GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L13814, doi:10.1029/2006GL026163, 2006

On the variability of African dust transport across the Atlantic

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Received 28 March 2006; revised 27 April 2006; accepted 30 May 2006; published 14 July 2006.

[1] We investigate the interannual variability of Saharan dust transport over the Atlantic by using the TOMS/Nimbus-7 and TOMS/Earth Probe daily aerosol data. We focus on the winter season, and on the area off the North-West African coast (15–30°N, 30–5°W). Previous studies have suggested that the variability of the Saharan dust can be partially explained by the North Atlantic Oscillation. In an alternative approach, we correlate the aerosol data with the positions and the surface pressure values of the two "Centers of Action" in the Atlantic, the Azores High and the Icelandic Low. This approach decouples the two semi-permanent pressure systems, and it reveals that the Icelandic Low does not play a role in the dust concentration for our region of interest. Instead, the position of the Azores High turns out to be the most important factor, with the Azores High latitude yielding the highest correlation (r = 0.48). **Citation:** Riemer, N., O. M. Doherty, and S. Hameed (2006), On the variability of African dust transport across the Atlantic, *Geophys. Res. Lett.*, *33*, L13814, doi:10.1029/2006GL026163.

1. Introduction

[2] The North African continent represents a dominant global source of mineral dust [*Prospero et al.*, 2002]. It has been known for a long time that large dust plumes are transported to the Atlantic Ocean and the Mediterranean Sea from the Saharan desert and surrounding regions [*Darwin*, 1846]. This export is subject to a strong interannual variability, which in turn is related to the large-scale circulation [*Mahowald et al.*, 2003]. Understanding this variability is key to quantifying the impact of mineral dust on the various processes in the climate system.

[3] Several recent studies using satellite data, in-situ measurements and global modeling suggest that the interannual variability can be explained to some extent by the North Atlantic Oscillation (NAO) [*Moulin et al.*, 1997; *Ginoux et al.*, 2004]. The NAO index [*Hurrell*, 1995] is based on the difference of the pressure anomalies between Stykkisholmur, Iceland (representing the Icelandic Low) and Lisbon, Portugal (representing the Azores High). This index, however, does not account for the positions of the semi-permanent pressure systems that it represents.

[4] Since the TOMS data retrieval algorithm has recently been updated (see http://toms.gsfc.nasa.gov/news/news.html) and a new data version is available (Version 8), we will first recalculate the correlation of NAO and the absorbing aerosol index (AAI) for the updated data set, which covers the years from 1979 – 1993 (TOMS/Nimbus-7) and 1997 – 2004 (TOMS/Earth Probe).

[5] In a second step we will apply a new approach to shed light on the variability and the underlying mechanisms of dust transport over the Atlantic Ocean. We consider the 23 years of TOMS satellite data in conjunction with the positions and the surface pressure values of the two "Centers of Action" (COA) in the Atlantic [*Rossby*, 1939], that is, the Icelandic Low and the Azores High. This concept has been successfully applied to a range of problems such as explaining the variations of zooplankton in the Gulf of Maine [*Piontkovski and Hameed*, 2002] and the position of the Gulf stream northwall [*Hameed and Piontkovski*, 2004]. With this approach we are able to explain the variability of dust transport to a higher degree and on a more fundamental level than it is possible with the NAO index.

2. Method

[6] Previous studies have demonstrated that TOMS satellite data clearly shows the occurrence of large dust events over the continents and the subsequent dust transport over the ocean [*Herman et al.*, 1997; *Chiapello and Moulin*, 2002].

[7] TOMS provides the Aerosol Index (AI) as a semi-quantitative measure for the atmospheric aerosol load [*Herman et al.*, 1997; *Torres et al.*, 1998]. For the Version 8 data this quantity is defined as

$$\mathrm{AI} = -100 \log_{10} \left[(I_{331}/I_{360})_{\mathrm{meas}} - (I_{331}/I_{360})_{\mathrm{calc}} \right], \qquad (1)$$

where I_{meas} is the measured backscattered radiance at a given wavelength and I_{calc} is the radiance calculated at that wavelength assuming a purely gaseous atmosphere. In Version 7 UV-absorbing aerosols such as dust and smoke resulted in a positive AI, whereas nonabsorbing aerosols yielded negative AI values. In Version 8 only positive values are made available. To be consistent with earlier studies, we will refer to this positive or absorbing AI as "AAI".

[8] The distinction between different types of UV absorbing aerosol requires additional assumptions, such as the choice of a certain domain where only one type dominates. Another known shortcoming of the TOMS aerosol index is its dependence on the height of the aerosol layer [*Torres et al.*, 2002; *Hsu et al.*, 1999]. For a certain total column aerosol concentration, the AAI will be larger if the aerosols are located higher in the atmosphere compared to the same amount of aerosol at a lower altitude.

[9] To compare our results with previous studies in the literature [*Chiapello and Moulin*, 2002; *Chiapello et al.*, 2005] we focus on the same region over the eastern part of the northern tropical Atlantic (15–30°N, 30–5°W). Although the aerosol in this region is thought to be mainly

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0094-8276/06/2006GL026163$05.00

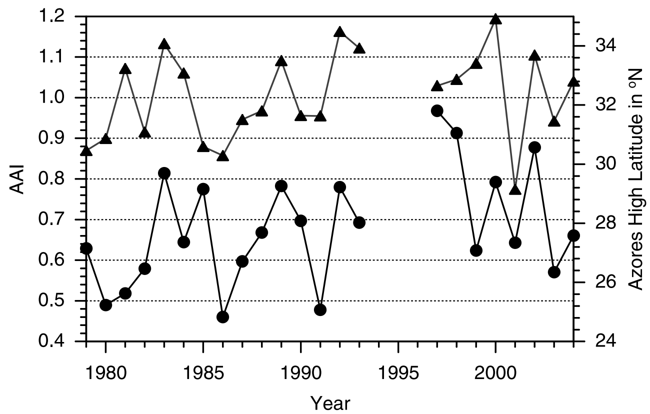

Figure 1. Comparison of the position of the Azores High latitude (triangles) and the AAI (filled circles) from 1979 to 1993 (Nimbus-7 data) and 1997 to 2004 (Earth Probe data). Both time series are averaged over the winter months (December – March), the AAI values are also spatially averaged over the area of 5–30°W, 15–30°N.

composed of mineral dust from the Sahara [*Herman et al.*, 1997; *Chiapello and Moulin*, 2002; *Chiapello et al.*, 2005], it is possible that there is some mixing of biomass aerosol loading in the region contributing an additional variation to the dust signal being studied, as shown, for example by *Husar et al.* [1997].

[10] Our analysis is performed in two steps. First, for comparison with earlier studies, we calculate the correlation of the NAO index and the average AAI for the area defined above and the time from 1979 – 2004 using the recently updated version (Version 8) of the TOMS AAI data.

[11] Second, we consider the variations of pressure and locations of Azores High and Icelandic Low separately using objectively defined indices as described by *Hameed and Piontkovski* [2004]. This procedure results in six parameters: Surface pressure, latitude and longitude for both the Icelandic Low and the Azores High. They are derived from gridded NCEP sea level pressure data [*Kalnay et al.*, 1996] in the following way. The pressure index I_p is defined as an area-weighted pressure departure from a threshold value over the domain (I, J):

$$I_p = \frac{\sum_{i,j=1}^{I,J} \left(P_{i,j} - P_t\right) \cos\phi_{i,j}(-1)^M \delta_{i,j}}{\sum_{i,j=1}^{I,J} \cos\phi_{i,j}\delta_{i,j}}, \tag{2}$$

where $P_{i,j}$ is the sea level pressure value at a grid point (i, j), P_t is the threshold sea level pressure value (P_t = 1014 hPa). $\phi_{i,j}$ is the latitude of grid point (i, j). $M = 0$ for the Azores High and 1 for the Icelandic Low. $\delta = 1$ if $(-1)^M(P_{i,j} - P_t) > 0$ and $\delta = 0$ if $(-1)^M(P_{i,j} - P_t) < 0$. The latitudinal index I_ϕ is defined as:

$$I_\phi = \frac{\sum_{i,j=1}^{I,J} \left(P_{i,j} - P_t\right)\phi_{i,j} \cos\phi_{i,j}(-1)^M \delta_{i,j}}{\sum_{i,j=1}^{I,J} \left(P_{i,j} - P_t\right) \cos\phi_{i,j}(-1)^M \delta_{i,j}}. \tag{3}$$

The longitudinal index I_λ is defined analogously. To denote the indices of a particular COA, we will add a second subscript (AH for Azores High, and IL for Icelandic Low). The domains that are covered by these indices are (40°N–75°N, 90°W–20°E) for the Icelandic Low and (20°N–50°N, 70°W–10°E) for the Azores High. We correlate each of the indices separately with the AAI to gain insight in the individual relationships of AAI and the Centers of Action.

3. Results

[12] Figure 1 illustrates the time series of the spatially averaged AAI over the course of the investigated time period. It confirms that the averaged AAI is highly variable from winter to winter with a minimum value of 0.46 in 1986 and a maximum of 0.97 in 1997. *Massie et al.*, 2004 show that the eruptions by El Chicon and Mount Pinatubo produce notable AAI signals in the Southern Hemisphere, but not for our study region; so volcanic corrections are not needed for 1982 and 1991.

[13] Table 1 summarizes our results for the correlation coefficients of AAI and the six COA parameters as well as AAI and the NAO index. The correlation of AAI and NAO is only r = 0.21 for winter if we consider the whole time series, and r = 0.45 if we only consider the years from 1979 to 1993. This means that by combining the TOMS/Nimbus-7 data set with the TOMS/Earth Probe, the correlation of AAI and NAO decreases. A similar result has been found by *Chiapello et al.* [2005].

[14] The correlation of the COA indices and the AAI reveals that the pressure values of both the Azores High and the Icelandic Low do not show significant correlations with the AAI. The positions of the pressure centers appear to be more important, where the Icelandic Low as a whole plays a secondary role. This is in agreement to findings of *Chiapello et al.* [1995] who suggested that the Azores High is important for the concentration of dust at Sal, Cape Verde Island.

[15] For our region of interest, the Azores High plays the dominant role, in particular the latitude of the Azores High with a correlation coefficient of r = 0.51 (1979–1993) and r = 0.48 (1979–2004), respectively. We note that only the correlations with the Azores High latitude are significant for both periods. To give a visual impression of this correlation, Figure 1 shows, in addition to the AAI values, the time series of the Azores High latitude over the course of the investigated time period. Figure 2 displays a map of the spatially varying correlation coefficient of AAI

Table 1. Correlation coefficients of the AAI with the NAO and the six indices for the Centers of Action[a]

	Winter 1979–2004	Winter 1979–1993
TOMS AAI - NAO	0.21	0.45
TOMS AAI - $I_{\lambda,\mathrm{AH}}$	0.32	0.41
TOMS AAI - $I_{\phi,\mathrm{AH}}$	0.48[b]	0.51[b]
TOMS AAI - $I_{p,\mathrm{AH}}$	0.18	0.40
TOMS AAI - $I_{\lambda,\mathrm{IL}}$	0.31	0.35
TOMS AAI - $I_{\phi,\mathrm{IL}}$	0.31	0.42
TOMS AAI - $I_{p,\mathrm{IL}}$	−0.14	−0.37
AVHRR AOT - NAO	0.37	0.46

[a]Winter averages include the months December to March. The AAI is also averaged over the area 15–30°N, 30–5°W. $I_{\lambda,\mathrm{AH}}$ is the longitude position of the Azores High. Please note that the time series for AVHRR AOT starts in 1982.

[b]Theses values are statistically significant on a 5% level.

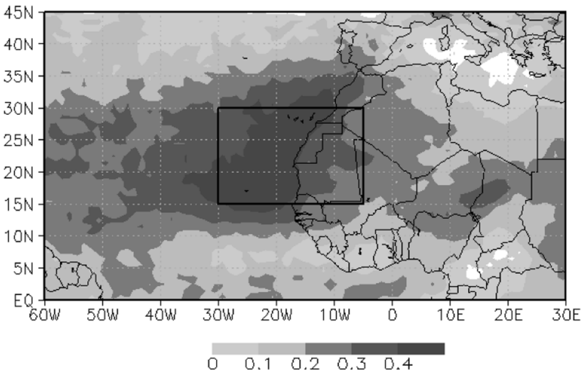

Figure 2. Spatial distribution of the correlation coefficient of the winter AAI and the Azores High latitude, averaged over the years 1979–2004.

and Azores High latitude averaged over all winters. Figure 2 shows that the maximal correlations with values over $r = 0.5$ occurs within our area of interest.

[16] We are aware that a drift in AAI data might affect the correlations after the year 2000 (see http://jwocky.gsfc.nasa.gov/aerosols/aerosols.html). To investigate this drift we calculate correlations only up to the year 2000. The correlations change slightly, and are r = 0.20 for AAI and NAO, and r = 0.48 for AAI and Azores High latitude. We then fit a linear trend to AAI for 2000–2004. Assuming that this trend is due to drifting calibration, we correct the AAI for this trend. The correlations for the corrected AAI (1979–2004) are r = 0.44 with Azores High latitude (significant at 5%) and r = 0.07 with NAO. We can conclude that the apparent instrument drift over the last 4 years does not affect the conclusion that AAI in this region is correlated primarily with the Azores High latitude and not with the NAO.

[17] To summarize, we find that while *Chiapello and Moulin* [2002] obtained an AAI-NAO correlation coefficient of r_{V7} = 0.67 for 1979 to 1993, our AAI-NAO correlation coefficient of r_{V8} = 0.45 for the same time period is obviously different. To explain this difference, two factors have to be considered.

[18] First, detailed analysis has shown that while Version 7 and Version 8 data can be roughly related by an affine mapping, there is scatter in the relationship, and moreover, the relationship varies from year to year. This scatter causes differences in seasonal and spatial averages from year to year. It seems that the correlation coefficient is sensitive to these changes.

[19] Another perspective on comparing the correlations is that there is statistical uncertainty in the correlation coefficient due to the limited length of the time series. For the result by *Chiapello and Moulin* [2002] of r_{V7} = 0.67, the 95% confidence interval is (0.23–0.88). For V8 for the same period 1979–1993 we obtain r_{V8} = 0.45, and the range (−0.08–0.78). Hence the two correlation coefficients, although different in their expectation values, have a large overlap in their 95% confidence intervals.

[20] To corroborate our result we carried out the same analysis for aerosol optical depth (AOT) measured by AVHRR which is available over the ocean only and for 1981 to 2004. These results are also displayed in Table 1. For the winter seasons of 1982–1993, the correlation coefficient of AVHRR-AOT and NAO is 0.46, and it decreases as the time period is extended to 2004 to 0.37.

[21] For the winter months of 1979 until 2004, the Azores High latitude varies between 29°N and 35°N. The position of the Azores High affects both the transport and the precipitation patterns in North Africa which in turn affect the dust concentration. To illustrate this, we show in Figure 3 the NCEP reanalysis composite maps of winter AAI, 1000 hPa wind anomalies and Palmer Drought Index. The data for Figure 3 was provided by the Climate Diagnostics Center, Boulder Colorado from their Web site at http://www.cdc.noaa.gov/.

[22] We averaged over the 5 years when the Azores High latitude was lowest (1980, 1982, 1985, 1986, 2001) and when it was highest (1983, 1992, 1993, 2000, 2002). According to our correlation, a low Azores High latitude corresponds to lower AAI and vice versa. The map of wind anomalies and the Palmer Drought Index are consistent with this finding. Figure 3a shows the difference field of the averaged wind anomalies and the corresponding AAI for the 5 years when the Azores High latitude was highest and for the 5 years when the Azores High latitude was lowest, and Figure 3b shows the difference of the average Palmer drought index for the two 5-year data sets.

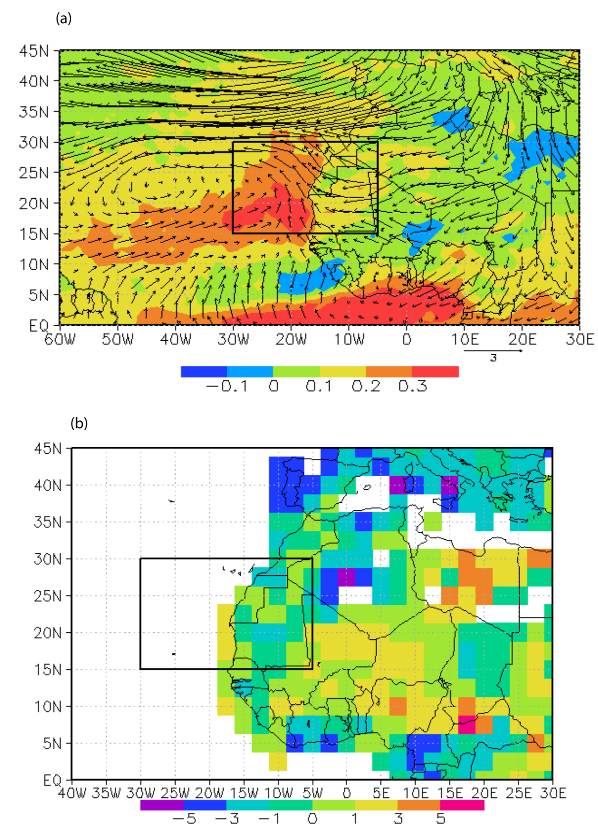

Figure 3. (a) Difference fields of AAI and wind anomalies; Average of the 5 years with highest Azores High latitude minus average of the 5 years with lowest Azores High latitude. (b) Difference of Palmer drought index: Average over the 5 years with highest Azores High latitude minus average over the 5 years with lowest Azores High latitude.

[23] In conjunction with low Azores High latitudes, hence low AAI, we find wind anomalies with small magnitudes over North Africa and a component toward East. The opposite applies for the years with high Azores High latitudes. In this case the wind anomalies have easterly components, and the magnitudes are larger. The resulting difference vector between high and low phase is directed westward which favors the export of dust and results in positive differences of the AAI values in our region of interest.

[24] Additional information is supplied by the average Palmer Drought index. Particularly in the central part of North Africa, it is higher for the years with high Azores High latitude. This corresponds to drier conditions, which suggests that the emission of dust is favored and is contributing to the positive differences in Figure 3a.

[25] Figure 3a also reveals that over large parts of the source regions in the Saharan desert, the differences in AAI are close to zero. Positive differences, hence more dust in the high phase, occur in the region over Mauretania, Morocco and parts of Algeria, as well as in the Sahel zone. Some source areas (Tunesia, Libya/Egypt) display negative differences.

[26] While *Prospero et al.* [2002] identified these areas as important source regions, it is difficult to draw conclusions concerning the activity of the sources in the high and low phase because the differences in dust load can be due to changes in transport and/or due to changes in source strength.

4. Conclusions

[27] Our results show that explaining the variability of dust transport over the eastern part of the northern tropical Atlantic using Center of Actions is more appropriate than using the NAO index, since the position of the semi-permanent pressure systems is a key factor. For the chosen region, the Azores High plays the dominant role. The latitudinal position of the Azores High is the parameter that displays the highest correlation with the spatially averaged AAI. The Icelandic Low plays a subordinate role.

[28] We emphasize that this result depends heavily on the choice of the target area. For other regions of the Atlantic Ocean a different COA parameter may gain in importance.

[29] **Acknowledgment.** We thank Omar Torres for his help in obtaining and analyzing TOMS data.

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