GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L20706, doi:10.1029/2008GL035042, 2008

Trends in Saharan dust and tropical Atlantic climate during 1980–2006

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Received 16 June 2008; revised 5 August 2008; accepted 23 September 2008; published 25 October 2008.

[1] Trends in tropical Atlantic sea surface temperature (SST), Sahel rainfall, and Saharan dust are investigated during 1980–2006. This period is characterized by a significant increase in tropical North Atlantic SST and the transition from a negative to a positive phase of the Atlantic multidecadal oscillation (AMO). It is found that dust concentrations over western Africa and the tropical North Atlantic Ocean decreased significantly between 1980 and 2006 in association with an increase in Sahel rainfall. The decrease in dust in the tropical North Atlantic tended to increase the surface radiative heat flux by 0.7 W m^{-2} which, if unbalanced, would lead to an increase in SST of 3°C. Coupled models significantly underestimate the amplitude of the AMO in the tropical North Atlantic possibly because they do not account for changes in Saharan dust concentration. **Citation:** Foltz, G. R., and M. J. McPhaden (2008), Trends in Saharan dust and tropical Atlantic climate during 1980–2006, *Geophys. Res. Lett.*, *35*, L20706, doi:10.1029/2008GL035042.

1. Introduction

[2] During the past century tropical North Atlantic sea surface temperatures (SST) have fluctuated strongly with a period of ~70 years [*Goldenberg et al.*, 2001] (Figure 1a). The oscillations are part of a basin-scale Atlantic multidecadal oscillation (AMO) thought to be driven by changes in the strength of the Atlantic thermohaline circulation [e.g., *Delworth and Mann*, 2000; *Knight et al.*, 2005]. The AMO exerts a significant influence on weather and climate in the tropical Atlantic sector, with positive phases of the AMO contributing to enhanced rainfall in the Sahel region of Africa [*Zhang and Delworth*, 2006] and above-normal hurricane activity in the Atlantic basin [*Goldenberg et al.*, 2001]. Superimposed on the AMO is a strong warming trend that has been attributed to anthropogenic greenhouse gas forcing [*Mann and Emanuel*, 2006].

[3] The Sahara and Sahel regions of western Africa export roughly 210 Tg of dust to the tropical North Atlantic Ocean annually, of which ~155 Tg is supplied during May–October [*Kaufman et al.*, 2005]. Dust in the atmosphere affects the heat budget of the upper ocean through scattering and absorption of incoming solar radiation [e.g., *Li et al.*, 2004; *Zhu et al.*, 2007]. Indeed, empirical and modeling studies suggest that seasonal to interannual changes in dustiness in the tropical North Atlantic exert a significant influence on the underlying SST [*Schollaert and Merrill*, 1998; *Foltz and McPhaden*, 2008; *Evan et al.*, 2008].

[4] Previous studies have identified a statistical link between atmospheric dust concentrations over the tropical North Atlantic Ocean and rainfall in the Sahel, with enhanced rainfall leading a reduction in dust the following summer [*Brooks and Legrand*, 2000; *Prospero and Lamb*, 2003; *Moulin and Chiapello*, 2004]. *Moulin and Chiapello* [2004] identified the northwestern Sahel as the dominant source of summertime dust variability over the tropical North Atlantic. In this study we examine the relationships between dust, rainfall, and atmospheric circulation during 1980–2006, a period notable for its dramatic increase in tropical North Atlantic SST and the transition from a negative to a positive phase of the AMO [*Goldenberg et al.*, 2001] (Figure 1). We focus on linear trends during the 27-year period, expanding on previous studies that mainly considered the relationships between these quantities on intraseasonal to interannual time scales.

2. Data

[5] We use a combination of monthly averaged satellite, in situ, and atmospheric reanalysis products for the time period 1980–2006. We obtained the *Reynolds et al.* [2002] combined satellite-in situ SST analysis, available for December 1981–present on a 1° × 1° grid, and the Extended Reconstructed SST (ERSST), which is based on the Comprehensive Ocean-Atmosphere Dataset (COADS) and available during 1854–present on a 2° × 2° grid [*Smith et al.*, 2008]. We use the *Reynolds et al.* [2002] SST for Dec 1981–Dec 2006 and the ERSST during Jan 1980–Nov 1981, when satellite-based measurements are unavailable. SST trends in the eastern tropical North Atlantic, where dust concentrations are highest, are similar when calculated from ERSST and *Reynolds et al.* [2002] SST, suggesting that infrared satellite-based measurements in the *Reynolds et al.* [2002] data set were not contaminated by trends in aerosols.

[6] Aerosol optical depth (AOD) at 380 nm was obtained from the Total Ozone Mapping Spectrometer (TOMS) and is used as a proxy for total atmospheric dust content [*Torres et al.*, 2002]. These data are available on a 1° × 1° grid for January 1980–April 1993 and August 1996–December 2001. AOD measurements at 550 nm are available from the Moderate Resolution Imaging Spectroradiometer (MODIS) [*Remer et al.*, 2005] during February 2000–present on a 1° × 1° grid. A seasonal mean bias correction was applied to the MODIS AOD based on a point-by-point comparison to TOMS during February 2000–December 2001, when both data sets are available. We use the adjusted

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0094-8276/08/2008GL035042$05.00

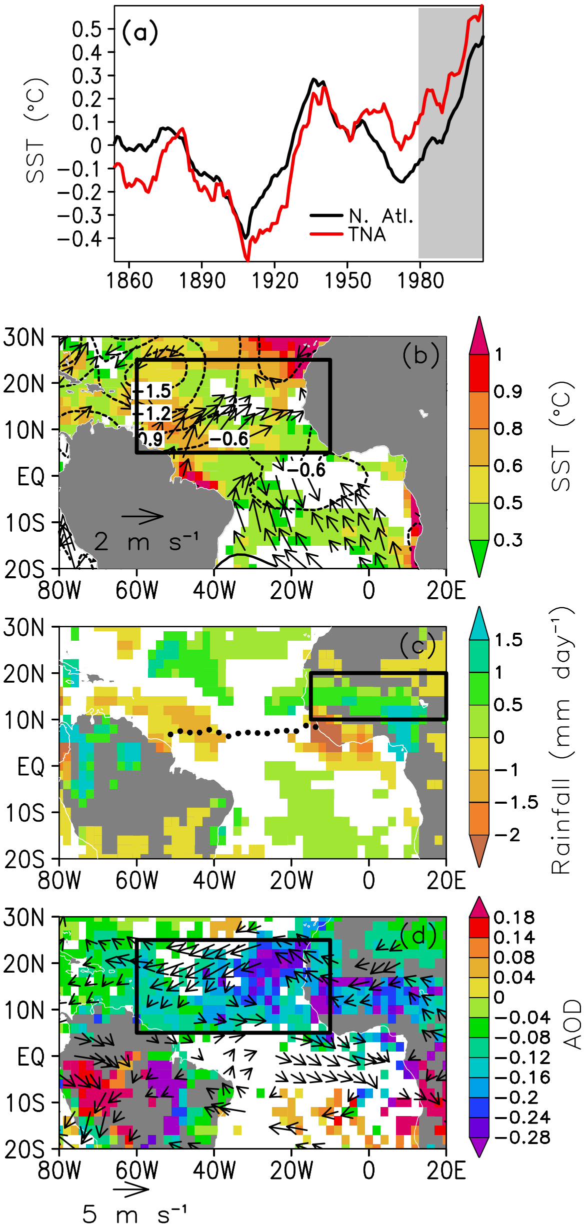

Figure 1. (a) North Atlantic (0°–60°N, 15°W–75°W; black) and tropical North Atlantic (5°N–25°N, 10°W–60°W; red) SST indices during 1854–2006. Grey shading indicates the time period considered in this study. (b) Linear trends in SST (shaded), surface pressure (contours), and surface winds (vectors) during June–September, 1980–2006. (c) Linear trends in JJAS rainfall (shaded) and mean JJAS ITCZ position (dotted line). (d) JJAS linear trends in aerosol optical depth (AOD, shaded) and 700 hPa winds (vectors). Climatological JJAS winds at 700 hPa are westward throughout the tropical North Atlantic. Trends in Figures 1b–1d are expressed as the total change between 2006 and 1980 and are shown only where they are significant at the 5% level based on a Student's t-test with 27 DOF. Boxes in Figures 1b–1d enclose regions used to form indices in Figure 2.

MODIS data during Jan 2002–Dec 2006, when TOMS AOD is unavailable. Trends in AOD based on this combined data set are similar to those from the shorter TOMS record. Satellite-based estimates of AOD include contributions from absorbing aerosols such as smoke and soot in addition to soil dust. During most years the aerosol load over the tropical North Atlantic is dominated by soil dust originating from North Africa [e.g., *Chiapello et al.*, 1999]. Exceptions are during 1983 and 1991, when aerosols from the eruptions of El Chichón and Mt. Pinatubo, respectively, spread globally in the upper atmosphere. Trends in AOD in the tropical North Atlantic are not significantly changed if these years are excluded from the analysis (Figure 2c).

[7] Surface and 700 hPa wind velocity were obtained from the NCEP-DOE reanalysis-2, available on a 2° × 2° grid for 1979–present [*Kanamitsu et al.*, 2002]. Cloud fraction is available from the International Satellite Cloud Climatology

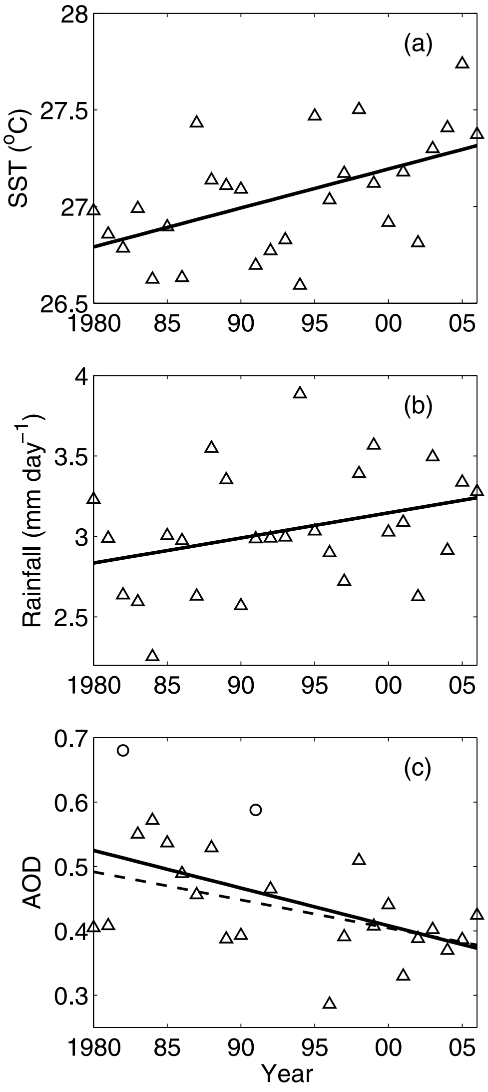

Figure 2. JJAS means (triangles) and linear trends (solid lines) in (a) tropical North Atlantic SST, (b) Sahel rainfall, and (c) tropical North Atlantic AOD. Figure 1 shows the averaging regions. Circles in Figure 2c denote the years of significant volcanic eruptions (1982 and 1991). Dashed line is the linear trend calculated after removing these data points.

Project (ISCCP) for July 1983–June 2007 on a 2.5° × 2.5° grid [*Rossow and Schiffer*, 1999]. We also use the Climate Prediction Center's Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1997] for 1980–2006 on a 2.5° × 2.5° grid and the climatological mixed layer depth (MLD) data set of *de Boyer Montégut et al.* [2007], which is based on in situ temperature and salinity profiles from the World Ocean Database and Argo.

3. Results

[8] In this section we examine linear trends during 1980–2006, with emphasis on the boreal summer season (June–September), when rainfall in the Sahel and atmospheric dust concentrations in the tropical North Atlantic are highest. Our procedure for calculating trends consists of first averaging JJAS values for each year, then regressing onto time. The spatial patterns of JJAS trends discussed in this section are similar to those obtained using all months, though the magnitudes of the dust and Sahel rainfall trends are smaller when averaged over all months.

[9] SST increased significantly throughout a large portion of the tropical Atlantic during 1980–2006. The largest warming occurred in the eastern basin between 20°N–30°N and in the west between the equator and 15°N (Figure 1b). Linear trends in surface winds are northeastward in the 5°N–15°N band, generally consistent with negative trends in surface atmospheric pressure centered near 20°N, 60°W and 25°N, 20°W. The negative surface pressure trends are in agreement with the expected atmospheric response of the North Atlantic to the AMO [*Knight et al.*, 2006]. There was a significant strengthening of the southeasterly trade winds throughout most of the tropical South Atlantic that may have been related to changes in the tropical North Atlantic through wind-evaporation-SST feedbacks [e.g., *Chang et al.*, 1997].

[10] Between 1980 and 2006 there was a northward shift in precipitation in the eastern tropical North Atlantic (Figure 1c). Rainfall increased significantly in the Sahel (10°–20°N, 15°W–20°E) and decreased in the Gulf of Guinea, consistent with the transition to a positive phase of the AMO [*Knight et al.*, 2006]. There is also a northward shift in precipitation in the western tropical North Atlantic. The region of positive rainfall trends is situated near 25°N, however, ~15° north of the mean position of the ITCZ, suggesting that the northward shift in rainfall cannot be interpreted simply as a meridional shift in the ITCZ. Instead, a significant negative trend in surface atmospheric pressure centered near 20°N, 50°W likely contributed to the positive trend in rainfall. The northward shift in precipitation throughout the tropical North Atlantic and Sahel is consistent with a global widening of the tropical belt since 1980 [e.g., *Seidel et al.*, 2008].

[11] The region of positive rainfall trends in the Sahel coincides with an area of significant negative trends in AOD (Figure 1d). There is also a significant decrease in AOD over the tropical North Atlantic Ocean downwind from the Sahara and Sahel. The negative trends in AOD over the tropical North Atlantic Ocean are consistent with the analysis of *Evan et al.* [2006], which is based on a different satellite dust data set. Positive trends in AOD over southwestern Africa and Brazil are likely associated with changes in smoke and soot from biomass burning [e.g., *Chatfield et al.*, 1998].

[12] The presence of significant negative trends in AOD over nearly all of western Africa and the tropical North Atlantic Ocean implies that there was a significant decrease in dust production. One might also expect decreased dust transport to play a role over the ocean, but easterly winds in the middle troposphere strengthened throughout most of the Sahel and the tropical North Atlantic, which would tend to enhance the westward transport of dust (Figure 1d). In addition, trends in surface wind velocity are significant only in the 5°N–15°N latitude band, which is located to the south of the strongest negative trends in AOD (Figure 1). It is therefore unlikely that the decrease in AOD over the tropical North Atlantic Ocean during 1980–2006 can be explained by trends in winds. The most likely explanation for the widespread decrease in dust in the tropical North Atlantic is the significant increase in rainfall over the Sahel, consistent with the anticorrelation of rainfall and dust on interannual time scales found by *Prospero and Lamb* [2003].

[13] Enhanced rainfall in the Sahel and reduced dust in the tropical North Atlantic are consistent with the observed warming trend in tropical North Atlantic SST (Figure 2). Previous studies have shown that warmer than normal SST in the tropical North Atlantic is associated with an increase in Sahel rainfall [e.g., *Giannini et al.*, 2003]. Enhanced rainfall in turn is associated with a decrease in the amount of dust exported from western Africa over the tropical North Atlantic Ocean [*Brooks and Legrand*, 2000; *Prospero and Lamb*, 2003]. It is therefore likely that the warming trend in tropical North Atlantic SST during 1980–2006 contributed to both the increase in Sahel rainfall and the decrease in dust.

[14] The existence of a significant negative trend in AOD in the tropical North Atlantic also suggests that dust may have contributed to the observed warming trend (Figure 2). To quantify the impact of dust on the underlying SST we first consider the effect of dust on downward surface shortwave radiation (SWR) and net longwave radiation (LWR). We calculate trends in SWR and LWR associated with trends in AOD using the dust forcing efficiencies of *Zhu et al.* [2007], which are based on multiple satellite data sets and a radiative transfer model. *Zhu et al.* [2007] found clear-sky forcing efficiencies of -70 W m^{-2} per AOD for SWR and 25 W m^{-2} per AOD for LWR during the high-dust season (JJA). The *Zhu et al.* [2007] clear-sky forcing efficiencies are scaled by the monthly climatological clear-sky fraction in order to obtain all-sky forcing efficiencies. These estimates represent a lower bound on dust radiative forcing since in reality the SWR and LWR forcing efficiencies are likely >0 when clouds are present, and it is possible that dust is misclassified as low clouds in the ISCCP data set. From the all-sky forcing efficiencies and satellite-based trends in AOD, we estimate trends in dust-induced SWR (LWR) averaged over the tropical North Atlantic Ocean (5–25°N, 15–60°W) of 3.4 W m^{-2} (-1.3 W m^{-2}) for the months JJAS and 1.2 W m^{-2} (-0.5 W m^{-2}) for all months. The combination of positive trends in SWR (i.e., tending to heat the ocean) and weaker negative trends in LWR results in net positive trends in dust-induced surface radiative

forcing of 2.1 W m^{-2} for JJAS and 0.7 W m^{-2} for all months.

[15] To convert dust-induced SWR and LWR trends to potential changes in SST we use the following expression: $\Delta SST = \Delta t/(\rho c_p) \sum_{i=1}^{324} F_i/h_i$, where ΔSST is the difference in SST between January 1980 and December 2006; F is the monthly dust-induced radiative heat flux (SWR or LWR) with respect to its value in January 1980; h is climatological monthly mean MLD, repeated for each year; and Δt is one month. Here we use data from all months during January 1980–December 2006 so that the summation is over 324 months. We account for penetrative SWR using climatological MLD and SeaWiFS chlorophyll-a concentration, following *Morel and Antoine* [1994]. Based on this simple one-dimensional heat balance, trends in dust-induced SWR (LWR) between 1980 and 2006, if unbalanced by any other processes, would have increased (decreased) the underlying SST by 5°C (2°C), resulting in a net warming of 3°C. Results are not significantly changed if penetrative SWR is ignored.

[16] Between 1980 and 2006 tropical North Atlantic SST increased 0.6°C, several times smaller than the SST trend due to dust-induced radiative heat fluxes would have suggested. Therefore, a significant portion of the anomalous dust-induced net radiative heating must have been balanced by a combination of latent and sensible heat fluxes, mixing at the base of the mixed layer, and northward transport in the upper branch of the meridional overturning circulation. The relative importance of these processes in relation to dust-induced radiative forcing requires a quantitative assessment of the upper ocean temperature balance, which is beyond the scope of this study. However, our results indicate that the potential effects of natural variations in Saharan dust on SST need to be considered in any decadal time scale assessment of tropical North Atlantic SSTs.

4. Summary and Discussion

[17] This study investigates linear trends in the tropical Atlantic sector during 1980–2006. Consistent with previous studies, we found that this period was characterized by a significant increase in tropical North Atlantic SST, a transition from a negative to a positive phase of the Atlantic multidecadal oscillation, and a significant increase in Sahel rainfall. Associated with the positive trend in Sahel rainfall, we also found a pronounced decrease in dustiness across western Africa and the tropical North Atlantic Ocean.

[18] Reduced dust loading in the tropical North Atlantic tended to increase the amount of solar radiation penetrating to the surface of the ocean and to increase the ocean's net emission of longwave radiation, resulting in a net positive trend in dust-induced surface radiative forcing of 0.7 W m^{-2} averaged over the tropical North Atlantic Ocean. The increase in radiative forcing due to dust in the tropical North Atlantic is of the same order as the globally-averaged anthropogenic-induced radiative heating of 1.6 [−1.0, +0.8] W m^{-2} and is similar in magnitude to the globally-averaged direct radiative forcing due to anthropogenic aerosols of −0.4 [−0.6, +0.2] W m^{-2} [*Forster et al.*, 2007]. Future decreases in anthropogenic aerosols in the Northern Hemisphere are expected to contribute to continued increases in tropical North Atlantic SST, leading to more frequent and severe drought in the Amazon [*Cox et al.*, 2008]. The results of this study suggest that natural aerosols such as dust also need to be considered in assessments of past and future climate change in the tropical Atlantic sector.

[19] The observed relationships between SST, dust, and rainfall during 1980–2006 may have important implications for numerical models simulating North Atlantic climate on multidecadal time scales. Recent studies suggest that coupled models tend to underestimate the amplitude of tropical North Atlantic SST variations associated with the AMO [e.g., *Delworth and Mann*, 2000; *Knight et al.*, 2005]. The inclusion of dust in the atmospheric component of these models may therefore lead to improved modeling and prediction of the AMO. Changes in dust concentration in the tropical North Atlantic may also influence the timing and intensity of the Atlantic meridional SST gradient mode, which affects rainfall in Brazil and the Sahel and tropical cyclone activity in the Atlantic basin [e.g., *Kossin and Vimont*, 2007].

[20] **Acknowledgments.** We are grateful to the NASA/GSFC TOMS group for providing AOD data. We thank two anonymous reviewers for their helpful suggestions. PMEL contribution 3236. JISAO contribution 1593.

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