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Temporal variability of mineral dust concentrations over West Africa: analyses of a pluriannual monitoring from the AMMA Sahelian Dust Transect

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Abstract

The Sahelian belt is known to be a region where the mineral dust content is among the highest observed on Earth. In the framework of the AMMA (African Monsoon Multidisciplinary Analysis) International Program, a transect of 3 ground based stations, the "Sahelian Dust Transect" (SDT), has been deployed in order to obtain quantitative information on the mineral dust content and its variability over the Sahel. The three stations, namely Banizoumbou (Niger), Cinzana (Mali) and M'Bour (Senegal) are aligned around 14° N along the east-west main pathway of the Saharan and Sahelian dust towards the Atlantic Ocean.

We discuss data collected between January 2006 and December 2008 to investigate the main characteristics of the mineral dust concentration over West Africa and their connection with the dominant meteorological situations. The succession of the dry season during which the Sahel is under the influence of the dry Harmattan wind and the wet season induced by the entrance of the monsoon flow is clearly identified from the basic meteorological parameters (air temperature and moisture, wind direction). Atmospheric dust concentrations at the three stations exhibit a similar seasonal cycle, with a monthly maximum during the dry season and a minimum occurring during the rainy season, indicating that the general pattern of dust concentration is similar at regional scale. This seasonal cycle of the dust concentrations is not phased with the seasonal cycle of surface wind velocity suggesting that it is mainly controlled by Saharan dust transport. A decrease in the dust concentration is observed when moving from Niger to Senegal. However, local dust emissions induced by strong surface winds are responsible for the occurrence of extremely high daily concentrations observed at the beginning of the rainy season.

1 Introduction

West Africa is the world's largest source of mineral dust. Satellite sensors consistently indicate that these aerosol plumes are the most widespread, persistent and dense found on Earth. Mineral dust directly impact visible and infrared radiation (e.g., Sokolik and Toon, 1999) and thus their effect on the Earth's radiative budget remains one of the largest uncertainties in the present-day capability to predict climate change (IPCC, 2007). This radiative effect also induces an interaction with local and regional dynamics. This interaction is sufficiently important to influence the quality of meteorological forecast over West Africa (Tompkins et al., 2005). A recent statistical study performed over the period 1982–2005, even if it does not establish a direct causal relationship, shows a significant relationship between the North Tropical Cyclone activity and Saharan dust cover (Evan et al., 2006). Finally, mineral dust is suspected to play a role in the occurrence of meningitis epidemics in the Sahelian "Meningitis Belt". Thompson et al (2006) suggest, for example, that excess dust in late autumn, prior to the seasonal peak of meningitis, may increase its incidence and could have a predictive value for epidemic forecast.

Long-time series of horizontal visibility observations performed in meteorological stations have been used to investigate the temporal and spatial variability of the mineral dust load over the Sahelian region (i.e. N'Tchayi et al., 1994, 1997; Goudie and Middleton, 1992). These studies mainly showed that horizontal visibilities exhibit a pronounced seasonal cycle, but also a high variability from the daily to the inter-annual scales. The seasonal cycle is commonly explained by the oscillation of the Inter Tropical Convergence Zone (ITCZ) leading to the alternation during the year of two meteorological regimes over the Sahel (Dubief, 1977): during the boreal winter, the "Harmattan", a northeastern dry wind, allows a very efficient transport of Saharan dust towards the Gulf of Guinea. On the opposite, during summer, due to the northern displacement of the Inter Tropical Convergence Zone (ITCZ), the Sahel is submitted to the wet monsoon flow from South-West. This monsoon flow, loaded with humidity, is responsible for the occurrence of precipitation which allows the development of annual vegetation preventing local aeolian erosion (Rajot, 2001).

In recent decades, remote sensing has offered the opportunity to document the aerosol load over Western Africa on a larger spatial and temporal scale than respectively meteorological stations or intensive field campaigns. However, the retrieval of the aerosol content over land surfaces remains much more complex than over ocean. As a result, the information available in terms of atmospheric dust content over desert surfaces or surfaces with low vegetation cover is still limited to semi-quantitative indicators (Absorbing Aerosol Index – AAI - from Total Ozone Mapping Spectrometer, Torres et al., 1998; Infrared Different Dust Index – IDDI –, from Meteosat, Legrand et al., 2001). The AERONET sunphotometers network (http://aeronet.gsfc.nasa.gov/) provides near-real-time observations of the aerosol spectral optical depth and sky radiance and derived parameters such as particle size distributions, single-scattering albedo and complex refractive index in several stations. Since 1994, 14 stations have been installed in western Africa by the PHOTONS component of the AERONET network, with different periods and durations of observations. They have allowed, for example, to establish the seasonal cycle of the vertically integrated content (Aerosol Optical Depth, AOD) of mineral dust in different stations of West Africa (Holben et al., 2001; Ogunjobi et al., 2008).

Mineral dust originating from the Sahara and Sahelian regions can be transported at different altitudes. Typically, during summer, mineral dust emitted in the Sahara is transported across the North Atlantic Ocean above the MBL within the Saharan Air Layer (SAL). This has been clearly shown by looking at the difference in the seasonal cycles of the surface concentrations and the column-integrated aerosol optical depth of mineral dust measured, for example over the Cape Verde Islands or by lidar measurements performed offshore western Africa (Karyampoudi et al., 1999; Immler and Schrems, 2003) and on the West African coast (Léon et al., 2009). Chiapello et al. (1995) showed a strong disconnection between surface concentrations and aerosol optical depth at the seasonal scale and pointed out that low level transport pattern of

Saharan dust over the Cape Verde islands during winter was mainly due to transport by Harmattan trade wind. Intensive field campaigns including aircraft measurements (CLAIRE-LBA, PRIDE, AEROSE, AMMA) also showed that long range transport of Saharan dust can take place within the surface layer (Formenti et al., 2001; Reid et al., 2002; Nalli et al., 2005, Rajot et al. 2008).

Because of the variability in the dust transport altitude, AOD cannot always be considered as a good proxy of the aerosol content in the surface boundary layer, especially in the Sahelian region. This is why additional surface measurements have been implemented in the Sahelian region in the framework of the AMMA (African Monsoon Multidisciplinary Analysis) international program. The objective is to provide a set of aerosol measurements for the determination of the mineral dust budget at regional scales. Since dust emissions and deposition occur at the surface, a monitoring of the aerosol concentration at surface level and of wet and dry deposition fluxes has been deployed in addition to the column-integrated aerosol optical depth provided by the AERONET/PHOTONS sunphotometers. Because of expected variations in the altitude of the dust layers in this region, surface concentrations also provide an indicator of air quality and human exposure better adapted for health issues. The so-called "Sahelian Dust Transect" – SDT is a set of three stations deployed along the main transport pathway of Saharan and Sahelian dust towards the Atlantic Ocean, between 13 and 15° N, in Niger, Mali and Senegal. Dust concentration is monitored at the sub-daily scale in order to properly document the variability from the dust event scale to the inter-annual time scale. Basic meteorology is also monitored in order to interpret these variations in relation with local and regional meteorological conditions.

In this paper we present the daily dust concentrations recorded since 2006 at the three stations and describe their variability at the intra-seasonal, seasonal and inter-annual time scales and discuss the factors controlling this variability at different space scales.

2 Material and method

2.1 Description of the stations

The three stations composing the SDT are located in the Sahelian region in M'Bour (Senegal; 14.39 N, 16.96 W), Cinzana (Mali, 13.28 N, 5.93 W) and Banizoumbou (Niger, 13.54 N, 2.66 E) (Fig. 1). The three stations are located in different regions in terms of annual precipitation (Fig. 1). Both Banizoumbou and M'Bour are located between the isohyets 500 and 700 mm yr^{-1} while Cinzana is located in a more rainy area. This is confirmed by the annual precipitation rates measured at the three stations during the three years monitoring (Table1). The three years average precipitation is of the order of 500 mm yr^{-1} in Banizoumbou and M'Bour and close to 800 mm yr^{-1} in Cinzana.

In M'Bour, the instrumentation is installed facing the Atlantic Ocean at the geophysical station of the French Institut de Recherche pour le Développement (IRD). The aerosol sampling and meteorological measurements are performed at respectively 9.5 m and 10 m above the ground (that means respectively 1.8 m and 2.3 m from the terrace of a building which is 7.7 m high).

The site of Cinzana (Mali), 40 km Eat South-East of Segou, is located in an 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. In Niger, the station is installed in a fallow located at 2.5 km from the village of Banizoumbou (60 km East of Niamey). For these two remote sites, specific installations have been built up, including solar panels in order to make the stations autonomous. On both stations, dust concentration measurements are performed at 6.5 m above the ground level. Meteorological measurements are performed at the same level at Banizoumbou, but in Cinzana, they are made at 2.3 m from the ground level, the meteorological tower being installed inside the ancient meteorological station of the SRAC.

All three stations are managed by local technicians trained by the technical responsible of the SDT (B. Chatenet). Instrumentation has been selected based on criterions of simplicity of use and maintenance and capability to resist to severe dust and meteorological conditions. The three stations are fully operational since January 2006.

2.2 Aerosol concentration

Atmospheric concentrations of Particulate Matter smaller than 10 µm (PM_{10}) are measured using a Tapered Element Oscillating Microbalance (TEOM 1400A from Thermo Scientific) equipped with a PM_{10} inlet. The inlet is installed outside on the roof of the building, while the instrument is located inside (about 3 m vertically below the inlet) and thus protected from dust, rain and excessive temperatures.

The main element in the instrument is an oscillating element on top of which is located a filter. The particles collected on the filter increase the mass of the oscillating element and thus decrease its oscillation frequency. The variation of the oscillation frequency is monitored and converted into a mass variation. The estimated mass is the mass of the oscillating element, the filter and the collected particles. As a result, the estimation of the particles mass is made by difference between two successive measurements. The sampled air volume being measured, the particulate concentration can be computed as the ratio between the mass measured over the acquisition time and the volume of the air sampled during the same time period.

The lower part of the sampling tube (60 cm length) and the microbalance are heated to 50°C, in order to allow a thermical stability of the particles and the filter and avoid water condensation interferences. But, the disadvantage of this heating is the possible loss of volatile compounds such as ammonium nitrates or organic compounds. TEOM measurements may thus not provide accurate mass concentrations in environments where such volatile species significantly contribute to the total mass concentration. Practically, this phenomenon can lead to negative values of concentration, as frequently observed for the measurements performed in M'Bour station at the onset of the sea breeze. Indeed at that time, the oceanic air masses bring significant amounts of sea salts or organic compounds to the station. Concentrations associated to anthropogenic aerosols or carbonaceous aerosols from biomass burning may also be underestimated. Mineral dust being composed of non-volatile compounds, PM_{10} concentrations associated with high levels of this aerosol may not be significantly affected by this biais. However, a selection procedure has been applied (see Sect. 2.4) to discard as much as possible measurements associated with other aerosols than mineral dust (anthropogenic aerosols, biomass burning aerosols, sea-salts).

Despite this limitation, this instrument is widely used, in particular in air quality monitoring networks (i.e. AIRPARIF network in Paris, France since it provides relevant measurements with a limited cost in terms of maintenance. This instrument allows measurement of particulate concentrations ranging from a few micrograms to a few grams per cubic meters. In terms of sensitivity, the detection limit of the instrument is about $0.06\,\mu g\,m^{-3}$ for a one hour sampling time.

Due to the very high dust concentrations that can be encountered in the Sahel, the filter of the instrument can saturate after a few days. Thus, to maintain a constant confidence level in the particulate concentrations measurements, the inlet is cleaned at least every month and the filters are changed two or three times a month both during the dusty periods (to prevent the filters from saturation) and during the rainy season (to avoid the surface alteration of the filters by the air moisture, leading to high instrumental noise).

2.3 Meteorological parameters

Basic meteorological measurements are performed to monitor wind velocity and direction, air temperature, air relative humidity and precipitation. All instrumentation used is from Campbell Scientific company. Wind velocity and wind direction are measured using a Windsonic 2-D, temperature and relative humidity using a 50Y or HMP50 sensor and precipitation with a ARG100 Tipping Bucket Raingauge. Data acquisition uses a CR200 data logger. Absolute humidity is computed from the air temperature and relative humidity.

2.4 Data selection

For the three stations, all measurements have a nominal data acquisition time of 5 min. The annual recovery rate for PM_{10} concentrations ranges between 92 and 99% for the three stations. Most of the time, the missing data correspond to particular events such as electricity failures or break down of the computer connections, episodic operations of maintenance on the instruments (filters changing, cleaning, control, etc.). In addition, in Banizoumbou, the location of the instrument has been slightly changed (∼100 m) during some of the AMMA special observation periods (June–July 2006; June 2007) and thus no data are available for the few days corresponding to the displacement of the instrument. Furthermore, for these specific periods, the acquisition time step has been increased to 2 min. However, to make the period of measurements comparable for the concentrations and the meteorological measurements, the data have been averaged on 10 min for the SOP periods in Banizoumbou.

From this initial large data set, a first selection is performed to discard all measurements for which technical problems have been recorded. Periods during which activities that could affect the representativity of the measurements (in-situ car traffic, cattle, maintaining activities, etc.) occurred in the immediate vicinity of the stations have also been discarded.

The second step in the data selection aims to select periods during which dust transport can be considered as the main contributor to the measured PM_{10} mass. This selection is critical for the M'Bour station which is located on the sea side, south of the town of M'Bour (∼180 000–200 000 inhabitants). Thus, the collected PM_{10} mass in this station can be significantly affected by particulates of marine or anthropogenic origins. Indeed, sea/land breezes are recorded almost everyday. Savoie and Prospero (1977) report daily average sea salts concentrations measured in the Cape Verde islands, in the North tropical Atlantic Ocean ranging between 10 and 50 $\mu g\,m^{-3}$, with an average fraction of PM_{10} of the order of 5%. Typical PM_{10} concentrations associated with sea salts on the Atlantic coast are thus expected to be of the order of 5 $\mu g\,m^{-3}$, and to rapidly decrease when progressing inland. However, to avoid situations where the dominant aerosol is not dust, we excluded the data for which the wind direction sectors corresponded to transport from the sea or from the town of M'Bour, and thus we retain only data for which the wind direction sector was included between 30 and 150°. This criterion leads to a very high rejection rate, especially during the wet season, where the monsoon flow promotes a westerly direction of the surface wind. Typically, on December or January, about 70% of the data are retained while their rejection rate can reach 95% at the maximum of the rain season (July and August).

At the two other stations, during the dry season, the Harmattan regime characterized by northern and north-eastern surface winds generally prevails. The "Harmattan Front" separates a low dusty layer in the North from an elevated biomass burning laden air to the South (Haywood et al., 2008). However, incursion of the monsoon flow to the North can occasionally occur during the dry season at the surface level, allowing transport of biomass burning aerosol from southern sources down to the ground level. An example of such biomass burning plume was identified in Banizoumbou based on the increase of the aerosol number concentration and the change in the aerosol angstrom exponent of the aerosol optical depth during the dry season intensive experimental phase of AMMA (SOP0; January–February 2006) (Rajot et al., 2008). It does not produce a strong increase in the aerosol mass concentration, since, for instance, a maximum of 9.6 $\mu g\,m^{-3}$ was measured at Banizoumbou during the large scale event of biomass burning transport over the whole Sahel (Rajot et al. 2008, Hesse et al. 2008). Because of the volatility of the organic fraction of biomass burning aerosol, the total mass concentration could be higher than the TEOM measurements. However, the organic matter mass concentration measured in the biomass burning aerosol layer over the region of Niamey during the SOP0 did not exceed 6 $\mu g\,m^{-3}$ (Capes et al., 2008). Anyway, to avoid such situations, concentration measurements associated with South wind sectors are discarded during the dry season months (November to May) in Banizoumbou and Cinzana.

For the selected acquisition time step (5 min), a maximum number of 288 data can be recorded every day. In Banizoumbou and Cinzana, this number is reached respectively 53% and 48% of the time. The daily number of selected values is higher than 100 for 97% of the time period. In Banizoumbou, the total number of selected data falls to 144 for the first 15 days of January 2006, June–July 2006 and June 2007 due to the 10 min averaging of the data set during the AMMA SOP campaigns. The situation is quite different in M'Bour, due to a larger occurrence of "forbidden" wind sectors. In addition, the number of selected data in M'Bour significantly decreases in the wet season due to the dominant monsoon flow. As a result, the maximum number of 288 selected data is reached only 2%, but daily numbers of selected values higher than 100 are obtained 55% of the whole time period and close to 70% during the dry season periods (October–April).

Globally, the data recovery rates for all stations are sufficiently high to investigate the variability of the dust concentrations from the daily to the interannual times scales along the STD.

3 Results

3.1 Daily concentrations

From the 5 min concentrations measurements associated with "dust wind sectors", daily mean concentrations have been computed, that can be used to investigate the temporal variability for the three years of monitoring.

Daily mean concentrations span over 3 orders of magnitude in Cinzana and M'Bour and even 4 orders of magnitude in Banizoumbou (Fig. 2). For the three years of measurements, the median values of the distribution are 87.2 $\mu g\,m^{-3}$ in Banizoumbou, 75.3 $\mu g\,m^{-3}$ in Cinzana, and 76.6 $\mu g\,m^{-3}$ in M'Bour. About 40 % of all the measured concentrations are higher than 100 $\mu g\,m^{-3}$ and less than 3% higher than 500 $\mu g\,m^{-3}$. The maximum daily concentration is slightly lower in M'Bour (2250 $\mu g\,m^{-3}$) than in Cinzana (2503 $\mu g\,m^{-3}$) and much higher in Banizoumbou (4020 $\mu g\,m^{-3}$) The range of daily mean concentrations is larger in Banizoumbou where more very low (<10 µg m^{-3}) and very high concentrations (>100 µg m^{-3}) are recorded compared to the two other stations. The daily mean concentrations in Cinzana and M'Bour exhibit similar distributions, with slightly more very low and very high concentrations in Cinzana. The differences between the stations can be partly explained by their geographical location and by local precipitation conditions (Table 1). The station of Banizoumbou is located in a more arid area than the station of Cinzana. In addition, it is closer from active sources such as the Bodélé depression that has been identified as the origin of several dust events during the dry season intensive experimental phase of the AMMA program (SOP0) (Rajot et al., 2008). In average, the station of M'Bour exhibits the lowest annual precipitation but in this coastal area vegetation cover is much higher than in the two other stations.

The daily mean PM$_{10}$ concentrations measured on the SDT appear as extremely high. As an example, over the three years of monitoring, the daily PM$_{10}$ concentrations associated with dust exceed the European standard for air quality (daily mean PM$_{10}$ concentrations of 50 µg m^{-3}) 240 days per year in Banizoumbou and Cinzana and 190 days per year in M'Bour, while this standard should not be exceeded during more than 35 days per year in Europe. They also exceed the USA air quality standard (daily mean PM$_{10}$ concentrations of 150 µg m^{-3}) 112 days per year in Banizoumbou, 84 days per year in Cinzana and 55 days per year in M'Bour.

The PM$_{10}$ concentrations measured on the STD can also be compared to other mass concentration measurements obtained either in other dust sources or in regions affected by the transport of Saharan or Sahelian dust transport.

In the framework of the ADEC Experiment (Aeolian Dust Experiment on Climate impact; Mikami, et al., 2002), PM11 concentrations have been measured in the Northern part of the Taklamakan desert from 2001 to 2004, by weighting filters collected with an Andersen-like cascade impactor (Yabuki et al., 2005). In Aksu, North from the Tarim Basin, the minimum daily PM11 concentration ranges between 54 and 70 µg m^{-3}. The maximum daily PM11 concentration exhibits a much higher year-to-year variability. It was as low as 645 µg m^{-3} in 2001 and as high as 3798 µg m^{-3} in 2003 but of the order of 2000 µg m^{-3} in 2002 (2632 µg m^{-3}) and 2004 (1864 µg m^{-3}). In Inner Mongolia (China), Hoffman et al. (2008) derived the PM$_{10}$ concentration from the number size distribution measured during the spring (March to May) 2005 and 2006. The estimated average PM$_{10}$ concentrations for the 34 sampled dust storms range from 189 to 9624 µg m^{-3}, with a median value of 415 µg m^{-3}.

Concentrations of mineral dust exported from the Saharan have been measured over the Atlantic Ocean. In Cape Verde Islands, total dust concentrations derived from elementary analysis of daily aerosol samples range between 65 and 264 µg m^{-3} during dust transport episodes (Chiapello et al., 1997). In the free troposphere over the Canary Islands, daily concentrations of PM$_{10}$ can be estimated from Total Suspended Particulate (TSP) measurements as 225 µg m^{-3} (Alonzo-Perez et al., 2007). During the intensive field campaign of the MINATROC European program, daily PM$_{10}$ concentrations of 312 µg m^{-3} have been measured in the free troposphere in Izana (Canary Islands), while surface concentration was 85 µg m^{-3} (Alastuey et al., 2005).

The daily concentrations measured on the STD appear as very consistent with the concentrations measured during Asian dust storms and measurements performed downwind of Saharan sources. The extremely high daily PM$_{10}$ concentrations measured in Banizoumbou are in the same order of magnitude than the daily PM11 concentrations measured in the Taklamakan desert and comparable to those obtained in Inner Mongolia (China). The PM$_{10}$ concentrations associated with Saharan dust transport are lower than those measured in the three Sahelian stations of the STD, which is quite consistent with the fact that they are located closer to the source regions.

3.2 Seasonal pattern

The time-series of daily mean concentrations at the three stations have been plotted on Fig. 3. The daily means are associated with standard deviations of comparable magnitude with the mean. A large day to day variability is also evident. At the three stations, a similar temporal pattern is observed with a clear and persistent seasonal cycle characterized by a minimum in summer and a maximum in winter and in spring. Daily concentrations higher than 100 $\mu g\,m^{-3}$ are recorded from about January to June, peaking between January and April. In May and June, i.e. at the very beginning of the rainy season, single daily concentrations significantly higher than the monthly "background" and associated with large daily standard deviations are observed at the three stations. The lowest daily concentrations are recorded between July and October. In M'Bour, the period of minimum concentration is slightly shifted toward the fall and the seasonal contrast is not as marked as in the two other stations.

The comparison between the three stations shows the consistency of the dust concentrations at the regional scale, in terms of magnitude and of temporal pattern. A very distinctive and persistent feature of this temporal pattern is the seasonal cycle, with a 6 months "dust" season from January to June. This is underlined by the 30-days sliding average of the daily mean concentrations (Fig. 4). The same seasonal trend is observed with a gradient in the intensity of the dust concentration from East (Banizoumbou) to West (M'Bour). This seasonal cycle is consistent with the average seasonal cycle of the aerosol optical thickness observed in Banizoumbou (2002–2004), Agoufou (Mali) (2005–2006) and Ouagadougou (Burkina-Faso) (1996–2003) by the sunphotometers of the AERONET/PHOTONS network (Ogunjobi et al., 2008).

Most of high daily concentrations are observed in the dry phase of the Harmattan season while the minimum dust concentrations are recorded during the core of the Monsoon season. The succession of these two regimes is illustrated by the temporal variations of the daily mean air moisture and of the daily precipitations measured at the three stations (Fig. 5). From November to March, water vapor content remains very low, i.e. typically of the order of 5 $\mu g\,m^{-3}$ in Cinzana and M'Bour and even lower in Cinzana. Occasionally, sudden increases in air humidity are recorded, revealing some incursions of moist air masses from the South. This is the case, between the 17 and 19 February 2006 where the southern air flow leads to biomass burning aerosol transport to Banizoumbou (Rajot et al., 2008). A similar situation is also recorded on

13 March 2008 in Banizoumbou. But from this 3-years monitoring, it appears that such incursion of southern airflow to the surface at the latitude of the three stations (∼13° N) is exceptional. From March to June, air humidity increases regularly from 5 to 20 µg m^{-3}, but large oscillations of short duration can be observed at this period. This period corresponds to the transition from the dry season to the wet season. As a general trend, the seasonal cycle appears as phased with the succession of the Harmattan dry season and Monsoon wet season.

Precipitation starts at the end of May or beginning of June in Banizoumbou and Cinzana and reaches a maximum in August (Fig. 5). There is a slight shift in the beginning and maximum of precipitation in M'Bour where only 64% of the total precipitation is recorded from June to August, compared to 80% in Banizoumbou and Cinzana. At this period, single extremely high daily mean concentrations, as high as in the Harmattan season, are recorded, associated with extremely high daily standard deviations (Fig. 3). These high daily mean differs significantly from the daily median concentrations, which is generally not the case for the high daily mean observed in the dry season. Annual precipitation amount and occurrence vary between the three stations. The average annual amount and occurrence are the highest in Cinzana (772 mm yr^{-1} and 66 days per year). In Banizoumbou annual precipitation is 553 mm yr^{-1} and it occurs 48 days per year. M'Bour has a comparable precipitation occurrence (49 days per year) but with lower annual precipitation (486 mm yr^{-1}). At the three stations, the temporal distribution of precipitation can explain the minimum concentrations observed at the maximum of the rainy season. However the observed regional gradient in concentration is not consistent with the difference in precipitation amount or occurrence at the three stations. Comparable precipitation is recorded in Banizoumbou and M'Bour but concentrations are much higher in Banizoumbou. On the opposite, Cinzana has much higher precipitation amount and occurrence but concentration levels are slightly higher than M'Bour.

Since mineral dust is emitted and transported by the wind, it is expected that the temporal and regional pattern of dust concentration can be related to surface winds.

Figure 6 represents the daily mean surface wind velocities and daily median directions recorded at the three stations of the STD for the selected "dust" situations. In Banizoumbou and Cinzana, the seasonal pattern of the wind direction clearly points out the seasonal shift between the Harmattan and Monsoon. In the dry season, wind direction is very stable and ranges around East (90°) at Banizoumbou whereas it is closer to the North East (45°) at Cinzana and M'Bour. The wind direction shifts to about 240° during the wet season but daily values are more scattered than during the dry season. The selection of the data as a function of wind sectors in M'Bour obviously produces a biased picture especially during the rainy season, with all wind directions within the "dust" sectors.

The temporal variation of the daily surface wind velocities does not exhibit such a contrasted succession of weather regimes. However, a clear seasonal cycle is observed, characterized by a maximum at the beginning of the wet season and a minimum in fall, with some peaks of high surface winds in the dry season. In Banizoumbou, the maximum daily mean wind velocity is 6.3 m s^{-1} and the minimum 0.95 m s^{-1}. In Cinzana, the recorded surface wind velocities are lower due to the fact that measurements are made at lower level (2.3 m) than in Banizoumbou (6.5 m). The maximum daily surface wind velocity is 4.85 m s^{-1} and the minimum 0.19 m s^{-1}. Assuming a roughness length of 0.05 m, i.e. of the order of magnitude of roughness length measured over a Sahelian field (Bielders et al., 2004), and neutral conditions, the surface wind velocity at 6.5 m can be estimated. The maximum wind velocity is then 6.1 m s^{-1} and the minimum 0.24 m s^{-1}, i.e. the same order of magnitude than the one measured in Banizoumbou. Surface winds are lower in M'Bour, with a maximum of 4.5 m s^{-1} and a minimum of 0.32 m s^{-1}. A similar seasonal pattern of the surface wind velocity has been observed in Mali (Agoufou, 15°20′ N; 1°28′ W), in the central part of the Sahel (Guichard et al., 2010). In this region, the maximum wind velocity is recorded in June and is driven by the difference in the diurnal cycle of the surface wind velocity between the dry and the wet season. Indeed the amplitude of the diurnal cycle of the wind velocity is larger in the dry season, due to very low night-time surface wind velocity. This is verified and confirmed by our data set for the stations of Cinzana and Banizoumbou (not shown). Such verification was not possible in M'Bour due to the daily shift in wind direction induced by the sea and land breezes.

The seasonal cycle of the surface wind velocity does not appear as phased with the seasonal cycle of the dust concentrations. The winter/spring dust concentration maximum is associated with the Harmattan regime during which the daily mean surface winds are relatively low. However, dust emission is a process involving a threshold wind velocity (Bagnold, 1941), and can thus result from short duration episodes of high wind velocity. Periods of high winds at the sub-daily scale may not be properly reflected by the daily means. From the nominal 5-min measurements, the daily frequencies of high surface wind velocities have been computed. To partly compensate the difference in the level of the measurements at the three stations, the threshold was set to $6\,\mathrm{m\,s^{-1}}$ in Cinzana and to $7\,\mathrm{m\,s^{-1}}$ in Banizoumbou and M'Bour. The frequency of high winds and the duration of the period of high winds decrease from Banizoumbou to M'Bour (Fig. 7). In Banizoumbou the highest frequencies of high surface wind speeds are recorded from March to July and even from January in 2008. In Cinzana, they are recorded from April to July for the 3 years. About 60 % of the cases in Banizoumbou and 80% in Cinzana are found within this period. The situation is not so clear in M'Bour, partly due to the data selection. However, in the selected dust wind sectors, the highest relative occurrences of high winds are recorded in June and July. From the Fig. 7, it thus appears that the maximum in the frequency of high winds is generally delayed compared to the maximum of the daily dust concentrations. As a result, the period with the highest daily concentrations is not associated with a high frequency of strong surface wind velocities.

These data show that the results obtained during the AMMA SOP0 in the dry season in Banizoumbou (Rajot et al. 2008) can be generalized at the seasonal and regional scales. They strongly suggest that the maximum of the seasonal cycle of dust concentrations is due to long range transport of Saharan dust and not to locally emitted dust. This maximum is consistent with the maximum of dust emission simulated over the Western Sahara and driven by surface winds in source regions (Marticorena and Bergametti, 1995; Marticorena and Bergametti, 1996; Laurent et al., 2008). Saharan dust can be very efficiently transported toward the Sahel and produce high surface concentrations since at this period, dust transport occurs mainly in the surface layers (Léon et al., 2009, Cavalieri et al., 2010). The difference in the level of concentration between the stations can be explained by differences in the distance from the stations to active dust sources. Considering the direction of the Harmattan winds, the station of Banizoumbou, where the highest daily concentrations are recorded is located downwind of the Bodélé Depression, known to be one of the most active sources of the Sahara (Prospero et al., 2002) but also downwind sources located east of the Tibesti and North of the Aïr (Laurent et al., 2008) and even West of the Aïr and north of Mali (Rajot et al., 2008). The station of Cinzana can be impacted by the same sources, but with a dilution of the dust plumes compared to Banizoumbou (See part 3). Regarding its geographical location, the station of M'Bour can be impacted by the large source area identified in the north-western Mauritania, on both sides of the border between Mauritania and Mali (i.e., the southern part of the Chech Erg, 21° N–24° N; 8° W–2° W) (Laurent et al., 2008). A systematic analysis of the backward trajectories of air masses associated with the dust events recorded during the dry season would be required to further quantify the impact of the different Saharan dust sources on the dust concentrations measured at the three stations.

By the end of the dust period, the highest frequencies of high surface winds correspond to a period where extreme daily mean concentrations, as high as the highest concentrations measured in the dry season, are recorded. This suggests that local dust emissions occur at the station or close to the station. This period is characterized by the beginning of the convective activity that brings most of the precipitation to the Sahel (Laurent et al., 1998). Based on a 4-year monitoring of aeolian activity over a cultivated field and a fallow in Banizoumbou, Rajot (2001) found that dust emission at this latitude was mostly due to the high surface winds in the front of the convective systems occurring at the beginning of the wet season. These extremely high daily means sharply peak above the background concentrations. They also differ strongly from the daily median concentrations (Fig. 3), which is generally not the case during the dry season. This indicates the PM_{10} concentrations measured during these days are not normally distributed, but biased by a small number of extremely high values recorded during a short time period. This behaviour also sustains the hypothesis that dust emissions by convective systems are responsible for the high daily concentrations at the beginning of the wet season. It must be noted that this can explain the secondary maximum detected in June on the monthly aerosol optical depth in Banizoumbou, Agoufou and Ouagadougou that the authors attributed to local dust sources (Ogunjobi et al., 2008).

The minimum concentrations are recorded during summer, in the middle or end of the monsoon season. This is the period where precipitations are the most frequent and the most intense and can thus induce strong wet deposition of dust transported from remote desert areas. Precipitation can also inhibit the local dust emissions by an increase in soil moisture and by the seasonal growth of vegetation (Rajot, 2001). In addition, the daily surface winds and the frequency of high surface winds tend to decrease from the beginning to the middle of the wet season. This is consistent with Marsham et al. (2008), who suggested that the higher downdraft convective available potential energy (from a drier midtroposphere) during the monsoon onset compared with retreat, may lead to higher surface winds from MCSs (with more dust) during onset compared with retreat. This indicates that the intraseasonal variations of the surface wind velocity in the front of the MCS and the associated precipitation act together to decrease the local dust emission and surface concentrations.

To further investigate the seasonal pattern of mineral dust along the STD, we computed the monthly frequency of high dust concentrations. The frequency of daily concentrations higher than $150\,\mu g\,m^{-3}$ exhibits a similar seasonal cycle at the three stations (Fig. 8). The maxima are observed at the same period than the dust monthly concentrations maxima. Despite an East-Western gradient, the range of frequencies of high dust concentration is similar at the three stations with maximum values of the order of 75%. It appears that the monthly frequency of daily concentrations higher than 150 µg/m^3 exhibits temporal variations that are comparable to those of the monthly concentrations (Fig. 8). The highest monthly concentrations (March 2006, 2007, 2008, January 2007) (Fig. 7) are associated with the highest number of days with high dust concentration (13 to 23 days). On the opposite, no daily concentration higher than 150 µg m^{-3} is recorded at the period where the monthly concentrations are minimum, i.e. typically in August, September and October. The year to year variability of the seasonal pattern is the same for the monthly concentration and the frequency of high concentrations. The year to year variations in the amplitude of the seasonal cycle vary in the same manner for the frequency of high dust concentrations as for the monthly mean concentrations. For the three years and the three stations, the frequency of high concentrations and the monthly mean concentrations are strongly correlated ($r^2>0.8$). This indicates that the seasonal cycle of surface dust concentrations and its interannual variability are largely controlled by the occurrence (number and duration) of high dust concentrations during the dry season.

From these results, a general seasonal pattern of mineral dust is clearly identified over the Sahelian Dust Transect, that appears as a typical trend of the mineral dust surface concentrations over Western Africa. Saharan dust transport is found to be the main responsible for the maximum of surface concentrations recorded between winter and spring over the Sahel. The differences in the dust concentrations observed in the three stations could be explained by the differences in the distance from the stations to the different Saharan source-regions. Extremely high daily dust concentrations are observed at the end of the spring and early summer, i.e. at the period where MCS associated with high surface wind velocities occur. As a result, local dust emission seems to play a significant role in the surface concentrations measured during this period. The decrease of the surface winds and the increase in precipitation amounts from the beginning to the middle of the wet season both contribute to the decrease in the daily dust concentrations at this period. The minimum dust concentrations recorded in the fall reflect the absence of local dust emission and the low level of dust emission activity over the Sahara (Laurent et al., 2008). Our results suggest that all along the year, i.e. both in dry and wet season, the number and duration of the dust events largely control the dust concentrations seasonal cycle and its interannual variability.

3.3 Typical dust events

Compared to the monthly mean concentration, the 30-days sliding average concentrations exhibit a large day to day variability. For example, in March 2006, January 2007, March 2007, December 2008, a significant increase of the 30-days average concentrations is observed in all three stations. This suggests that intense dust transport occurs during several days at the scale of the whole Sahara and Sahel and is thus recorded at the three stations. Such a huge continental dust storm affecting the whole Sahara and West Africa in March 2006 was well described by Slingo et al. (2006) and Tulet et al. (2008) and will be detailed below for the 3 stations. A dust event of high intensity but shorter duration has also been observed out of the "dust season", from the 5 to the 7 November 2007 during which daily concentrations up to 750 $\mu g\,m^{-3}$ have been measured. In other cases, the increase in the sliding average is observed in Banizoumbou and Cinzana only (April 2007, February 2008), or in Banizoumbou only (December 2007) and sometimes in M'Bour only (October 2006 and 2008). However, this result tends to indicate that the major dust events observed over West Africa have regional to continental extent. This provides further insight on the dust seasonal cycle. In addition to a highest dust load, a highest probability of dust events occurrence is found at the end of winter and in spring. But even with a low probability of occurrence, a very intense dust event can occur at any time during the dry season, and especially in late fall. In addition, high values in the 30-days sliding average concentrations are observed in June in Banizoumbou and Cinzana due to the extremely high daily values associated with convective activity over the region.

In the following we illustrate the contrasted temporal pattern of dust events typically observed during the dry and the wet seasons.

3.3.1 Dry season dust events

A typical but extreme example of a dry season dust event is given by the dust storm of March 2006. This dust storm, described by Slingo et al. (2006) and further analysed by Tulet et al., (2008) was initiated by a cold front in the lee of the Atlas that progressed southward and westward, producing dust emissions all along its path. A comparable storm, in terms of spatial extend and duration was recorded in 2004 (Knippertz and Fink, 2006).

The spreading of this huge plume leads to the highest 5-min concentrations recorded in the dry season at the three stations during the 3 years monitoring. A first rapid increase of surface concentration is recorded at the station of Banizoumbou on the 7 March (~09:00 h). Surface concentration initially ranging from 44 to 96 µg m^{-3} raised to 2383 µg m^{-3} within 80 min (Fig. 10). A similar but less intense increase in the surface concentration is recorded a few hours later in Cinzana (~15:00 h), with concentrations rising from about 100 µg m^{-3} up to 1000 µg m^{-3}. The storm finally reached M'Bour one day later (8 March), leading to one order of magnitude increase of the surface concentrations (from 100 to 1470 µg m^{-3}). During this event, the maximum recorded PM$_{10}$ concentration was of the order of 5000 µg m^{-3} in Banizoumbou, 3500 µg m^{-3} in Cinzana and 2500 µg m^{-3} in M'Bour. This timing is confirmed by the sequences of images given on Fig. 11. This figure shows several images of SEVIRI (Spinning Enhanced Visible and Infrared Imager) special dust products made from EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) algorithm and data base available on the RADAGAST (Radiative Atmospheric Divergence using Arm mobile Facility, GERB and AMMA Stations) home page (http://radagast.nerc-essc.ac.uk/Home.htm). These images illustrate the evolution of the dust plumes from the 7 to the 9 March 2006, the presence of dust being represented by the pink and magenta colours and the location of the stations by the stars. The image of the 8 March 2006 at 10:15 h shows that at this time, the station of Banizoumbou is over passed by a dust plume, while another dust plume is located North West of the station of Cinzana.

Several dust clouds spread over the Sahara, progressing southward. On the early morning of the 8 March, all this plumes have produced a large dust cloud present over the three stations. In the afternoon of the 8 March, additional dust plumes are observed North-East of the stations of Banizoumbou and Cinzana, that tends to form again a huge dust cloud over the three stations in the morning of the 9 March. From these images, the temporal pattern of this event and the difference in the relative intensity of the dust peaks at the three stations can be explained by differences in the dust plumes, i.e. in the dust sources that impacted the stations.

In addition to these features, some variability at the sub-daily scale is observed at the three stations. The dust concentrations tend to follow the diurnal variations of the surface wind velocity (not shown). The diurnal cycle of the surface wind exhibits a maximum in the morning due to the mixing of momentum from the nocturnal low level jet (Parker et al, 2005). As already described by Rajot et al. (2008), the diurnal cycle of the dust concentrations is super-imposed to the synoptic scale intense dust transport, that explains the variations in the intensity of the daily concentration maximum from one day to the other.

Shorter periods of high dust concentration can also be observed during the dry season, that last only one day. This is typically the case in the station of M'Bour, whose location allows the transport of dust from sources that do not impact the two other stations, such as the one located North and North-East Mauritania, North of Mali or along the Atlantic coast (Mauritania and Western Sahara) (Laurent et al., 2008). An example of such a short duration dust event was observed on the 29 May 2006. As illustrated on Fig. 12 the concentration raised from values less than 150 $\mu g\,m^{-3}$ the previous day to concentrations higher than 1000 $\mu g\,m^{-3}$ at noon. This event is associated with AOD ranging between 1 and 1.5, high OMI aerosol indexes and backward trajectories having a Northern origin. Once again, a diurnal cycle of the concentration is observed, similar to the diurnal cycle of the surface wind velocity. But it is also very clear in this case that the concentrations are not correlated with surface wind velocity and thus not due to local dust emissions, since comparable wind velocities recorded on the day before are not accompanied by comparable dust concentrations.

The dry season dust events are responsible for the maximum monthly mean dust concentrations. Their durations range between 1 and 6 days, with an average duration of 2.5 days. Each year, 20 to 30 dust events are recorded at each station during the dry season. Many of these events are recorded by two or three stations of the STD, suggesting their regional to continental extent. These events are not associated with intense local winds and thus not due to local dust emissions. They result from mineral dust transport from different Saharan sources, depending on the period and on the location of the station. A further step in the interpretation of these results would be to identify the meteorological situations responsible for these dust events. Indeed, in addition to the continental dust storms identified in March 2004 (Knippertz and Fink, 2006) and March 2006 (Slingo et al., 2006; Tulet et al., 2007), several meso-scale patterns of Saharan dust emissions and redistribution have been recently identified based on observations from the AMMA program (e.g. Flamant et al., 2007, 2009; BouKaram et al., 2008),the SAMUM experiments (Saharan Mineral Dust Experiment; May 2006; Morocco) (e.g. Knippertz et al., 2007, 2009) or the GERBIL field campaign (Geostationary Earth Radiation Budget Intercomparison of Longwave and Shortwave Radiation, June 2007; Niger to Mauritania) (Marsham et al., 2008). However, it is difficult to evaluate their relative and respective role without a systematic investigation of the involved meteorological processes over a representative time scale. The data set collected on the STD can constitute a valuable contribution for developing such an approach and identify the main pattern responsible for Saharan dust emissions and transport toward the Sahel and the Atlantic Ocean

3.3.2 Wet season dust events

To illustrate and analyse the type of events recorded during the wet season, the period of 4 to 8 June 2006 in Cinzana has been selected. During this period, two sudden and strong increases of the surface wind velocity have been recorded, associated with a sudden change in the wind direction (Fig. 13). On the evenings of the 5 (21:30 h) and 7

June (18:50 h), very sharp increases in the surface wind velocity are recorded (from 0.7 to 10.5 m s^{-1} on the 5 and from 1 to 9.5 m s^{-1} on the 7 June). In both cases, wind direction shifts from a Northern (300–360°; 0–20°) to an Eastern or South-Eastern direction (100–150°) in less than 15 min. Such sudden changes in the wind velocity and direction are typical signature of the passage of mesoscale convective systems. Similar increase of the surface winds has been described for a "black storm", i.e. the most intense dust storms in Asia, caused by a squall line on the 5 May 1993, with reported surface wind velocities higher than 20 m s^{-1}, reaching locally 37.9 m s^{-1} (Takemi, 1999). The presence of convective systems influencing the station of Cinzana at these two dates is confirmed by the SEVIRI special dust and pseudo visible products (Fig. 14). The image of the 5 June at 21:30 h shows the presence of a huge cloud (∼5°×5°) centred south of Cinzana, generating a dust plume on its northern edge. This convective system was generated from a small cell located over Niger (15° N; 0–2° E) in the morning (∼09:00 h, Fig. 14) that progressively grew and moved south-eastward. A similar situation is observed on the 7 June at 19:00 h, with a MCS of comparable size that initially formed North of Benin (12–12° N; 2° E) in the early morning (05:00, Fig. 14) and progressed eastward during the day.

Simultaneously to the surface wind velocity increase, dust concentration increased by two orders of magnitude in less than 10 min (Fig. 15), reaching 5-min average values as high as 14 000 µg m^{-3}. Then the dust concentrations continuously decrease during several hours, while the monsoon flow is progressively restored. The concentrations are then one order of magnitude lower than before the dust event, even if no rain is recorded. This can be explained by the progressive return to southern wind sectors where the air mass was not impacted by the dust emitted by the convective system.

It is clear from Fig. 15 that during the passage of the MCS, dust concentrations and wind velocity have the same temporal variations, while it is not the case out of these periods. When plotting the dust concentrations as a function of the wind velocity (Fig. 16), it can be seen that extremely intense dust concentrations occur only for local wind velocities higher than 5 m s^{-1}. In fact, such high wind velocities are encountered only when MCS are passing above the station. During the passage of the MCS, dust concentrations are well correlated with the surface wind velocity ($r^2 = 0.79$ on the 5 June and $r^2 = 0.84$ on the 7 June for a logarithmic regression) while the correlation is lower than 0.5 out of these events. Such a relation clearly indicates that dust concentrations correspond to local dust emission and transport.

From these results, it appears that the summer dust events are mainly controlled by local surface wind velocity and thus due to local dust emissions by MCS's. Such events generally last no more than a few hours but with extremely high concentrations, which explains the difference between the daily mean and median concentrations. In Banizoumbou and Cinzana, the recorded high daily concentrations are systematically associated to the typical meteorological pattern (change in wind direction, increase of the surface winds and synchronous increase in dust concentration). The maximum 5-min dust concentrations are higher at the very beginning of the wet season, mainly because the 5-min surface winds are higher at this period and precipitation rates are relatively low. When progressing in the wet season, they are associated with increasing precipitation rates. 15 to 20 of such events are observed every year in Cinzana and M'Bour between May and August. Surface wind and precipitation are thus playing a key role in variability of the daily dust concentrations during the wet season. Further analysis based on a systematic detection of these events is necessary to estimate to what extend they contribute to the seasonal and interannual variability of the atmospheric dust content in summer over Western Africa. Such an approach was developed to investigate the role of mesoscale cloud systems on the development of dust storms over Asia using synoptic data of dust weather (Takemi and Seino, 2005).

4 Conclusion

In the framework of the AMMA Extensive Observation Period, surface concentrations of PM_{10} and surface meteorological conditions have been monitored from January 2006 to December 2008 in three stations located along the main transport pathway of Saharan and Sahelian Dust toward the Atlantic Ocean: Banizoumbou (Niger), Cinzana (Mali) and M'Bour (Senegal). Regarding the local environmental conditions in terms of dust content and temperature, the data recovery rates (from ~70 to 99%) are remarkable at the three stations due to the resistance of the selected instrumentation and to the efficiency of the local technical support.

The daily mean PM0 concentrations associated with mineral dust spread over three orders of magnitude, from less than 10 µg m^{-3} to more than 1000 µg m^{-3}. Daily concentrations exhibit a similar seasonal cycle at the three stations, characterized by a maximum in late winter and spring and a minimum in summer. A gradient in the dust concentrations is observed from Banizoumbou to M'Bour, i.e. from East to West.

The analysis of the local meteorological conditions and in particular of the surface wind velocities and directions allowed to identify the different types of events responsible for this seasonal cycle. The winter-spring maximum of dust concentrations appears to be due to Saharan dust transport and not local dust emissions. During the dry season, the variability of the dust concentrations measured along the transect mainly reflects the variability in the dust emission by different sources of Sahara. The duration of Saharan dust transport events ranges from 1 to 6 days, leading to local to continental dust plumes. On the opposite, extremely high daily concentrations and monthly means are recorded at the beginning of the rainy season, i.e. from the end of May to the end of July. These high concentrations have been found to be linked to the maximum daily surface winds and the highest frequency of high surface winds. These high surface winds are produced by the passage of Mesoscale Convective Systems (MCS) that also bring precipitation in the Sahel. The correlation between surface winds and surface concentrations during the passage of such MCS indicates that the dust concentrations are due to local dust emissions. The events are extremely intense (5-min concentrations of the order or higher than 100 mg m^{-3}) but of short duration (generally less than 1 h). The decrease of the surface wind velocity and of the occurrence of high surface winds and the increase of the precipitation rates during the wet season may be among the factors explaining the minimum of dust concentration observed from the end of July to the beginning of September. This minimum coincides with the maximum in precipitation rates which inhibits dust emission by increasing soil moisture and vegetation cover, but which also suggests an additional influence of wet scavenging of dust concentration.

Both in dry and wet season, the intraseasonal and interannual variability of the dust concentrations appears as connected to the frequency of intense dust events, i.e. to their number and duration. A systematic detection of the different types of dust events recorded during the dry and wet seasons associated with an analysis of the synoptic situations and air mass backward trajectories in the dry season or a specific analysis of the MCS's characteristics in the wet season is now required to further investigate the variability of the dust concentrations at these time-scales. Due to the selected acquisition rates, this data set also offers a unique opportunity of investigate the diurnal cycle of the dust concentrations at the regional scale.

Finally these results illustrate the fact that, when operated with a relevant acquisition step and over a long time period, relatively basic measurements provide a unique insight on the variability of the dust content over West Africa, that can be given neither by synoptic measurements nor by photometric measurements (day time AOD) or satellite observations.

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Yabuki, S., Mikami M., Nakamura, Y., Kanayama S., Fu F., Liu M., and Zhou H.: The Characteristics of Atmospheric Aerosol at Aksu, an Asian Dust-Source Region of North-West China: A Summary of Observations over the Three Years from March 2001 to April 2004, J. Meteorol. Soc. Jpn., 83A, 45–72, 2005.

Table 1. Annual precipitation measured at the three stations of the Sahelian Dust Transect from 2006 to 2008.

	Annual precipitation mm yr^{-1}				
Station	2006	2007	2008	3 yrs-mean	Std. Dev.
Banizoumbou	503	456	701	553	130
Cinzana	708	911	696	772	121
M'Bour	570	321	568	486	143

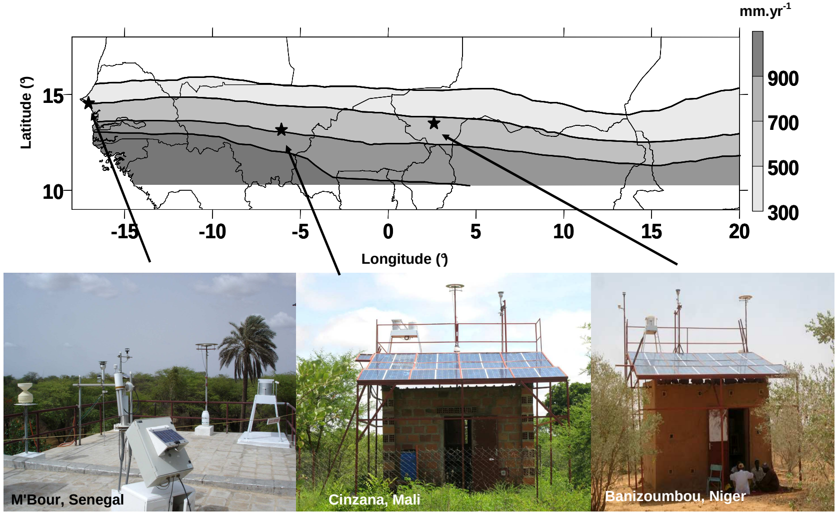

Fig. 1. Location of the three experimental sites compared to the annual precipitation rates over West Africa (figure adapted from Lebel and Ali, 2009) and views of the aerosol sampling stations of Banizoumbou (Niger), Cinzana (Mali) and M'Bour (Senegal).

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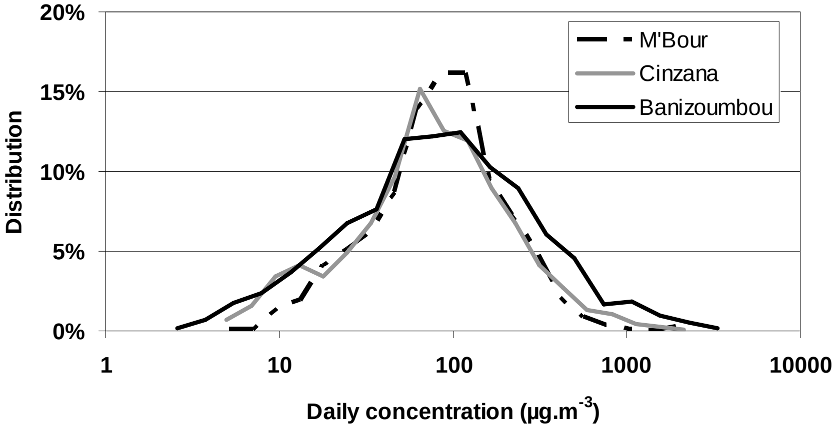

Fig. 2. Relative distribution of the daily mean PM_{10} concentrations from the three stations of the STD between January 2006 and December 2008.

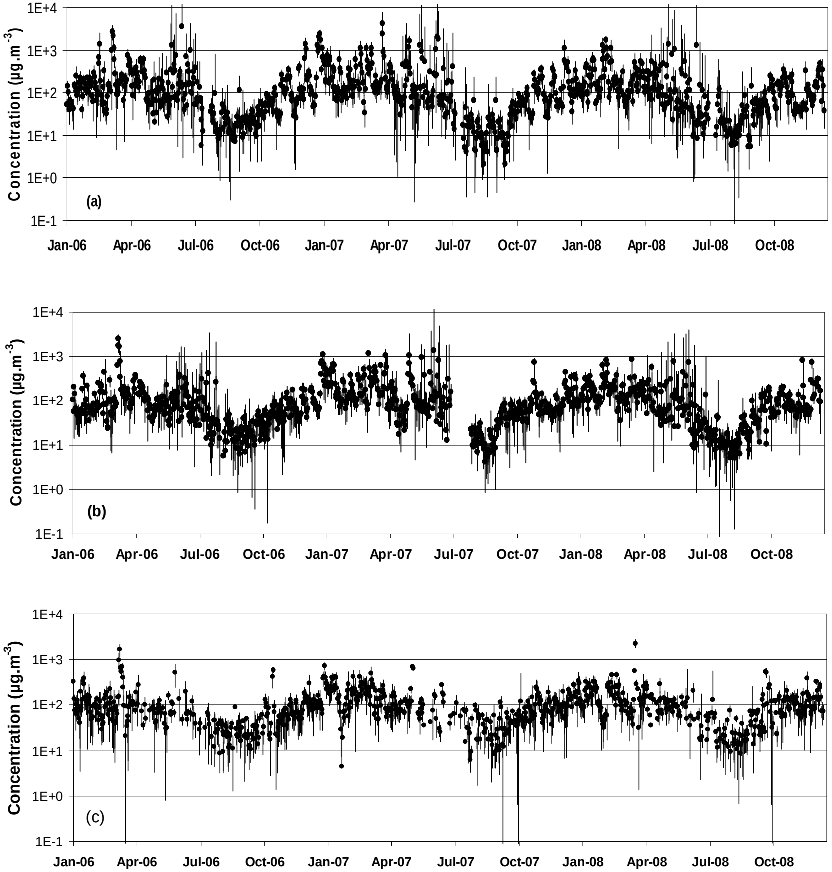

Fig. 3. Daily mean PM_{10} concentration and standard deviation in Banizoumbou **(a)**, Cinzana **(b)** and M'Bour **(c)** for the selected "dust" wind sectors.

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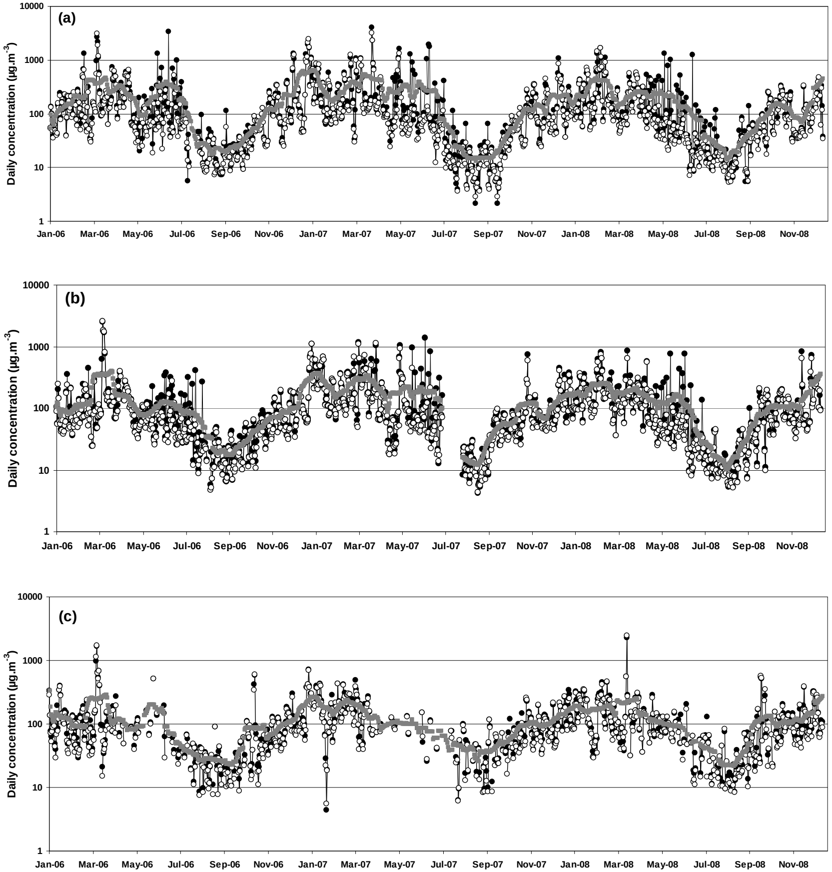

Fig. 4. Daily mean (black circle) and median (open circle) concentrations and 30-days sliding average on the daily mean (grey line) in Banizoumbou **(a)**, Cinzana **(b)** and M'Bour **(c)** from January 2006 to December 2008.

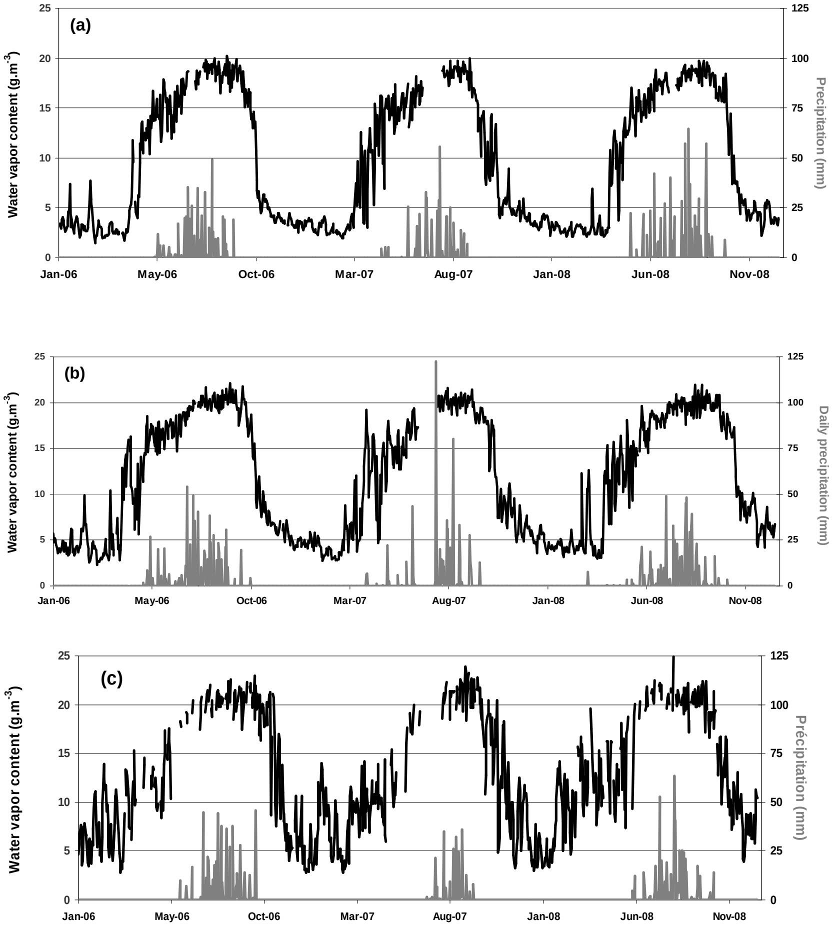

Fig. 5. Daily water vapour content (black) and daily precipitation (dark grey) measured in Banizoumbou **(a)**, Cinzana **(b)** and M'Bour **(c)** from January 2006 to December 2008.

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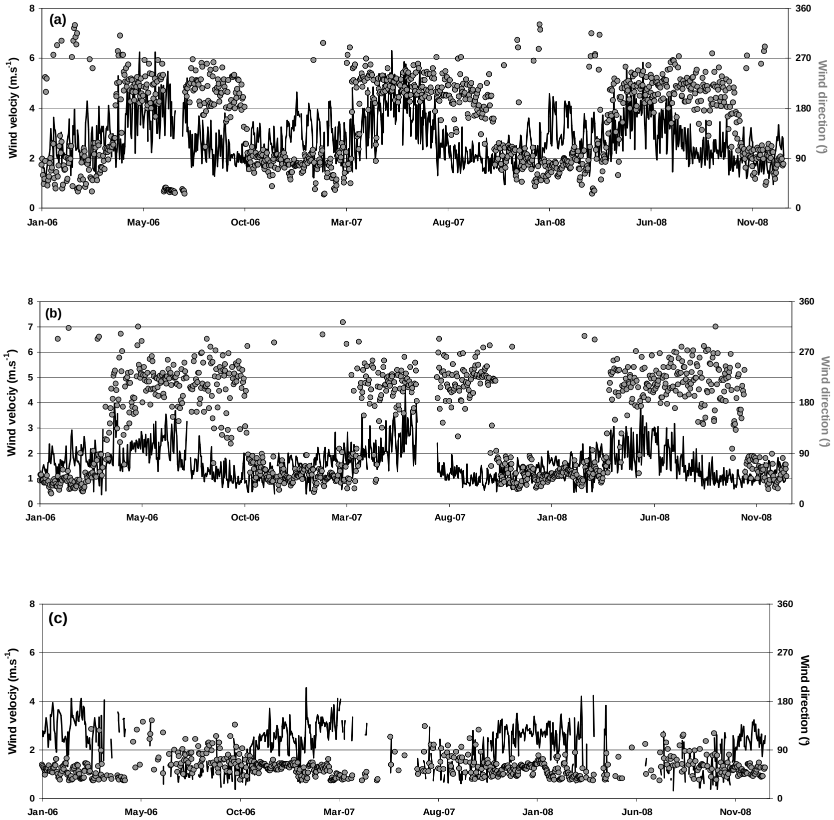

Fig. 6. Daily mean surface wind velocity (line) and daily wind direction (dots) in Banizoumbou **(a)**, Cinzana **(b)** and M'Bour **(c)** from January 2006 to December 2008 (*note that the wind velocities are lower in Cinzana due to a lower position of the wind sensor*).

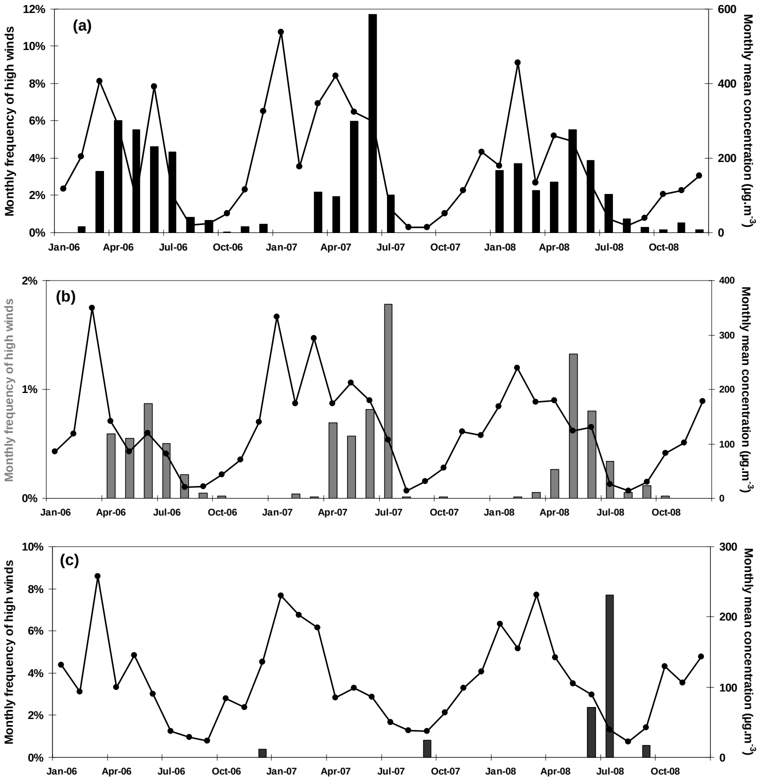

Fig. 7. Monthly frequency of high wind speeds (black bars: >7 m s^{-1}; grey bars : >6 m s^{-1};) and monthly mean concentration of dust (black line with black circles) in Banizoumbou **(a)**, Cinzana **(b)** and M'Bour **(c)** from January 2006 to December 2008.

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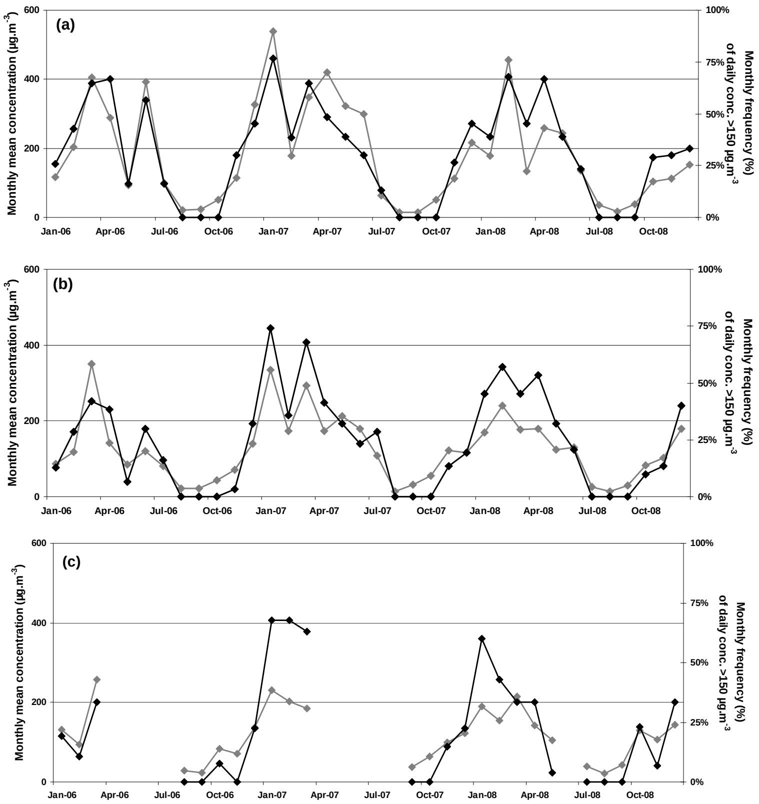

Fig. 8. Monthly mean concentrations (black) and monthly frequencies of daily concentrations higher than 150 µg m^{-3} (grey) in Banizoumbou **(a)**, Cinzana **(b)** and M'Bour **(c)** from January 2006 to December 2008 (*For M'Bour, values are given only if the number of daily data per month is higher than 15*).

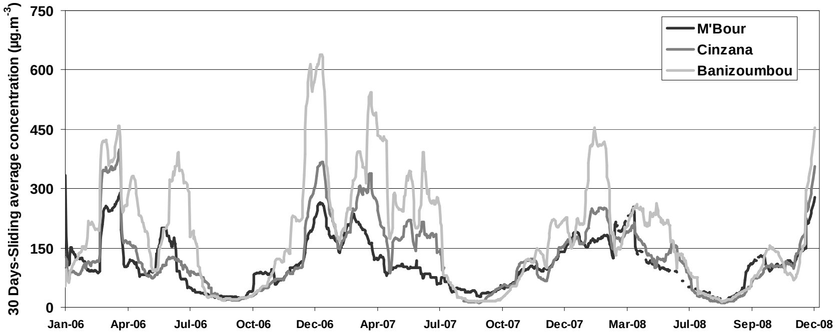

Fig. 9. 30-days sliding average of the daily mean concentration at the three stations of the Sahelian Dust Transect from January 2006 to December 2008.

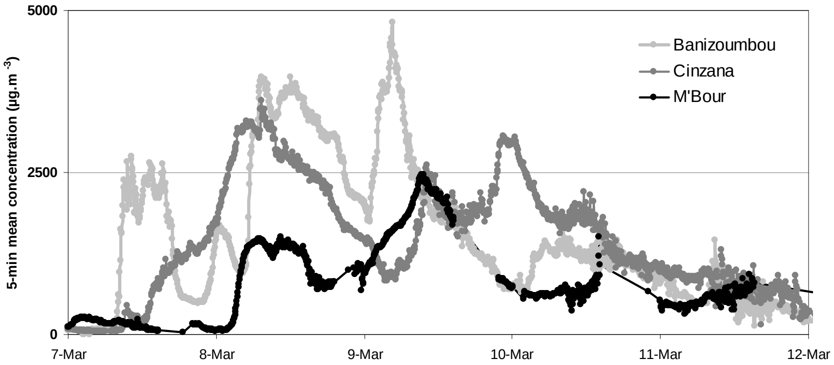

Fig. 10. 5-min mean PM_{10} concentrations measured in Banizoumbou (Niger), Cinzana (Mali) and M'Bour (Senegal) from the 7 to the 12 March 2006.

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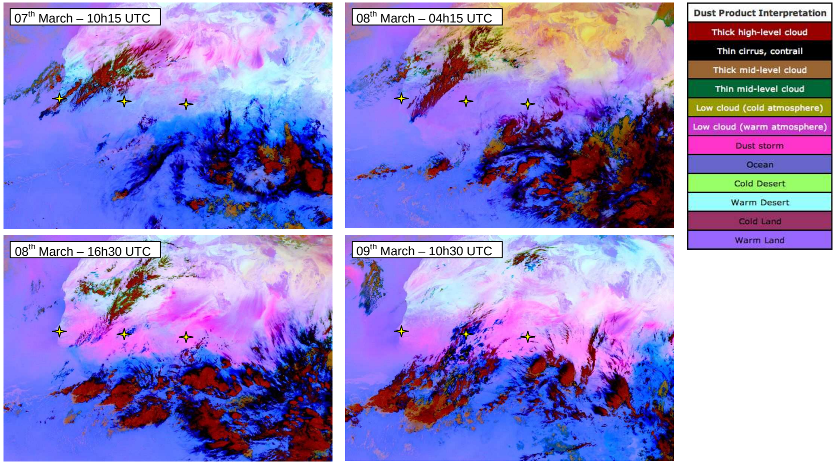

Fig. 11. SEVIRI special dust and pseudo visible products generates using Eumetsat algorithm and data from Eumetsat (infrared channels 12.0, 10.8 and 8.7 mm) of the SEVIRI by the RADAGAST Team (Radiative Atmospheric Divergence using Arm mobile Facility, GERB and AMMA stations: http://radagast.nerc-essc.ac.uk/Home.htm) on the 7 March 2006 at 10:15 h, on the 8 March 2006 at 04:15 h and 16:30 and on the 9 March 2006 at 10:30 h. Dust appears pink or magenta and thick high-level clouds appear in red- brown, showing the presence of convective systems. The yellow stars represent the stations of M'Bour (left), Cinzana (center) and Banizoumbou (right).

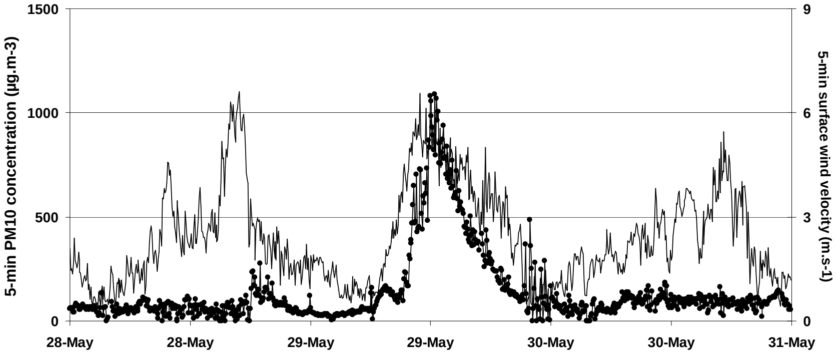

Fig. 12. 5-min PM_{10} concentrations (black dots) and surface wind velocities (black line) measured in M'Bour from the 28 to the 31 May 2006.

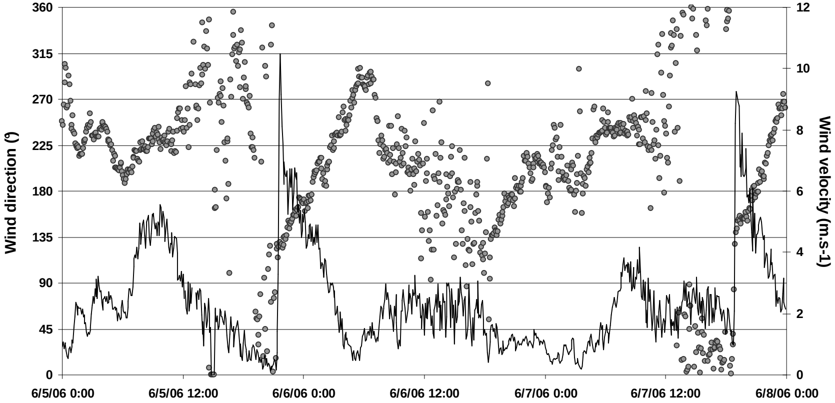

Fig. 13. 5-min surface wind directions (grey dots) and velocities (black line) measured in Cinzana from the 5 to the 8 June 2006.

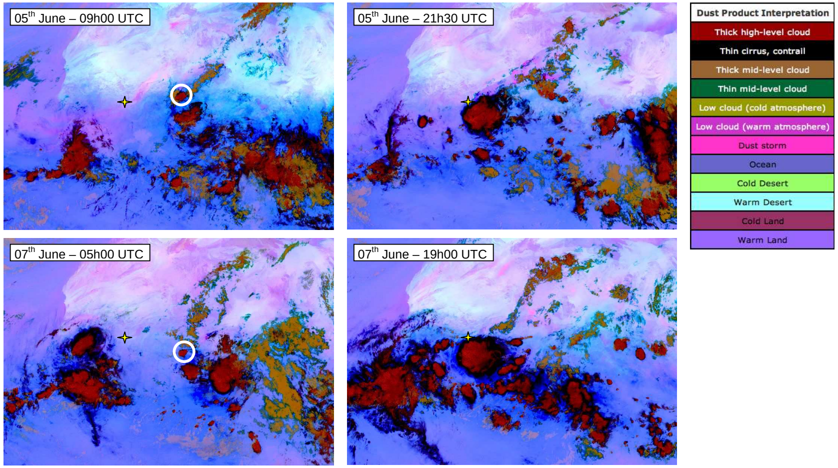

Fig. 14. SEVIRI special dust and pseudo visible products generates using Eumetsat algorithm and data from Eumetsat (infrared channels 12.0, 10.8 and 8.7 mm) of the SEVIRI by the RADAGAST Team (Radiative Atmospheric Divergence using Arm mobile Facility, GERB and AMMA stations: http://radagast.nerc-essc.ac.uk/Home.htm) on the 5th June 2006 at 09:00 and 21:30 h and on the 7 June 2006 at 05:00 and 19:00 h. Dust appears pink or magenta and thick high-level clouds appear in red- brown, showing the presence of convective systems. The yellow star represents the station of Cinzana (Mali).

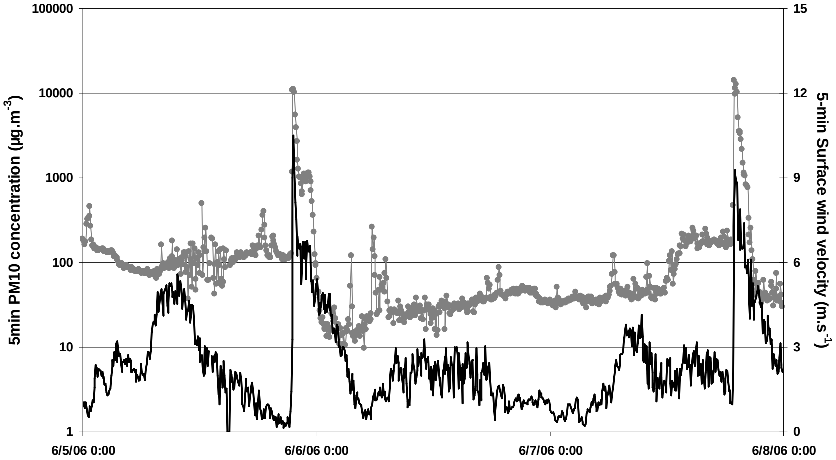

Fig. 15. 5-min surface wind velocities (black line) and PM_{10} concentrations measured in Cinzana from the 5 to the 8 June 2006.

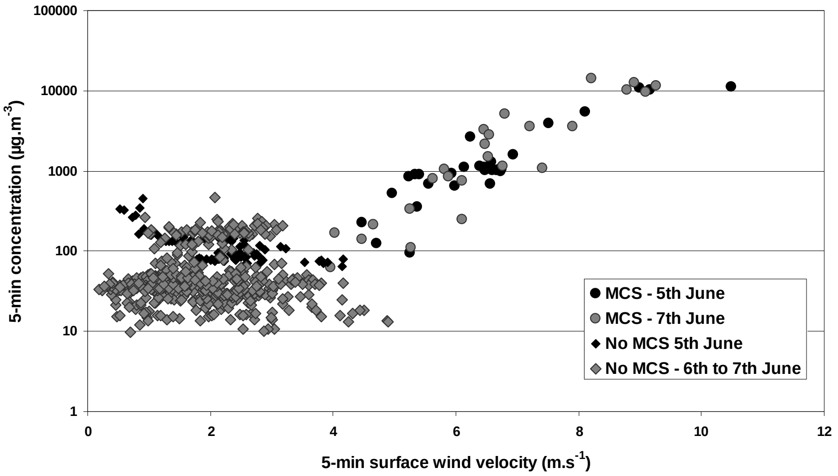

Fig. 16. 5-min PM_{10} concentrations as a function of the 5-min surface wind velocities measured in MCS and no MCS conditions in Cinzana from the 5th to the 8th June 2006.