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RESEARCH LETTER

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Key Points:

- Vegetation anomalies in the Sahel estimated from satellite short-wave infrared bands persist throughout the dry season
- Vegetation anomalies explain 50% of Sahelian aerosol optical depth variance during the dry season over 2002–2015
- Dry-season vegetation cover is important for Sahelian aerosol optical depth variability and its modeling

Supporting Information:

- Supporting Information S1

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Influence of dry-season vegetation variability on Sahelian dust during 2002–2015

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Abstract The drivers of dust emission interannual variability in North Africa, the largest dust source on Earth, are still debated. Early studies outlined the role of previous-season rainfall and vegetation growth, while some recent studies emphasize the role of wind variability. Here we use a newly developed estimation of dry-season nonphotosynthetic vegetation cover in the Sahel based on Moderate Resolution Imaging Spectroradiometer (MODIS) short-wave infrared bands over the 2002–2015 period. The vegetation growth anomalies caused by variability of rainfall in June–September translate to anomalies of dry vegetation cover that persist throughout the dry season until May. These vegetation anomalies explain 43% (50%) of the year-to-year variance in Sahelian-mean dry-season aerosol optical depth (AOD) as derived from MODIS Deep Blue (Sun photometers). Similar explained variance is found with 10 m wind speed and dust uplift potential. The central Sahel proves more important than the western Sahel for dry-season AOD variability.

1. Introduction

Although North Africa has long been recognized as the largest dust source on Earth, the drivers of dust emission variability are still debated, especially those involving the land surface. Early studies have identified a correlation between dust over North Africa [Middleton, 1985; Brooks and Legrand, 2000], African dust crossing the Atlantic ocean and reaching Barbados [Prospero and Nees, 1977; Prospero and Lamb, 2003], or dust optical depth over the Atlantic [Moulin and Chiapello, 2004; Chiapello et al., 2005] with previous-year Sahelian precipitation and previous-year Sahelian vegetation greenness measured by the normalized difference vegetation index (NDVI). Such a correlation is supposed to result from the persistence of the rainfall-induced green vegetation anomalies over a couple of months at least, which would inhibit dust emission and reduce the AOD. The high atmospheric dust loadings of the 1970s and 1980s would then be related to highly negative vegetation anomalies at that time [N'tchayi Mbourou et al., 1997].

Some recent studies, however, point to a modest role, if any, of vegetation changes in controlling dust emission variability as opposed to a dominant effect of wind variability. A model-based attribution study by Ridley et al. [2014] indicates that simulated aerosol optical depth (AOD) responds to wind variability and not to vegetation variability. Cowie et al. [2013] used 10 m wind and dust occurrence data from synoptic stations in the Sahel to show that changes in wind speed rather than in surface emission wind threshold were consistent with changes in dust loadings. Interestingly, Cowie et al. [2013] further hypothesize that changes in the wind field may be caused by vegetation-driven changes in surface roughness. Trying to reconcile the effects of wind and rainfall, Wang et al. [2015] suggest that wind weakening associated with above-normal Sahelian rainfall explains dust emission reduction and thus induces a negative correlation between rainfall and dust emissions. This mechanism only operates during the monsoon season (June to September). Coinciding with the studies advocating a dominant wind effect [Evan et al., 2016], Prospero and Mayol-Bracero [2013] report that the correlation between Barbados AOD and previous-year Sahelian rainfall tends to fade away when the data of the last two decades are included, spanning the 1965–2009 period. Variability of atmospheric circulation over the Atlantic, which affects dust transport, was found responsible for the change in correlation, but altered relations between dust emission and precipitation and vegetation were also suggested. More recently, however, the Atlantic AOD was found again to correlate strongly with Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)-derived AOD [Yu et al., 2015], albeit over a recent and much shorter time period (2007–2013).

To date, there is no clear consensus on the respective role of winds and surface conditions in shaping North African interannual variability in dust emissions and this probably contributes to the failure of earth system models to simulate dust properly [Evan *et al.*, 2014].

By contrast, at a smaller spatial scale, field studies in the Sahel have repeatedly underlined the importance of land surface conditions, especially vegetation cover and soil moisture, in controlling wind erosion [Nickling and Gillies, 1993, Sterk, 2003, Maurer *et al.*, 2009, Bielders *et al.*, 2002, Ikazaki *et al.*, 2011, among others]. Toure *et al.* [2011] suggested that a value as low as 10 g/m² of crop residues (~2% cover) may significantly inhibit wind erosion in southwestern Niger. The comparison of wind erosion over fallow fields and millet fields, with or without millet residues left over in the dry season, also points toward the importance of Sahelian vegetation to limit dust emission, especially in the late dry season (April–June). Similar findings are reported by Daboua *et al.* [2015] in southeastern Niger, for an area where erosion can occur during the whole dry season. Most of these studies focus on the comparison of different vegetation types and do not address the influence of interannual variability of surface conditions.

The uncertain impact of vegetation raises important issues because the drivers of vegetation dynamics and wind fields are different. Indeed, many factors may prompt vegetation changes irrespective of the atmospheric pressure patterns that drive winds. These notably include crop residue management, erosion mitigation policies [Sterk, 2003], land use change [Tegen and Fung, 1995], long-term trends such as Sahel regreening or local desertification [Dardel *et al.*, 2014a, 2014b; Pierre *et al.*, 2016], or changes in fire regime, CO₂ concentration, nutrient cycle, and herbivory.

The divergent conclusions reported in the literature call for a need to decipher the drivers of dust emission in West Africa. In particular, the impact of vegetation has often been estimated via green vegetation data or monsoon rainfall (as a proxy for vegetation), while dust emission can take place throughout the year, i.e., beyond the relatively short period during which vegetation is green. Here we take advantage of methods recently developed to monitor dry-season vegetation in the Sahel with Moderate Resolution Imaging Spectroradiometer (MODIS) data to jointly investigate the interannual variability of the Sahelian AOD, vegetation, and winds. More precisely, we address the following questions:

1. What is the persistence of vegetation anomalies during the dry season? What is the interannual variability of dry-season vegetation cover in the Sahel?
2. What is the correlation between dry-season vegetation and Sahelian AOD? Where and when does this correlation exist? What kind of ecosystems are involved?

2. Data and Methods

2.1. Dry-Season Vegetation

Dry-season vegetation cover is derived from the Soil Tillage Index [Guerschman *et al.*, 2009], hereafter STI, which is the ratio of MODIS short-wave infrared bands at 1.6 and 2.1 μm . Jacques *et al.* [2014] and Kergoat *et al.* [2015] have shown that the mass of herbaceous plants in Sahelian rangelands is linearly related to STI up to 1500 kg dry matter/ha in both rainy and dry seasons. Kergoat *et al.* [2015] further found that the fraction of dry-vegetation cover for rangelands and millet residues is linearly related to STI up to 20% cover. This makes STI well suited for dry-season vegetation monitoring in areas with less than 20% vegetation cover, which is common for the Sahelian region. STI is calculated with MODIS nadir bidirectional reflectance distribution function-adjusted surface reflectance, which is available every 8 days at a 5 km spatial resolution, starting in 2000 for MODIS onboard Terra and 2002 for MODIS onboard Aqua. STI is converted into vegetation cover and mass using the linear equations (3) and (5) from Kergoat *et al.* [2015]. NDVI is used to characterize green vegetation during the rainy season. Rainfall data are from the TRMM3b42v7 product [Huffman *et al.*, 2007]. Land use and land cover are taken from the Permanent Interstate Committee for Drought Control in the Sahel (CILSS) map [Permanent Interstate Committee for Drought Control in the Sahel (CILSS), 2016].

A time series of Sahelian vegetation is obtained by averaging STI over a Sahel box (longitude 20°W to 20°E, latitude 12°N to 18°N), and anomalies are calculated by removing the average seasonal cycle. Dry seasons are labeled with the year when they start (i.e., 2014 dry season stands for October 2014 to June 2015).

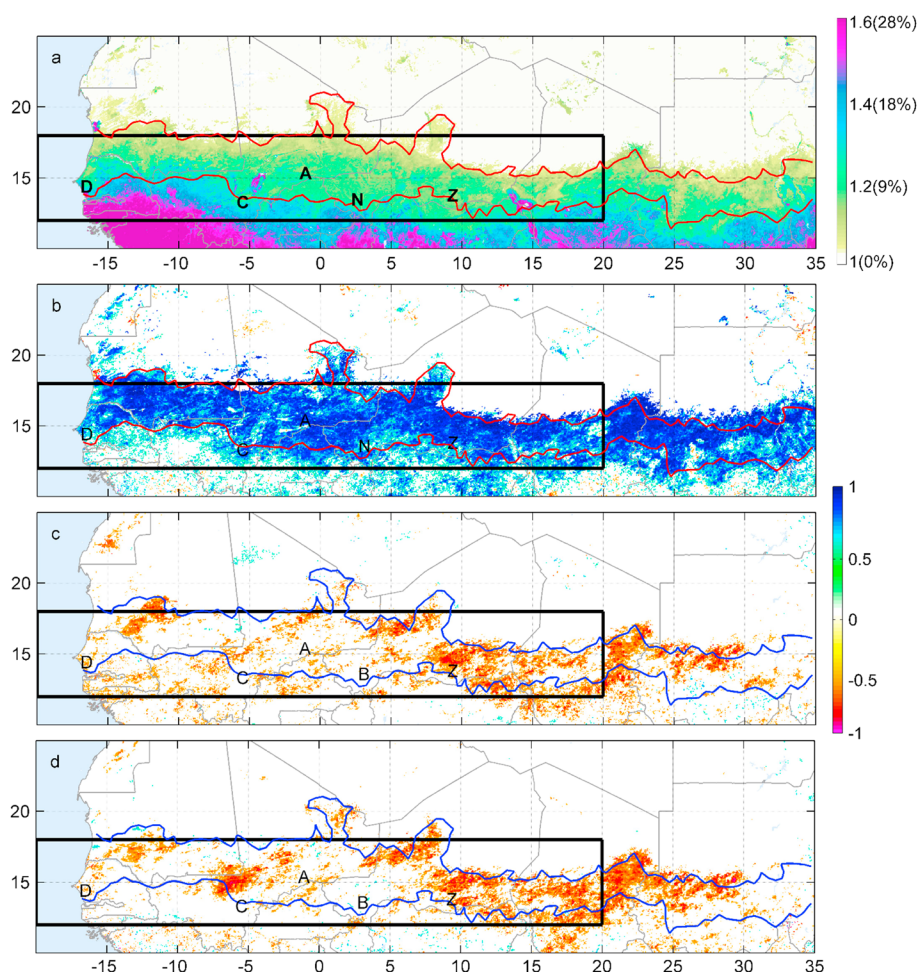


Figure 1. (a) Dry-season STI and corresponding vegetation cover in % (October–June average) from MODIS. Letters mark the AERONET stations (D: Dakar, C: Cinzana, A: Agoufou, N: Niamey, Z: Zinder), and the black rectangle delineates the Sahel box. The red lines are the 600 mm and 100 mm isohyets. (b) Map of correlation of dry-season STI (October–June) with previous growing-season NDVI (July–September). (c) Map of correlation between dry-season STI and Sahelian AOD from MODIS. (d) Same as Figure 1c but with previous July–September NDVI. Only pixels with correlation significant at the 90% level are shown.

2.2. Sahelian AOD

AOD is estimated with the Deep Blue product (collection 6) derived from MODIS on board Aqua [Sayer *et al.*, 2014]. The Deep Blue algorithm is specifically designed for the bright soils commonly found in the Sahel and Sahara [Hsu *et al.*, 2004] and merged with a dark target algorithm suited for more humid areas. Monthly mean AOD time series covering July 2002 to June 2015 are extracted and averaged over the Sahel box (Figure 1). An independent estimate of AOD over this box is built with five Aerosol Robotic Network (AERONET) Sun photometers located from west to east in Dakar (Senegal), Agoufou and Cinzana (Mali), Niamey, and Zinder (Niger, locations shown in Figure 1). Monthly time series of Level 2 AOD at 675 nm are averaged to build a composite AERONET AOD. The most recent months have been filled with Level 1.5 AOD instead of level 2 for a few sites. Although all stations have long AOD time series, they span slightly different periods. Here months with at least data from two stations are retained. This AOD series is independent of MODIS data from which STI and Deep Blue are derived.

2.3. Wind

Wind parameters are derived from the 10 m wind speed (U) of the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis (hereafter ERA-I) available every 6 h on a $1^\circ \times 1^\circ$ grid [Dee *et al.*,

2011]. For each grid point, the monthly mean values of wind speed and dust uplift potential (DUP) (computed from wind speed as $DUP = U^3 (1 + ut/U) (1 - ut^2/U^2)$ when $U > ut$, which is set to 7 m/s, and 0 otherwise [Marshall *et al.*, 2011]) are averaged over the Sahel box to provide time series. Interannual fluctuations of the roughness length are not considered in ERA-I. Hereafter, only DUP is used, since monthly mean wind speed gives very close results.

2.4. Correlations and Analyses

Thirteen dry-season average values are available from MODIS Aqua STI, DUP, and AOD (12 for AERONET since 2002 is missing). The relationships between these different Sahelian time series are investigated with linear regression. Shorter periods within the dry season are also studied (October–December, January–March, April–June, and July–September).

In addition, vegetation and DUP time series for every pixel in a larger domain (20°W to 35°E, 10°N to 25°N) are regressed against the Sahel-averaged AOD time series in order to determine which areas of West Africa and which eco-climatic zones correlate best with Sahelian dry-season AOD.

3. Results

3.1. Dry-Season Vegetation Variability

The dry-season STI map (average over 2002–2015) displays a marked gradient over the Sahel (Figure 1a), with a cover fraction on the order of 15% in southern Sahel decreasing to less than 1% in the Sahara. Vegetation cover anomalies during the dry season are primarily caused by the strong interannual variability of Sahelian vegetation growth in response to rainfall variability [Dardel *et al.*, 2014a]. Over the 2002–2015 period, there is a strong correlation between the dry-season vegetation cover and the green vegetation of the previous growing season over a well-delimited area that coincides with the Sahel band defined by the 600 and 100 mm/yr isohyets (Figure 1b). The correlation rapidly collapses in the Sahara as well as in the Sudanian area (Figure 1b).

The persistence of vegetation anomalies extends across the dry season, as shown in Figure 2. For the Sahel box average, the correlation of monthly STI anomaly with previous rainy-season NDVI is remarkably strong and stable until May. It declines in June when a new rain and vegetation cycle starts in the southernmost pixels (Figure S1 in the supporting information).

3.2. Correlations of Sahelian AOD With Dry Vegetation and Winds

We further found that the October to June averaged Sahelian AOD is significantly correlated with dry-season vegetation (Figure 3b and Table 1). STI explains 43% and 50% of the variance of AOD derived from MODIS and AERONET, respectively. Overall, years that were particularly wet (2010 and 2012; Figure 2c) cluster in the “high STI low AOD” quadrant and the opposite holds for dry years like 2004 (Figures 3a and 3b). Year 2002 (missing from the AERONET time series) is the only year which does not follow this scheme, with a very low STI, explained by a strong drought in western Sahel [Lebel and Ali, 2009] and a close-to-average AOD. Note that the correlation is substantially higher over 2007–2013 ($r^2 = 0.72$), which is consistent with Yu *et al.* [2015], who report r^2 between previous Sahelian rainfall and CALIOP AOD ranging from the 0.59 to 0.86 over the same period.

The variance of MODIS AOD explained by DUP is fairly similar (46%, $p = 0.01$) but lower for AERONET AOD. Interestingly, the typical wet and dry years do not cluster in terms of wind (Figures 3c and 3d). Indeed, DUP and dry-season vegetation are not correlated ($r^2 = 0.02$).

At shorter time scales, when 3 month periods are considered instead of the whole dry season, the correlation of AOD with vegetation cover decreases slightly for most periods (Table 1). Conversely, the correlation with DUP tends to increase at shorter periods, especially for January–March and April–June.

For October–June anomalies, a linear model based on both STI and DUP anomalies explains as much as 79% of AOD variance when derived from MODIS and 56% of AOD variance when derived from AERONET (Figures 3e and 3f). DUP and STI anomalies are mostly unrelated, which explains the gain in correlation when the two variables are taken into account. Most years over the 2002–2014 period fit the model rather well (Figures 3e and 3f) with the exception of 2009, which is close to average in terms of vegetation (although it shows an unusual and marked east-west gradient; see Figure S2) and DUP but exhibits high AOD.

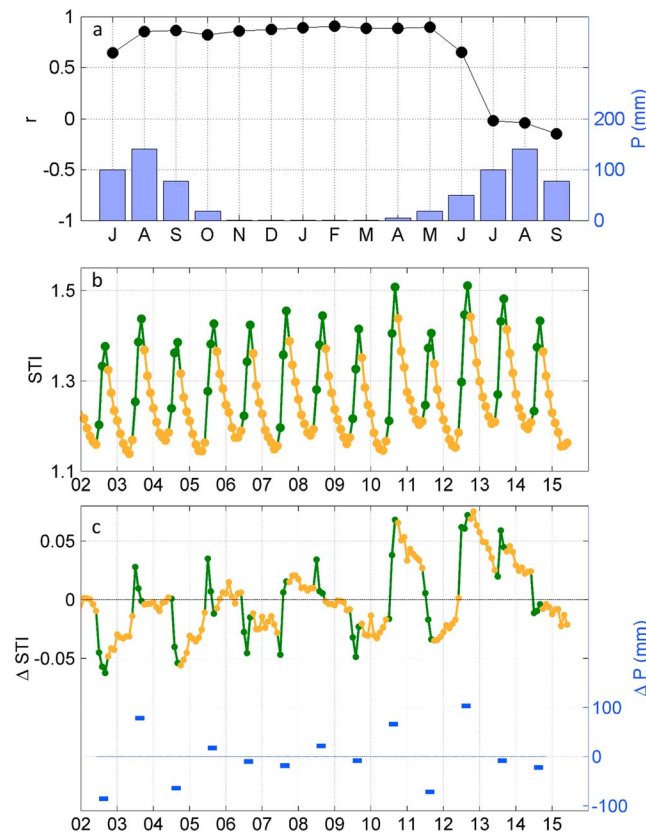


Figure 2. (a) Annual cycle of the correlation (r) of Sahel-box averaged monthly STI with previous growing-season (July–August–September (JAS)) NDVI (black line) and monthly mean precipitation (blue bars). (b) Time series of monthly STI over 2002–2015 averaged for all pixels correlated with the Sahelian AOD ($p < 0.10$). The orange (green) indicates the dry (rainy) season. (c) Same as Figure 2b but for monthly anomalies (left axis), with JAS precipitation anomalies (right axis).

segments; Figures 2b and 2c), are due to above or below normal rainfall (Figure 2c, bottom) and vegetation productivity.

3.3. Spatial and Temporal Scales

The strong persistence of STI anomalies until the next rainy season (Figures 2 and S1) implies that the drivers of vegetation decay in the dry season, namely, grazing, bush fires, residues management, decomposition, and oxidation are not fluctuating enough to generate noticeable interannual variability at the Sahel scale over 2002–2014. This persistence also supports the use of previous summer’s NDVI as an indicator of dry-season vegetation variability for two reasons: First, the correlation of NDVI and dry-season STI with AOD are fairly close, and second, from a physical process point of view, the dry-season cover fraction identified here is close to plausible thresholds of inhibition of dust emission [Toure *et al.*, 2011]. The shape of the persistence time series also calls for using a calendar starting in July and ending in June, rather than January to December, when studying at vegetation impact on dust emissions with annual data.

We found that the correlations between vegetation and AOD (MODIS or AERONET) and between wind and AOD were similar. These correlations, however, do not operate over the same areas nor at the same time scale. The highest correlations with wind arise at shorter time scales (and typically in winter, when the wind interannual fluctuations are the strongest, not shown), whereas for vegetation they are found at the scale of the whole dry season. The emergence of these two time scales pertains to the distinct nature of the underlying mechanisms associated with the variability of the wind and vegetation cover, as emphasized by Zender and Kwon [2005]. Occasional strong winds profoundly affect monthly mean AOD [Cowie *et al.*, 2015], while

MODIS pixels showing significant correlation of dry-season STI with the Sahelian AOD ($p < 0.1$; Figure 1c) are mostly found between the 600 mm and 100 mm isohyets, and more so in the central Sahel (eastern Niger, Chad, and Sudan) than in the western Sahel (Mali and Mauritania). This corresponds to regions where DUP is strictly positive but less than $20 \text{ m}^3/\text{s}^3$ (see Figure S3). Previous rainy-season NDVI and dry-season STI lead to very similar correlation maps (Figures 1c and 1d), which both point to the importance of the central Sahel. The STI time series averaging all pixels with significant correlation peaks in September at STI values corresponding to $\sim 20\%$ cover and reaches a minimum in May corresponding to $\sim 7\%$ cover (Figure 2b). STI monthly anomalies range from -0.08 to 0.08 (Figure 2c), which translates to $\pm 3.8\%$ cover. These anomalies contain two types of information. The narrow peaks at the start or end of the rainy season (green segments; Figure 2c) reflect phenological variability (e.g., the peak in July 2005 caused by early rainfall and vegetation growth), whereas the long-lasting anomalies, which persist throughout the dry season (orange

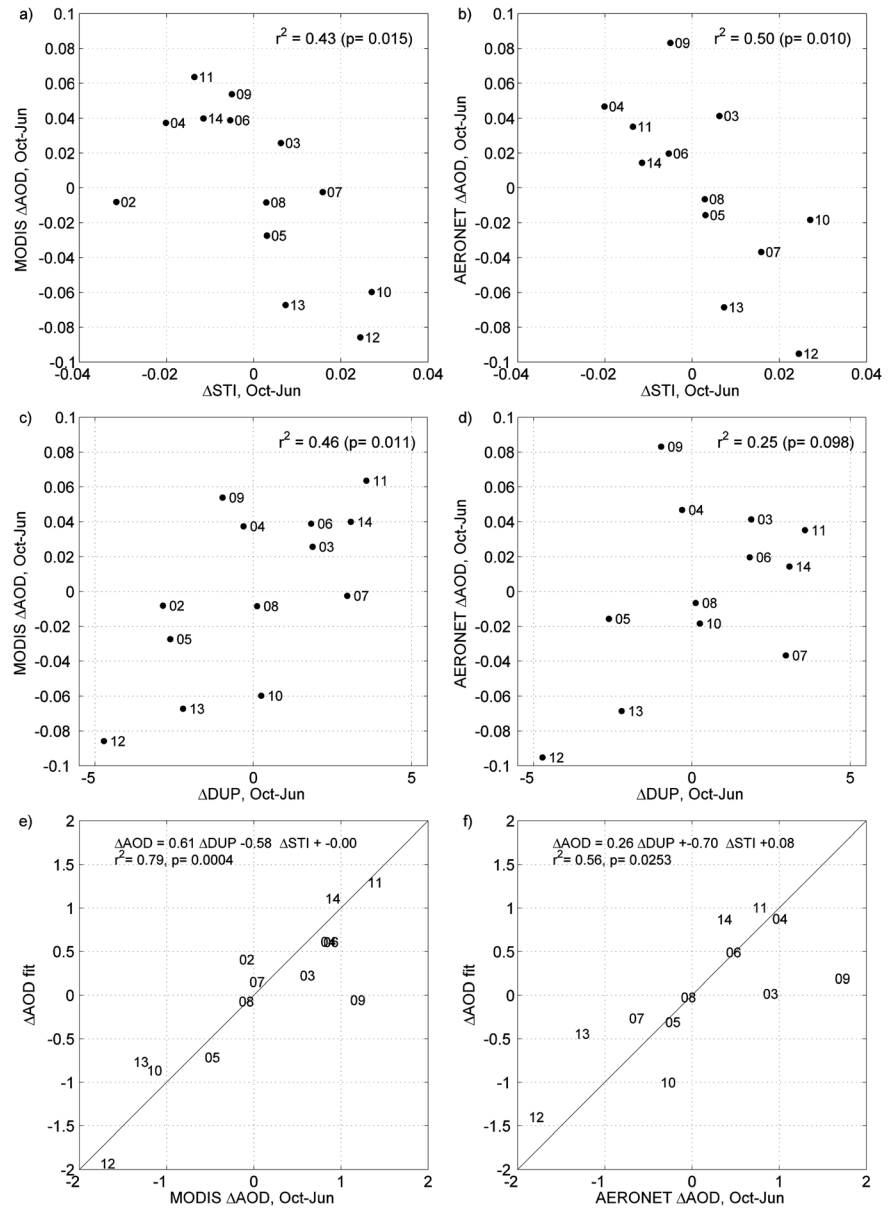


Figure 3. (a) Scatter diagrams of dry-season STI anomalies with MODIS and (b) AERONET AOD anomalies; numbers refer to years, e.g., 12 for year 2012. (c and d) Same as Figures 3a and 3b for DUP anomalies. (e and f) Results of a two-variable linear model for MODIS and AERONET AOD.

the long-lasting vegetation anomalies systematically influence the series of erosion events arising throughout the whole dry season. In addition, the highest correlation with wind is found in well-known source areas, where wind is accelerated like in the Bodélé depression [Washington et al., 2006] and other

Table 1. Correlation of STI and DUP Anomalies With Sahelian AOD for 3 Month Periods of the Dry Season and for the Full Dry Season^a

| | Oct-Dec ² (P Value) | Jan-Marr ² (P Value) | Apr-Jun ² (P Value) | Oct-Jun ² (P Value) |
|------------------------|--------------------------------|---------------------------------|--------------------------------|--------------------------------|
| AOD MODIS versus STI | 0.41 (0.019) | 0.25 (0.084) | 0.31 (0.050) | 0.43 (0.015) |
| AOD MODIS versus DUP | 0.48 (0.009) | 0.65 (0.001) | 0.52 (0.005) | 0.46 (0.011) |
| AOD AERONET versus STI | 0.15 (0.220) | 0.42 (0.023) | 0.33 (0.050) | 0.50 (0.010) |
| AOD AERONET versus DUP | 0.09 (0.350) | 0.30 (0.063) | 0.35 (0.043) | 0.25 (0.098) |

^aBold is for significant values.

topographic basins in Niger [Schepanski *et al.*, 2012] (Figure S4), and where vegetation is scarce or absent. In line with previous studies, this correlation is strongest in January to April. Conversely, the correlation with vegetation is more diffuse, with the strongest signal from eastern Niger to Sudan. No clear relation is found with land use. Indeed, according to the CILSS maps [CILSS, 2016], 15.56% of the pixels where STI is correlated with AOD ($p < 0.1$; Figure 1c) correspond to croplands, which is very close to the 15.77% of croplands found in the Sahel box. The difference between the central and western Sahel echoes the results of Cowie *et al.* [2014], who established that dust emission is stronger in the central Sahel during the dry season, whereas the western Sahel is more tightly influenced by the Saharan heat low circulation with stronger emissions in the early monsoon season. The maximum of the STI/AOD correlation occurs later in the southern Sahel than in the northern Sahel (the clusters of pixels with maximum correlation in January–March are usually located north of the ones with maximum correlation in April–June, in eastern Niger or Chad for instance; Figure S3).

4. Discussion

These results are in line with ground-based studies pointing to the importance of vegetation in the dry season for dust emission. However, we did not find a predominance of the late dry season, neither for the correlation with DUP nor with STI. It is likely that the correlation with the wind is underestimated, in particular because ERA-I wind fields do not represent the wind gusts associated with the first deep convection events observed in May–June in the Sahel [Largeron *et al.*, 2015]. This period often corresponds to the annual maximum of wind erosion found in Sahelian ground-based local studies but not to the highest STI/AOD correlation. One reason might be that the STI/AOD correlation is stronger in areas that are more arid than southwestern Niger, where most experimental studies have been carried out. Indeed, preliminary results in eastern Niger [Daboua *et al.*, 2015] suggest that erosion and dust emission may occur during any part of the dry season for crops and rangelands. This agrees with the SYNOP diagnostics of Cowie *et al.* [2014] and with the STI/AOD correlation we observe. Cloud cover may also affect the detection of AOD variability in May–June for both MODIS and Sun photometers, which possibly lowers the STI/AOD correlation. In addition, a part of the variability of Sahelian AOD is probably due to transport of dust of non-Sahelian origin, especially from the Sahara. Because the combination of Sahel STI and DUP explains ~80% of the AOD variance, this exo-Sahelian dust likely does not comprise a major component of the Sahelian AOD interannual variability.

Previous rainy-season NDVI and dry-season STI produce similar maps and statistics. Such a consistency supports the use of the newly developed STI, by reducing the risk of having spurious correlation when using STI and AOD anomalies recorded over the same periods. STI further provides information on a variable, dry vegetation cover, which is physically sound for wind erosion. In addition, decorrelation between rainy-season NDVI and dry-season STI is likely to occur at local (field) scale, as a result of residue management, for instance, or at longer time scale, at which slow processes like Sahel-wide land use change, woody plants or livestock dynamics operate.

In terms of mechanisms, it is difficult to assess whether there is an impact of dry-season vegetation on the trade wind circulation, as proposed by Cowie *et al.* [2013], or on local emission thresholds. DUP from ERA-I does not account for surface roughness interannual variability nor for dry-season vegetation cover. Data assimilation in ERA-I is unlikely to compensate for these lacking parameterizations, which is consistent with the absence of correlation found between wind speed and STI. Over 2002–2014, the variability of dry-season vegetation is mostly caused by the variability of the growth of annual plants (grasses and crops rather than trees and shrubs). Crop residues, straw, and litter are known to impact dust emission thresholds, but their impact on the large-scale circulation is not documented. On the longer term though, land use change and tree population dynamics potentially change wind speed more efficiently than annual plants.

The MODIS-Aqua period (2002 to present) is characterized by a strong year-to-year variability in Sahelian rainfall and vegetation [Dardel *et al.*, 2014a], which is well suited for correlation studies. Longer time series are needed though, if climatic trends and fluctuations are to be addressed. Time series starting in the early 1980s span the extreme droughts of 1983 and 1984 and a gradual recovery of rainfall and vegetation. It is well established, from ground data, advanced very high resolution radiometer NDVI, and modeling, that vegetation growth was severely impaired during the driest years. Since the dry-season wind anomalies were not especially strong (DUP anomalies being -0.95 for 1983 and 0.97 for 1984, to be compared with values in

Figure 3c), it is plausible that dry-season vegetation anomalies played a critical role in the high AOD recorded over the Atlantic ocean [Prospero and Lamb, 2003] or over the continent [Brooks and Legrand, 2000] at that time. Furthermore, over such a long period, there is room for a modulation of dry season vegetation by changes in land use [van Vliet et al., 2013], residue managements, grazing pressure [Pierre et al., 2016], or trends in woody cover [Brandt et al., 2016], and the magnitude of these potential effects needs to be estimated with more accuracy.

5. Conclusion

We used a newly developed estimation of dry-season nonphotosynthetic vegetation cover in the Sahel over the 2002–2015 period. We found that the anomalies caused by variability of rainfall in June–September translate to anomalies of dry vegetation cover that persist throughout the dry season until May. These vegetation anomalies explain 43% of the year-to-year variance in Sahelian-mean dry-season AOD. Similar explained variance was found with 10 m wind speed and DUP. Wind and dry-season vegetation anomalies together explained a large part of the Sahelian AOD variability, with relatively similar importance. The central Sahel proved more important than the western Sahel for dry-season AOD variability.

Since vegetation anomalies build during the monsoon season, they have a significant prediction potential for Sahelian AOD, especially when they are observed over the central Sahel ecosystems. The quantification of dry-season vegetation with STI opens ways to develop physically based models of dust emissions and coupled vegetation-dust models with explicit plant canopies in the dry season [Pierre et al., 2015, 2016].

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