Impact of Saharan air layer on hurricane peak intensity

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[1] The Saharan air layer (SAL), which is associated with African dust outbreaks, forms as air moves across the Sahara Desert, containing substantial amounts of mineral dust. While the relationships of Sahel rainfall with African dust outbreaks and Atlantic hurricane activity have been documented in previous studies, analyses of various independent datasets show that the Sahel rainfall, SAL activity and hurricane peak intensity in the Atlantic basin are highly correlated. The long-term trend in hurricane peak intensity generally follows the Sahel rainfall and SAL activity. The decreasing trend in hurricane intensity by the mid-1980s was associated with the enhancing SAL activity (drying relative humidity and enhancing vertical shear) and the severe drought in the Sahel, while the recent moderate increasing trend in hurricane intensity is consistent with the weakening SAL activity (wetting relative humidity, weakening vertical shear and decreasing dust load) and the ameliorating Sahel drought. This study suggests that the SAL may act as a link between the summer African monsoon and Atlantic hurricane activity. Citation: Wu, L. (2007), Impact of Saharan air layer on hurricane peak intensity, Geophys. Res. Lett., 34, L09802, doi:10.1029/2007GL029564.

1. Introduction

[2] Maximum potential intensity (MPI) theories [Emanuel, 1987; Holland, 1997] and numerical experiments using environmental thermodynamic conditions from global warming experiments [Knutson et al., 1998] suggested that hurricanes tend to intensify with increasing sea surface temperature (SST). It has been argued that the tropical Atlantic SST that has been increasing since the 1970s contributes to the recently heightened Atlantic hurricane activity [Emanuel, 2005; Webster et al., 2005].

[3] However, the SST is only one of the factors that affect tropical cyclone activity [Gray, 1968]. Recent studies have suggested that the Saharan Air Layer (SAL) can play an important role in the formation and intensity of Atlantic tropical cyclones [Dunion and Velden, 2004; Wu et al., 2006]. Dunion and Velden [2004] found that tropical cyclones that interacted with the SAL tend to weaken or have difficulty intensifying into mature hurricanes, primarily through three mechanisms. First, the intrusion of the dry air associated with the SAL promotes the downdrafts and disrupts the convective activity within tropical cyclones. Second, strong horizontal temperature gradients associated with the SAL produce a mid-level easterly maximum, increasing vertical wind shear in the Atlantic hurricane basin. Third, the warm SAL air acts to stabilize the environment, suppressing deep convection that is necessary for tropical cyclone formation and intensification [Gray, 1968]. In addition, studies have shown that the Saharan dust can affect the cloud microphysics [DeMott et al., 2003; Sassen et al., 2003], which are closely associated with tropical cyclone intensity. By now little is known about how the SAL can affect the long-term trends in hurricane intensity. This study only addresses how the warmness and dryness of the SAL affects tropical cyclone intensity.

[4] The Sahel, a semiarid region between the Saharan Desert and the rainforests of Central Africa and the Guinean Coast, experienced a severe drying trend from the 1950s to the 1980s, from which there has been partial recovery. Previous studies have shown that the Sahel rainfall is closely associated with the African dust emissions and transport [Prospero and Lamb, 2003]. Prospero and Lamb [2003] reported that the dust concentrations at Barbados are anticorrelated with concurrent rainfall amount in the Sahel. Gray [1990] and Landsea and Gray [1992] found that North Atlantic hurricane activity is closely tied with Sahel rainfall. Intense (category 3–5) hurricane activity is greatly enhanced when the Sahel region has above-average precipitation, and intense hurricane activity is much suppressed when concurrent Sahel rainfall is below average. It is conceivable that the SAL may act as a link between the summer African monsoon and Atlantic hurricane activity. That is, the precipitation in the Sahel may affect Atlantic hurricane activity through altering the SAL activity. The objective of this study is to show that the SAL is closely associated with both the Atlantic hurricane intensity and Sahel rainfall using various independent datasets.

2. Parameters for the SAL Activity

[5] Dust storms often swirl off the Sahara Desert at intervals of 3–5 days during the summer months. They transport substantial amounts of mineral dust to the tropical Atlantic. Long-term changes in Saharan dust activities have been studied with the satellite-derived dust information and station-based dust concentrations [Prospero and Lamb, 2003; Geogdzhayev et al., 2005]. Recently, Evan et al. [2006] examined found a relationship between interannual variations in North Atlantic atmospheric dust transports and tropical cyclone days. However, the long-term variations in the warmness and dryness of the SAL that are directly associated with hurricane activity have not been documented.

[6] The warm, dry air associated with the SAL can be clearly seen from the monthly averaged 700 hPa temperature and relative humidity fields in September 2003, which are derived from the combined measurements of the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave

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Sounding Unit (AMSU), and the microwave Humidity Sounder of Brazil (HSB) aboard NASA’s Aqua satellite [Chahine et al., 2006]. The warm, dry air originates from the west coast of Africa, extending with the easterly flow to the tropical Atlantic and the Caribbean Sea (Figure 1). In general, the SAL is indicated with the relative humidity of less than 40% and the temperature of higher than 282K at 700 hPa between 10-30N. As the SAL air approaches the West African coastline, the SAL makes an anticyclonic rotation with the driest and warmest air in the ridge region. This agrees with the SAL conceptual model proposed by Carlson and Prospero [1972] and Karyampudi et al. [1999]. Note that the monthly relative humidity in the southern part of the SAL between the coastline and trough is not very dry, possibly because of the frequent SAL-induced tropical disturbances [Karyampudi and Carlson, 1988].

The dry air of the SAL is shown with little vertical change in relative humidity from 900 to 600 hPa between 15° and 25°N (Figure 2a). There is a sharp contrast in the relative humidity between 10° and 20°N. At 700 hPa, for example, the relative humidity is about 60% at 10°N, but less than 30% at 25°N. The large temperature gradients primarily occur between 10° and 25°N below 700 hPa (figure not shown). As a result, a maximum in the geostrophic wind occurs at 650–700 hPa due to thermal wind considerations, increasing the local vertical shear in the lower troposphere (Figure 2b). Thus the warmness and dryness of the SAL can be parameterized with the 850 hPa relative humidity and vertical wind shear between 850 and 600 hPa, respectively.

The long-term relative humidity and vertical wind shear data are obtained from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis in this study. The 850 hPa relative humidity is averaged over 10–20°N, 30–80°W, roughly covering the main region of the SAL activity (Figure 1). The vertical wind shear is calculated as the difference in the zonal wind speed between 850 and 600 hPa averaged over 15–25°N, 30–50°W, a region with strong south-north temperature gradients associated with the SAL (Figure 1b).

3. Relationships of the SAL With Hurricane Peak Intensity and Sahel Rainfall

In this study, the tropical cyclone intensity is represented by the maximum sustained wind speed and the peak intensity is the maximum intensity reached by a tropical cyclone during its lifetime. The annual basin-wide mean peak intensity is calculated by averaging peak intensities of all the Atlantic tropical cyclones (maximum wind speeds larger than 17 m s⁻¹) each year in the National Hurricane Center (NHC) best-track dataset. One reason for discussing the peak intensity is that hurricane MPI theories and numerical simulations use it to measure hurricane responses

Figure 1. 700 hPa monthly mean structures of the SAL indicated by (a) AIRS relative humidity (%) and (b) temperature (K), superimposed by the corresponding mean 700 hPa NCEP-NCAR reanalysis wind fields (arrows). Lighter shading indicates the warm and dry air associated with the SAL. The contour intervals are 0.5 K and 5% for temperature and relative humidity, respectively.

Figure 2. Monthly mean profiles of (a) the AIRS relative humidity (%) and (b) zonal wind (m s⁻¹) derived from the NCEP-NCAR reanalysis wind fields along 20°W. The contour intervals are 5% and 2 m s⁻¹ for relative humidity and wind, respectively.
to the SST warming [e.g., Emanuel, 1987; Knutson et al., 1998].

Figure 3a shows the relationships of the hurricane peak intensity (thick red) with the relative humidity (orange) and vertical wind shear (blue) associated with the SAL. For comparison, the time series have been standardized (subtracting the mean and dividing by the standard deviation of the respective time series). A three-year running smoother is applied twice to reduce the effect of interannual variability. Note that the shear time series are on an inverse scale. The relative humidity is high in the early 1950s with a decreasing trend in hurricane intensity by the mid-1980s was associated with drying relative humidity and enhancing vertical shear, while the recent moderate increasing trend has been accompanied by wetting relative humidity and weakening vertical shear. The correlation coefficients of the mean peak intensity with relative humidity and vertical shear are 0.73 and −0.75, respectively, all statistically significant at the 99% level. Thus a SAL effect index (SEI) can be defined as: SEI = 0.469RH-0.501V, where RH and V are the relative humidity and vertical wind shear. The combined index has a correlation coefficient of 0.85 with the peak intensity. The higher correlation is due to both of the vertical shear and relative humidity can affect tropical cyclone intensity [Gray, 1968]. The long-term changes in the mean peak intensity followed the SEI, especially after the mid-1960s, when the satellite-based measurements were available [Emanuel, 2005], suggesting that the SAL plays a dominant role in controlling the long-term trends in hurricane intensity (Figure 3b).

[12] Giannini et al. [2003] showed that the rainfall variability associated with the northern summer African monsoon is dominated by two distinct patterns that are well separated geographically and act on different time scales. The rainfall in the Sahel between 10° and 20°N is dominated by interdecadal variability. Thus the mean Sahel rainfall is calculated over 10–20°N, 5–20°W for the hurricane peak season from 1948 to 2005. The Sahel rainfall data from station gauge observations are obtained from the precipitation reconstruction (PREC) project [Chen et al., 2002].

As shown in Figure 3b, the long-term changes in the Sahel rainfall are remarkably consistent with those in the SEI. The Sahel rainfall has correlation coefficients of 0.87 and −0.77 with the relative humidity and vertical shear associated with the SAL, respectively. The Sahel rainfall has a correlation of 0.82 with the hurricane peak intensity.

While the close relationships of Sahel rainfall with African dust outbreaks and Atlantic hurricane activity have been documented in previous studies [e.g., Prospero and Lamb, 2003; Gray, 1990], these high correlations suggest that the SAL may act as a link between the summer African monsoon and Atlantic hurricane activity. That is, the weak (strong) SAL activity indicated by high (low) relative humidity and weak (strong) vertical wind shear corresponds with rainy (droughty) Sahel summers.

4. Discussion

The recent increasing hurricane activity has been related to the SST warming that occurred in the tropical Atlantic since the 1970s [Emanuel, 2005; Webster et al., 2005] and the Atlantic Multi-decadal Oscillation (AMO) [Goldenberg et al., 2001]. In this study, the mean SST for the hurricane peak season is averaged over 6–18°N, 20–60°W, the same area used by Emanuel [2005]. The SST data are obtained from the Extended Reconstructed SST (ERSST) dataset of the National Oceanic and Atmospheric Administration (NOAA) and the AMO index is obtained from the NOAA Climate Analysis Branch. The mean SST is not statistically correlated with the mean peak intensity (Figure 3c). On the other hand, the AMO index is statistically correlated with the peak intensity. The index has a
correlation coefficient of 0.46 with the peak intensity. The hurricane peak intensity was consistent with the decreasing trend in the AMO index by the 1970s, but after the 1980s the intensity has been trending upward at a much slower rate than the SST and AMO index. The combined SAL effect index or the Sahel rainfall can better account for the 58-year trend in the mean peak intensity than the SST or AMO index. However, this is not to say that the SST and AMO have nothing to do with the hurricane intensity trends. Sahel is one of the most climatically sensitive zones in the world [Zeng, 2003]. The variability of the Sahel rainfall is closely associated with the global SST changes, the summer African monsoon, and even anthropogenic influences [Gianinni et al., 2003; Held et al., 2005]. The tropical SST and AMO may affect hurricane intensity through the SAL.

One may question whether the changes in the relative humidity and vertical wind shear shown in Figure 3a are related to the physical processes other than the SAL activity. Since the coherent changes in the humidity and vertical shear are closely associated with the dryness and warmness of the SAL, as an example, the dust outbreaks during 1–12 September 2003 are examined using the NCEP-NCAR reanalysis data (Figure 4a). The relatively low humidity indicates three dust outbreaks that occurred on September 3, 8 and 12. The outbreaks were accompanied with enhanced low-level vertical shear. The two time series have a correlation coefficient of −0.63, indicating that the responses of the vertical wind shear and relative humidity to the dust outbreaks are very similar to the relationship revealed from the monthly NCEP-NCAR reanalysis dataset. Therefore, in spite of uncertainties, the changes in the relative humidity and vertical wind shear from the reanalysis data are physically consistent with the SAL activity.

In addition, the recent weakening SAL activity is also indicated by the decreasing SAL dust load. Using the aerosol records from the NASA Global Aerosol Climatology Project (GACP) from 1982 to 2004 [Geogdzhayev et al., 2005], the 23-year mean aerosol optical thickness for the hurricane peak season is averaged over 20–30°N, 25–40°W, a region with the driest and warmest air (Figure 1). In this region, the Saharan dust load is one of the most climatically sensitive zones in the world [Carlson, 1972]. The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic, its linear trend (thick), and the GACP aerosol optical thickness (AOT, closed dots) averaged over 10–20°N, 10–30°W, respectively, which are derived from NCEP-NCAR reanalysis data. The relatively low (negative) values of aerosol optical thickness indicate years with more (less) dust transports to the tropical North Atlantic. The two time series have a correlation coefficient of −0.55, significant at the 99% level.

5. Summary

While the close relationships of the Sahel rainfall with African dust outbreaks and Atlantic hurricane activity have been documented in previous studies, in this study evidence is provided through analyses of various datasets associated with African dust outbreaks, Sahel droughts and Atlantic hurricane peak intensity, suggesting that the SAL may act as a link between the summer African monsoon and Atlantic hurricane activity. The combined SAL effect index or Sahel rainfall can much better account for the trend in the mean peak intensity over the past 58 years than the tropical SST or AMO index. The long-term trend in hurricane intensity generally follows the Sahel rainfall or SAL activity. Since these high correlations of the peak intensity with the SAL activity and Sahel rainfall are derived from the independent datasets, uncertainties involved in datasets may not qualitatively affect the results of this study. In summary, the decreasing trend in hurricane intensity by the mid-1980s was associated with the enhancing SAL activity (drying relative humidity and increasing vertical shear) and the severe drought in the Sahel, while the recent moderate increasing trend in hurricane intensity is accompanied with the weakening SAL activity (wetting relative humidity, decreasing vertical shear and dust load) and the ameliorating Sahel drought.

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References


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