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Cooling of the North Atlantic by Saharan dust

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Popular Summary

An article entitled "How nature foiled the 2006 Atlantic Hurricane forecasts" (Lau and Kim 2007) published in *EOS*, *Transaction of the American Geophysical Union* has generated much public interests and a new debate in the science community regarding important factors affecting hurricane formation. In that paper, based on satellite observations, the authors noted the large and abrupt cooling of the entire North Atlantic following about a week the maximum Saharan dust loading over the region in June 2006 relative to 2005. The cooling amplified and lasted through the entire hurricane season. They argued that the initial cooling was due to the presence of excessive Saharan dust over the North Atlantic, which shielded sunlight from reaching the surface, thus causing sea surface temperature to drop. Noting that SST is not the only factor affecting hurricane formation, they further suggested that the initial cooling by dust may be instrumental in triggering the abrupt change in large-scale precipitation and wind conditions which are unfavorable for development of hurricanes in 2006 compared to 2005. This paper is a following-up of the Lau and Kim study, focusing on the cooling of the North Atlantic by Saharan dust. Previous studies by other authors have indicated some SST cooling off the coast of North Africa associated with Saharan dust outbreak. This is the first study, thanks to availability of research-quality NASA satellite data, providing evidence of large-scale, sustained cooling of the North Atlantic by Saharan dust.

Using aerosol optical depth, sea surface temperature, top-of-the-atmosphere solar radiation flux, and oceanic mixed-layer depth from diverse data sources that include NASA satellites, NCEP reanalysis, *in situ* observations, as well as long-term dust records from Barbados, we examine the possible relationships between Saharan dust and Atlantic sea surface temperature. Results confirmed the much larger Sahara dust loading in June 2006 compared to June 2005 over the North Atlantic. Calculations show that the estimated anomalous cooling pattern of the North Atlantic due to attenuation of solar radiation by Saharan dust remarkably resemble observations, accounting for approximately 30-40% of the magnitude of observed change in sea surface temperature. Historical data analysis show that there is a robust negative correlation between atmospheric dust loading and Atlantic SST supporting the notion that increased (decreased) Saharan dust is associated with cooling (warming) of the Atlantic during the early hurricane season (July- August-September). The results suggest that Saharan dust may be an important factor in seasonal hurricane formation and forecasts, that can no longer be ignored.

Cooling of the Atlantic by Saharan dust

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Abstract

Using aerosol optical depth, sea surface temperature, top-of-the-atmosphere solar radiation flux, and oceanic mixed-layer depth from diverse data sources that include NASA satellites, NCEP reanalysis, *in situ* observations, as well as long-term dust records from Barbados, we examine the possible relationships between Saharan dust and Atlantic sea surface temperature. Results show that the estimated anomalous cooling pattern of the Atlantic during June 2006 relative to June 2005 due to attenuation of surface solar radiation by Saharan dust remarkably resemble observations, accounting for approximately 30-40% of the observed change in sea surface temperature. Historical data analysis show that there is a robust negative correlation between atmospheric dust loading and Atlantic SST consistent with the notion that increased (decreased) Saharan dust is associated with cooling (warming) of the Atlantic during the early hurricane season (July- August-September).

1. **Introduction**

An estimated amount of 60-200 million tons of dust particles are lifted annually from the Saharan desert surface and transported westward by the easterly winds over the Atlantic Ocean [Prospero and Lamb, 2003]. During the peak season of June through August, airborne dust particles reach the western Atlantic and Caribbean, and can be detected as far west as Florida, and the Gulf of Mexico [Colarco *et al.*, 2003; Wong *et al.*, 2006]. Saharan dusts have been shown to affect the development of clouds and precipitation over oceanic areas across the Atlantic, as well as modulating thunderstorm activities over the Caribbean, and the southeast US [Kaufman *et al.,* 2005; Sassen *et al.* 2003]. Hot dry air, known as the Saharan Air Layer (SAL), which often accompanies Saharan dust outbreaks, can suppress tropical cyclogenesis and inhibit Atlantic hurricane formation [Dunion and Velden, 2004; Wu, 2007]. Studies have also found significant positive correlation between dust cover and Atlantic tropical cyclone days [Evan *et al.*, 2006].

Recently Lau and Kim [2007] found significant increase in Saharan dust and reduction of sea surface temperature (SST) over the West Atlantic and Caribbean region during the hurricane season, June through November, of 2006 compared to 2005. They argued that the attenuation of solar radiation reaching the ocean surface by excessive Saharan dust in June-July, 2006 (relative to 2005) may have been instrumental in initiating the rapid cooling of the entire Atlantic Ocean. The cooling subsequent metastasized through atmospheric-oceanic coupled feedback to become a part of an altered climate state in the North Atlantic and West Africa regions unfavorable for hurricane formation. In this paper, we present observational evidences of possible large-scale cooling of the Atlantic by Saharan dust attenuation effect for 2006 relative to 2005, and examine statistical dust-SST relationships based on long-term historical records.

The data used for this study are drawn from a wide range of independent sources, including daily Aerosol-Index (AI) (Hsu et al. [1999]) for absorbing aerosols (dust and black carbon) from the Ozone Monitoring Instrument (OMI), aerosol optical depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) [Remer *et al.*, 2005], daily sea surface temperature from Tropical Rainfall Measuring Mission Microwave Instrument (TMI), top-of-the atmosphere solar radiation from the National Center for Environmental Prediction (NCEP) reanalysis data, and climatological oceanic mixed layer depth from the Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques (LOCEAN). Also used for the historical data analysis are long-term data from the Barbados dust record [Prospero and Nees, 1986], and the SST record from the Hadley Center [Rayner *et al.*, 2003].

2. Results

a. Dust and SST variation during 2005-2006

From the daily variation (smoothed by a 5-day running mean) of dust loading (OMI-AI) and SST over the Western Atlantic/Caribbean region [70°W-40°W, 15°N-30°N] in 2006, (shown as the deviation from 2005 in Fig. 1), dust loading is clearly higher for most of the year in 2006 compared to 2005 (Fig. 1a). The dust loading shows large fluctuations from June through September, reflecting the dynamical nature of the dust outbreak and transport processes. This region experienced episodic cooling in SST throughout 2006 (Fig. 1b), with two significant episodes in mid-March through May, which seemed to follow two dust events (Fig. 1a) during the same period. The most pronounced cooling occurred in mid-June, about one-two weeks after the major dust event in June. The cooling rapidly reached its maximum in late June and mid-July, and lasted through the end of September. Given that dust outbreaks and loadings are highly dependent on fast atmospheric processes, and SST on relatively slow ocean processes, any relationship that may exist between dust events and Caribbean SST is likely to be highly nonlinear, involving multi-scale interactions.

b. Solar attenuation effect of dust

To illustrate the possible solar attenuation effect on SST by dust, and to minimize the interactive effects between dust and atmospheric dynamical processes, we focus on the early part of the season when hurricanes are few and dust events are frequent. During June 2006, excessive dust loading (relative to 2005) is found over the entire Atlantic from 5° N -25° N, as evident in the distribution of MODIS AOD, with maximum (> 0.2) in the main propagation path of Saharan dust along 5° N -20° N (Fig. 2a). The observed SST pattern (Fig. 2b) shows widespread cooling of the Atlantic coinciding with the positive AOD anomaly, with pronounced signals of 0.5–0.8 $^{\circ}$C in the Caribbean, the eastern Atlantic and regions off the coast of North Africa.

The SST cooling due to solar attenuation by Saharan dust depends not only on the amount of solar radiation reduction at the surface, but also on the depth of the oceanic mixed layer (OML). Fig. 2c shows the climatological distribution of OML depth in June for the North Atlantic [de Boyer Montégut *et al.*, 2004]. Here, it is clear that the OML is relatively deep (> 40 m) in the central tropical Atlantic (40 -50° W), but shallow (< 25m) in the subtropical Atlantic, Caribbean, and regions off the coasts of North Africa and northern South America (Fig. 2c). For a given change in surface solar radiation, the SST in the shallower region is more sensitive, because the energy is distributed over a smaller volume of water. To estimate the shortwave radiation at the ocean surface, we scale the shortwave flux at the top of the atmosphere from NCEP by the daily MODIS AOD with an attenuation factor e^{-AOD} following the procedure used bySchollaert and Merrill [1998]. The estimated surface shortwave fluxes have magnitudes ranging from 20-30 Wm^{-2} over the North Atlantic, which is comparable but somewhat higher than observed [Li *et al.*, 2004], possibly because of the neglect of longwave fluxes as well as cloud effects. The surface shortwave flux is then applied to a slab OML model with climatological mixed layer depths, and integrated with initial condition from May 31 to obtain the cumulative SST change due to solar attenuation for June 2005 and 2006 respectively for the North Atlantic.

The estimated June SST anomaly (2006-minus-2005) due to changes in dust loading (Fig. 2d) is remarkably similar to the observed (Fig. 2b). The areas of strong warming and cooling off the coast of North Africa, and the large body of colder water over the western Atlantic and Caribbean are reproduced. The magnitude of the estimated cooling (0.2 -0.4° C) in the Atlantic is about 40-50 percent of the observed (0.5 - 0.8° C). In reality, the shortwave cooling will be partially offset by longwave heating by the dust and the accompanying hot and dry air. Previous study [Li *et al.,* 2004] has shown that for Saharan dust, the longwave heating is of the order of 20-30% of the shortwave cooling. Reducing the solar attenuation by that percentage yields a crude net dust radiative forcing contribution of approximately 30-40% to the observed SST cooling between June 2006 and 2005. Such a contribution clearly cannot be ignored.

c. Long-term correlations

In this section, we examine the long-term relationship between dust and Atlantic SST. For dust, we use the in-situ measurements from Barbados [Prospero and Lamb, 2003], which is the only multi-decadal continuous in-situ dust data available. The data have been tested, and shown to be representative of dust loadings over large areas of the North Atlantic region [Chiapello *et al.*, 2005]. The one-point correlation map between Barbados dust record and Hadley Center SST for July-August-September (JAS) has been computed for the period (1980-1999) for the domain 20° S -40° N, 100° W-20° E (Fig. 3a). The larger domain is chosen to provide the large-scale context for the correlations, and to compare with similar one-point correlation map with the Niño3 SST anomalies (Fig. 3b).

The linear correlation between Niño3 SST anomalies and the Barbados dust record is found to be insignificant for the chosen period, indicating that El Niño and dust events over the Atlantic can be considered, to a first order, mathematically independent. However, a lack of correlation between two variables does not preclude the possibility that they may be related through nonlinear effects. Fig. 3a shows that there is generally an inverse relationship between SST and dust over the entire Atlantic Ocean, *i.e.*, more dust and lower SST and *vice versa*. The most significant correlations are found over the western Atlantic and southwestern Caribbean region (40°-60°W), and the subtropical eastern Atlantic off the coast of North Africa. In contrast, the El Niño-SST correlation (Fig.3b) features large positive correlations over the eastern Pacific (as expected) and the Gulf of Mexico that extends and tapers off into the western subtropical Atlantic. Large negative SST correlations are found over the equatorial eastern Atlantic near the Gulf of

Guinea. The negative SST in the Gulf of Guinea may be related to an atmospheric zonal circulation linking eastern Pacific and eastern Atlantic SST anomalies associated with El Niño [Janicot *et al.*, 1998]. Over the western Atlantic (40°- 60°W), where hurricanes making landfall on US east and southeast coasts tend to spawn and intensify, the SST signal associated with El Niño is a slight warming effect. The 2006-2005 observed JAS SST anomaly in the Atlantic (Fig. 2 in Lau and Kim [2007]) bears some resemblance to the dust-SST correlation pattern (Fig. 3a), but is distinctly different from the El Niño – SST pattern (Fig. 3b). If historical data can be applied to the 2005-2006 season, these results would further support the notion that radiative effect of Saharan dust may play an important role in the cooling of the Atlantic in 2006 relative to 2005.

3. Conclusions

Based on estimates of SST cooling due to solar attenuation by Saharan dust, and analyses of correlations from historical data, we have provided preliminary evidences supporting the notion that solar attenuation effects due to increased (decreased) Saharan dust loading over the Atlantic may contribute to widespread cooling (warming) of the underlying sea surface in the early hurricane season. Our results are consistent with the idea that anomalous dust loading over the West Atlantic Caribbean region may have been instrumental in initiating the large-scale SST cooling in the Atlantic in June 2006. Since dust loading in the West Atlantic and Caribbean typically peaks in the early hurricane season (June-August), such pre-conditioning may have predictive value in terms of SST effects, in fine-tuning seasonal hurricane forecasts.

Finally, the solar attenuation estimates in this study represent very crude estimates only. More detailed computations of dust radiative fluxes require knowledge of the ambient atmospheric temperature and moisture soundings, size distribution, radiative properties and vertical profiles of dust. These calculations need to be carried out in future studies. The radiative fluxes should also be examined in the context of the total surface heat fluxes including those due to wind-evaporation and oceanic processes, in order to obtain better quantitative estimates of the relative roles of radiative effects of Saharan dust on Atlantic SST.

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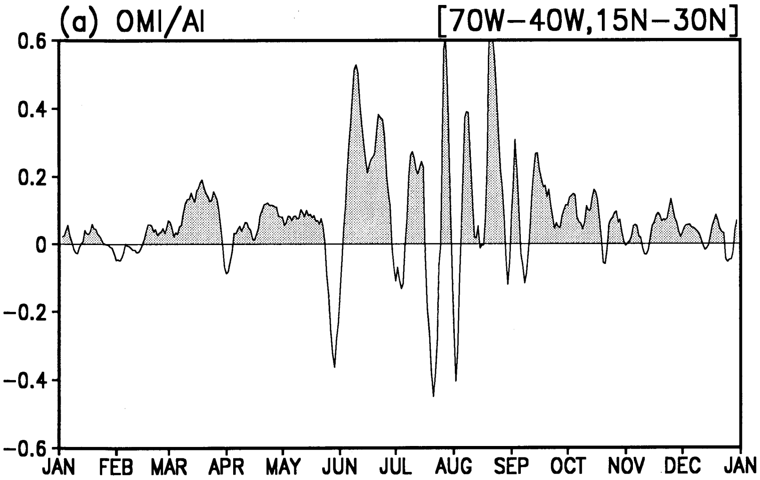
Figure Captions

Fig. 1 Time series of 2006-minus-2005 daily (smoothed by a 5-day running mean) of (a) daily TOMS AI index, and (b) TMI SST in °C, averaged over the western Atlantic/Caribbean region [70W-40W, 15N-30N].

Fig. 2 Spatial pattern of (a) MODIS AOD difference, defined as the monthly mean of June 2006 minus June 2005, with positive anomalies shaded (b) observed SST (°C) difference from the Tropical Rainfall Measuring Mission Microwave Instrument with negative anomalies shaded, (c) climatological OML depth (m) with values less than 35m shaded, and (d) estimated SST difference due to solar attenuation by dust (°C), with negative contours are shaded.

Fig. 3 One-point correlation map of SST with (a) Barbados dust index, and (b) Niño3 SST. Light (dark) shading marks regions with correlation exceeding the 90% (95%).

(a) OMI/AI



(b) TRMM/TMI SST

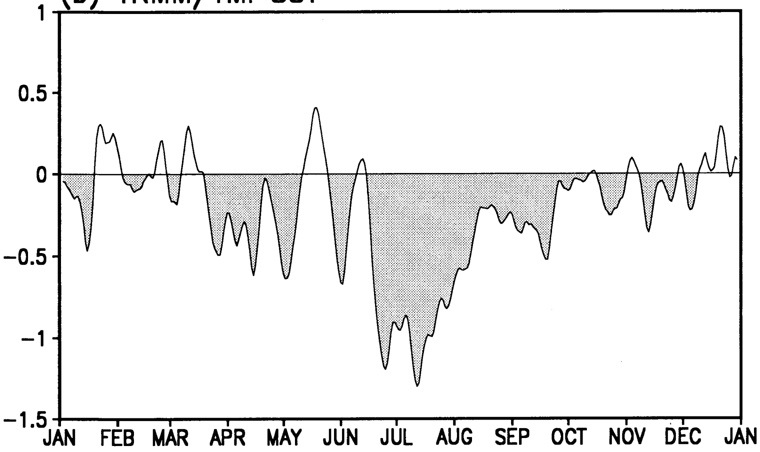
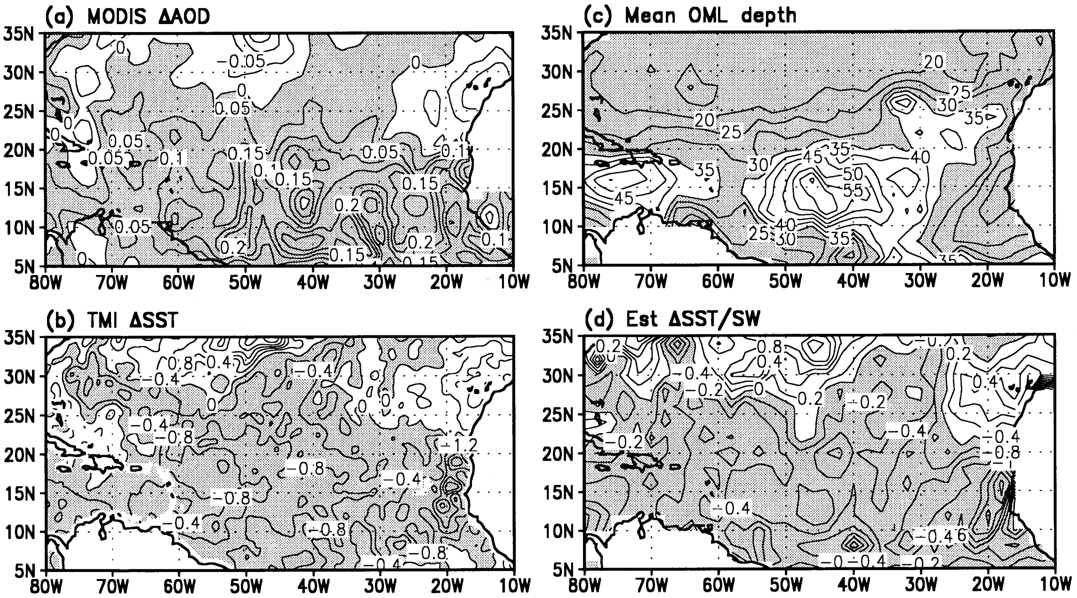


Figure 1

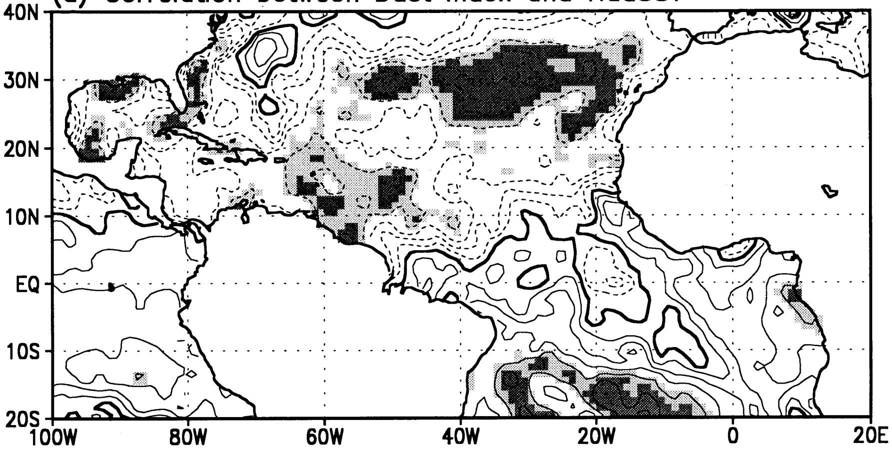

(a) MODIS ΔAOD

(b) TMI ΔSST

(c) Mean OML depth

(d) Est ΔSST/SW

Figure 2


(a) Correlation between Dust Index and HadSST

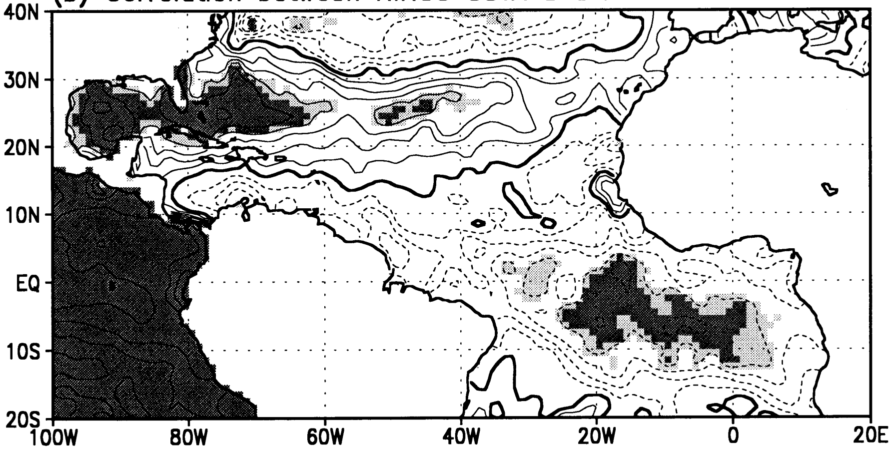

(b) Correlation between NINO3 SSTA and HadSST

Figure 3