000−2007)	0.19 (2000−2007)	26.70 (1950−2000)	26.82 (1950−2000)	38.02 (1950−2000)	−0.73 (1950−2000)

dry air was related to the low-middle level easterly winds. Figures 2a and 2b show that easterly winds at low to middle level (700−500 hPa) mostly originated from Africa and stretched further to the western Atlantic region, transporting dust further westward in 2007 than in 2005 (Figure 1b). As coincident with the easterly winds (Figures 2a and 2b) and dust aerosol distribution shown in Figures 1b and 1c, dry air (RH < 35% in blue color) extended further westward and lower levels in 2007 (Figure 3c) than in 2005 (Figure 2d). As a result, the RH at 700 hPa was lower or the low-middle level air was drier in 2007 than in 2005. The decreasing relative humidity at 700 hPa is expected to increase the atmospheric stability and reduce convection. As such, fewer TCs developed over the WNA in 2007 (Figure 1b) as compared to 2005 (Figure 1c).

[18] Globally, aerosols generally act to cool both the top of the atmosphere and the surface. Certain aerosol types (e.g., absorbing aerosols like dust and black carbon) can increase temperatures in certain portions of the atmosphere due to their absorbing characteristics [*Ramanathan et al.*, 2001]. The temperature difference between 2007 and 2005 (Figure 3a) reveals warming in the middle troposphere in the east dusty region, and cooling near the surface at the MDR. This is because the MDR is part of a larger region which is most frequently affected by dust [*Husar et al.*, 1997]. While in the western region, near-surface temperature was also lower in 2007 compared to 2005, but the cooling was much smaller than that in the MDR.

[19] The U-W wind difference vectors (Figure 3b) show the induced anomalous over-turning circulation as rising at the warming region in the east and sinking to the west at the cooling region. The moisture transport difference (Figure 3c) shows an anomalous upward transport of wet air from lower to upper troposphere in the east, and downward of the upper troposphere dry air to lower levels. As a result, humidity differences between 2007 and 2005 (Figure 3d) suggest increasing moisture (from increased convection most likely) in the east and significant drying (subsidence) in the west in 2007. The anomalous rising and sinking motions between the eastern Atlantic and the WNA are consistent with the observed east-west contrasts in precipitation and water vapor across the tropical Atlantic between 2006 and 2005 [*Lau and Kim*, 2007b].

[20] Moreover, the zonal wind (U) difference in Figure 3b also shows that at the western region (100°−50°W), easterly winds at low to middle level (1000−500 hPa) originated from Africa and increased in 2007, while at high level (400 hPa and up) the westerly winds increased, therefore the vertical wind shear increased, which should also further suppress the hurricane activity at the WNA in 2007.

5. A Zonal Wind Stretch Index and Its Relationship With Moisture Fields

[21] From the above analysis, we can see whether the dust aerosols and dry air transported to the WNA are most
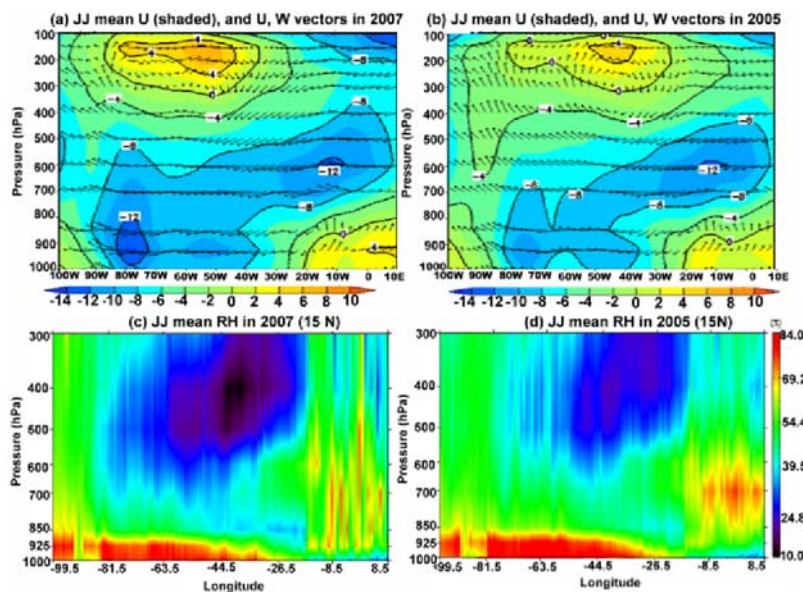
Figure 2. Cross section (15°N) of U (m/s, contours), U (m/s) and W (-mb/s) vectors during early summer (June−July or JJ mean) in (a) 2007 and (b) 2005 and cross section of RH (5) in (c) 2007 and (d) 2005. Please note the approximate longitude of the African coast on these plots is 16°W.
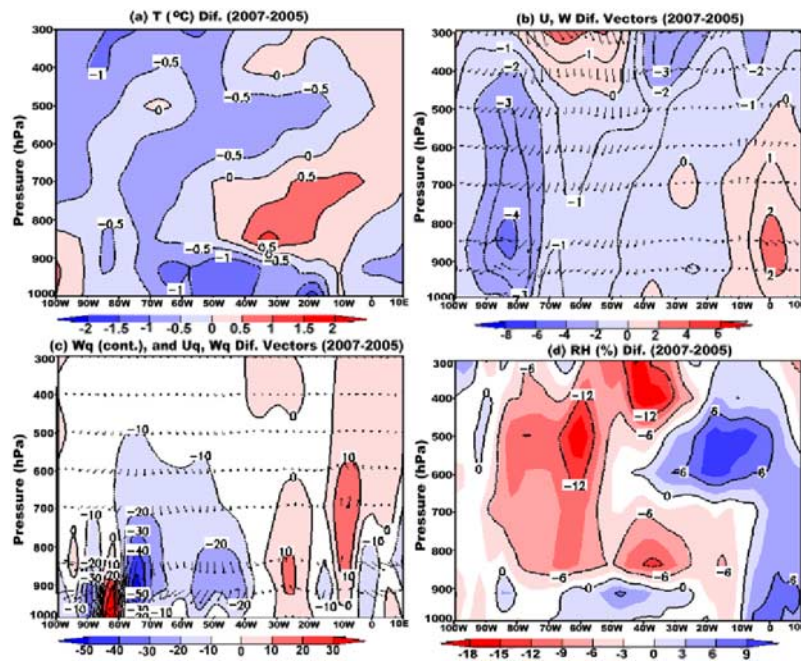
Figure 3. Cross section (15°N) of (a) temperature difference (°C); (b) U difference (m/s, shaded and contours), zonal wind U (m/s) and vertical speed W (-mb/s) difference vectors between 2007 and 2005; (c) Wq difference (-mb/s.g/kg; contours), Uq (m/s.g/kg) and Wq (-mb/s.g/kg) difference vectors; and (d) RH difference (%) during early summer (JJ mean) between 2007 and 2005. The approximate longitude of the African coast on these plots is 16°W.

likely related to the low-middle level easterly winds which originated from Africa (Figures 2a and 2b). To better quantify the advection effect, we define a zonal wind stretch index as the difference of low-middle level (600 hPa) mean U-wind (U_{600}) between the longitudes of 80°W and 60°W at 15° N latitude ($U_{stretch}$):

$$U_{stretch} = U_{600}(15°N, 80°W) - U_{600}(15°N, 60°W) \qquad (1)$$

$U_{stretch}$ is associated with large-scale air circulation pattern similar to "zonal stretching deformation" which affects hurricane activity [*Hoyos et al.*, 2006]. From equation (1), negative (positive) value of $U_{stretch}$ means net easterly (westerly) wind acceleration across the longitude sector, and therefore a strong (weak) advection of dust to the WNA by easterly trades. Since the dust sources are over the Saharan desert, a high dust loading from advection over this longitudinal sector is likely to be associated with high dust loading in the upstream region over the eastern MDR. The $U_{stretch}$ is found to be correlated with the humidity averaged over the MDR (r = 0.56) and WNA (r ($U_{stretch}$, RH_{700}) = 0.69) with confidence level above 99%. This means that if the midlevel easterly winds can stretch further to the west, the dry air could be transported and spread to the WNA.

[22] Table 1 summarizes the key environmental controls associated with SST, dry air and wind stretch index for 2007, 2006, 2005 and the long-term climatology. The years 2007 and 2006 were quite similar to each other, with warmer SST in the MDR, near normal relative humidity in the WNA compared to climatology. Clearly, the year 2005 was highly anomalous with SST warmer by more than 0.5−1°C in the WNA and MDR, and the WNA much wetter (RH_{700} = 43.67%) than climatology (RH_{700} = 38.02%).

Most telling is the variation of the stretch index which had very similar negative value in 2007 (-1.51 ms^{-1}) and in 2006 (-1.54 ms^{-1}). These values are significantly more negative compared to the climatology (-0.73 ms^{-1}), indicating *an easterly* acceleration associated with above-normal advection of dry air and/or dust into the WNA in 2007 and 2006. By contrast, the stretch index is large positive (= 1.00 ms−1) for 2005, reversing the sign from the climatology, indicating highly anomalous *westerly* acceleration, suppressing transport of dry air and dust into the WNA. This can be a factor contributing to the interannual variation of relative humidity in the WNA, in addition to surface evaporation and dry air intrusion from the subtropics.

6. Discussion and Summary

[23] Based on the expected lack of an El Niño event, the continuation of above average SSTs in the Atlantic MDR, and weak wind shear, many forecasters predicted a much above-normal hurricane season for 2007 (http://typhoon.at-mos.colostate.edu/forecasts/2007/nov2007/nov2007.pdf). However, the 2007 hurricane activity in the Atlantic basin was near normal.

[24] In 2007, dust aerosol loading during the early summer, the most active period for African dust outbreaks, were found to be much stronger over the Atlantic Ocean compared to 2005. As coincident with the increasing dust aerosol concentration in 2007, the U-W wind difference vectors provide evidence of induced anomalous over-turning circulation as compared to the normal circulation in each year. The temperature difference between 2007 and 2005 shows warming in the middle atmosphere in the east dusty region, and cooling (>0.5°C) in the MDR. The humidity and wind differences between 2007 and 2005

suggest an increasing moisture (from increased convection most likely) in the east and significant drying (subsidence) in the west in 2007. This can partially explain why very few TCs were found to form and intensify over the WNA in 2007. To quantify the zonal advection of Saharan dry air and dust into the WNA, a zonal wind stretch index was proposed. The index shows significant long-term correlation with the WNA area averaged mid-level humidity (r = 0.69). Comparing the basic controls of SST [*Kafatos et al.*, 2006], relative humidity and zonal wind index, we find that 2006 and 2007 were similar to each other and to the climatology, with slightly higher SSTs in the MDR and the WNA, and westward penetration of the Saharan dry air and dust. The hurricane season of 2005 was highly anomalous with significantly higher SST and higher relative humidity in the MDR and WNA. Most strikingly, the wind stretch index showed a large reversal from climatology, indicating highly suppressed advection of Saharan dry air and dust into the WNA. Based on the results presented, we conclude that the difference in westward penetration of the Saharan dry air and dust can be an important factor in contributing to the difference between the near- normal 2007 and 2006, and the very active 2005 hurricane seasons. Because the hurricane peak season in the Atlantic basin usually occurs during August–September–October (ASO), the moisture field anomaly associated with peak dust aerosol outbreak during early summer before the peak hurricane season may have some practical implication for the prediction of Atlantic hurricane activities.

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