Dust Uplift Potential in the Central Sahel: An Analysis Based on 10 years of Meteorological Measurements at High Temporal Resolution

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Key Points:
- Wind speeds above the threshold for wind erosion occur for only 1.5% of the time in the central Sahel and 80% last for less than 3 h
- More than 2/3 of the dust uplift potential is produced by the high wind speeds occurring between 15 April and 21 July
- Nocturnal haboobs make a larger contribution to the annual dust uplift potential than the breakdown of the nocturnal low-level jet

Supporting Information:
- Supporting Information S1

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Dust Uplift Potential in the Central Sahel: An Analysis Based on 10 years of Meteorological Measurements at High Temporal Resolution

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Abstract A 10 year data set of wind speed and precipitation recorded in two Sahelian stations located in Niger and Mali is used to investigate the duration and the diurnal and seasonal cycles of high wind speeds and Dust Uplift Potential (DUP). The results indicate that high wind speeds, those greater than the threshold wind velocity required to initiate wind erosion (TWV) over a bare soil occurred in the middle and late morning during the dry and wet seasons but also at nighttime during the wet season. However, the morning wind speeds are only slightly greater than TWV leading to low DUP. On the opposite, the high wind velocities associated to the nocturnal mesoscale convective systems crossing the Sahel during the wet season are responsible for the highest potential wind erosion events. This leads to a strong seasonality of DUP with more than 70% occurring in less than 90 days, from mid-April to mid-July. The duration of the high wind speed events is very short since more than 80% last for less than 3 h, suggesting that the frequency of the observations performed in SYNOP meteorological stations is not sufficient to correctly quantify the contribution of such events to DUP. Finally, by combining precipitation and DUP, we estimated that precipitation should have a relatively limited role in terms of inhibition of wind erosion in this region with precipitation only affecting 25% of total DUP.

1. Introduction

The North African arid and semiarid regions are recognized to be the major dust sources on Earth (e.g., Ginoux et al., 2004; Laurent et al., 2008). While the arid Sahara Desert is the main provider of dust to the atmosphere, studies based on direct measurements (e.g., Prospero & Nees, 1977), satellite observations (e.g., Moulin & Chiapello, 2004), or model simulations (e.g., Zender & Kwon, 2005) suggest that both the interannual and seasonal variabilities of dust exports toward the tropical North Atlantic Ocean are controlled by the changes occurring in dust emissions from the semiarid Sahel. Indeed, the Sahel is a region where the vegetation cover, a key factor for dust emission, is very sensitive to small changes in climatic conditions, especially precipitation. One of the most spectacular consequences of such changes is the huge increase in dust concentrations measured at Barbados in connection with the drought that the Sahel has undergone in the 1970–1980s (Prospero & Nees, 1986). Moreover, in contrast to the arid Sahara Desert, a significant part of the Sahelian region is used for agropastoral activities, which highly modify the surface cover at certain periods of the year (e.g., Abdourhamane Touré et al., 2011; Mulitza et al., 2010; Pierre et al., 2014; Sterk, 2003). Thus, it is thought that the combined effects of climatic changes and of the increasing anthropogenic pressure could lead to significant changes in the dust amount emitted into the atmosphere from the Sahelian belt during the next decades (e.g., Evan et al., 2016; Prospero & Lamb, 2003; Ridley et al., 2014).The high wind speed events able to produce wind erosion, and dust emissions in the Sahel are known to be strongly connected to two main processes:

1. The diurnal cycle of the Nocturnal Low-Level Jet (NLLJ) is responsible for most of the high wind speeds occurring during morning in the Sahelian and Saharan regions. Many articles have been published on this subject, mainly based on case studies, treatment of meteorological reanalysis or climatological simulations (e.g., Fiedler et al., 2013; Knippertz, 2008; Lothon et al., 2008; Marsham et al., 2013; Parker et al.,

2005). Briefly, a wind speed maximum frequently forms in the lower troposphere (generally below 1,500 m above ground level (agl)) at nighttime, commonly known as a nocturnal low-level jet. Different meteorological conditions can generate NLLJ, but the most common process is a decoupling of the airflow from surface friction which then oscillates around the geostrophic wind (Blackadar, 1957). One of the requirements for the formation of the NLLJ is a radiative cooling creating a surface inversion that stabilizes the surface layer. In the morning, from sunrise to about 1200 UTC (i.e., local time minus 1 h), the turbulence grows by surface heating, allowing downward mixing of momentum from the NLLJ to produce surface wind speeds that can be sufficient to initiate wind erosion and dust emission. By 1200 UTC, the turbulence is the highest in the planetary boundary layer and a strong mixing reduces vertical gradients of momentum and totally dissipates the jet. Based on radio soundings and UHF (ultrahigh frequency) wind profiler measurements, Lothon et al. (2008) identified some of the main characteristics of the NLLJ in Niamey (Niger): on average, the NLLJ is centered around 400 m agl and reaches its maximum of intensity at 0500 UTC. It forms throughout the year, with a higher occurrence during the dry and moistening periods (about 80% of the time) than during the wet season (about 60%).

2. During the wet season, very high wind speeds are associated with convective cells that develop into Mesoscale Convective Systems (MCS). MCSs propagate westward along the southern side of the Intertropical Discontinuity (ITD), a moisture boundary separating at the ground level dry and hot northern air from cool and moist southern air. Such storms are predominantly nocturnal (Bouniol et al., 2012; Nesbitt & Zipser, 2003), vary in scale but most of them have sizes ranging from tens to hundreds of kilometers (Laing & Fristch, 1993; Marsham et al., 2008; Roberts & Knippertz, 2012). Recently, Vizy and Cook (2017) revisited the origin of the MCSs over the southern Sahel (11°N–14°N) west of 15°E. They suggest that MCSs originate less than 1000 km upstream (to the north and east) in the afternoon, in a region largely devoid of significant orography. They link the development of the MCSs to the interaction between the Sahel ITD and to the expansion of the vertical mixing to the level of free convection in combination with a midtropospheric African easterly wave disturbance to the east. Squall lines, a linear type of MCS, represent about half of the major precipitating events over the central Sahel (D'Amato & Lebel, 1998; Laurent et al, 1998). In areas where the soils are easily erodible, the dust is lofted quasi-continuously along these fronts producing dust walls, called "haboobs," extending over altitudes ranging from 2,000 to 5,000 m agl (Williams et al., 2009).

Because of the importance of the Sahelian region for the dust cycle, various studies have investigated proxies of dust in this area. The long-time series of horizontal visibility and wind speed observations recorded in the SYNOP meteorological reports were used to point out the increase in both the frequency of occurrence and the annual duration of dusty conditions at the surface during the drought periods 1970–1974 and 1983–1987 (N'Tchayi et al., 1997). These records also permitted to investigate the temporal and spatial variability of dust content over the Sahelian region (Cowie et al., 2014; Goudie & Middleton, 1992; N'Tchayi et al., 1994, 1997). In particular, it was shown that the horizontal visibility in the Sahel exhibits a pronounced seasonal cycle directly connected to the shift from the Harmattan to the African monsoon regime at the transition between the boreal winter and the boreal summer. More recently, Cowie et al. (2015) suggested that rare high wind events are responsible for most of the interannual variability for the time period 1984–2012 in large part of the Sahara and Sahel regions. These studies allowed a better understanding of the temporal variability of the dust and wind patterns in the Sahel at low frequency. However, they failed to provide information on the variability at shorter time scales, especially that of dust emissions. Indeed, the SYNOP observations were reported in the best case every 3 h (and frequently every 6 h in Mali and Niger) and many meteorological stations did not record observations during nighttime.

Marticorena et al. (2010) and Kaly et al. (2015) reported the first observations of long-term and highly time resolved dust surface concentrations in the Sahelian region. These authors combined measurements of PM_{10} performed in three Sahelian stations with an analysis of the local meteorological conditions to identify the different types of dust events responsible for the observed seasonal cycle of the PM_{10} concentrations. They showed that the winter-spring maximum of dust concentrations is mainly due to Saharan dust transport in the Harmattan flow rather than Sahelian dust emissions. On the opposite, extremely high daily concentrations were recorded at the beginning of the wet season, that is, from the end of May to the end of July. These authors underlined that these high concentrations but short duration events (less than 1 h) were linked to the maximum daily surface wind speeds and that these high surface wind speeds were associated with the passage of MCS.

It is clear that the existing data, especially those having a too low frequency of observation like those recorded in the SYNOP meteorological stations or satellite observations, are not well suited to characterize precisely the duration, frequency, and dynamics of Sahelian dust emissions. In the same way, various authors (e.g., Cowie et al., 2015; Largeron et al., 2015; Roberts et al., 2017) have shown that reanalysis misrepresent major features of the mesoscale dynamics, and especially the increase of the surface wind speed associated with deep convection. On the other hand, recent field campaigns (AMMA, SAMUM, DABEX…) conducted in or in the vicinity of the Sahel have allowed to obtain detailed measurements of aerosol content and to perform meteorological observations with a higher frequency (e.g., Marsham et al., 2011). Thus, the results strongly suggested the key role of haboobs in creating high winds early in the monsoon season. Even in the Central Sahara, dust emission seems to be dominated by haboobs during summer (Marsham et al., 2013).

However, the observing periods of such campaigns are limited in time, making difficult to derive quantitative and/or representative climatological patterns of the dust emissions and to evaluate the respective role of the different drivers of wind erosion. As an example, the respective role of LLJ and MCS in dust uplift in the Sahel still remains in debate (Knippertz, 2014). In this paper, we use a 10 year data set of 5 min meteorological measurements recorded in two Sahelian observing stations to analyze the specific role that wind speed plays at various time scales on wind erosion and dust emissions in the central Sahel.

2. Materials and Methods

2.1. Data Acquisition

We use continuous measurements of meteorological data recorded from 2006 to 2015 in two dust observing stations belonging to the Sahelian Dust Transect (SDT) (Marticorena et al., 2010). These stations, located close to the small villages of Cinzana (Mali, 13.28°N, 5.93°W) and Banizoumbou (Niger, 13.54°N, 2.66°E), are about 900 km away from each other. They are positioned on the main transport route of Saharan and Sahelian dust toward the north-tropical Atlantic Ocean. The site of Cinzana, 40 km east-southeast of Segou, is embedded inside the agronomical research station of the Institut d'Economie Rurale (IER), 1.5 km away from the main SRAC (Station de Recherche Agronomique de Cinzana) buildings. The rainfall is about 770 mm, and the area of the meteorological station is protected by a vegetation cover mainly composed of small shrubs. In Niger, the station is installed in a more than 20 years old fallow embedded in a traditional fallows/fields area located at 2.5 km from the village of Banizoumbou (60 km east of Niamey). The rainfall is about 550 mm.

Meteorological measurements are performed at 6.5 m above ground level (agl) in Banizoumbou and at 2.3 m agl in Cinzana. Instrumentation has been selected based on criteria of simplicity of use and maintenance and capability to resist to severe dust and meteorological conditions. A Windsonic 2-D anemometer (Gill® Instruments Ltd.) provides the wind speed and direction averaged over a 5 min time step and the instantaneous (10 s) maximum wind speed observed over the 5 min period (only from 2007). Rainfall is monitored using an ARG100 aerodynamic precipitation sensor (Campbell® Scientific Instruments) working according to the principle of the "tipping bucket" mechanism. It provides a contact closure at each tipping (i.e., for each 0.2 mm of rainfall) and the number of tips is cumulated over a 5 min time step. Temperature and relative humidity are measured using a 50Y or HMP50 sensor. The energy is provided by solar panels. Both stations are maintained by local technicians trained by the technical responsible of the SDT. Data acquisition is performed using a CR200X Campbell® Scientific Instruments data logger. In this paper, we only use wind speed averaged over a 5 min time step and precipitation data.

Annual recovery rate for wind speed data for both sites and for the period 2006–2015 (Table S1 in the supporting information) is always greater than 90% except in 2013 in Cinzana where it is only 85% due to a failure of the solar panel and to the time required for its replacement. More precisely, the number of weeks for which less than 90% of the data were collected is 3.6% on both sites and 42% of them (16/38) occurred in November and December, that is, a period of the year during which wind speed is always low and no precipitation occurs.

As the dry and wet seasons are subject to very different meteorological conditions in the Sahel, we decided to distinguish these two seasons for presenting certain results. Based on precipitation data, we define the dry period as starting in November and ending at the end of March and therefore the wet period as covering the remaining months, that is, from 1 April to 31 October.

Table 1
Cumulative Occurrence of the Different Wind Speed Classes Above TWV for the Period 2006–2015 for Banizoumbou and Cinzana and Their Contribution to DUP (See Text for Details)

	Banizoumbou									
	>7 m s^{-1}	>8 m s^{-1}	>9 m s^{-1}	>10 m s^{-1}	>11 m s^{-1}	>12 m s^{-1}	>13 m s^{-1}	> 14 m s^{-1}	> 15 m s^{-1}	> 16 m s^{-1}
Wind speed	1.52%	0.56%	0.23%	0.12%	0.066%	0.037%	0.020%	0.011%	0.007%	0.004%
DUP	100%	82.1%	59.5%	43.5%	32.2%	23.2%	15.7%	10.7%	7.7%	5.0%
	Cinzana									
	>5.5 m s^{-1}	>6 m s^{-1}	>6.5 m s^{-1}	>7 m s^{-1}	>8 m s^{-1}	>9 m s^{-1}	>10 m s^{-1}	>11 m s^{-1}	>12 m s^{-1}	>13 m s^{-1}
Wind speed	0.40%	0.20%	0.101%	0.053%	0.018%	0.006%	0.0025%	0.0010%	0.0005%	0.0001%
DUP	100%	89.2%	71.1%	54.1%	31.1%	16.0%	8.7%	4.1%	2.53%	0.82%

2.2. Dust Uplift Potential

In the absence of quantitative information on dust emission in meteorological reports, Marsham et al. (2011) proposed to evaluate the dust emitting "power" of the wind by computing a Dust Uplift Potential (DUP) which allows to isolate the role of meteorology from that of the land surface on dust uplift. The computation of this parameter is derived from a formula expressing the horizontal flux of windblown sediment initially proposed by White (1979):

$$\mathrm{DUP} = u^3\left(1 + {}^{u_t}/_{u}\right)\left(1 - {}^{u}_{t}2/_{u^2}\right) \text{ for } u > u_t \text{ and 0 otherwise;}$$

where u is the wind speed at a given height and u_t the threshold wind velocity (TWV), that is, the minimum wind speed initiating the wind erosion. This threshold is controlled by surface characteristics such as the presence of solid obstacles (stones, pebbles …) or vegetation which increase the TWV by absorbing a part of the wind momentum. Rainfall events generate an increase in soil moisture which can also affect the wind erosion threshold (e.g., Bergametti et al., 2016; Fécan et al., 1999) and could lead to a decrease or a total suppression of dust emissions.

Since DUP characterizes only the potential contribution of wind speed to wind erosion, we use for both sites, a unique and constant TWV corresponding to a Sahelian bare soil. We fixed the TWV to 7 m s^{-1} at 6.5 m height to be consistent with the determination of the TWV performed by Abdourhamane Touré et al. (2011) on a bare soil in Banizoumbou. This value of the threshold wind speed for wind erosion and dust emission is in close agreement with the TWV = 8 m s^{-1} at 10 m height derived from SYNOP observations by Cowie et al. (2015) for their central Sahel group. In Cinzana, the wind speed being measured at 2.3 m height, it is necessary to convert the TWV = 7 m s^{-1} at 6.5 m height into an equivalent TWV at 2.3 m. This requires an assumption on the roughness length in the vicinity of the site. No measurement of this parameter being available, we estimate the roughness length from the literature. Xue (2006) recommend a roughness length of 0.06 m for surfaces corresponding to bare soil with shrubs. This value is consistent with the value previously retained for this site by Marticorena et al. (2010) following Bielders et al. (2004), that is, 0.05 m and with the measurements performed by Tuzet et al. (1994) over a fallow savannah (0.07 m) in Niger. With such a roughness length the TWV at 2.3 m equivalent to TWV = 7 m s^{-1} at 6.5 m is about 5.5 m s^{-1}. Table S2 reports the number of wind speed measurements above TWV for each site and for each year. Table 1 shows that wind speeds higher than 9 m s^{-1} in Banizoumbou and 7 m s^{-1} in Cinzana are responsible for more than 50% of the DUP, in agreement with Cowie et al. (2015) who showed that wind speeds between 2 and 5 m s^{-1} above the threshold cause the most dust emission. Thus, we also defined a TWVS corresponding to wind speeds significantly above TWV (i.e., = TWV + 2 m s^{-1} for Banizoumbou and TWV + 1.5 m s^{-1} for Cinzana).

2.3. Consistency of Data

To ensure the quality of the wind speed data, comparisons were conducted using two independent data sets: the data recorded in the meteorological station of Segou in Mali (located about 40 km from Cinzana) and the meteorological data set recorded from the Wankama station (Leauthaud et al., 2016) located at 13 km north of the station in Banizoumbou. At Segou, the wind speed measurements are performed following the protocol used in the SYNOP meteorological stations (wind speed measured at 10 m agl every 3 h). To make the comparisons significant, data from Cinzana were reformatted on the same time basis (computation of the

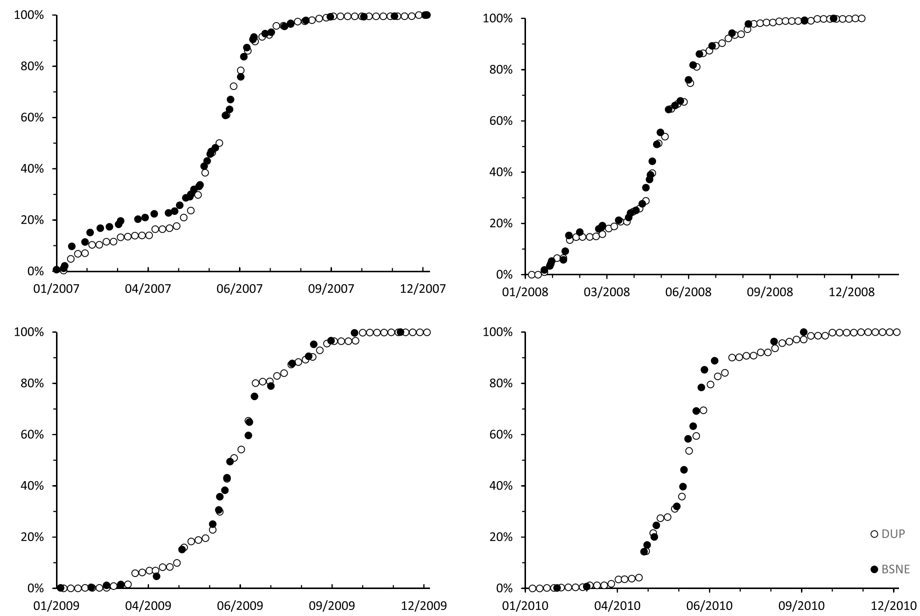

Figure 1. Comparison between cumulative weekly Dust Uplift Potential (DUP) and cumulative horizontal sediment fluxes measured using BSNE catchers in Banizoumbou from 2007 to 2010.

mean wind speed over the 10 min preceding each 3 h term). Because the time interval is large, we compared only the slope and the correlation coefficient, *r* of the two wind speed data sets. The correlation coefficient is always highly significant (greater than 0.5 for an annual number of couples of data ranging from 900 to 2700 depending on the number of available measurements performed each year). The slopes, even slightly variable from 1 year to another, do not show any trend that would suggest a possible drift in the instruments. In Wankama the wind speed is measured at 7.88 m agl and averaged over 30 min time step, and thus, the data from Banizoumbou were averaged over the same 30 min time step. In this case, we could directly compare the weekly computed DUP. The correlation coefficient *r* was 0.90 for 518 couples of data, and the slope between the annual DUP computed from each data set does not vary significantly from 1 year to another.

Rainfall is known to be highly inhomogeneous in space and time in the Sahel (e.g., Ali et al., 2005), mainly because more than 90% of the precipitation in this region are associated with MCS (e.g., Mathon et al., 2002). Thus, direct rainfall comparisons are difficult to perform, even between sites that are only few kilometers away from each other. However, the mean rainfall we measured and its seasonality are typical of the precipitation patterns observed from a climatological point of view at both sites (Ali et al., 2005; Lebel & Amani, 1999).

In order to check if the choice of a TWV of 7 m s^{-1} at 6.5 m height is reasonable, we compare the weekly cumulative DUP computed from the 5 min wind speed data in Banizoumbou with the cumulative horizontal fluxes of windblown sediment measured at the same location from 2007 to 2010 over a bare soil by using BSNE (Big Spring Number Eight, Fryrear, 1986) catchers mounted on poles at heights of about 5, 15, and 35 cm, that is, in the saltation layer (see for details, Abdourhamane Touré et al., 2011). The BSNE were continuously sampling throughout these years and were collected after each observed event. Figure 1 shows that the dynamics of the measured horizontal fluxes is well reproduced by the computed DUP suggesting that the value of TWV for a bare soil is correctly estimated and will allow to provide correct estimates of the wind erosion occurring over a sandy Sahelian bare soil.

3. Results

3.1. The Frequency of High Wind Speeds

The occurrences of the different wind speed classes above TWV cumulated over the period 2006–2015 for Cinzana and Banizoumbou are given in Table 1. The percentage of wind speeds exceeding TWV is low: only 1.5% in Banizoumbou and 0.4% in Cinzana. This means that the cumulative time during which wind erosion could have occurred is very short: only 132 h by year in Banizoumbou and 36 h per year in Cinzana on average over the period 2006–2015. The percentage of the highest wind speeds (higher than TWVS) is even lower, but these winds strongly impact the DUP: 60% of the annual DUP in Banizoumbou and more than 50% in Cinzana results from these high wind speeds that account for less than 0.25% of the wind speed distribution. Cowie et al. (2015), by using observations provided by the SYNOP meteorological stations, indicated that in regions where TWV is low, like in the Sahel, 25% of DUP results from events that only occur between 0.1% and 1.4% of the time. Based on better time-resolved wind speed measurements our results significantly reevaluate this estimation upward.

The frequency of TWVS also exhibits a large variability from year-to-year: in Banizoumbou and Cinzana, it varies by a factor of 2 between the most and the least windy years (respectively 0.36% (2008) to 0.15% (2014) and 0.072% (2006) to 0.036% (2008)). This suggests that the annual frequency of the rare but very high wind speed events controls the larger part of the interannual variability of DUP (Figure S1) and thus probably a large part of that of wind erosion and dust emission from the central Sahel as also reported by Cowie et al. (2015) for the time period 1984–2012 for five of the six regions of the Sahara/Sahel. Thus, considering their intensity, their scarcity and their year-to-year variability, intense wind erosion events in the Sahel should be considered as extreme meteorological events.

3.2. The Duration of High Wind Speed Events

The capability of identifying dust emissions from existing meteorological records or from satellite observations strongly depends on the adequacy between the duration of such events and the frequency of these types of observations. In addition, the duration of the high wind speed events in the Sahel should be accounted for in dust emission models. This raises questions on the time step of the meteorological fields the models use as input data. In this context, quantifying the duration of the high wind speed events is extremely valuable.

Assessing the duration of the high wind speed events implies to define criteria for identifying the beginning and the ending of such events. We considered that a high wind speed event starts when the wind speed exceeds TWV during one 5 min time step. It is less easy to define a criterion for defining when a high wind speed event ends: after testing, we decided that a high wind speed event stops after a wind speed greater than TWV if no wind speed greater than TWV is recorded during the two following hours. In other words, we classify two periods where winds are above threshold which are less than 2 h apart as one single event. In fact and as mentioned previously, the periods of high wind speeds are generally well defined and associated with meteorological processes that occur systematically in the morning (those linked to the NLLJ) or more sporadically during nighttime (those linked to MCS), making them generally well separated and their identification quite easy. We classified these high wind speed events into 5 min classes of duration and we computed the DUP for these classes and for each station.

Over the 10 year period, 1,079 events of wind speed above TWV are identified in Banizoumbou with durations ranging from 5 to 625 min and 703 events in Cinzana with durations ranging from 5 to 530 min. The cumulative distribution of the durations (Figure 2) shows that these high wind speed events are very short: 20% of the events with wind speeds greater than TWV last for less than 10 min and correspond, for the most part, to wind speeds very close to TWV. More interestingly, about 50% last for less than 1 h in Banizoumbou and of less than 30 min in Cinzana. Moreover 82% of the events in Banizoumbou and 93% in Cinzana last for less than 3 h. These results show that high wind speed events in the Sahel are very short: both in Banizoumbou and Cinzana, no period of high wind speed have a duration exceeding half a day during the 10 years of records.

Concerning DUP, the contribution of the short events to the total DUP remains dominant even if it is less pronounced than for the number of events: 50% of the DUP on an annual scale are due to high wind speed events having a duration less than 2 h45 in Banizoumbou and less than 1 h20 in Cinzana. This strongly suggests that observing systems having a too low frequency of observations are not suited to investigate the frequency and timing of the high wind speed events in the Sahel and thus cannot provide precise quantitative estimates of DUP in this region.

3.3. Diurnal and Seasonal Cycles of DUP

As mentioned before, the contribution of haboobs to dust emissions in the Sahel is still a debated question. For example, Engelstaedter and Washington (2007) analyzed Aerosol Indexes derived from TOMS (Total

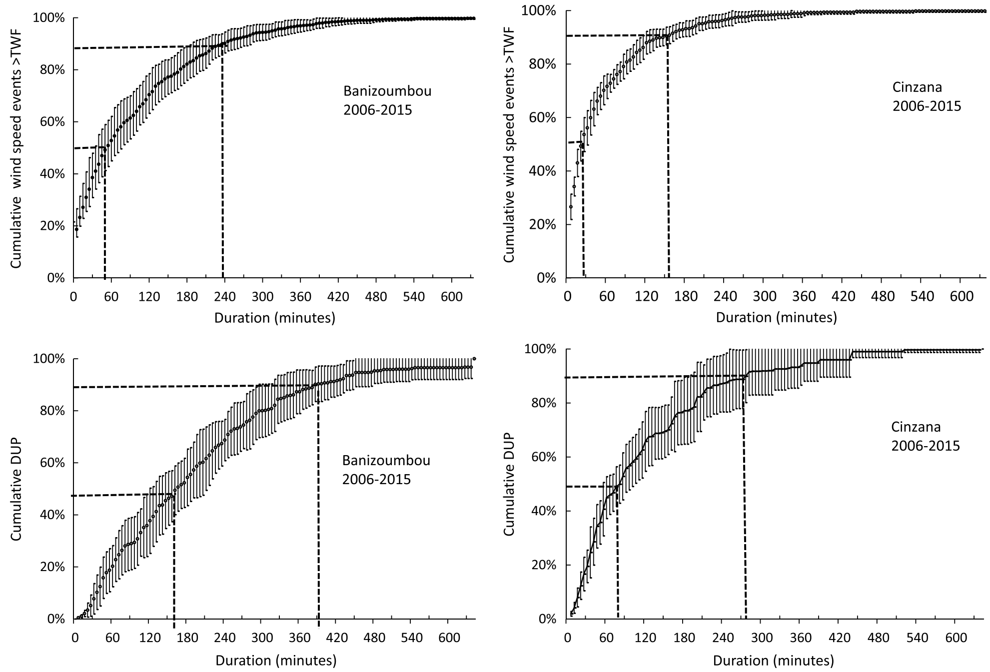

Figure 2. Cumulative distributions of the duration of wind speed events >TWV (top) and of DUP (bottom) for Banizoumbou (left) and Cinzana (right) averaged over the period 2006–2015. The gray envelope corresponds to the minimum and maximum cumulative percentages observed for each class during the 10 years of measurements.

Ozone Mapping Spectrometer) satellite observations to identify the main dust sources in North Africa. They concluded that in the Sahel emissions were highest in winter. The publication of this paper initiated a discussion focused on how the haboobs can be (or not) detected by TOMS in presence of summer cirrus clouds (Engelstaedter & Washington, 2008; Williams, 2008). In addition, the fact that the TOMS instrument provides observations once a day at ~12 h may result in a sampling bias. In particular, this could lead to the underrepresentation of the dust generated by haboobs and thus limit the capability of such instrument to quantify their contribution to the Sahelian dust emissions. Moreover, simulations performed by Heinold et al. (2013) suggested that up to 90% of the dust mobilized from afternoon to night are partly covered by clouds, while up to 60% of the dust emissions between morning and noon occur under clear-sky conditions. This was also underlined by Kocha et al. (2013) who showed that the undersampling of the diurnal cycle by satellites plus the impact of cloud masks on the spaceborne aerosol optical depth retrievals induce an underestimation of the dust emissions in convective regions and an overestimation over morning source areas. In the same way, Cowie et al. (2014) underlined that the lack of data during nighttime in the SYNOP meteorological reports from the Sahelian stations could induce a bias when interpreting the diurnal cycle of the wind speed and DUP derived from these observations. As mentioned by Knippertz and Todd (2012), there is a clear need to better quantify the contribution of haboobs to dust emissions. An analysis of the diurnal cycle of DUP depending on the season can provide quantitative elements on what are the respective contributions of morning and nocturnal high wind speed events to the annual DUP.

To analyze the diurnal pattern of the wind speeds and DUP in Banizoumbou and Cinzana over the 10 year period, we computed, for both the dry and the wet seasons, the hourly number of wind speeds (i) above TWV and (ii) above TWVS. We also computed the hourly DUP for both the dry and the wet seasons for the two sites (Figures 3a and 3b).

The results clearly show that the wet season is significantly more windy than the dry season, even by considering that the wet season we defined (April to October) is longer than the dry season (November to March): the mean DUP by day (in $m^3\ s^{-3}$) during the dry and the wet season in Banizoumbou and Cinzana are 372 and 2,043 and 5.6 and 224, respectively. This is striking in Cinzana: over the 10 year period, 587 5 min periods of wind speeds above TWV are recorded in the dry season against 7,927 in the wet season. In Banizoumbou,

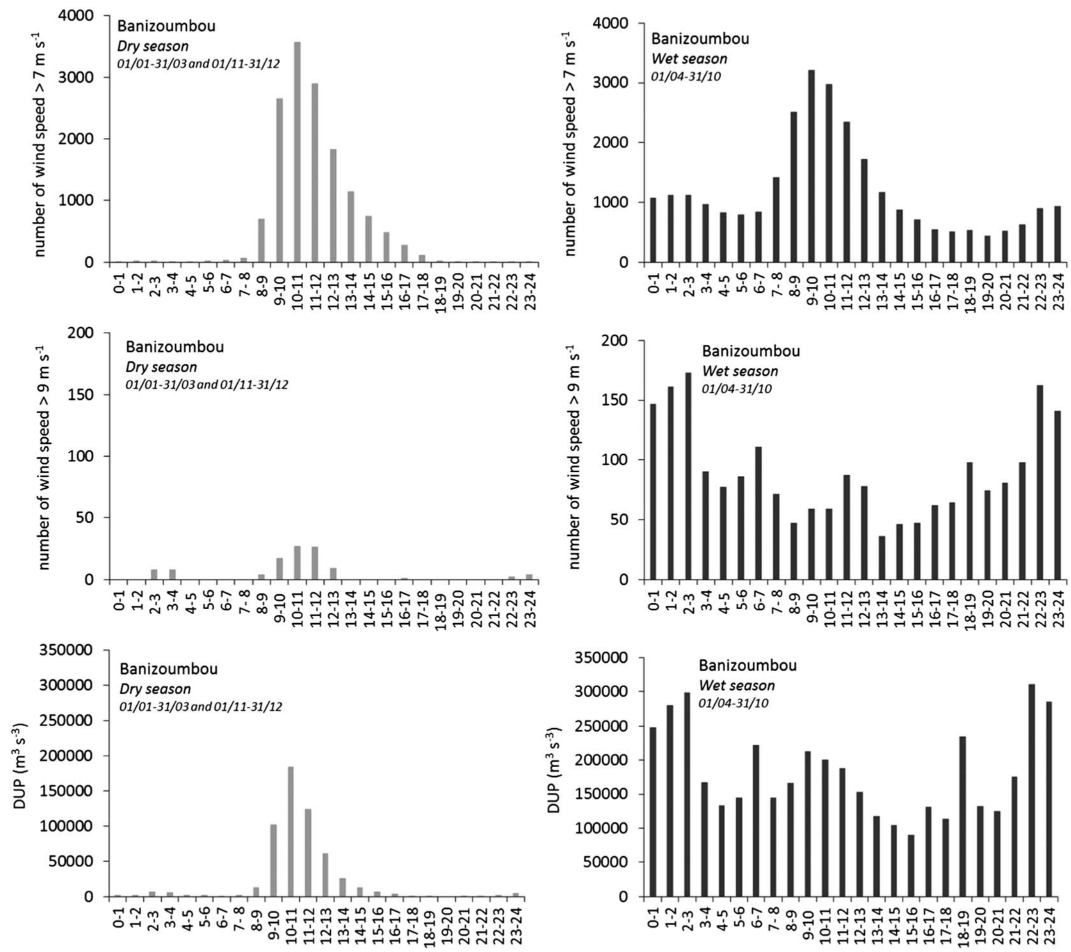

Figure 3a. Diurnal cycle of the number 5 min periods of wind speeds >7 m s^{-1} (top), >9 m s^{-1} (middle) and DUP (bottom) in Banizoumbou (Niger). Left: dry season, right: wet season.

the difference between the dry and wet seasons (14,674 versus 28,629) is less impressive but remains highly significant (about a factor of 2).

During the dry season, wind speeds above TWV are mainly observed during the morning and early afternoon both in Banizoumbou and Cinzana: more than 80% of the wind speeds higher than TWV are recorded between 0800 and 1400 UTC with higher occurrences peaking between 1000 and 1100 UTC. However, these wind speeds are relatively weak, exceeding TWV only slightly: indeed, at that time, TWVS account for only 0.72% in Banizoumbou and 1% in Cinzana of the total wind speeds exceeding TWV. Very few wind speeds greater than TWVS are recorded during the dry season: they occur mainly in the late morning in Banizoumbou, while they are only observed in midafternoon in Cinzana. As a consequence, the maximum of DUP in the dry season occurs in the late morning in Banizoumbou, while DUP exhibits two maxima in Cinzana: one in the late morning and another one in the late afternoon. This is consistent with the conclusions reported by Kaly et al. (2015) derived from hourly PM_{10} measurements performed in Banizoumbou and Cinzana. Indeed, these authors mentioned that during the dry season the magnitude of the PM_{10} concentrations is rather controlled by the intensity of the dust transport from the Sahara than by Sahelian local emissions.

During the wet season, the diurnal cycles of wind speeds above TWV in both sites are quite similar to those observed during the dry season. The occurrence of wind speeds above TWV is peaking again in the morning, but the maximum appears 1 h earlier than during the dry season. Moreover, compared to the dry season, wind speeds above TWV occur more frequently throughout the day, and the wind speeds above TWV recorded between 8 h and 14 h contribute only about 50% to the total number of wind speeds above

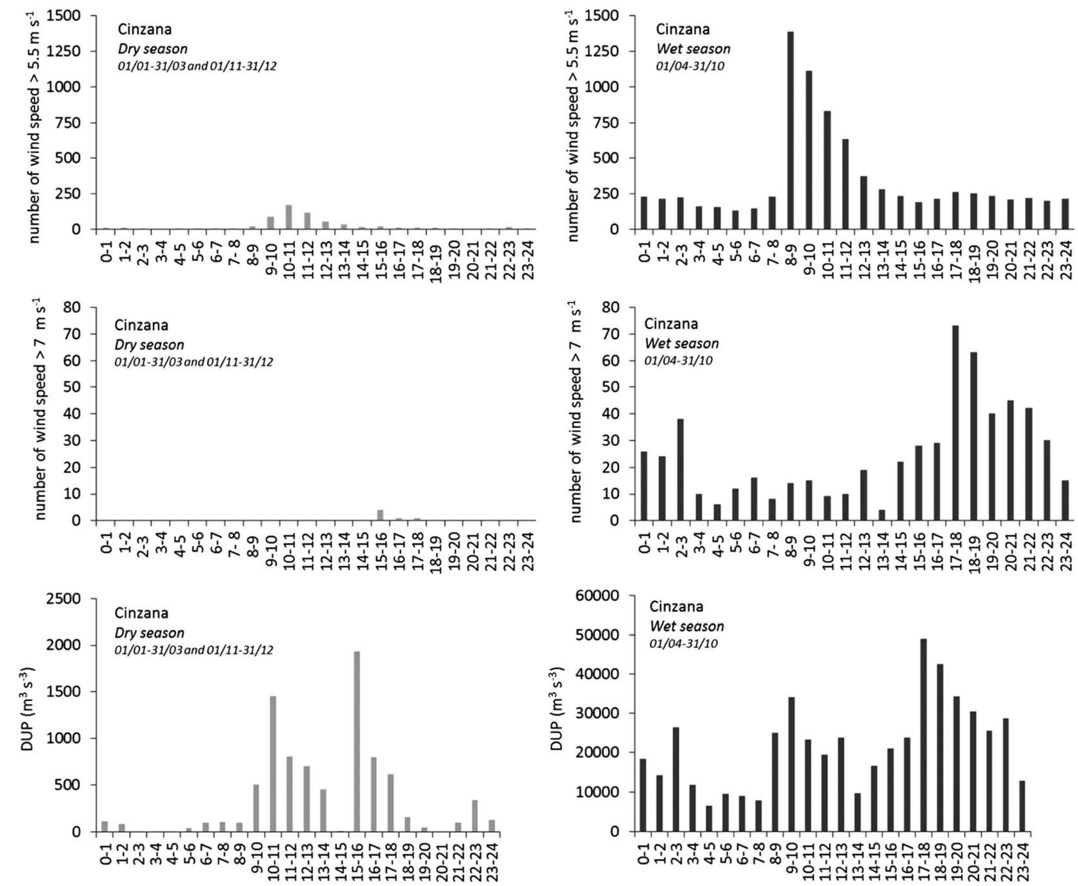

Figure 3b. Diurnal cycle of the number 5 min periods of wind speeds >5.5 m s^{-1} (top), >7 m s^{-1} (middle), and DUP (bottom) in Cinzana (Mali). Left: dry season, right: wet season.

TWV during the wet season. However, the main difference between dry and wet season is the highest occurrence of wind speeds above TWVS during the wet season. These highest wind speeds are most frequently recorded during the night (between 2200 and 0300 UTC) in Banizoumbou and in the late afternoon (between 1700 and 2200 UTC) in Cinzana as also observed by Marsham et al. (2013) for the Central Sahara. Thus, in the wet season, 50% of DUP in Cinzana and 58% in Banizoumbou are due to wind events occurring between 18 h and 6 h.

The results show that the systematic intrusion of the nocturnal low-level jet at the surface in the morning is the major process generating wind speeds above TWV during the dry season in the central Sahel. Indeed, high wind speeds occurring between 0600 and 1400 UTC contributed 95% to DUP in Banizoumbou and 49% in Cinzana during the dry season. However, most of these wind speeds are just above TWV suggesting that they can generate frequent but only weak wind erosion events. During the wet season, the morning contribution of the NLLJ to DUP is maintained but is much less dominant (32% and 29% in Banizoumbou and Cinzana, respectively) since sporadic but intense wind speed episodes very likely connected with the passage of MCS are recorded during late afternoon and nighttime. During this period, the diurnal cycle of DUP exhibits a maximum between 2200 and 0300 UTC in Banizoumbou and in the late afternoon in Cinzana with a second maxima for both sites in the morning (similar to that observed in the dry season). At the annual scale, the contribution of the morning high wind speeds (from 0600 to 1400 UTC, i.e., the contribution of NLLJ) to DUP was 38.8% in Banizoumbou and 29.4% in Cinzana. Assuming that the high wind speed events occurring between 1700 UTC–0400 UTC during the wet season are mainly MCS generating haboobs, we can conclude that these MCS accounted for 46.2% of the annual DUP both in Banizoumbou and Cinzana, suggesting that these events are probably the dominant sources of DUP in the central Sahel. It should also be noted that high wind speed events occurring in the afternoon (i.e., between 1400 and 1800 UTC) contribute for 21.3% to the

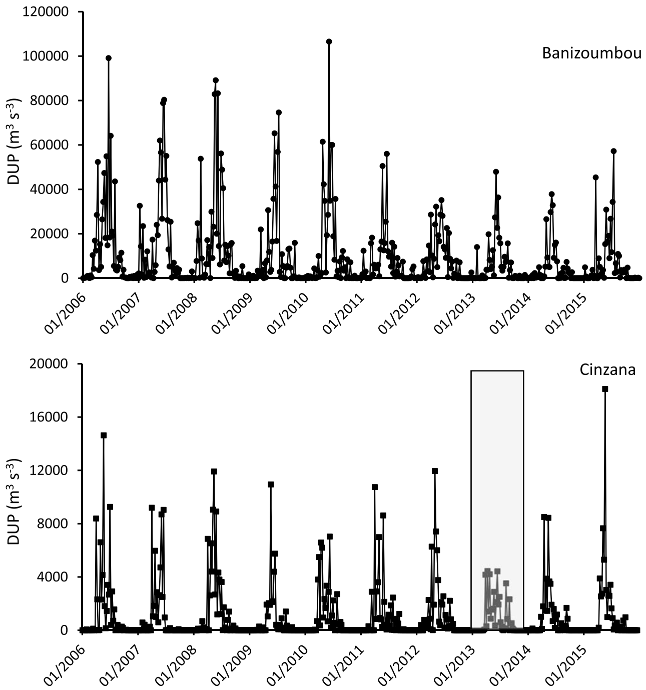

Figure 4. Weekly Dust Uplift Potential (DUP) from 2006 to 2015 in Banizoumbou and Cinzana. The gray area in Cinzana corresponds to 2013, a year for which the rate of recorded wind speeds is only 85%.

annual DUP in Cinzana and are probably also linked to convective processes (75% of the high wind speed events occurring in the afternoon are associated with precipitation and the events associated with precipitation exhibit higher wind speeds). Moreover, simulations performed by Heinold et al. (2013) have pointed out that during the core of the wet season (from 25 July to 2 September), aging cold pools can glide up over a radiatively formed stable nocturnal boundary layer and trigger NLLJ formation over a wide area by locally induced pressure gradients. When looking at the median panels of Figures 3a and 3b, it can be noted that the frequency of the morning wind speeds >TWVS are slightly higher in the wet season than during the dry season. This suggests that the convective systems have also an indirect effect on DUP at this period by contributing to increase the frequency and the intensity of the morning wind speeds associated to the breakdown of the NLLJ.

Figure 4 reports the year-to-year variation of the DUP from 2006 to 2015 and shows that DUP followed a well-marked seasonal cycle with a maximum observed during the wet season at both sites. However, this seasonal cycle (i) does not exhibit the same interannual variability at the two stations and (ii) does not have the same amplitude from 1 year to another. In Banizoumbou, the period 2006–2010 appears to have been windier than the recent years. The ratio between the maximum (2008) and minimum (2014) annual DUP is 3.2 which is a huge difference mainly due, as mentioned in section 3.1 and shown in Figure S1, to changes in the frequency of the highest wind speeds. In Cinzana, the interannual variability of DUP was almost 2 times lower (1.7 between the maximum (2008) and the minimum (2009) annual DUP). Concerning the amplitude of the seasonal cycle, the dry season contributed 15 and 20% to the annual DUP in Banizoumbou in 2007, 2008, 2011, and 2015 but for only less than 6% in 2010, 2013, and 2014. In Cinzana, the contribution of the dry season to the annual DUP is very limited, the maximum being observed in 2011 and 2012 (6.8 and 4.1%, respectively), while the dry seasons of all the other years have contributions to the annual DUP lower than 2%.

The annual cumulative DUP averaged over the period 2006–2015 as reported in Figure 5 shows that DUP was mainly produced by events occurring between April and mid-July since 87% and 68% of DUP are generated between 15 April and 21 July in Cinzana and Banizoumbou, respectively. This high wind speed period at the early stage of the wet season can be illustrated by the occurrence of the different wind speed classes throughout the year (Figure 6). The higher the wind speed class is, the later in the year the 50% of occurrence (F50) is reached. There is a gradual change in wind speed toward higher values as the installation of the rainy season progresses: in Banizoumbou, the F50 is reached at the end of April for the wind class 7–8 m s^{-1}, at end of May for the class 9–10 m s^{-1} and mid-June for the highest wind speed classes. However, as it can be seen in Figure 6, the cumulative curves of occurrence for the different wind classes crosses at the end of July showing that the highest wind speeds are less frequent during the core of the wet season as observed by Rajot (2001).

Moreover, over the 10 year period, the 5 weeks with the most intense wind speeds (i.e., leading to higher DUP) in the year occur in 90% (in Banizoumbou) and 96% (in Cinzana) of the cases between 15 April and 21 July the remaining 10% being recorded during the dry season and not during the core of the wet season. This is in agreement with Marsham et al. (2008) that reported that there is both more dust and more downdraft convective available potential energy (DCAPE) during the monsoon onset than during its retreat. These authors suggested that DCAPE is higher during monsoon onset due to a drier free troposphere, a drier midtroposphere consistently leading to more intense cold pools, as inferred by Barnes and Sieckman (1984).

Over this period (15 April to 21 July), the contribution of the morning high speeds to DUP is 31 and 29% in Banizoumbou and Cinzana, respectively, and is very similar to that observed during the whole wet season.

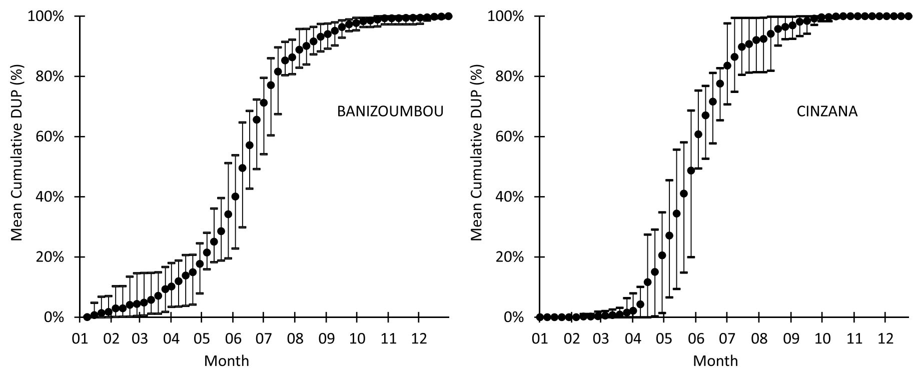

Figure 5. Annual cumulative DUP averaged over the period 2006–2015 in Banizoumbou (top) and Cinzana (bottom). Minimum and maximum over the period (vertical bars) are also reported.

High wind speeds, mainly linked to MCS that occur in the late afternoon or during nighttime, represent respectively 54 and 48% of the DUP during this early stage of the wet season.

Our results show that the occurrence of the highest wind speeds during the first stage of the monsoon period explains to a large part the seasonal cycle of DUP and probably that of dust emissions. This timing has strong implications for wind erosion since these highest wind speeds blow when the agricultural fields have been cleared by the farmers in order to be ready for the new planting season. At that time agricultural soils are bare, and thus, it is the time of the year during which they are the most erodible (Abdourhamane Touré et al., 2011; Pierre et al., 2014). In the same way, during this period, due to pasture and/or natural decomposition, rangelands exhibit a minimum residue of the vegetation of the previous year and thus are also potentially more erodible than at any other time of the year (Kergoat et al., 2017; Pierre et al., 2015). This suggests that at least in this part of the Sahel, there is a near perfect conjunction between the period of the year during which the soil surface is the most erodible and the period during which the frequency of strong winds is maximum.

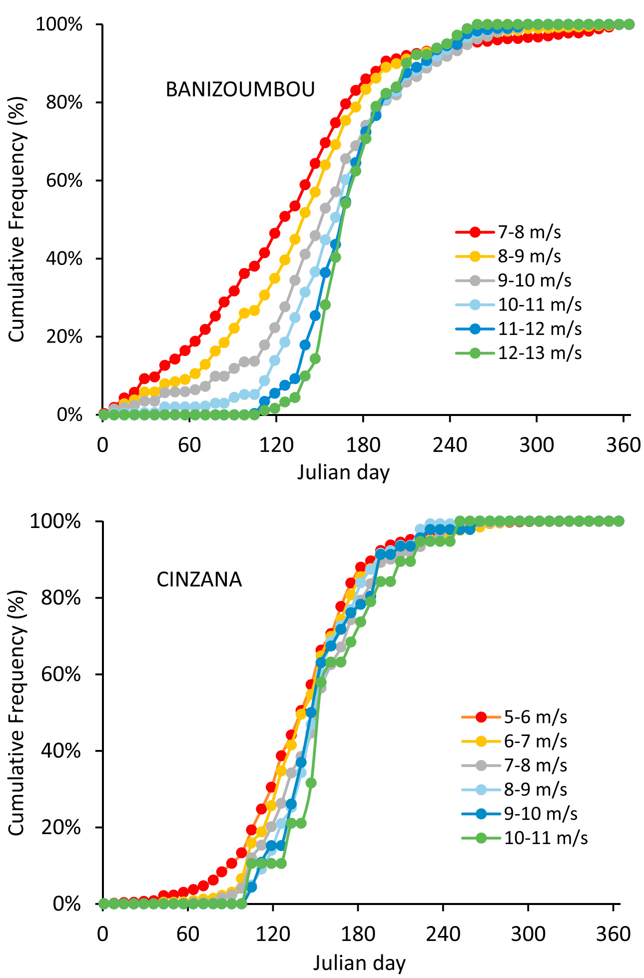

Figure 6. Cumulative frequency of different wind speed classes in Banizoumbou (top) and Cinzana (bottom) averaged over the 2006–2015 period.

3.4. DUP and Rainfall

In agreement with our results, Williams et al. (2009) assumed that the production of dust in the Sahel maximizes in the early wet season (June and July) but he also evokes the fact that the wetting of the soil by rainfall could suppress the lofting of dust as the wet season progresses. Indeed, rain increases soil moisture and allows capillary forces to develop between soil grains, reinforcing soil cohesion, thus increasing the minimum threshold wind velocity required to initiate the movement of soil by wind (e.g., Belly, 1964). Recently, Bergametti et al. (2016) investigated the role of rain events in the inhibition of saltation in Banizoumbou. They used simultaneous 5 min measurements of saltation, wind speed, and rainfall performed before, during, and after 18 rain events. Their results point out that wind erosion is not totally inhibited once rain begins and that less than 12 h was necessary after a rain event to almost fully restore the sand transport potential in this region.

Thus, to try to quantify the effect of the rain events on wind erosion and dust emission in the central Sahel, we computed a "DUP inhibited by rain." This new DUP is computed like the previous one but with a total inhibition of the erosion (DUP = 0) as soon as precipitation equals or exceeds 0.4 mm and during the 12 h following the end of a rain event, as suggested by Bergametti et al. (2016). We also computed for each year and with a 1 week time step, the cumulative rainfall, number of

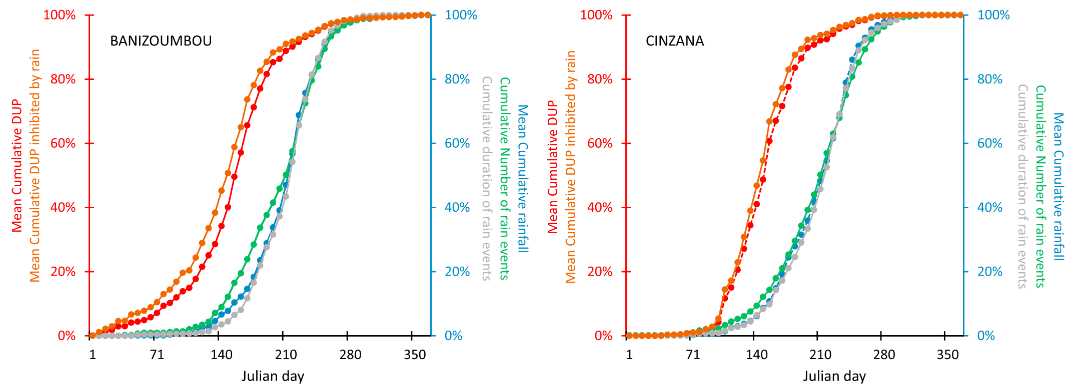

Figure 7. Annual (averaged over the period 2006–2015) cumulative rainfall, number, and duration of rain events, DUP and DUP inhibited by rain for Banizoumbou (left) and Cinzana (right).

rain events, and duration of the rain. Figure 7 reports the results of these computations averaged over the 10 year period.

We observe that for both sites, there is almost no differences in the annual trend of the cumulative rainfall, number, and duration of rain events. This is consistent with the observations reported by Marticorena et al. (2017) who have shown that in this region the cumulative rainfall and the duration of the rain events are well correlated. On average over 10 years, the rainy season starts about 1 week earlier and ends 1 week later in Cinzana (1 April and 1 November on average) than in Banizoumbou.

Figure 8 confirms that DUP is clearly at its maximum in May, June, and July. Its slow increase during the dry season (i.e., before the start of rainy season) is only due to the wind speeds just above TWV linked to the NLLJ. There are few differences between DUP and DUP inhibited by rain (Figure 7). Obviously, the inhibition of DUP is maximum when both high wind speed and frequent rain occurred in conjunction, that is, mainly in June and July. Earlier in the season, rain has not arrived or is not sufficiently frequent to significantly reduce DUP and later in the season, as seen in section 3.4, the wind speed decreases, and there is less DUP to be inhibited by rain. However, rain has a significant but relatively limited role in terms of inhibition of wind erosion in this region (precipitation only affecting 25% of the DUP on average in Cinzana (maximum: 36% in 2009; minimum: 12% in 2006) and 26% in Banizoumbou (maximum: 34% in 2015; minimum: 18% in 2010). This limitation of the inhibiting effect of the precipitation results from the specific timing of occurrence of high winds compared to the occurrence of precipitation. This suggests that the seasonality of the wind erosion is mainly driven by the variability of the wind speed and not by the precipitation.

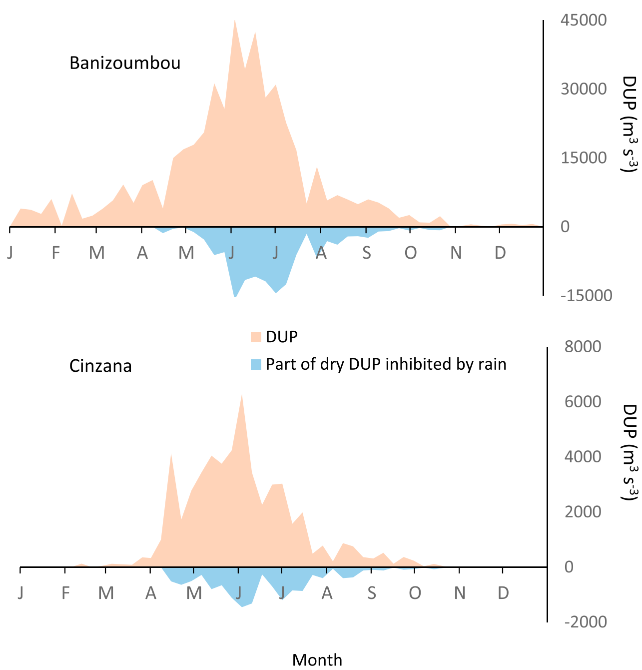

Figure 8. Annual dry DUP (brown area) and part of this DUP inhibited by rain (blue area) averaged over the period 2006–2015.

4. Conclusions

Ten years of unprecedented high temporal resolution meteorological data recorded at two observing stations located in Niger and Mali have provided a more complete picture of the temporal dynamics of DUP (and thus indirectly of dust emissions) in the central Sahel. In particular, the frequency of the data and their continuity over 10 years enabled to better define the diurnal and seasonal cycles of DUP and to quantify the respective roles of NLLJs and convective systems (including haboobs) in its dynamics.

Results first show, in agreement with Cowie et al. (2015) that wind erosion and dust emissions in the Sahel are rare events, the wind speeds greater than TWV accounting for only 1.5% and 0.4% of the time in Banizoumbou and Cinzana, respectively. Moreover, the periods exhibiting the highest wind speeds, those responsible for the major wind erosion events, are even less frequent since they never represented more than 0.2% of the time. The duration of the wind erosion events is very short in the Sahel: more than 80% of the high wind velocity periods have duration of less than 3 h. Thus, intense wind erosion events in the Sahel should be considered as extreme meteorological events for which the determination of climatological patterns or trends should require multidecennial observations at high temporal resolution. This strongly argues for the implementation in this region of an observing network allowing to acquire more long-term series of basic meteorological parameters (wind speed and direction, rainfall, …) measured at relatively high frequency. Indeed, this appears to be a prerequisite in order to obtain a better quantification of the role of the different processes involved in dust emissions over the whole Sahelian region. The two 10 year measurement series we collected for this study demonstrate the technical feasibility of such a network.

The diurnal cycle of the DUP is significantly different between the dry and the wet season. In the dry season, whatever the wind velocity class, most of the periods exhibiting wind velocities above TWV occur in the late morning, mostly between 0800 and 1400 UTC. Thus, the DUP is also maximum at that time. During the wet season, the diurnal cycle is characterized by a higher occurrence of wind velocities above TWV around midday but with wind velocities just slightly above TWV. Indeed, the diurnal cycle of DUP for wind velocities higher than TWVS has a maximum between 2100 and 0300 UTC in Banizoumbou and between 1700 and 0300 in Cinzana, and not in late morning. These results are in agreement in terms of occurrence with the analysis performed by Schepanski et al. (2009) of the 15 min observations from the instrument SEVIRI (Spinning Enhanced Visible and Infrared Imager) aboard Meteosat Second Generation (MSG) to detect dust source activation. They concluded that the maximum frequency of dust initiation was in the midmorning period for all dust sources and all seasons in the Sahara and Sahel. Our results also show that in the central Sahel, the NLLJ controls the frequency of wind erosion events. However, the diurnal cycle of DUP in Banizoumbou and Cinzana suggests that in this region, most of the annual DUP (and probably of dust emission from a quantitative point of view) is due to rare but intense events occurring in the late afternoon and during nighttime in the beginning of the rainy season. This highlights the need for distinguishing between the most frequent and the most intense dust source regions.

DUP exhibits a strong seasonal cycle with more than 70% of the annual DUP occurring between April and mid-July, that is, during the early stage of the rainy season in agreement with the analysis performed by Marsham et al. (2008) using satellite retrievals and European Centre for Medium-Range Weather Forecasts model fields. Indeed, the Mesoscale Convective Systems occurring at that time are those associated with the highest wind speeds and some of them are dry squall lines with no rain reaching the ground. Moreover, during this period of the year, the vegetation cover is low, both in natural grassland where the remaining dry vegetation of the previous wet season is at its minimum and in agricultural fields which have been completely cleared in anticipation of the new rainy season. Thus, the DUP is maximum when the surface is the most erodible leading to intense wind erosion events at this period. The second part of the wet season, from 15 July to end of October is rainier but less windy as mentioned by Abdourhamane Touré et al. (2011) and Kaly et al. (2015). The computation of the DUP also suggests that wind erosion events occurring during the dry season have low intensity, since the highest wind speeds at that time are only slightly exceeding the TWV. As an example, in Banizoumbou, the wind speeds exceeding the TWV in the dry season represents about 35% of the time in the year but they contribute on average to less than 11% of the annual DUP.

Precipitation seems to affect wind erosion in the Sahel in a limited way: when considering the inhibiting effect of rain on wind erosion, DUP is only reduced by about 25% both in Banizoumbou and Cinzana. Rain mainly affected DUP when high wind speed and frequent rain events are in conjunction, that is, in June and July. However, beside this direct impact, precipitation controls the growth of vegetation, which in turn can impact wind erosion during the ongoing season. Vegetation of the ongoing season also impacts the wind erosion and the dust emissions of the following season through the presence of dry residue that can protect the surface from wind erosion (Abdourhamane Touré et al., 2011; Kergoat et al., 2017).

Finally, the fact that a large part of DUP results from intense but short-lived convective events raises questions about the reliability of dust simulations resulting from large-scale models, at least for this region. Indeed, these simulations are based on wind fields provided by weather or climate models which do not explicitly solve the moist convection and thus which miss most of the convective events. There is therefore an urgent need to develop suitable parameterizations of convective dust storms for improving dust simulations from large-scale models. Fortunately, works are ongoing in this direction (e.g., Pantillon et al., 2015, 2016).

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