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Isabelle Chiapello, Cyril Moulin, Joseph M; Prospero. Understanding the long-term variability of African dust transport across the Atlantic as recorded in both Barbados surface concentrations and large-scale Total Ozone Mapping Spectrometer (TOMS) optical thickness. *Journal of Geophysical Research*, 2005, 110 (D18), 10.1029/2004JD005132 . hal-03132736

HAL Id: hal-03132736

<https://hal.science/hal-03132736>

Submitted on 5 Feb 2021

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Understanding the long-term variability of African dust transport across the Atlantic as recorded in both Barbados surface concentrations and large-scale Total Ozone Mapping Spectrometer (TOMS) optical thickness

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Received 16 June 2004; revised 15 September 2004; accepted 17 November 2004; published 30 April 2005.

[1] The interannual variability of African dust transport over the north tropical Atlantic is monitored using in situ surface concentrations measurements performed at Barbados since 1966, along with the Total Ozone Mapping Spectrometer (TOMS) and Meteosat dust optical thickness (DOT) records covering the last two decades. Despite their differences in spatial coverage, the two dust records are in good agreement at both monthly and annual timescales over the 22 years of common operation. This demonstrates that the Barbados dust record is representative of the year-to-year variability of dust export over the north tropical Atlantic during both winter and summer. The satellite DOT are used to assess the characteristics of the impact of climate factors, i.e., North Atlantic Oscillation (NAO) and Sahel drought, on dust emission and export as a function of season, and in terms of spatial extend of their influence. The analysis shows a large regional impact of Sahel drought on dust emissions and transport both in winter and in summer, whereas the influence of the NAO dominates the winter export and is more geographically limited to the eastern Atlantic north of 15°N, and possibly some localized source regions (southern Mauritania and the Bodele depression). Overall, the combination of the 35 years of Barbados measurements of African dust with 22 years of satellite dust survey over the Atlantic highlights very high dust loads in the mid-1980s related to the severe Sahel drought (maximum impact in 1983) and persistently high dusty conditions in the 1990s, most probably due to the continuation of relatively dry conditions in Sahel in the recent years.

Citation: Chiapello, I., C. Moulin, and J. M. Prospero (2005), Understanding the long-term variability of African dust transport across the Atlantic as recorded in both Barbados surface concentrations and large-scale Total Ozone Mapping Spectrometer (TOMS) optical thickness, *J. Geophys. Res.*, 110, D18S10, doi:10.1029/2004JD005132.

1. Introduction

[2] Mineral dust, emitted by wind erosion of arid and semiarid areas of the Earth, is thought to play an important role in climate processes. However, it has been difficult to quantify because of the relatively complex and highly uncertain effect of dust on radiative forcing [*Intergovernmental Panel on Climate Change (IPCC)*, 2001; *Sokolik et al.*, 2001]. Dust can have either a net positive or negative radiative effect depending on the surface albedo and the aerosol single scattering albedo [*Liao and Seinfeld*, 1998]. The Saharan Dust Experiment (SHADE) experiment [*Tanré et al.*, 2003], held off the coast of West Africa during

September 2000, shows that the diurnal mean net radiative impact of African dust, if extrapolated to the anticipated dust distributions from all sources of the entire Earth, would be approximately -0.4 W m^{-2} . However, it is difficult to generalize such studies to global scales because of the many uncertainties about dust emissions and the highly variable and poorly characterized properties of dust [*Sokolik et al.*, 2001]. Because of the complexities of the competing solar and terrestrial radiative forcings, even the sign of the net effect is unknown [*IPCC*, 2001], suggesting a dust radiative forcing in the range $+0.4$ to -0.6 W m^{-2} . Additionally, mineral dust may exert an indirect radiative effect by modifying cloud properties and precipitation process [*Rosenfeld et al.*, 2001; *Sassen et al.*, 2003].

[3] The quantification of the dust impact on climate change is however particularly uncertain because of the

lack of knowledge about the natural variability of dust emissions and the temporal and spatial variability of transported dust. Another major uncertainty is due to the lack of reliable estimates of the anthropogenic fraction of mineral dust in the atmosphere [Haywood and Boucher, 2000]. This fraction cannot be readily be extracted from in situ and satellite long-term measurements because of the large inter-annual variability of dust transport, and is difficult to parameterize within numerical models because of the lack of knowledge about the processes that control human-induced dust emissions. The most recent estimate of this anthropogenic fraction using climate models is of about 10% of the global dust load [Teegen *et al.*, 2004], which is considerably lower than previous estimates of 20–50% [Teegen and Fung, 1995; Sokolik and Toon, 1996]. The Barbados sampling station [Prospero and Nees, 1986] provides the unique continuous record of dust long-term evolution since the mid-1960s and might thus be suitable to investigate a potential trend in dust export related to human activity in Africa. This data set has been used [Prospero and Nees, 1986; Prospero and Lamb, 2003] to study the interannual variability of dust load and to show the correlation between Sahel drought and dust concentration at Barbados. This correlation suggests that Sahel drought and meteorological conditions associated with the drought control the Atlantic dust export. However, it is not clear how well the Barbados station, located at about 6000 km from African dust sources, is representative of the large-scale dust export over West Africa and the north tropical Atlantic.

[4] Satellites are unique tools to monitor the spatial patterns of the dust transport at both seasonal and inter-annual scale. Recent studies based on Meteosat/visible light spectrometer (VIS) and Total Ozone Mapping Spectrometer (TOMS) observations (22 years from 1979 to 2000) have established the link between Sahel drought, dust emissions in Sahel and summer dust export over the Atlantic [Moulin and Chiapello, 2004], and have shown the role of the North Atlantic Oscillation (NAO) on winter dust transport [Chiapello and Moulin, 2002]. Here we combine the Barbados dust record with the TOMS/Meteosat satellite dust record to examine the consistency of satellite and ground-based long-term dust records and to evaluate the representativeness of the Barbados station. Such an approach is also expected to clarify the respective contributions of Sahel rainfall and the NAO on African dust emissions and export as a function of space and time.

2. Analysis of the Dust and Climate Data Sets

2.1. Satellite and Ground-Based Dust Records

[5] The Barbados sampling station (13°10'N, 59°30'W) provides the most extensive long-term record of surface dust concentrations (SDC), with daily mineral dust measurements made almost continuously since August 1965 [Prospero and Nees, 1986; Prospero and Lamb, 2003]. As previously stated, this unique surface dust record has been extensively used for the analysis of year-to-year variability of long-range African dust transport into the Caribbean [Prospero and Nees, 1986; Prospero and Lamb, 2003].

[6] The long-term operation periods of TOMS and Meteosat spaceborne sensors make them suitable to inves-

tigate the African dust variability over the 1980s and 1990s. Observations from TOMS/Nimbus 7 (1979–1992), Meteosat/VIS (1984–1997) and TOMS/Earth Probe (1997–2000) have been combined to monitor the variability of African dust over the last two decades [Chiapello and Moulin, 2002; Moulin and Chiapello, 2004]. Over the Atlantic ocean, the daily maps of Meteosat derived dust optical thickness (DOT) [Moulin *et al.*, 1997b] have been projected on the TOMS Absorbing Aerosol Index (AAI) [Herman *et al.*, 1997] grid (1° latitude × 1.25° longitude) to allow direct comparison between the two products, for each TOMS pixel. As described by Chiapello and Moulin [2002] and Moulin and Chiapello [2004], statistical linear relationships have been established between the coincident daily TOMS AAI and Meteosat DOT in 1986–1988 for TOMS/Nimbus 7 and in 1997 for TOMS/Earth Probe, which uses different wavelengths. From this analysis, the following relationships have been used to convert daily TOMS AAI pixels into DOT: for TOMS/Nimbus 7, DOT = 0.71 AAI – 0.22 in winter (October–March), and DOT = 0.43 AAI – 0.28 in summer (April–September) [Chiapello and Moulin, 2002]. For TOMS/Earth Probe, DOT = 0.75 AAI – 0.14 in winter (October–March) and DOT = 0.45 AAI + 0.01 in summer (April–September) [Moulin and Chiapello, 2004]. The TOMS DOT estimated by this approach have been validated by comparison with ground-based Sun photometer measurements of aerosol optical thickness over both ocean (Cape Verde Island) and Africa (Banizoumbou, Gao, Dakar) available in the 1980s from field experiments and since the mid-1990s from the AERONET network [Moulin and Chiapello, 2004]. The resulting satellite dust record encompasses 18 years of TOMS DOT over the north Africa (1979–1992 and 1997–2000), and 22 years over the eastern part of the Atlantic ocean (1979–2000). Meteosat DOT are used to fill the gap in TOMS data between 1993 and 1996.

[7] Figure 1 shows the evolution of the monthly and annual means of the entire SDC record at Barbados (35 years from 1966 to 2000) and that of spatially averaged satellite DOT over the north tropical Atlantic (15–30°N, coast to 30°W) (22 years from 1979 to 2000). As stated by previous studies [Prospero and Nees, 1986; Moulin *et al.*, 1997a; Chiapello and Moulin, 2002], the high variability of the dust loads at both seasonal and interannual timescales is evident. The Barbados annual SDC record highlights the lowest dust loads in the late sixties (~5 µg/m³ in 1966–1967–1968), the highest levels being reached in the 1980s (~23 µg/m³ in 1983–1984–1987). Over the period 1979–2000, the maximum variability of the annual SDC at Barbados is roughly of a factor of 2 between 1979 (11 µg/m³) and 1983 (24 µg/m³). The maximum variability recorded by the annual satellite DOT is in the same range with a mean DOT of 0.13 in 1979 and 0.31 in 1983, i.e., about a factor of 2.

[8] Despite this large interannual variability, the Barbados SDC record presents a general increase in the annual dust loads from 1966 to 2000 (8 ± 2 µg/m³ in 35 years, R = 0.50). This data set however shows a dramatic increase in dust loads between 1966 and the mid-1980s, which contrasts with a rather flat evolution from 1986 to 2000. The decadal evolution of SDC at Barbados and satellite DOT over the north tropical Atlantic over the period 1979–2000 present similarities both at monthly timescales (R = 0.70,

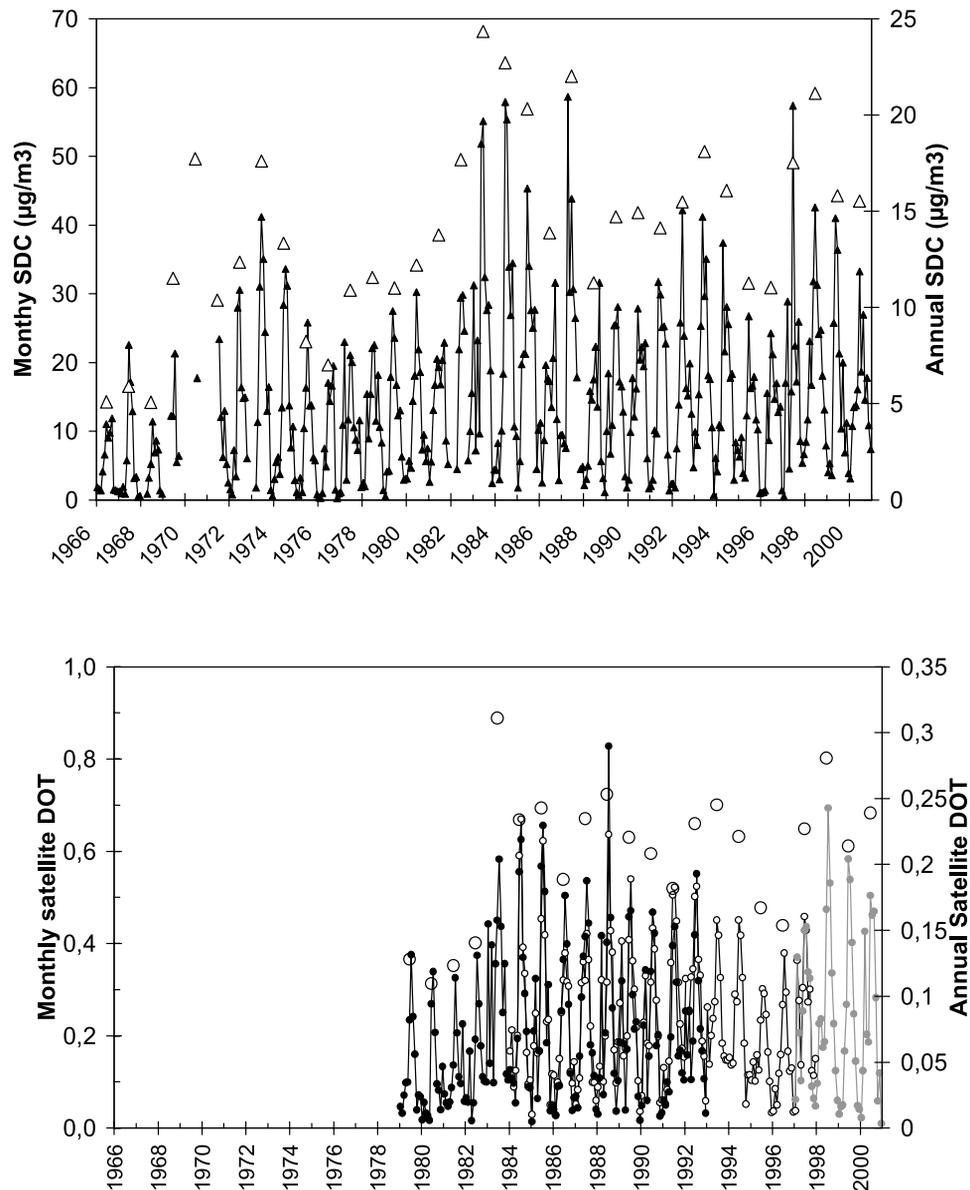


Figure 1. Time evolution of the monthly and annual mean of (top) surface dust concentrations (SDC) at Barbados (1966–2000) and (bottom) satellite dust optical thickness (DOT) over the northern tropical Atlantic (1979–2000). The solid circles indicate the monthly means of TOMS/Nimbus 7 DOT (1979–1992), the open circles indicate the monthly means of Meteosat/VIS DOT (1984–1997), and the shaded circles indicate the monthly means of TOMS/Earth Probe DOT (1997–2000). The large open circles (Figure 1, bottom) indicate the annual averages of satellite DOT, and the large open triangles (Figure 1, top) indicate the annual averages of Barbados SDC.

$N = 256$) and yearly timescales ($R = 0.68$, $N = 22$). Table 1 presents a classification of the annual dust loads recorded by both Barbados SDC and satellite DOT over the north tropical Atlantic from very high dust years ($\text{SDC} > 20 \mu\text{g}/\text{m}^3$, $\text{DOT} \geq 0.25$) to low dust years ($\text{SDC} < 10 \mu\text{g}/\text{m}^3$ and $\text{DOT} \leq 0.15$), including “high” and “moderate” dust levels. With the exceptions of years 1982 and 1988, the SDC and satellite dust records show consistent retrievals in terms of dustiness of the different years considered. A possible explanation of the differences in 1982 is the missing of four months of measurements at Barbados (January to March, plus September), although this is not the case in 1988 so that no evident reason is susceptible to

explain the difference between the two data sets. Despite the deviations in 1982 and 1988, both records show the highest dust load for year 1983, and if some differences exist for certain years, they do not exceed one category (as for years 1984, 1985, 1987 classified in the “very high” category from the Barbados SDC and in the “high” class from satellite DOT). These kinds of differences can be considered as acceptable since the two classifications are only indicative as they do not cover the same number of years. An interesting point is that such a classification highlights very high dust loads in the 1980s, persistent high dust levels in the 1990s, and the lowest dust levels in the late 1960s and early 1980s prior to 1983. It can be noticed that the two

Table 1. Classification of the Annual Dust Loads Recorded at Barbados From 1966 to 2000 (i.e., 35 years) and by Satellite DOT (TOMS+Meteosat/VIS) Over the North Tropical Atlantic From 1979 to 2000 (i.e., 22 years)^a

“Dust Load” Category	Annual Barbados SDC for 35 years, $\mu\text{g}/\text{m}^3$	Annual Satellite DOT for 22 years
Very high 1960s and 1970s		
1980s	1983 , 1984, 1985, 1987	1983 , 1988 ^b
1990s	1998	1993, 1998
High 1960s and 1970s	1970, 1973	
1980s	1982	1984, 1985, 1987, 1989
1990s	1992, 1993, 1994, 1997, 1999, 2000	1990, 1992, 1994, 1997, 1999, 2000
Moderate 1960s and 1970s	1969, 1971, 1972, 1974, 1977, 1978, 1979	
1980s	1980, 1981, 1986, 1988, ^b 1989	1986
1990s	1990, 1991, 1995, 1996	1991, 1995
Low 1960s and 1970s	1966, 1967, 1968 , 1975, 1976	1979
1980s		1980 , 1981, 1982
1990s		1996

^aVery high corresponds to $\text{SDC} > 20 \mu\text{g}/\text{m}^3$ and $\text{DOT} \geq 0.25$, high corresponds to SDC between 15 and $20 \mu\text{g}/\text{m}^3$ and DOT between 0.20 and 0.25, and moderate corresponds to SDC between 10 and $15 \mu\text{g}/\text{m}^3$ and DOT between 0.15 and 0.20, and “Low” to $\text{SDC} < 10 \mu\text{g}/\text{m}^3$ and $\text{DOT} \leq 0.15$. Bold indicates the years of maximum and minimum dust loads for the two data sets.

^bDifferences between satellite and SDC retrievals.

most recent years, i.e., 1999 and 2000 appear in the “high” dust load category, both from Barbados SDC and satellite DOT.

2.2. Climate Indices

[9] We use two climate indices which have been identified by former studies to be linked to African dust variability, the North Atlantic Oscillation (NAO) [Moulin *et al.*, 1997a; Chiapello and Moulin, 2002] and the rainfall in the Sahel region [Prospero and Lamb, 2003; Moulin and Chiapello, 2004]. A NAO index has been defined by Hurrell [1995] from the difference between normalized winter sea level atmospheric pressures between Lisbon, Portugal, and Stykkisholmur, Iceland. The NAO exerts a strong control on the climate of the Northern Hemisphere, especially in winter, and is known to produce large changes in the mean wind speed and direction over the Atlantic and the heat and moisture transport between the Atlantic and the neighboring continents, thus affecting many environmental fields. The time series of NAO indices used here are computed since 1864 and updated each year.

[10] Our analysis of the impact of rainfall variability over the Sahel region on dust export is based on the Sahelian annual rainfall index of L’Hôte *et al.* [2002], which covers the period 1896–2000. Dust export to the Atlantic [Moulin and Chiapello, 2004] and to Barbados [Prospero and Lamb, 2003] are most highly correlated with Sahel rainfall of the previous year (i.e., the rainy season preceding the dust occurrence). Consequently, we use a Sahelian Annual Drought (SAD) Index defined as the negative of the Sahelian annual rainfall index of the previous year. Thus high positive SAD index values indicate severe drought conditions whereas the negative/low SAD values correspond to rainy/normal periods. Note that the consistency of the various existing time series of both NAO and Sahel rainfall departures has been verified. L’Hôte *et al.* [2002] also showed that the period 1970–2000 is overall dry or very dry over Sahel, with only three wet years (1975, 1994, and 1999), among which two are recent. Their analysis indicates that the drought was still going on at the end of 2000, even if the 1990s were less dry than the 1970s and 1980s, but still it was the third driest decade of the century. Indeed, even if the extents of drought areas during the

recent dry years are smaller than during the earliest ones, the wet years are still very isolated from each other.

3. Relationships Between Large-Scale Dust Transport and Climate Indices Over the Last Two Decades

[11] Chiapello and Moulin [2002], using TOMS and Meteosat/VIS observations over the Atlantic, show a high year-to-year variability of African dust export during winter, which is linked to the variability of the NAO. On the basis of the TOMS dust record, Moulin and Chiapello [2004] demonstrate a large-scale correlation between summer dust transport over the Atlantic, dust emissions in the North West Sahel region, and Sahel drought during the previous year. Satellites serve as a unique tool to characterize the spatial extension of the impacts of these two climate factors on dust export.

[12] Figure 2a shows the winter mean TOMS DOT and partial correlation maps between year-to-year variability of winter TOMS DOT and that of the NAO and SAD index over the period 1979–2000. The resulting correlation maps suggest that the impact of the NAO on the year-to-year variability of winter African dust extends over southern Mauritania, the tropical Atlantic (mainly north of the 15°N), and to a lesser extent over the Bodele depression in central Chad.

[13] The Sahel drought also appears to exert a strong impact on both winter dust emissions over a large Sahelian region, located mainly south of 18°N , and winter dust transport over the Atlantic mainly south of 15°N latitude.

[14] Figure 2b shows the summer mean TOMS DOT and the same partial correlations obtained between interannual variability of summer DOT over the period 1979–2000 and both NAO and SAD index. The NAO year-to-year variability appears to exert a weak influence on summer dust emission and transport, whereas the Sahel drought shows a large-scale correlation with dust emissions over Sahel and transport over the Atlantic. Thus Figures 2a and 2b clearly show a large spatial impact of Sahel drought on dust emission and transport during both following winter season (~ 6 months after the rainfall season) and summer season

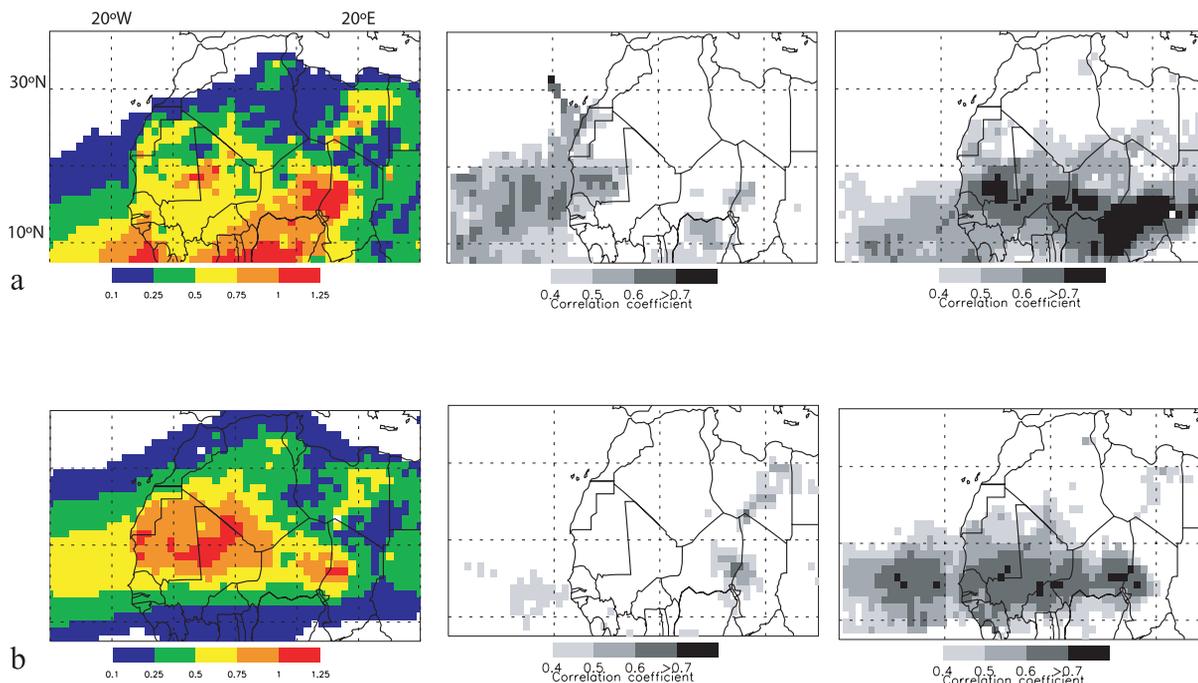


Figure 2. (a) (left) Winter mean TOMS DOT (January–March, 1979–2000) and partial correlation maps obtained between year-to-year winter mean DOT evolution and that of (middle) North Atlantic Oscillation (NAO) index and (right) Sahelian Annual Drought (SAD) index. (b) Same as Figure 2a except for the summer season (June–August).

(~12 months after the rainfall season). It is noticeable that in winter the area of correlation is located at southern latitudes that in summer, a seasonal shift which is also evident when confronting winter and summer averaged TOMS DOT maps (Figures 2a and 2b, left). In winter, the Sahel drought probably influences both mineral dust and biomass burning aerosols, since it has been established that biomass burning is an important contributor to the high aerosol optical depth in the tropical Atlantic during this season [Tanré *et al.*, 2001]. The influence of the NAO appears to be dominant during the winter season and covers mainly some geographically localized source regions (southern Mauritania, Bodele depression) and the transport over the tropical Atlantic north of 15°N, in agreement with the simulations shown by Ginoux *et al.* [2004].

4. Extending the Relationships to the Last 35 Years Using Barbados Data

[15] The winter surface dust concentrations (SDC) at Barbados, which are normally at a seasonal low, have been shown to be much more variable from year to year than are the summer concentrations [Prospero and Nees, 1986]. Chiapello and Moulin [2002], on the basis of TOMS and Meteosat observations over the northeastern part of tropical Atlantic, also highlight the high amplitude of the variability of winter transport of dust in comparison to summer transport. Figure 3 shows that the interannual variability of winter SDC at Barbados is strongly coherent with that of satellite DOT over the north tropical Atlantic, almost exactly in the region of maximum NAO influence (see Figure 2a, middle). Such a correlation demonstrates that in winter Barbados SDC are representative of the intensity of the

north tropical Atlantic dust export. It could also suggest that the NAO is responsible for most of the interannual variability of winter SDC at Barbados. Figure 4 shows the year-to-year evolution of both NAO index and satellite and ground-based dust records in winter, with the scatterplots shown in Figure 5. The high correlation between winter SDC at Barbados and satellite mean DOT over the northeastern tropical Atlantic ($r = 0.73$) clearly appears on Figure 4 (bottom) and Figure 5 (left). The correlation coefficient between satellite DOT and NAO index is 0.52,

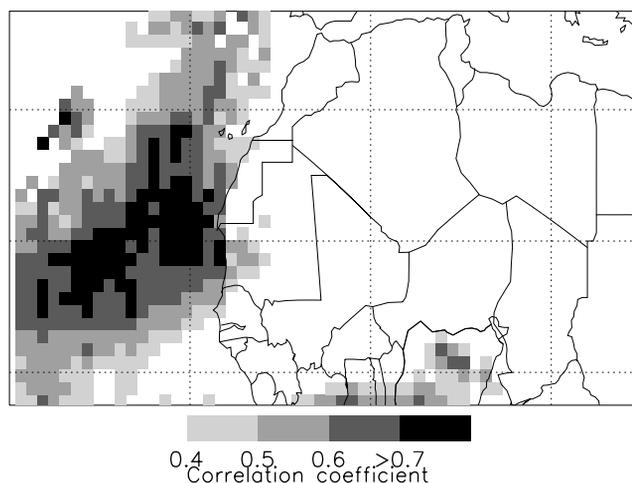


Figure 3. Correlation map between the interannual variability of winter mean SDC (January–March) at Barbados and winter mean TOMS DOT (17 years, 1979–2000 except for 1982, and 1993–1996).

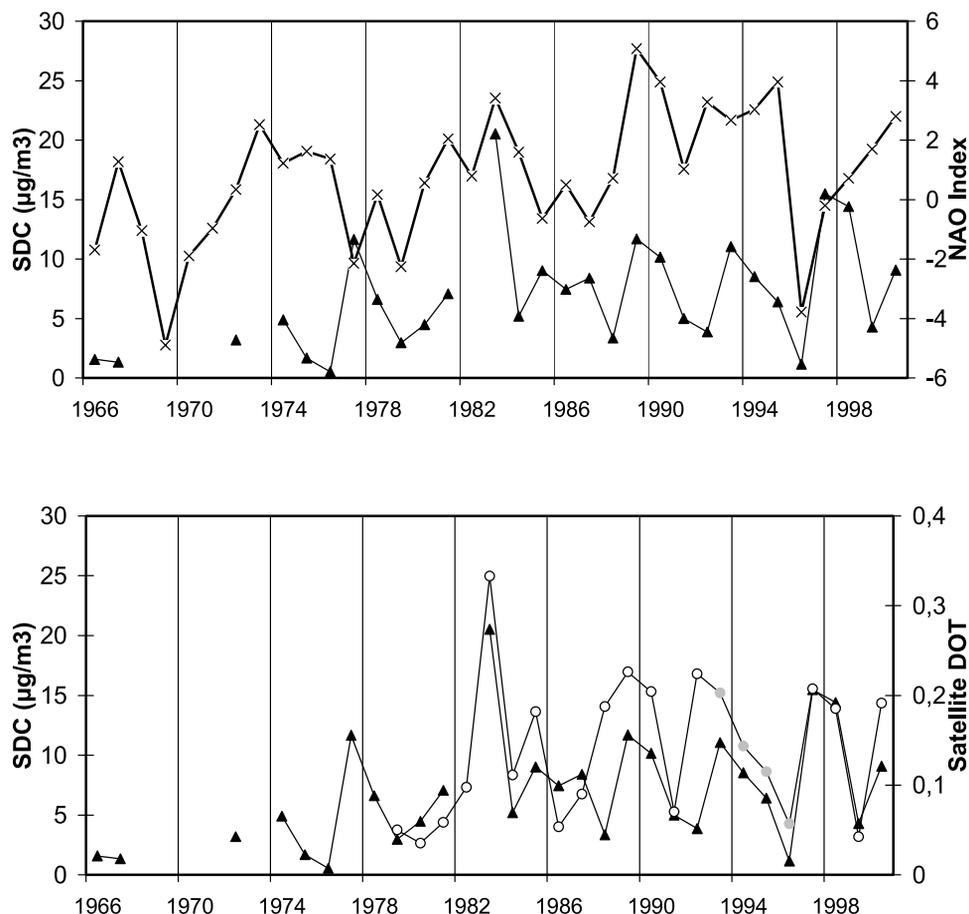


Figure 4. Wintertime relationships between Barbados dust, the NAO index, and satellite measures of aerosols. (top) Time series of winter mean Barbados SDC (solid triangles) along with Hurrell’s NAO Index (cross). (bottom) Winter mean Barbados SDC (solid triangles) and winter mean satellite DOT over the north tropical Atlantic, 15–30°N (open circles from TOMS, shaded circles from Meteosat/VIS).

that between Barbados SDC and NAO index is significantly lower (0.30), as previously shown by *Ginoux et al.* [2004] (not shown). The low correlation of SDC and the NAO index does not necessarily mean that the NAO is not controlling dust transport over the western part of the north Atlantic; the

poor correlation can be related to the location of Barbados at the northern edge of the winter dust transport belt [*Ginoux et al.*, 2004]. It is also probable that during low NAO periods, the Azores High shifts so that the dust transport does not reach Barbados anymore. The year-to-year variability of the

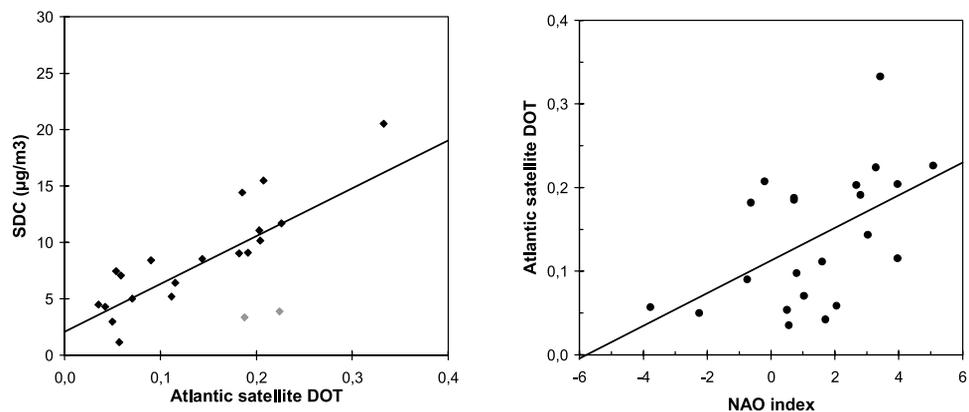


Figure 5. Scatterplots between the year-to-year evolution of winter. (left) Barbados SDC and Atlantic satellite DOT ($R = 0.73$, 21 years). Points corresponding to years 1988 and 1992 are reported as shaded. (right) Atlantic satellite DOT and NAO index of *Hurrell* [1995] ($R = 0.52$, 22 years). The year-to-year evolution of these data sets can be visualized on Figure 4.

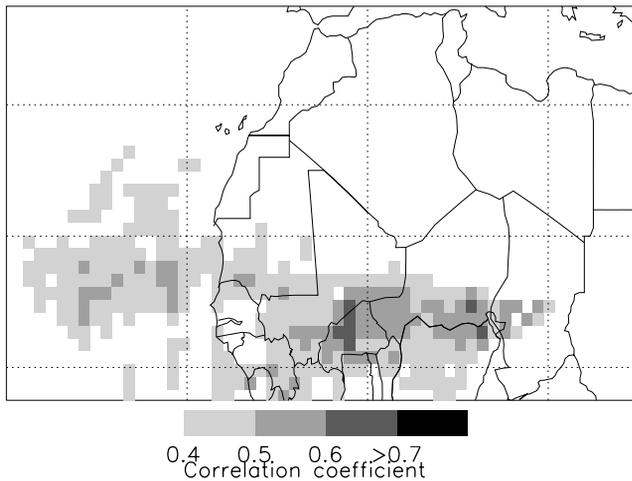


Figure 6. Correlation map between the interannual variability of summer mean SDC (June–August) at Barbados and summer mean TOMS DOT (18 years, 1979–2000 except for 1993–1996).

winter SDC recorded at Barbados present a low correlation with that of SAD index ($r = 0.25$) suggesting that the influence of Sahelian drought on winter dust transport occurs primarily over the eastern part of the Atlantic and over latitudes south of Barbados as shown by the seasonal shift in the latitudinal dust plume seen over the tropical Atlantic (Figures 2a and 2b, left). It could be noted that Figures 4 and 5 show some differences between winter Barbados SDC and Atlantic satellite DOT for years 1988 and 1992 (values indicated as shaded on Figure 5 (left)). The Pinatubo eruption which occurred in mid-1991 may be an explanation for the year 1992, although 1988, as mentioned in section 2.1. (Table 1) seems to be an unusual year.

[16] Figure 6 shows that the interannual variability of SDC at Barbados during summer correlates with that of satellite DOT over north tropical Atlantic and Sahel, but the correlation is less pronounced than in winter over the eastern Atlantic ($R \sim 0.5$). As shown by Figure 2b (right), it suggests that changes of SDC at Barbados are representative of that of dust emissions over the Sahel during the summer season. Figure 7 presents the time series of mean SDC at Barbados, L'Hôte SAD index (Figure 7, top), and summer satellite DOT over the tropical Atlantic and over Sahel (Figure 7, bottom). Figure 8 shows the scatterplots and correlation coefficients obtained between the different data sets. Clearly, the SAD index and summer SDC at Barbados show similar year-to-year evolution during the 34 years of record (1966–2000, $r = 0.65$), as previously stated by Prospero and Lamb [2003], using another Sahelian rainfall index. Moreover, the year-to-year variability of both summer SDC at Barbados and satellite DOT over Sahel and Atlantic are remarkably similar, indicating a strong link between Sahelian drought, dust emissions over Sahel, and export over the Atlantic. This suggests that the drought itself, rather than meteorological and climate factors associated with the drought, exerts a large-scale influence on both dust emission and long-range transport over the Atlantic during the summer season. Again, Figures 7 and 8 show an unusual behavior for year 1988, characterized by a relatively high satellite DOT

and low Barbados SDC, as previously observed in winter. More investigations and detailed analysis of the transport pattern of this particular year should be performed to explain such a difference.

5. Concluding Remarks

[17] This paper attempts a comprehensive analysis of the link between climate variability and African dust export on the basis of the longest satellite and ground-based dust records available. The consistency between these two data sets is examined as well as the influence of climate factors as a function of season, and in terms of spatial extend of their impact. The ground-based dust concentration measurements at Barbados constitute the longest existing record (35 years analyzed from 1966 to 2000) of African dust and for this reason can be considered as a reference. On the other hand the satellite record (22 years) enables us to assess how representative the Barbados measurements are in a spatial context and how climate indices affect dust export. The analysis of the dust loads recorded by Barbados SDC and satellite DOT shows a good consistency in the evolution of both monthly and annual mean dust contents over the common period which covers 22 years. Both vertically integrated DOT recorded by satellite and surface dust concentrations at Barbados highlight very high dust levels in the 1980s (the “dustiest” year being 1983) and persistent high loads in the 1990s. Such an evolution is related to the severe Sahel drought of the early 1980s, and to the persistent, albeit less intense dry conditions in recent years.

[18] The drought in Sahel is shown to have a large-scale impact on both following winter and summer dust emissions and dust transport over the eastern and western part of the Atlantic. In contrast the NAO acts mostly on the winter transport, and is shown to be limited spatially to the northern part of the Atlantic, and possibly to some well-identified source regions like the southern Mauritania and the Bodele Depression. The significant correlations obtained between interannual variability of summer SDC at Barbados, and that of TOMS DOT over both Sahel and northeastern tropical Atlantic suggest that Sahel sources significantly contribute to the dust transport over the western Atlantic. Thus the Sahelian region, if not of first importance in terms of intensity of dust emissions compared to the Saharan sources [Prospero *et al.*, 2002], is probably critical in controlling the year-to-year variability of dust export. Moreover the strong correlation between winter DOT and winter SDC at Barbados indicates that Barbados measurements actually “record” the variability of the intensity of the tropical Atlantic dust export during the whole year and can thus be used with confidence for long-term studies.

[19] Although in situ measurements (available since the middle of the 1960s) and satellite observations (available since the late 1970s) are not sufficient to explain the processes responsible for the impact of NAO and Sahel drought on African dust long-term variability, they constitute unique data sets to identify the climatic parameters controlling the long-term evolution of dust contents and to investigate the spatial and temporal characteristics of their influence. Thus they are essential to constrain and validate the multiyear simulations provided by dust numerical mod-

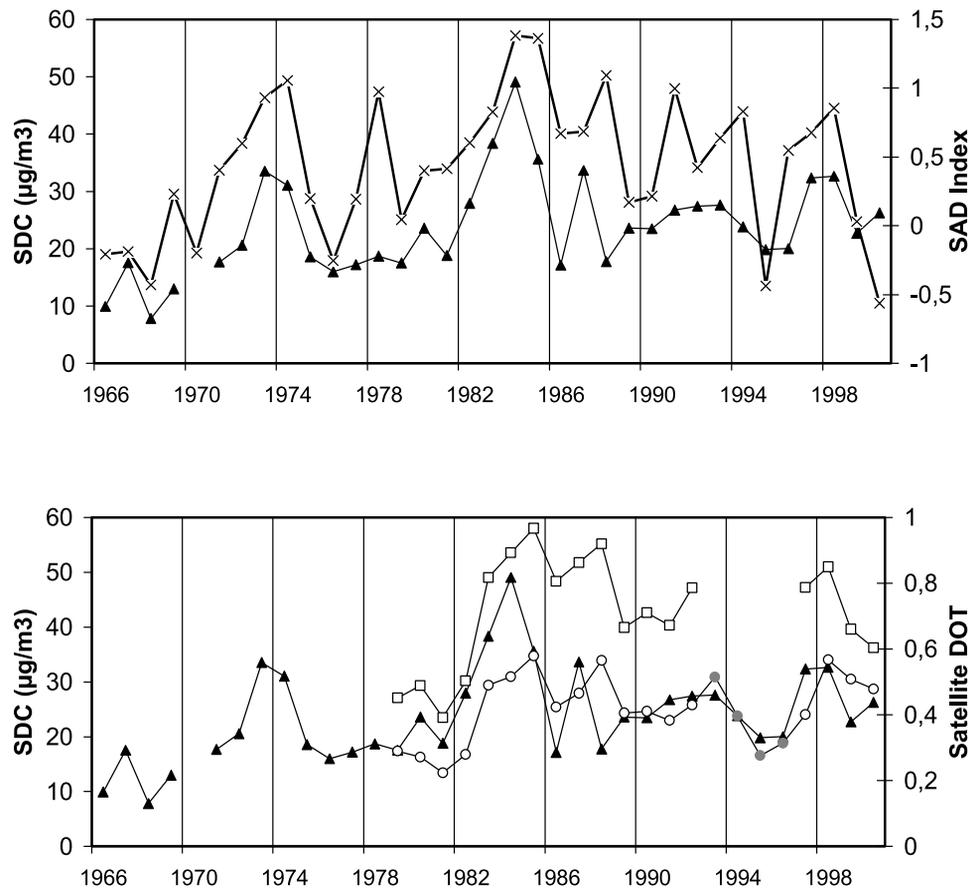


Figure 7. Summertime relationships between Barbados dust, Sahel drought, and satellite measures of aerosols. (top) Time series of summer mean Barbados SDC (solid triangles) along with SAD Index (cross). (bottom) Summer mean Barbados SDC (solid triangles) and summer mean satellite DOT over the north tropical Atlantic between 15–30°N (open circles from TOMS, shaded circles from Meteosat/VIS) and the Sahel (15–17°N, squares).

els, which should allow to progress in the understanding of the mechanisms of influence of these climatic parameters, and to provide more accurate estimates of the anthropogenic fraction of mineral dust. Especially, our analysis shows that the multiannual simulations provided by numerical models will have to account for the variability

of rainfall in the Sahelian fringe. This might be more complicated than representing the NAO impact on dust transport as done recently by *Ginoux et al.* [2004] and *Mahowald et al.* [2003] because rainfall likely controls the vegetation cover and subsequently dust sources on a yearly basis.

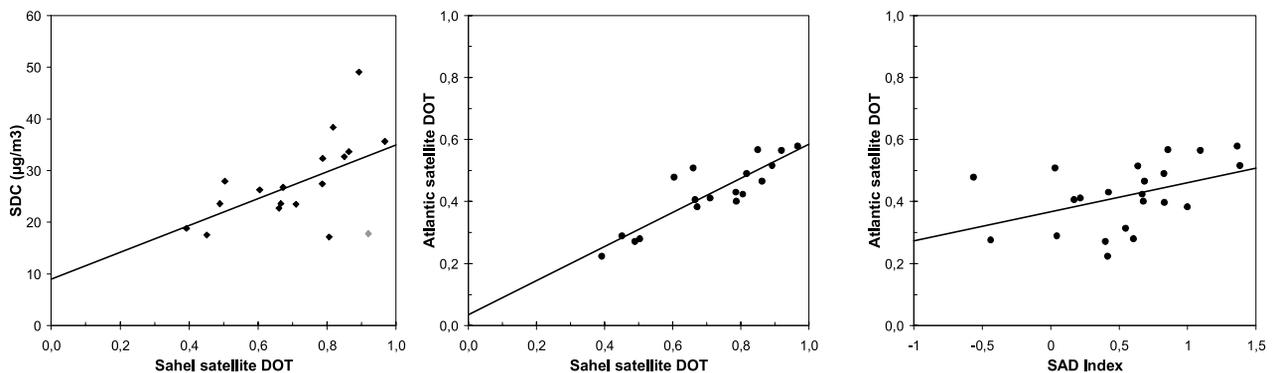


Figure 8. Scatterplots between the year-to-year evolution of summer. (left) Barbados SDC and Sahel satellite DOT ($R = 0.53$, 18 years). The point corresponding to year 1988 is reported as shaded. (middle) Atlantic satellite DOT and Sahel satellite DOT ($R = 0.88$, $N = 18$). (right) Atlantic satellite DOT and the Sahelian Annual Drought Index computed from rainfall data of *L'Hôte et al.* [2002] ($R = 0.44$, 22 years). The year-to-year evolution of these data sets can be visualized on Figure 7.

[20] The TOMS observations used in this study are unique because of their coverage in space (global ocean and land including deserts) and time (since 1979 to present), but certainly suffer of large uncertainties due to the large footprint of the measure ($\sim 50 \text{ km} \times 50 \text{ km}$), strong altitude dependence [Torres et al., 1998], and possible contamination by subpixel clouds [Cakmur et al., 2001]. Despite these limitations, their agreement with both Meteosat dust retrievals [Chiapello and Moulin, 2002], and different kinds of ground-based measurements (aerosol optical thickness [Moulin and Chiapello, 2004] and mineral dust concentrations [Chiapello et al., 1999]) allows their analysis with a reasonable confidence level. The quality of the satellite retrievals of aerosols will certainly progress in the near future with the launch of sensors like MODIS, OMI, or CALIPSO, which will provide among other advances the first global view of the vertical distribution of mineral dust. The new generation of sensors will enable us to continue to monitor desert dust transport, and also to analyze the variability of aerosol properties and characteristics, spatially, vertically, and at the different timescales (event, seasonal, and interannual). Such data will be essential for constraining and validating dust models.

[21] **Acknowledgments.** Updated values of the Hurrell's NAO index are available at <http://www.cgd.ucar.edu/~jhurrell/nao.stat.winter.html>. The Sahelian Annual Drought (SAD) index are computed from the rainfall index data published by L'Hôte et al. [2002]. Daily TOMS aerosol index products are available at <http://jwoccky.gsfc.nasa.gov/aerosols/aerosols.html>.

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