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TOMS and METEOSAT satellite records of the variability of Saharan dust transport over the Atlantic during the last two decades (1979–1997)

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[1] We combined aerosol observations of TOMS/Nimbus-7 (1979–1993) and Meteosat/VIS (1984–1997) to investigate the variability of Saharan dust transport over the Atlantic over nearly 20 years. We first used three years (1986–1988) of coincident daily Meteosat images over the northern tropical Atlantic (15–30°N, 5–30°W) to convert the TOMS semi-quantitative index into dust optical thickness by means of two (“winter” and “summer”) linear relationships. We then processed the whole TOMS/Nimbus-7 archive and found that both seasonal and interannual variability of the mean dust optical thickness over the Atlantic retrieved by TOMS and Meteosat are consistent. This consistency offers an unique opportunity to monitor the export of Saharan dust over the Atlantic during the last two decades. This analysis provides the first evidence of the high year-to-year variability of dust transport during winter, and confirms the importance of meteorological factors, through the North Atlantic Oscillation, in affecting its occurrence at this season. *INDEX TERMS*: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801)

1. Introduction

[2] Airborne African dust has a complex relationship with climate. It has a significant impact on the Earth radiative budget [Andreae, 1996], but the African dust export is in turn strongly controlled by climate variability. In-situ measurements of mineral dust concentration at Barbados since the 1960's [Prospero and Nees, 1986] clearly show, on a year-to-year basis, the association of dry conditions in northern Africa with enhanced long-range transport of Saharan dust in summer. Moulin *et al.* [1997a], on the basis of 11 years of Meteosat observations suggest that the year-to-year variability of Saharan dust transport is more related to the large-scale meteorology, through the North Atlantic Oscillation. There is thus a need for additional large scale and long term information to better understand the interaction of climate variability and dust transport.

[3] One of the interests of TOMS/Nimbus 7 and Meteosat/VIS Saharan dust observations is that both cover long time periods (e.g., more than 10 years). Meteosat allows the retrieval of quantitative information, through dust optical thickness (DOT) over oceanic surfaces only, whereas the TOMS derived Aerosol Index (AI) is a semi-quantitative product, but available over both oceanic and continental regions. In this paper we used three years (1986–88) of daily Meteosat DOT over the northern tropical Atlantic to convert the TOMS/Nimbus-7 AI into DOT. We then analyzed the whole TOMS/Nimbus-7

archive (1979–93) to verify its consistency with the Meteosat archive (1984–97) and to infer both seasonal and interannual variability of African dust transport over the northern tropical Atlantic.

2. Data and Method

[4] A detailed description of the TOMS AI product is given in Herman *et al.* [1997] and Torres *et al.* [1998]. For the TOMS/Nimbus-7 instrument, the AI was determined using the 340- and 380-nm bands. Briefly, the AI relies on the spectral attenuation of the Rayleigh scattering due to aerosol absorption. The AI is defined so that positive values generally correspond to UV-absorbing aerosols (e.g., desert dust and carbonaceous particles) and negative values correspond to non-absorbing aerosols (e.g., sulfate aerosols). Thus we selected the positive values of the AI defined here as the AAI (absorbing aerosol index). The TOMS/Nimbus-7 data used in this work are daily gridded level-3 product at a resolution of 1°latitude x 1.25°longitude available from November 1978 to May 1993.

[5] The method used to monitor the daily African DOT over ocean from Meteosat [Moulin *et al.*, 1997b] relies on former works by Dulac *et al.* [1992] and Jankowiak and Tarré [1992]. It is based on the analysis of daily low-resolution (ISCCP-B2 format) images of the solar (VIS) channel taken at 1145 UT with an apparent resolution of 30 × 30 km at nadir. For every clear-sky marine pixel of every images, a radiative transfer model is used to retrieve the DOT at 550 nm with an accuracy of ±25%. Calibration of the different sensors (Meteosat-2 to -5) was accounted for over the 14-year period used here, from 1984 to 1997 [Moulin *et al.*, 1996; Moulin and Schneider, 1999]. Note that the contribution of both stratospheric and tropospheric sulfates is corrected for within the DOT inversion procedure [Moulin *et al.*, 1997b].

[6] For this study, we focused on an oceanic region located over the eastern part of the northern tropical Atlantic (15–30°N, 30–5°W, indicated on Figure 4) where mineral dust is dominant throughout the year. By using 15°N as a southern boundary we seek to avoid most of the strong wintertime transport of carbonaceous aerosols from African regions north of the equator [Herman *et al.*, 1997]. We selected the 3-year period ranging from 1986 to 1988 to perform the comparison between TOMS AAI and Meteosat DOT because it is when the calibration of both sensors is the most stable [Moulin *et al.*, 1996; Herman *et al.*, 1997]. Daily maps of Meteosat DOT were projected on the TOMS grid to allow direct comparison between the two aerosol products. Given the respective resolution of both products, one TOMS grid cell can be filled with up to 20 clear-sky Meteosat DOT cells.

[7] Former comparisons between the TOMS AAI and sun-photometer DOT measured over Africa and surrounding oceanic regions [Hsu *et al.*, 1999; Chiapello *et al.*, 1999] have shown that the AAI is sensitive to the altitude of the aerosol layer, as predicted by theoretical simulations [Torres *et al.*, 1998]. Saharan dust being transported at relatively low altitude during

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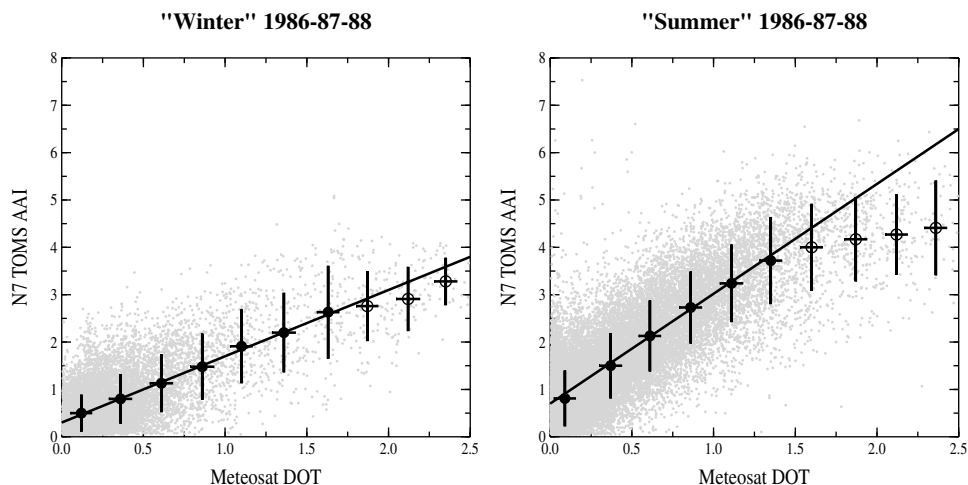


Figure 1. Relation between daily TOMS AAI and Meteosat DOT retrievals for the northern tropical Atlantic zone for “Winter” (October to March) 86–88, and for “Summer” (April to September) 86–88. Note that data for which TOMS AAI or Meteosat DOT is equal to zero have been removed. The range of Meteosat DOT (0 to 2.5) has been divided into 10 classes of 0.25 DOT wide. For each class the mean Meteosat DOT, the mean TOMS AAI and standard deviations are computed. The linear regressions between the mean TOMS AAI and mean Meteosat DOT are in “Winter” for DOT lower than 1.75 (filled circles), $AAI = 1.41 * DOT + 0.31$, $r = 0.999$; in “Summer” for DOT lower than 1.5 (filled circles), $AAI = 2.32 * DOT + 0.65$, $r = 0.999$.

winter [Chiapello *et al.*, 1995] in comparison to the high altitude transport of summer [Carlson and Prospero, 1972], we perform the comparison for a “winter” period (October to March) and a “summer” period (April to September). Further analysis on a monthly and quarterly basis have shown that such a division of the year into two extended seasons is suitable to account for the seasonal variations in the height of the dust transport.

[8] Figure 1 shows the comparison for each TOMS pixel for both “winter” (11073 cases) and “summer” (25886 cases) periods. The range of Meteosat DOT from 0 to 2.5 has been divided in classes of 0.25. For each class, we computed the mean Meteosat DOT, the mean TOMS AAI, and the standard deviations. This class approach allows us to assign a similar weight to each range of DOT and thus to avoid any bias on the regression due to the largest number of data for low DOT. Note that in addition to the strong altitude dependence, other factors

such as angular dependence or cloud contamination probably contribute to the large spread in the TOMS AAI data. Figure 1 shows that the relationship between TOMS AAI and Meteosat DOT is linear up to DOT of 1.75 in “winter” and of 1.5 in “summer”, in agreement with theoretical simulations reported by Hsu *et al.* [1999]. Our results also confirm that the ratio AAI/DOT increases with increasing altitude of the aerosol layer [Torres *et al.*, 1998].

[9] Linear regressions established in Figure 1 can be used to convert the daily gridded TOMS AAI into TOMS DOT at 550 nm: $DOT = 0.71 * AAI - 0.22$ for “winter” and $DOT = 0.43 * AAI - 0.28$ for “summer”. The negative offsets suggest that AAI values lower than 0.30 in “winter” and 0.65 in “summer” are not significant. These thresholds are within the TOMS detection limits for Saharan dust reported by Herman *et al.* [1997] and Hsu *et al.* [1999]. It is important to note that these two relationships are only valid for Saharan dust over our region

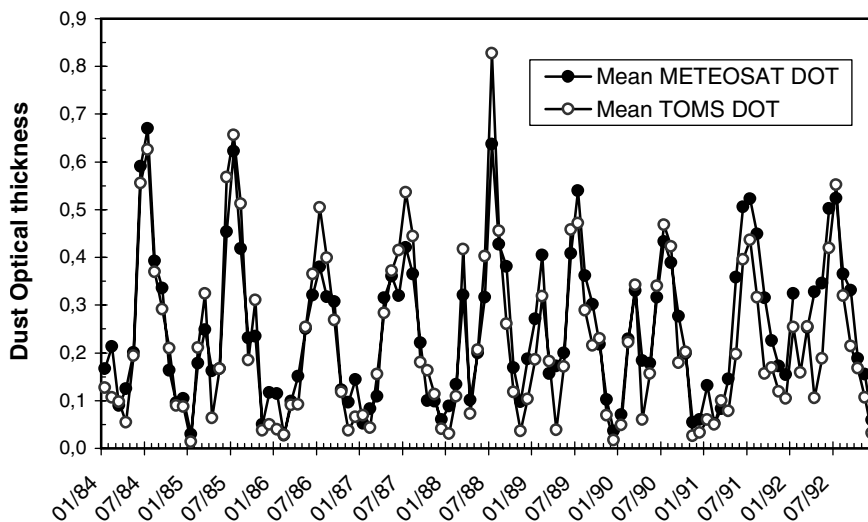


Figure 2. Monthly and spatial averages over the oceanic part of the northern tropical Atlantic zone of the TOMS estimated dust optical thickness (white circles) and Meteosat derived dust optical thickness (filled circles) from 1984 to 1992.

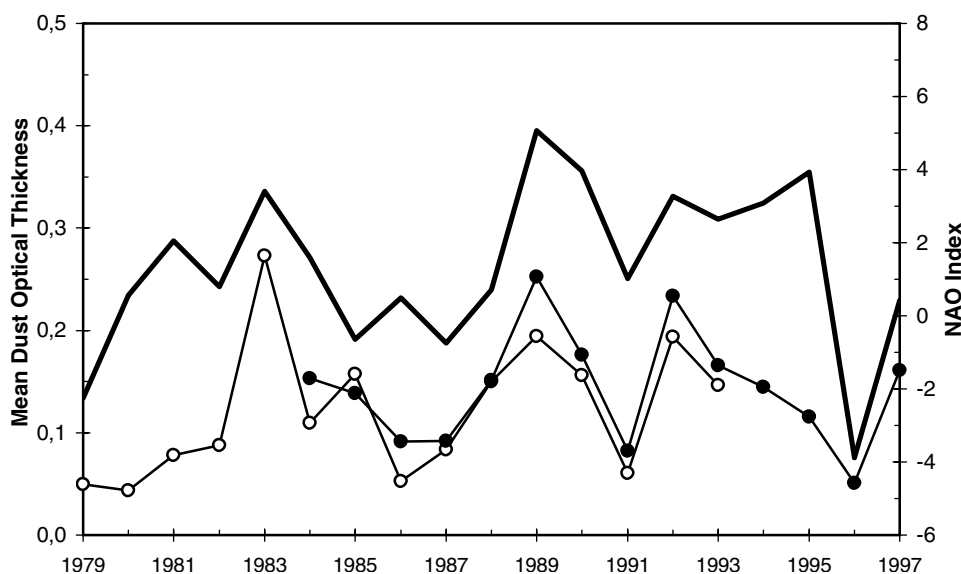


Figure 3. Comparison between the North Atlantic Oscillation (NAO) index (bold continuous line) and the mean dust optical thickness (DOT) in winter (December–March) derived from TOMS Nimbus 7 from 1979 to 1993 (open circles) and from Meteosat from 1984 to 1997 (filled circles) over the northern tropical Atlantic zone.

of interest, and that their validity over other regions such as Africa would have to be verified.

3. Results

[10] We applied these relationships to the daily gridded AAI for the whole TOMS/Nimbus-7 archive over our region of interest (15–30°N, 30–5°W). Figure 2 shows the monthly means of both Meteosat and TOMS DOT between 1984 and 1992 when the two sensors were simultaneously in operation. Over this 9-year period, seasonal cycles of the Saharan dust load are consistent in terms of both phase and amplitude. A summer maximum, with a peak in July, is regularly observed, and is sometimes associated with a secondary peak occurring during winter (maximum in February or March). For most of the peaks the TOMS and Meteosat DOT are in the same range, with differences generally within 30%.

[11] Figure 2 suggests that there is an important year-to-year variability of the winter transport of Saharan dust; it is almost absent for some years (e.g., 1986) or of an intensity almost equal

to that of the summer transport for other years (e.g. 1989). Figure 3 reports the year to year variations of the winter mean DOT (December–March) derived from TOMS Nimbus 7 (1979 to 1993) and from Meteosat (1984 to 1997) over the northern tropical Atlantic. During the 10 years of coincident observations, although TOMS leads generally to slightly lower DOT than Meteosat, the year to year variations of the DOT retrieved by the two instruments are well correlated ($r = 0.92$). Both TOMS and Meteosat show that the dust transport occurring during the winter season is highly variable from year to year. It varies by a factor of three between 1984 and 1992 whereas both annual and summer transports vary only by a factor of 1.5. The contribution of this winter transport of dust to the total annual transport varies from 9% in 1986 to 30% in 1989. This suggests that the winter transport has a significant impact on the interannual variability of Saharan dust export.

[12] Figure 3 also shows the year to year variations of the NAO index defined by *Hurrell* [1995] from the difference between normalized sea-level atmospheric pressures between Lisbon, Portugal, and Stykkisholmur, Iceland. The NAO Index covaries with

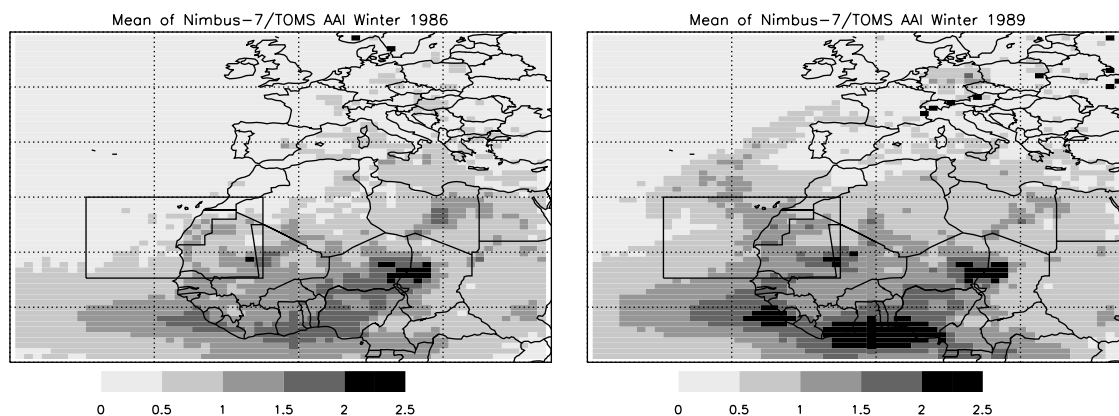


Figure 4. Maps of the winter (January–March) TOMS Absorbing aerosol index for 1986 and 1989, corresponding respectively to a low-NAO year (NAO Index = 0.5) and a high-NAO year (NAO Index = 5.07). The analysis of TOMS and Meteosat Saharan dust observations is performed for the oceanic part of the zone indicated on the images (15–30°N, 5–30°W).

the winter DOT as inferred by TOMS ($r = 0.67$ from 1979 to 1993) and Meteosat ($r = 0.74$ from 1984 to 1997). These correlation coefficients are improved in comparison to those reported in Moulin *et al.* [1997a] based on the summer dust loads ($r = 0.49$ for the Atlantic). This can be related to the fact that the NAO is stronger during winter, so that its effect on the Saharan dust transport is more important during this season. Over the 19 years presented on Figure 3 the maximum winter dust loads occur in 1983, 1989, and 1992, these years being characterized by high NAO indices (respectively 3.41, 5.07, and 3.27). For the two years with the lowest NAO indices, i.e., -2.25 in 1979 and -3.88 in 1996, the winter dust transport is at its lowest level. Figure 4 illustrates the differences in spatial distribution of the winter dust export between a low-NAO year (1986) and a high-NAO year (1989). In 1989 the TOMS image shows a general intensification of the dust transport as well as the occurrence of a second dust plume extending to the North toward Europe. It is likely that the NAO directly controls the winter dust export through changes in strength and location of the Azores anticyclone, which is known to be an important agent for the transport of dust from Africa in the trade-winds layer [Chiapello *et al.*, 1995].

4. Conclusion

[13] We combined TOMS/Nimbus 7 and Meteosat observations to investigate the variability of Saharan dust transport over the northern tropical Atlantic over 19 years (1979–1997). These long-term Saharan dust records are consistent and provide first evidence of the strong inter-annual variability of the winter transport of dust, which can be very weak for certain years, or of an intensity comparable to that of the summer transport for other years. Both TOMS and Meteosat dust records show that the occurrence of this winter transport is linked to the year to year variations of the NAO index. While the impact of other factors, especially rainfall deficits in Africa, can not be excluded, our results provide further evidence of the importance of large-scale meteorological circulation patterns in affecting the dust transport during the winter season.

[14] Moreover, it is the first time that TOMS/Nimbus 7 long-term observations are successfully used to derive an information on interannual variability of Saharan dust transport. One of the next challenges is to take advantage of the TOMS observations over the African continent to better understand how the emissions contribute to the interannual variability of Saharan dust export, and with the help of modeling studies, how the NAO exerts its control. This unique aerosol data set will be extended to most recent years with the help of Meteosat-7 (since June 1998) and TOMS/Earth Probe (the successor of TOMS/Nimbus-7 since July 1996). A recently developed method enables retrieval of aerosol optical thickness and optical properties directly from TOMS/Earth Probe measurements [Torres *et al.*, 2001]. This latter sensor is different from its predecessor and the efficiency of this new approach for the monitoring of the year-to-year variability of Saharan dust export would have to be investigated.

[15] **Acknowledgments.** We thank the TOMS group at NASA Goddard Space Flight Center for providing the TOMS data, Omar Torres and Didier Tanré for comments and helpful discussions on this paper and Aurelia Marchand for her computer skills.

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