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Observational evidence of African desert dust intensification of easterly waves

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[1] This paper presents indirect observational evidence that desert dust can modulate the amplitude of easterly waves in the Atlantic Ocean. Twenty two years of NCEP/NCAR reanalysis and dust from a global transport model are used to characterize the evolution of enhanced easterly waves. Lag composites of analysis increments (analysis minus first–guess) of geopotential height (700–hPa) anomalies indicate larger amplitudes in the analysis than in the first-guess fields. The results indicate that the temperature structure in the lower troposphere associated with easterly waves is warmer in the analysis than in first–guess fields by about 0.25 K per day. We hypothesize that the differences in the amplitudes are due to radiative effects associated with African dust, which have been incorporated in the reanalysis by data assimilation but absent in the model first–guess. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1610 Global Change: Atmosphere (0315, 0325); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Jones, C., N. Mahowald, and C. Luo (2004), Observational evidence of African desert dust intensification of easterly waves, *Geophys. Res. Lett.*, *31*, L17208, doi:10.1029/2004GL020107.

1. Introduction

[2] It has been widely recognized that mineral aerosols are an important component of Earth's climate through interaction with radiative [e.g., *Miller and Tegen*, 1998], biogeochemical [e.g., *Swap et al.*, 1992] and photochemical [e.g., *Dentener et al.*, 1996] processes. Although some substantial progress has been made, the sources, spatial and temporal distributions, radiative forcing and biogeochemical impacts are still not well understood [*Prospero and Nees*, 1986; *Alpert et al.*, 1998; *Mahowald et al.*, 2002, 2003; *Mahowald and Luo*, 2003].

[3] Desert dust from North Africa is an important source of mineral dust to the atmosphere. *Alpert et al.* [1998] examined satellite-derived dust events and the differences between NASA GEOS-1 reanalysis and first-guess fields (incremental analysis update–IAU). They found that the spatial patterns of monthly mean IAU closely resemble the spatial patterns of dust in the eastern tropical Atlantic. They were able to statistically estimate that, for an average event, African dust plumes have a heating effect in the lower troposphere (1.5 to 3.5 km) of ~0.2 K per day.

[4] African easterly waves (AEW) are frequent in the tropical Atlantic Ocean and western Africa during boreal summer [*Norquist et al.*, 1977; *Diedhiou et al.*, 1999] and are important in modulating the variability of desert dust [e.g., *Westphal et al.*, 1987; *Karyampudi et al.*, 1999]. *Jones et al.* [2003] investigated the relationships between easterly wave activity and model simulations of desert dust entrainment and transport. Their results indicate that ~20% of dust entrainment into the atmosphere over a broad region of North Africa is associated with easterly wave activity, suggesting that easterly waves may regulate desert dust entrainment into the atmosphere. Likewise, about 10% to 20% of the seasonal variability of desert dust concentrations across the North Atlantic is related to easterly waves, which indicates that easterly waves modulate the transport of dust. The objective of this paper is to show indirect observational evidence that mineral dust can modulate the intensity of easterly waves formed in western Africa and tropical Atlantic Ocean.

2. Data and Dust Transport Model Experiments

[5] We use NCEP/NCAR reanalysis and model first–guess fields at 6–hourly intervals (00Z, 06Z, 12Z and 18Z) from 1 June to 30 September 1979–2000 [*Kalnay et al.*, 1996; *Kistler et al.*, 2001]. The difference between analysis and model first–guess is called analysis increments (AI) and provide a quantitative measure of the quality of the reanalysis over regions with large number of observations [*Kistler et al.*, 2001]. We note that the NCEP/NCAR reanalysis model does not include appropriate parameterizations to account for the radiative and microphysical effects of mineral dust. Our hypothesis is that large values of AI in regions with high dust concentrations can provide important signatures of dust in the easterly waves development. A similar assumption was used by *Alpert et al.* [1998] using NASA GEOS-1 to estimate the mean heating rates associated with African dust.

[6] The following analysis and first–guess fields were analyzed: vertical component of relative vorticity (700–hPa), geopotential height (700–hPa) and temperature (1000, 925, 850 and 700–hPa). To focus on the time scale of easterly waves, a Murakami band-pass recursive filter with cut-off periods of 2.5 and 10 days [*Jones et al.*, 2003] was applied (hereafter called anomalies). AI's were computed as the difference analysis minus first–guess.

[7] Dust variability is investigated with a 22–year simulation (1979–2000) of dust transport with the model described in *Luo et al.* [2003], *Mahowald et al.* [2002, 2003], and *Zender et al.* [2003]. The transport model is the

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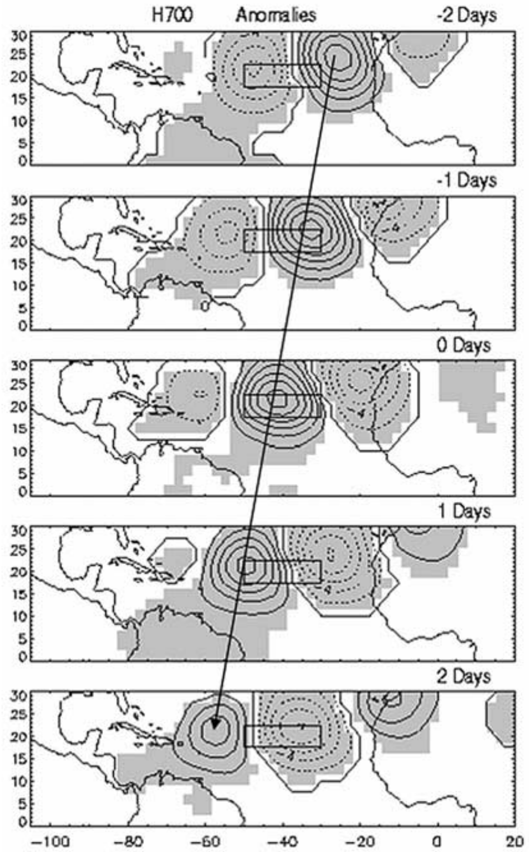

Figure 1. Lag composites of geopotential height (700–hPa) anomalies (12Z). Solid (dashed) contours indicate positive (negative) anomalies (interval: 2 m). Box in the Atlantic Ocean indicate reference region to define periods of enhanced easterly wave activity. Shaded regions indicate anomalies statistically significant at 95% level. Large arrow across panels connects centers of positive anomalies.

Model of Atmospheric Transport and Chemistry [*Rasch et al.*, 1997] driven by meteorological fields from the NCEP/NCAR reanalysis. For the desert dust modeling, we use NCEP/NCAR reanalysis at T62 resolution ($\sim$1.8 $\times$ 1.8 degrees), using 28 sigma levels available every 6 hours [see *Luo et al.*, 2003; *Mahowald et al.*, 2002, 2003]. Daily averaged surface dust concentrations generated by the model during June, July, August and September are used. To remove the seasonal cycle, a daily climatology was first computed by averaging the 22 years at each day from 1 June to 30 September and smoothing 50 times with a 1-2–1 filter. The smoothing is necessary to remove noise due to interannual variations. The daily climatology was subtracted from the surface dust time series to produce surface dust anomalies (DUSTA).

3. Easterly Waves and African Desert Dust

[8] To identify periods of enhanced AEW activity, we define an index based on the anomalies of relative vorticity at 700–hPa (VORA) spatially averaged in a reference region bounded by (22.5°N–17.5°N) and (50°W–30°W). This region exhibits VORA standard deviations exceeding 0.5×10^{-5} s^{-1} (not shown) and is observed on the northern side of the climatological position of the African easterly jet [*Jones et al.*, 2003]. The reference region is used as the key location (Figure 1) for a composite analysis to investigate the possible influence of desert dust on AEW amplification. We selected days in which the values of VORA in the key region were below minus one standard deviation as cases of strong AEW occurrences. This sample had 411 days (273 independent events). The results are insensitive to reasonable choices of size and location of the reference region as well as thresholds of VORA.

[9] Figure 1 shows lag composites obtained by averaging geopotential height at 700–hPa (H700) anomalies at 12Z. The lag composites were computed by introducing time lags in the dates of high AEW activity. Local *t-tests* at 95% level were calculated to indicate regions of statistically significant anomalies (shading). At lag = −2 days, a region of positive H700 anomalies is observed off the coast of Western Sahara and Morocco, whereas large negative H700 anomalies are found near the key region and in north Africa. In subsequent time lags, the positive H700 anomalies propagate westward following a latitudinal track between 20°N and 25°N. The region of positive H700 anomalies takes $\sim$6 days to travel from the western coast of North Africa to the West Indies. Note that as the center of positive H700 anomalies propagates westward, a new center develops off the coast of Western Sahara demonstrating the high frequency of AEW.

[10] Lag composites of DUSTA anomalies were computed on the same dates of intense AEW activity (Figure 2). At lag = −2 days, positive DUSTA are observed on the eastern half of the reference region with maximum values exceeding 10 μg kg^{-1}. Two regions of negative DUSTA straddle the positive anomalies. The region of positive DUSTA anomalies propagate westward following a similar latitudinal path of H700 positive anomalies. An interesting aspect to observe is the 1 to 2 days phase lag between DUSTA and H700 anomalies. From lag = −2 days to lag = +1 day, positive DUSTA anomalies are observed on the western side of the ridge of H700 anomalies. As the easterly waves start to decay after lag = +1 day, positive anomalies of DUSTA are roughly in phase with positive H700 anomalies (see Figures 1 and 2).

[11] To investigate a possible signature of African dust plumes on easterly wave, we computed AI of anomalies of H700 and temperature at 1000, 925, 850 and 700–hPa. The computation was performed at 00Z, 06Z, 12Z and 18Z. Our analysis revealed the AI to be, in general, rather small in the Atlantic Ocean (70°W–30°W and 10°N–30°N) and large near Africa, the Americas and Caribbean especially at 00Z, 06Z and 18Z (not shown). This is somewhat expected, since the analysis tends to be close to the model first–guess in data sparse regions [*Kistler et al.*, 2001]. To summarize the presentation, we discuss only the AI–12Z results, since this time showed the largest signal related to AEW. Figure 3 shows lag composites of AI–12Z of H700 anomalies on the same dates of enhanced AEW activity discussed previously. Anomalies statistically significant at 95% are shaded. To emphasize the possible radiative effect of dust on easterly waves development, the composites begin at lag = −3 days, when a broad region of positive anomalies of AI in H700 is observed over the Western Sahara and Mauritania. At lag = −2 days, the positive region of AI–12Z of H700 anomalies enlarges and moves over the western coast of Africa. The

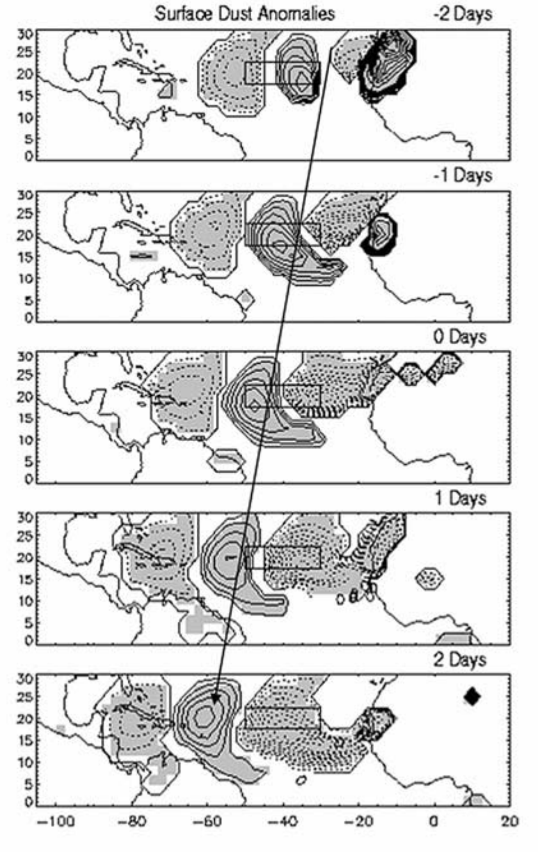

Figure 2. Same as in Figure 1, but for lag composites of daily surface dust anomalies. Solid (dashed) contours indicate positive (negative) anomalies (interval: 2 μg kg^{-1}). Shaded regions indicate anomalies statistically significant at 95% level.

westward propagation is still clear at lag = −1 day. The signal in subsequent lags (not shown) is less clear and likely result from less data being assimilated in the analysis in the Atlantic Ocean. Lag correlations between H700 from analysis and first−guess fields were also computed and no phase lags were detected. The consistent signal in AI−12Z of H700 anomalies shows that the amplitudes of easterly waves in the analysis are larger than the amplitudes represented in the first-guess fields. We argue that the differences in the amplitudes may be due to radiative effects associated with African dust, which have been incorporated in the reanalysis but absent in the model first−guess.

[12] Lag composites of the difference between temperature anomalies from analysis and first−guess fields at several pressure levels were computed on the dates of enhanced AEW activity. The spatial patterns and statistical significance follow very closely the AI−12Z H700 anomalies discussed in Figure 3 (not shown). To summarize the results, Figure 4 displays two vertical profiles of AI−12Z of temperature anomalies from 1000−hPa to 700−hPa. The first profile (solid line) shows AI−12Z averaged in the region (17.5°N−22.5°N, 5°W−12.5°W) and lag = −3 days. This location coincides with the development phase of easterly waves over Mauritania and Western Sahara (see Figure 3). The second vertical profile (dashed line) shows AI−12Z of temperature anomalies at lag = −2 days averaged just off the western coast of Africa (15°N−20°N, 20°W−27.5°W). Both AI−12Z vertical profiles, which were averaged in regions of statistically significant temperature anomaly differences, demonstrate that the analysis is warmer than the first−guess field. Both profiles suggest maximum temperature anomaly differences at 850−hPa of ∼0.0625 K per 6 hours analysis increment (0.25 K per day). The maximum temperature AI difference at 850−hPa is somewhat in agreement with the vertical profile of dust, which is maximum at the top of the boundary layer [*Luo et al.*, 2003]. Note that this value of maximum temperature anomaly difference during enhanced AEW periods is consistent with the value reported by *Alpert et al.* [1998] (∼0.2 K per day). The impact of desert dust on easterly waves is not statistically significant after day −1, for reasons which are not clear.

4. Summary and Conclusions

[13] Mineral aerosols are an important component of Earth's climate system and it is important to further understand the associated feedbacks that can have significant impacts on regional to global scales [*IPCC*, 2001]. North Africa is among the major sources of aerosols to the atmosphere and desert dust is transported over large distances. Likewise, African easterly waves are important atmospheric circulations and their role in transporting dust has been widely recognized [e.g., *Westphal et al.*, 1987; *Jones et al.*, 2003]. Thus, a noteworthy research topic that needs to be investigated is whether or not there are important feedback mechanisms involving desert dust that are critical to the characteristics of easterly waves. In this paper, we present indirect evidence of possible amplification of easterly waves.

[14] We developed a statistical analysis using 22 years of dust concentrations from a global transport model and differences between NCEP/NCAR analysis and model first−guess fields (i.e., analysis increments). Our hypothesis is that since the NCEP/NCAR reanalysis model does not include specific parameterizations to account for radiative and microphysical effects of mineral dust, large differences

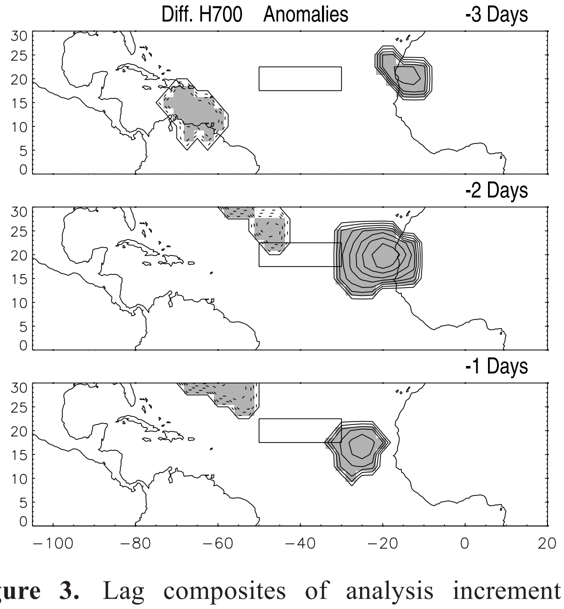

Figure 3. Lag composites of analysis increment of geopotential height (700−hPa) anomalies (12Z) (analysis minus first−guess). Solid (dashed) contours indicate positive (negative) anomalies (interval: 0.1 m per 6 hours).

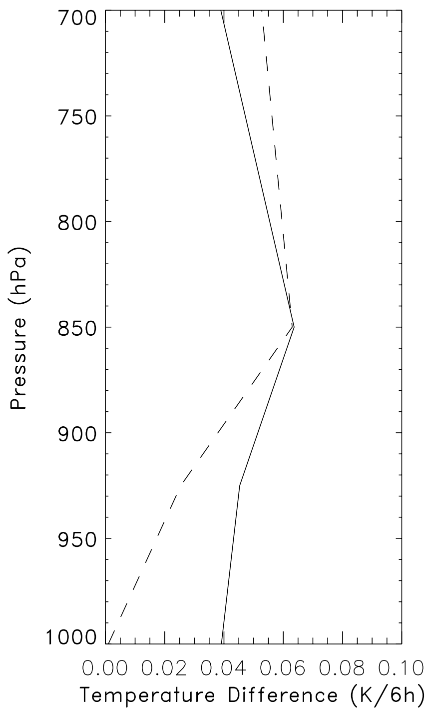

Figure 4. Vertical profile of analysis increment of temperature anomalies (12Z) (analysis minus first–guess). Solid line shows analysis increment in the region (17.5°N–22.5°N, 5°W–12.5°W) and lag = −3 days. Dashed line shows analysis increment in the region (15°N–20°N, 20°W–27.5°W) and lag = −2 days.

in analysis increments in data–rich regions near dust sources indicate possible signatures of the dust's modulation. Other model-deficiencies such as in the radiation, large scale moist processes, moist convection or boundary layer parameterization may also contribute to these errors, suggesting that in our results, we can only argue that they are consistent with the impact of dust on easterly waves, not that the impacts are definitely due to dust.

[15] The results of lag composites show the typical easterly waves formation over the west coast of Africa, intensification in the Atlantic Ocean and decaying in the Caribbean region. Likewise, large anomalies in surface dust concentrations are associated with the easterly waves propagation. During the development and mature stages, surface dust concentrations precede the maximum geopotential height anomalies (700–hPa) by about 1–2 days. Furthermore, analysis increments at 12Z of geopotential height (700–hPa) indicate statistically significant anomalies over Africa and the eastern Atlantic Ocean. The anomalies, which are coherent in space and time with the easterly waves propagation, indicate larger amplitudes in the analysis than in the first-guess fields. Results from general circulation models which include the radiative forcing of dust suggest that while there is a local impact of warming in the atmosphere where the dust is, there are also signals away from the dust region [e.g., *Miller and Tegen*, 1998]. One would expect the dust to not instantaneously heat up the atmosphere, but take some time to do so. That time appears to be about 1–2 days. Additional investigation of the difference between analysis and first–guess fields of temperature shows robust signals near Africa and eastern Atlantic Ocean. Vertical profiles of analysis increments show maximum positive temperature anomaly differences at 850–hPa of about 0.25 K per day, which implies that the temperature structure in the lower troposphere associated with the easterly waves is warmer in the analysis than in the first–guess fields. The results give observational support for a possible modulation of desert dust on the amplification of African easterly waves and motivate future observational and modeling studies.

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