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Cyril Moulin, Isabelle Chiapello. Impact of human-induced desertification on the intensification of Sahel dust emission and export over the last decades. *Geophysical Research Letters*, 2006, 33 (18), pp.L18808. 10.1029/2006gl025923 . hal-03189006

**HAL Id: hal-03189006**

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Submitted on 2 Apr 2021

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# Impact of human-induced desertification on the intensification of Sahel dust emission and export over the last decades

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Received 1 February 2006; revised 30 June 2006; accepted 28 July 2006; published 23 September 2006.

[1] Human-induced soil degradation in Sahel is a major concern for regional climate change. A significant increase in long-range atmospheric dust transport due to human activities would indeed modify the radiative budget and the water cycle over both Africa and the tropical Atlantic. Here we use two independent long-term datasets, i.e., surface concentration measurements at Barbados between 1965 and 2000 and maps of TOMS dust optical thickness between 1979 and 2000, to evidence an increase of a factor of two of background dust loads over the Atlantic since the mid 60's, independently of any climatic phenomenon. Satellite imagery suggests that this trend can be attributed to an intensification of dust emissions in a Sahel region centered on southern Mali. The desertification caused by the doubling of the population in Sahel over the last 40 years likely explains the observed intensification of the Atlantic dust export. **Citation:** Moulin, C., and I. Chiapello (2006), Impact of human-induced desertification on the intensification of Sahel dust emission and export over the last decades, *Geophys. Res. Lett.*, 33, L18808, doi:10.1029/2006GL025923.

## 1. Introduction

[2] Mineral dust is the major component in mass of the atmospheric aerosol over both Africa and Tropical Atlantic Ocean [*Intergovernmental Panel on Climate Change (IPCC)*, 2001]. The largest dust plumes can darken the sky over thousands of km<sup>2</sup> and often reach the Americas. The climatic impact of African dust is however not accounted for in most climate change simulations because mineral dust is considered as a natural aerosol, which is not affected by human activities [*IPCC*, 2001]. The existence of significant dust sources due to soil degradation by land use (mostly agriculture and pasture) in Sahel is uncertain [*Prospero et al.*, 2002] and has never been observed yet [*Brooks and Legrand*, 2000]. The concept of human-induced desertification itself is actually still debated in the scientific community [*Nicholson et al.*, 1998; *Brooks*, 2004] because it is difficult to separate the respective contributions of climate and human activities on soil degradation in Sahel.

[3] A decade ago however, a couple of modeling studies [*Sokolik and Toon*, 1996; *Tegen et al.*, 1996] have shown that disturbed soils in Sahel might contribute significantly to the amount of dust transported over the Tropical Atlantic Ocean. These studies suggest that African dust has an

important anthropogenic fraction that can possibly evolve rapidly during the next century. These results have however been recently cancelled out by another couple of modeling studies, which show respectively that this anthropogenic contribution is small [*Tegen et al.*, 2004] and that current global models are likely not accurate enough to address this issue [*Mahowald et al.*, 2004]. Here we perform a careful examination of existing long-term satellite and ground-based measurements in order to assess if there is any observational evidence of the impact of human-induced soil degradation in Sahel on African dust export.

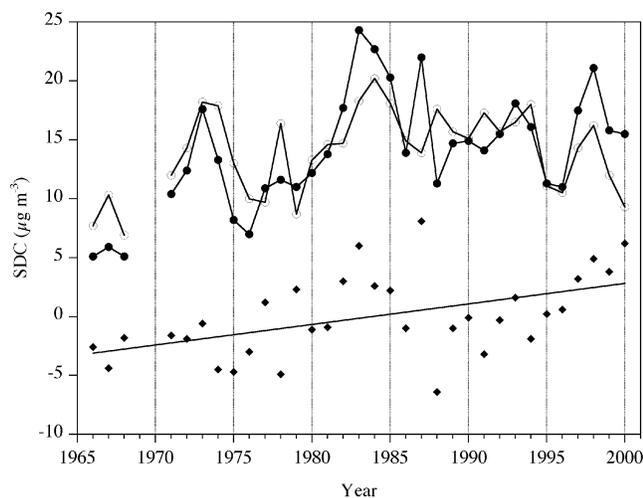
## 2. Long-Term African Dust Data Sets

[4] Satellite images are well suited to observe large-scale dust plumes [*Kaufman et al.*, 2002]. The longest satellite archive for tracking African dust plumes over both Africa and Atlantic is made of only 18 years of daily maps of the dust optical thickness (DOT) [*Chiapello et al.*, 2005] estimated from the aerosol index product [*Herman et al.*, 1997] of the Total Ozone Mapping Sensor (TOMS). This dataset goes back to 1979, but no data are available between 1993 and 1996 because of the lack of sensor in orbit, and data after 2000 cannot be used because of an unexplained calibration drift of the sensor (<http://jwocky.gsfc.nasa.gov/aerosols/aerosols.html>). Note that another satellite archive made of METEOSAT images can be used to complement the TOMS dataset over the Atlantic [*Chiapello and Moulin*, 2002], and that data from OMI (Ozone Monitoring Instrument) will be used in the future to continue the satellite dust archive.

[5] These satellite measurements have been used to study the seasonal cycle of dust emissions [*Alpert et al.*, 2006] as well as the inter-annual variability of the export of African dust [*Moulin and Chiapello*, 2004]. They have shown that the Sahelian Annual Drought (SAD) controls the mean dust export of the following year through a change in the intensity of dust emissions in Sahel. The North Atlantic Oscillation (NAO) also participates to this variability [*Moulin et al.*, 1997], but mostly during winter [*Chiapello et al.*, 2005]. This natural variability of African dust export over the tropical Atlantic is so high that it makes difficult to evidence any potential trend due to a human-induced desertification over a period of time of 20 years. The only other dataset that provides measurements over a longer period is the dust station at Barbados [*Prospero and Nees*, 1977, 1986], with systematic and consistent measurements of surface dust concentrations (SDC) since 1966. Here we use 33 years of annual mean SDC recorded at Barbados between 1966 and 2000, years 1969 and 1970 being discarded because less than 6 months of measurements were available. In this paper, the 18 years of TOMS DOT

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**Figure 1.** Annual mean Surface Dust Concentration (SDC) measured at Barbados between 1966 and 2000 (filled circles) and predicted using a multiple regression depending on both North Atlantic Oscillation (NAO) and Sahel Annual Drought (SAD) indices (open circles). Diamonds show the difference  $\Delta$ SDC between measured and predicted SDC values. The equation of the linear regression is  $\Delta$ SDC =  $0.175 (\pm 0.054) \times \text{Year} - 347 (\pm 108)$ , with  $R = 0.50$ .

(1979–2000, years 1993–1996 missing) are used to complement the long-term Barbados dust record and to infer the geographical distribution of the dust variability.

### 3. Results

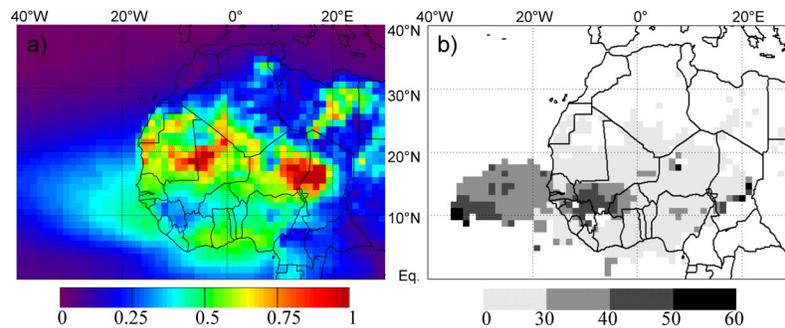
[6] The inter-annual variability of the SDC at Barbados has been shown to be very similar to that of the mean TOMS DOT over the Tropical Atlantic [Chiapello *et al.*, 2005]. The Barbados dust time-series can thus be used as a good proxy for the long-term monitoring of African dust export to the Atlantic. Figure 1 shows that the variability of annual mean SDC can be predicted with a good accuracy using a multiple linear regression on both NAO and SAD indices. The equation of this regression is  $\text{SDC} = 6.09 \times \text{SAD} + 0.85 \times \text{NAO} + 10.36$  and its correlation coefficient  $R^{\text{multi}}$  is of 0.71 for the 33 years (two-tailed probability  $p > 99.9\%$ ). For comparison, a lower correlation coefficient of 0.62 is found if the NAO index is not considered to perform the regression. These two indices are computed from in situ measurements, i.e. from difference in atmospheric pressure at two Atlantic stations for NAO [Hurrell, 1995] and from precipitation anomalies of the previous year over Sahel for SAD [L'Hôte *et al.*, 2002], and have been shown to account for most of the inter-annual variability of the two meteorological phenomena. Except for three specific years (1983, 1987 and 1988), both intensity and temporal evolutions of the dust loads are generally well captured using such a simple parameterization. An explanation for the poor agreement in 1983 is that the SAD index used in this study gives a less intense drought for this year than other indices, which were not used because they do not cover the whole period [Nicholson *et al.*, 2000]. However this explanation does not

hold for 1987 and 1988 for which the various SAD indices available are similar and lead to a drier year in 1988 than in 1987, contrary to what would suggest the measurements.

[7] With the exception of these three specific years, the general tendency shown in Figure 1 is to get too high predicted SDC in the late 60's before the major drought episodes, and too low predicted SDC in the late 90's, when the drought intensity decreases. It is noteworthy that SAD indices were about the same in 1999–2000 as in 1966–1968, whereas measured SDC values are two to three times higher during the most recent period. The analysis of the difference between measured and predicted annual mean SDC, reported in the lower part of Figure 1, confirms a significant temporal trend that corresponds to an increase of  $6 \mu\text{g m}^{-3}$  over the 35 years, which approximately corresponds to a factor of two considering a background SDC value of  $6 \mu\text{g m}^{-3}$  in the late 60's. The correlation coefficient of this linear regression,  $R^{\text{year}}$ , is equal to 0.50 for the 33 years (two-tailed probability  $p > 99\%$ ). If this tendency in Barbados data corresponds a regular increase of the dust export at the large-scale, it should be detectable in the TOMS DOT dataset and should be also of the order of 30% between 1979 and 2000 (see Figure 1).

[8] As for the Barbados dataset, a multiple regression was thus performed on the annual mean TOMS DOT in function of both SAD and NAO indices for each grid cell over Africa and tropical Atlantic. The temporal trend of the difference between measured and predicted DOT values was computed for each grid cell for which the climatological mean annual DOT is greater than 0.1 and the multiple regression is significant ( $R^{\text{multi}} > 0.6$ ; two-tailed probability  $p > 99\%$ ). These two criteria enables to remove artificial temporal trends that might show up in regions of low DOT or in regions where the NAO and the SAD do not satisfactorily account for the natural inter-annual variability of DOT. Figure 2 shows that the difference between measured and predicted DOT has increased by 30–50% between 1979 and 2000 in the region of maximum dust export over the tropical Atlantic. Considering the difference between the two datasets, this trend is consistent with that of 30% at the Barbados station (see Figure 1) and confirms an intensification of the background dust transport, i.e., in the absence of any specific meteorological perturbation such as a drought, over the last decades.

[9] Figure 2 also shows that the only region of Africa that shows a significant increase (30–50%) is centered on southern Mali and extend approximately from 10 to 15°N. This region is characterized by relatively low annual mean DOT values (between 0.3 and 0.4) compared to the rest of the Sahel (annual mean DOT around 0.5), which suggests that southern Mali was likely not a strong dust source in late 70's but is intensifying rapidly. It is also important to note that in Figure 2 the two main Saharan dust sources located between 15 and 22°N respectively on the Mauritania-Mali and Niger-Chad borders — the latter source being known as the Bodele depression [Prospero *et al.*, 2002] — do not show any significant trend over the 20 years, despite the relevance ( $R^{\text{multi}} > 0.6$ ) of the multiple regression on DOT in function of NAO and SAD indices. The trend shown in Figure 2b for the annual mean DOT are very similar to that obtained for the summer mean DOT, suggesting that the perturbation due to absorbing aerosols generated by bio-



**Figure 2.** (a) Climatological (1979–2000) mean annual TOMS Dust Optical Thickness (DOT) at  $0.55 \mu\text{m}$ . (b) Cumulated increase (in %) of the TOMS DOT between 1979 and 2000 as retrieved with a temporal linear regression applied to the difference between the measured and predicted (using a multiple regression on both NAO and SAD indices) annual mean DOT. Note that the correlation coefficient  $R^{\text{year}}$  of the temporal linear regression is greater than 0.5 (two-tailed probability  $p > 95\%$ ) for every pixel associated with a cumulated increase greater than 30%, and that grid cells that do not fulfill the two quality criteria (annual mean DOT  $> 0.1$  and  $R^{\text{multi}} > 0.6$ ; see text) are in white.

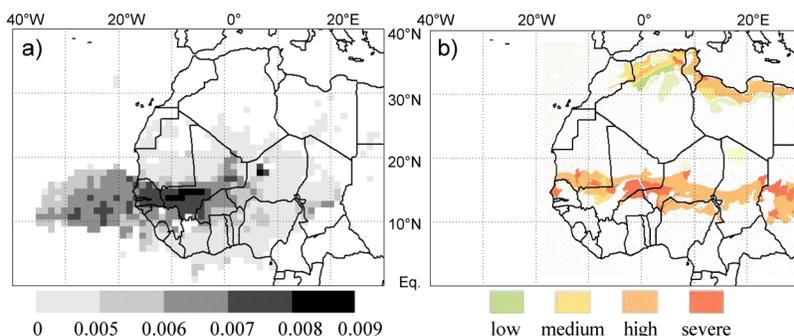
mass burning in Sahel during winter is either small or constant throughout the years. The TOMS dataset thus demonstrates that the observed increase in Atlantic dust export is due to an intensification of dust emissions in western Sahel, as previously suggested by *N'Tchayi Mbourou et al.* [1997] who studied changes in dust storm frequency between the 50's and the 80's.

#### 4. Discussion

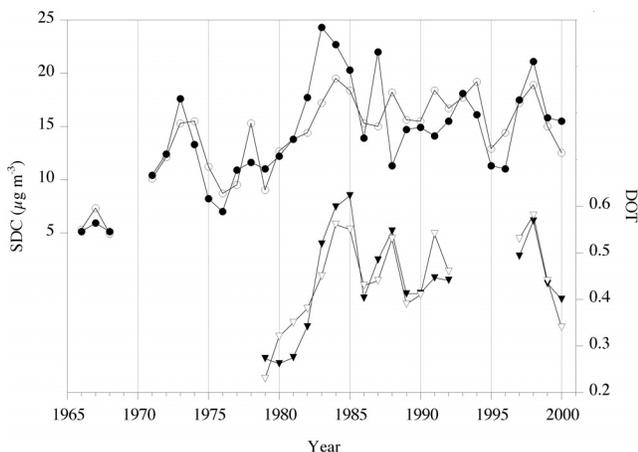
[10] This observed intensification might result from increasing dust emissions by human-induced degraded soils in Sahel because of the intensification of both agriculture and pasture associated with the doubling of the population during the same period [Cour, 2001]. Figure 3 shows that the region of southern Mali with the highest temporal trend, corresponds well to the region of maximum desertification due to wind erosion on human-induced degraded soils [United Nations Environment Programme, 1997]. This part of Mali, centered on the Niger loop and located between  $13^\circ\text{N}$  and  $15^\circ\text{N}$  and between  $3^\circ\text{W}$  and  $10^\circ\text{W}$ , is one of the most inhabited region in Sahel (FAO). It is widely used for both pastoralism and agriculture [Raynaud, 2001] and is thus

directly affected by the increasing demand of fast-growing cities in Sahel [Cour, 2001]. Note that a small region in Niger, in the vicinity of the city of Agadez ( $17^\circ\text{N}$ ,  $8^\circ\text{E}$ ), also shows a DOT increase that seems to coincide with severe soil degradation. This provides the first observational evidence that human-induced desertification in Sahel, whatever its extent and intensity, is likely responsible for an increase of 30 to 50% of the background dust export (i.e., the dust export for normal drought and NAO conditions) to the tropical Atlantic over the last two decades of the 20th century, and probably for an increase of about a factor of two since the mid 60's. This increase is lower than that due the inter-annual variability due to drought, but it is permanent and thus significant in terms of climatic impact.

[11] Figure 4 shows that adding the year as a third parameter of the multiple regression to account for the anthropogenic increase in dust emissions leads to a very accurate predicted annual mean DOT over southern Mali. The equation for southern Mali in Figure 4 is  $\text{DOT} = 0.190 \times \text{SAD} + 0.009 \times \text{NAO} + 0.007 \times \text{Year} - 18.153$  and its correlation coefficient  $R^{\text{multi}}$  is equal to 0.88 for the 18 years (two-tailed probability  $p > 99.99\%$ ), which has to be compared to a correlation coefficient of 0.70 when



**Figure 3.** (a) Same as Figure 2b but for the slope of the temporal linear regression ( $\text{year}^{-1}$ ) applied to the difference between the predicted and the measured annual mean DOT. Note that the correlation coefficient  $R^{\text{year}}$  of the temporal linear regression is greater than 0.5 (two-tailed probability  $p > 95\%$ ) for every pixel associated with a cumulated increase greater than  $0.005 \text{ year}^{-1}$ . (b) Severity map of wind erosion on soils degraded by human activities in western Sahel. (<http://www2.gtz.de/desert/english/factlibrary.htm>).



**Figure 4.** (top) Annual mean Surface Dust Concentrations (SDC) measured at Barbados between 1966 and 2000 (filled circles; same as in Figure 1) and predicted using a multiple regression depending on both NAO and SAD indices to account for the inter-annual variability, and on the year to include the human-induced trend on Sahel dust emissions (open circles). (bottom) Annual mean Dust Optical Thickness (DOT) at  $0.55 \mu\text{m}$  measured over southern Mali ( $12-15^{\circ}\text{N}$  and  $4-11^{\circ}\text{N}$ ) by TOMS (filled triangles) and predicted using a multiple regression depending also on both NAO and SAD indices and on the year (open triangles).

only NAO and SAD indices are considered and of 0.67 when only the SAD index is considered (not shown). At the Barbados station the predicted annual mean SDC is also closer to the measurements that when the year is not taken into account in the multiple linear regression (see Figure 1). The equation for Barbados in Figure 4 is  $\text{SDC} = 5.55 \times \text{SAD} + 0.54 \times \text{NAO} + 0.20 \times \text{Year} - 382.24$  and its correlation coefficient  $R^{\text{multi}}$  is equal to 0.80 for the 33 years (two-tailed probability  $p > 99.99\%$ ), which is higher than the values of 0.71 in Figure 1. Beyond these statistical results, Figure 4 demonstrates that it is possible to estimate accurately the inter-annual variability of African dust emission and transport over the whole “dust zone” using only these three indices. The approach used by Prospero and Lamb [2003] to estimate the past variability of dust transport during the last century from the SAD index only could thus be refined by adding the NAO index and the year, although the anthropogenic trend probably did not exist before the 50’s or so because the population increase in Sahel is recent (Food and Agriculture Organization, <http://www.fao.org>, 2005).

## 5. Concluding Remarks

[12] Our analysis of African dust observations provides a new insight on the contribution of human impact on dust long-term evolution. It shows that, in addition to the highly variable effect of Sahel drought, dust emissions in Sahel and Atlantic dust export have regularly increased since 1965. Our analysis also suggests that this trend is compatible with anthropogenic soil degradation in certain parts of Sahel. This latter conclusion has strong implications for the sim-

ulation of climate change in this part of the world [Alpert *et al.*, 1998; Rosenfeld *et al.*, 2001] because it means that it is necessary to represent accurately the mineral dust cycle in climate numerical models and to develop realistic scenarios to account for the future evolution of anthropogenic dust sources. However our findings have also strong implications in terms of population health in Africa but perhaps also in Europe and Americas, which experience frequent dust intrusions. Dust has indeed been shown to irritate lungs and thus to create propitious conditions for the transmission of the bacteria responsible for Meningococcal meningitis during the dry season in Sahel [Sultan *et al.*, 2005], and to carry viable fungi and bacteria up to Florida in southern USA [Prospero *et al.*, 2005]. A permanent increase in the export of dust from Sahel could thus have large sanitary impacts in forthcoming decades.

[13] **Acknowledgment.** We thank L. Menut for helpful comments on this manuscript and J. M. Prospero for providing us with the Barbados data and for discussions.

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