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Variability of mineral dust concentrations over West Africa monitored by the Sahelian Dust Transect

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ABSTRACT

The "Sahelian belt" is known as a region where mineral dust content is among the highest in the world. In the framework of the AMMA international Program, a transect of three ground based stations, the "Sahelian Dust Transect" (SDT), has been deployed in order to obtain quantitative information on the mineral dust content over the Sahel. These three stations: Banizoumbou (Niger), Cinzana (Mali) and M'Bour (Senegal) are aligned at 13°N along the east–west main pathway of the Saharan and Sahelian dust toward the Atlantic Ocean. The SDT provides a set of aerosol measurements and local meteorological parameters to describe and understand the mechanisms that control the temporal and regional variability of mineral dust content in these regions.

In this work we analyze the seasonal and diurnal variability of the dust concentrations over the period 2006–2010. The analysis of the dust concentrations measured between 2006 and 2010 confirmed a regional seasonal cycle characterized by a maximum in the dry season, with median concentration ranging from 205 μg m^{-3} at Banizoumbou to 144 μg m^{-3} at M'Bour, and a minimum (11–32 μg m^{-3}) in the wet season. The five year data set allowed the quantification of the variability of the monthly concentrations. The range between the percentiles 75 and 25 varies linearly with the median concentration: it is of the same order than the median value in M'Bour, 17% slightly higher in Cinzana and 50% higher in Banizoumbou. The range between the accepted maximum and minimum is also correlated with the median value, with slopes ranging from 14 in Banizoumbou to 7 in M'Bour. Part of the variability of the concentration at the monthly scale is due to interannual variability. Extremely high or low monthly concentration can be recorded that significantly impacts the five year median concentration and its range. Compared to the 3-year data set analyzed by Marticorena et al. (2010), the two additional years used in this work appear as the less dusty year (2009) and one of the dustier years (2010).

The sampling time step and the high recovery rates of the measurement stations allowed to investigate the diurnal cycle of the dust concentration for the first time. During the dry season, the hourly median concentrations range from 80 to 100 μg m^{-3} during the night to 100–160 μg m^{-3} during the day-time maximum. The diurnal cycle of the PM_{10} concentrations is phased with the diurnal cycle of the surface wind speed and thus modulated by the interactions between the nocturnal lower level jet (NLLJ) and the surface boundary layer. The NLLJ appears as a major agent to transport Saharan dust toward the Sahel. During the wet season, the median PM_{10} concentrations are maximum at night-time (<50 μg m^{-3}). The night-time concentrations are associated with a large range of variability and coincide with the periods of higher occurrence of meso-scale convective systems. The amplitude of the diurnal cycle is of the order of 60 μg m^{-3} in the dry season and 20 μg m^{-3} in the wet season. Both in the dry and in the wet season, despite a month to month variability of the daily dust concentration, a typical diurnal pattern has been established suggesting that this temporal pattern is mainly driven by local meteorological conditions.

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1. Introduction

The Sahara and Sahel regions are the largest arid to semi-arid areas of the world and the most important sources of mineral dust with annual emissions estimated between 400 and 2200 Tg (e.g. Huneeus et al., 2011).

These aerosols influence the Earth's radiative budget directly by scattering and absorbing solar radiation in the atmosphere and indirectly by affecting cloud formation and, thus, cloud albedo (Sokolik and Toon, 1999). Mineral dust radiative forcing represents therefore a significant uncertainty in predicting climate change. Their radiative effects also have an impact on atmospheric dynamics at the local and regional scales and mineral dust may be responsible for the inhibition of hurricane activity on the tropical North Atlantic (Evan et al., 2006). This interaction between mineral dust and radiations is such that it affects the quality of forecasts of West Africa (Tompkins et al., 2005). Mineral dust transported over long distances can play a decisive role in the availability of nutrients (such as iron and phosphorus) for large oceanic and some continental ecosystems (Swap et al., 1992; Jickells et al., 2005).

Finally, mineral dust is suspected to play a role in the occurrence of meningitis epidemics in the Sahelian "meningitis belt". Indeed, meningitis outbreaks occur during the dry season, a few weeks after the maximum levels of mineral dust that can act as irritant and thus favor the development of the disease (Martiny and Chiapello, 2013; Deroubaix et al., 2013). Thomson et al. (2006) also suggest that the high dust concentrations anomaly in late autumn could increase the incidence of meningitis epidemics.

The evaluation of the different impacts of mineral dust requires the quantification of its atmospheric content, in particular near source areas. Such quantification must take into account the strong variability of the atmospheric concentrations induced by weather conditions, which affect emissions, transport and deposition of these aerosols.

Seasonality and variability of mineral dust occurrence over the North tropical Atlantic Ocean have been extensively studied in recent decades. In the Sahel and the Sahara, aerosol optical depths (AODs) measured by sun photometers from the AERONET network (http://aeronet.gsfc.nasa.gov/) have allowed to investigate the seasonal cycle of the vertically integrated atmospheric dust content in different stations of West Africa (Holben et al., 2001; Ogunjobi et al., 2008). Based on aerosol indexes (AIs) from the TOMS (Total Ozone Mapping Spectrometer) spatial instrument, Engelstaedter et al. (2006) showed a well-marked annual cycle of the mineral dust load in North Africa. On a longer time-scale, the analysis of 11 years (1982–1997) of AOD derived from the Meteosat satellites revealed a relationship between the transport of aerosols from the Saharan desert and the Sahel toward the Mediterranean Sea and the Atlantic Ocean and the North Atlantic Oscillation (NAO) (Moulin et al., 1997).

The aerosol optical depth may not always be a good indicator of the variability of mineral dust concentration at the surface due to the variability in the altitude of dust transport. The relationship between the surface concentrations and the AOD can vary significantly depending on the meso-scale meteorological conditions over the Sahel (Yahi et al., 2013). As a result, the seasonal cycles of the surface concentration and the AODs are not phased, with maximum dust concentrations observed several weeks (3 to 8) before the maximum of AOD (Deroubaix et al., 2013). Another proxy of the dust concentration is the horizontal visibility, with high concentrations producing severe reductions in the horizontal visibility. N'Tchayi M'Bourou et al. (1994, 1997) or Ozer (2001), for example, has used the horizontal visibility from weather reports to quantify the spatial and temporal variability of surface dust atmospheric content. Such measurements are thus mainly used to describe the occurrence of dust storm and dust events (i.e., Goudie, 1983), whereas visibility measurements by local operators are not totally reliable from a quantitative point of view, and can vary from one station to the other or from one operator to the other (Middleton, 1986). The analysis of weather reports from meteorological stations showed that from 1983 to 2008 dust events in the Sahel were mainly reported as "dust in suspension" and were due to Saharan dust transport rather than to local dust emissions (Klose et al., 2010). The synoptic patterns associated to the major dust events recorded during the studied period have been analyzed to identify the meteorological conditions responsible for the annual maximum of the dust event intensity in the spring (Klose et al., 2010). Cowie et al. (2014) also used the dust synoptic observations and wind speed measurements from meteorological stations over the Sahara and the Sahel (1984–2012) to propose a climatology of dust emission frequency and an estimation of the dust emission potential. They showed a maximum in the dust occurrence at the end of winter and early spring in the central Sahel, but a more complex pattern in the west Sahel. They also discuss the seasonal variation of the diurnal cycle of the dust emission frequencies. Despite a limited number of night-time observations in the Sahelian stations, their results suggest a strong influence of the nocturnal lower level jet (NLLJ) on the diurnal cycle of dust event occurrence. Low level jets (LLJs) are most commonly observed at night-time and can occur over all desert surfaces worldwide. They are characterized by horizontal wind speed maximum in the lowest few kilometers of the atmosphere (e.g., Blackadar, 1957; Holton, 1967; Banta et al., 2006). Over the Sahara, the NLLJ is suspected to play an important role for dust emission (Washington et al., 2006; Bou Karam et al., 2008; Knippertz and Todd, 2012; Heinold et al., 2013). After sunrise, surface heating causes the atmospheric boundary layer to grow in depth and mixes momentum from the LLJ down to the surface creating the distinctive peak of surface wind speeds from morning to midday observed in many Saharan locations (Todd et al., 2008; Schepanski et al., 2009; Marsham et al., 2011, 2013).

A limitation of the studies based on synoptic observations is that they allow to investigate the dust event occurrence only. Dust emissions or dust uplift potential can be computed from the measured surface winds which are available with a 3 h time step and not always measured during the night in the Sahelian region (e.g. Cowie et al., 2014).

In the framework of the AMMA (African Monsoon Multidisciplinary Analysis) international program, three stations, the "Sahelian Dust Transect", have been deployed in the Sahelian zone to document more precisely the variability of mineral dust and in particular the surface dust concentrations. Based on a three year data set of daily concentrations (2006–2008), Marticorena et al. (2010) showed that the dust concentrations at the three stations exhibit a marked seasonal cycle. This seasonal cycle is characterized by a monthly maximum during the dry season (February to April) and a minimum occurring during the rainy season (August–September). The results indicate that the general pattern of dust concentration is similar at regional scale. A decreasing gradient of the dust concentration is observed from Niger to Senegal, that they explained by the dilution of the most intense dust plumes moving from east to west. The seasonal cycle of the dust concentrations is not phased with the seasonal cycle of the local surface wind speed. This suggests that the maximum dust concentrations observed in the spring are mainly controlled by dust transported by the Harmattan flow from remote Saharan sources, in agreement with the analysis of Klose et al. (2010). Marticorena et al. (2010) also showed that local dust emissions generated by strong surface winds associated with meso-scale convective systems are responsible for the occurrence of extremely high daily concentrations observed at the beginning of the rainy season in Banizoumbou (Niger) and Cinzana (Mali). Indeed, strong dust-emitting winds occur at the leading edge of the cold-pool outflow generated by evaporating precipitation from convective systems, with scale ranging from local microburst to well organized squall lines of several hundreds of kilometers (e.g., Knippertz and Todd, 2012; Marsham et al., 2008). Moist convection also plays a critical role on the precipitation regime in these regions, the annual rainfall amount being provided by a limited number of organized convective systems (Mathon et al., 2002). Precipitation can efficiently scavenge local dust emissions