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Key Points:
- Annual deposition is of the order of 100 g m^{-2}
- Wet deposition is the main source of variability
- Dry deposition is primarily controlled by dust concentration

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Mineral dust over west and central Sahel: Seasonal patterns of dry and wet deposition fluxes from a pluriannual sampling (2006–2012)

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Abstract Total and wet mineral dust deposition has been monitored since 2006 at three Sahelian stations in Senegal, Mali, and Niger, respectively at the weekly and the event time scale. Average annual deposited mass fluxes range from 75 to 183 g m^{-2} yr^{-1}, from west to east. Deposition fluxes exhibit a clear seasonal cycle in Mali and Niger. High wet deposition fluxes result from an optimum phasing between dust concentration and precipitation: the maximum occurring at the beginning of the wet season, after the maximum of dust concentration and before the precipitation maximum. The contribution of wet to total deposition varies from 67% in Mali to 8% in Senegal. It is the main factor of variability of the deposition fluxes from year to year and at the seasonal scale in Niger and Mali. Wet deposition fluxes in Mali and Niger are mainly due to the wash out of dust emitted by convective systems. In Senegal, the deposition fluxes are lower and dominated by dry deposition (92% of the annual deposition flux). This is due to the low occurrence of convective systems producing local dust emissions and intense wet deposition. The dry deposition fluxes are primarily driven by the variability of the dust concentration. The dry deposition velocities derived from our measurements are consistent with those estimated by theoretical models. Scavenging ratios computed from the measured wet deposition fluxes, dust concentrations, and precipitation are anticorrelated with precipitation amounts. This suggests that most of the atmospheric dust is scavenged at the very beginning of the precipitation events.

1. Introduction

Mineral dust is recognized as a key element of the Earth climate system due to its contribution to the Earth radiative budget [e.g., *Sokolik and Toon*, 1999; *Tegen et al*., 1997] and its implication in the biogeochemical cycles of nutrients (P, Fe, etc.) [e.g., *Jickells et al*., 2005] that may affect the oceanic primary productivity and thus the global carbon cycle [*Mahowald*, 2011]. In dust source region, soil losses due to wind erosion and dust exportation contribute to soil degradation [e.g., *Larney et al*., 1998; *Bielders et al*., 2002]. In addition, sand and dust storm are responsible for strong reduction of the horizontal visibility and severe atmospheric dust loads and thus have significant socioeconomic and health impacts [e.g., *De Longueville et al*., 2010].

Regarding the spatial and temporal scales involved in the mineral dust cycle, the evaluation of its impacts is often based on dust distributions simulated by regional and global models. As part of the AEROCOM (Aerosol Model Intercomparison European program) exercise of intercomparison of global aerosol models, the simulations dedicated to the mineral dust cycle performed by different global models have been specifically evaluated [*Huneeus et al*., 2011; *Bergametti and Forêt*, 2014]. This comparison shows that most of the models, used in their nominal configurations, reproduce the vertically integrated aerosol load (aerosol optical depth, AOD) within a factor of 2. However, in the same time, the measured surface concentrations and deposition fluxes are simulated within a factor of 10. When the same emissions, initial size distribution and injection height are prescribed, the discrepancies between models for the simulated dry and wet deposition fluxes of mineral dust are respectively of a factor 2 and 7. These differences in the intensity of the simulated deposition fluxes induce differences in the dust life time between the different global models (1.5 to 7 days). This allows the global models using the highest (lowest) dust emissions to simulate reasonable AOD by having a shorter (longer) dust life time. These results clearly show that the mass budget of the mineral dust is not sufficiently constrained in global models since dust emission and deposition fluxes can be modulated to fit the measured aerosol optical depth, via the simulated life time.

The identification of the location of dust sources and the determination of their emissions frequency have strongly progressed during the last fifteen years, especially by using satellite observations [e.g., *Prospero et al*., 2002; *Schepanski et al*., 2007]. However, because no techniques allow their direct measurement, the quantities of dust emitted in the atmosphere remain still highly uncertain.

The Sahara and Sahel region is the largest source of atmospheric mineral dust [e.g., *Prospero et al*., 2002], and satellite sensors consistently indicate that the dust plumes originating from this region are the most widespread, persistent, and dense observed on Earth [e.g., *Husar et al*., 1997; *Huang et al*., 2010]. Based on global simulations of the mineral dust cycle, the median annual dust emissions from the North of Africa are estimated to be ~1000 Tg yr^{-1}, with a standard deviation in the same order of magnitude (952 $\pm$ 750 Tg yr^{-1}). Their contribution to the global dust emissions is estimated to 62% [*Huneeus et al*., 2011] and the uncertainty on the dust deposition is obviously as large as that on the dust emission. The mineral dust deposition fluxes simulated by several models involved in the model intercomparison project AEROCOM have been compared to measured mineral dust fluxes monitored during 3 years in Florida (USA) [*Prospero et al*., 2010]. This data set documents the deposition fluxes of Saharan dust after long-range transport across the Atlantic Ocean associated with both dry and wet deposition. The authors founded that it was not possible to ascribe the differences between the models to specific processes (emissions, transport, and deposition) but pointed out large disagreement in the ratio of wet and dry deposition. They also highlighted the need for high quality data sets that document the deposition fluxes that allow to account for their episodic nature.

In the framework of the AMMA (African Monsoon Multidisciplinary Analysis) international program, three monitoring stations composing the so-called Sahelian Dust Transect—SDT—dedicated to the measurements of mineral dust atmospheric surface concentrations, vertically integrated content, and deposition have been installed in January 2006. These stations are located in Niger, Mali, and Senegal along a pathways of several thousands of kilometers. They can be affected by emission, transport, and deposition of dust from Saharan and/or Sahelian dust sources located at various distances.

This paper analyzes the deposition measurements performed from 2006 to 2012 over the three SDT stations. The location of the stations provides a unique opportunity to quantify the dust deposition flux in the vicinity of major dust sources, while most of the available observations are located in middle-range to long-range transport regions. They also allow to sample deposition of dust emitted at regional scale during the wet season, which is a first step toward the estimation of a regional "net" budget between deposition and emission in the Sahelian region.

2. Materials and Methods

The location of the stations and the instrumentation for aerosol concentration and local meteorology measurements have been described in details in *Marticorena et al*. [2010], and thus, they are only briefly reminded here.

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) (Figure 1). They are located between the isohyets 500 and 800 mm yr^{-1}.

On each site, the aerosol concentration at the surface level and of wet and dry deposition is measured in addition to the AOD provided by Aerosol Robotic Network/PHOTONS sunphotometer. Basic meteorological parameters such as rainfall, temperature, humidity, wind direction, and speed are also recorded.

Up to now, only the measured surface concentrations and their variability at various time scales have been analyzed [*Marticorena et al*., 2010; *Kaly et al*., 2015]. The dust concentrations measured at the three stations exhibit a decreasing gradient from Niger to Senegal that has been attributed to the increasing distance between the stations and the main dust source regions [*Marticorena et al*., 2010]. A similar seasonal cycle of the dust concentrations is observed at the three stations, with the highest monthly mean concentrations recorded in late winter and early spring in relation with the transport of Saharan dust in the Harmattan flow [*Kaly et al*., 2015]. Very intense but sporadic Sahelian dust emissions are observed at the beginning of the

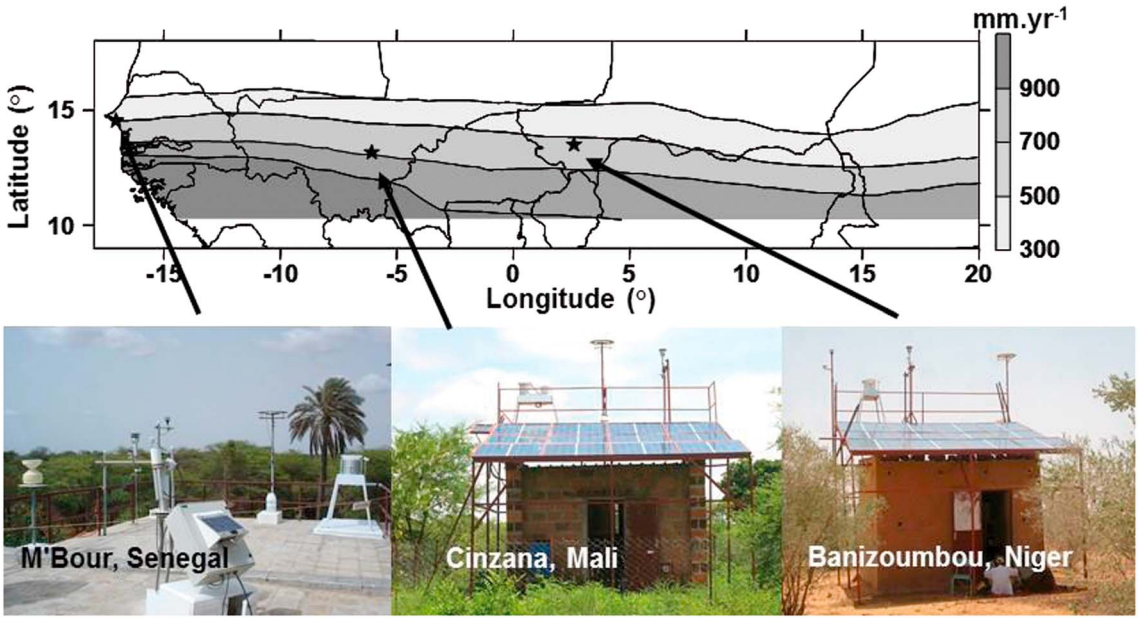


Figure 1. Location of the three stations composing the Sahelian Dust Transect compared to the annual precipitation rates over West Africa (figure adapted from *Lebel and Ali* [2009]) and views of the stations.

monsoon season (May–October) in Niger and Mali, producing daily mean concentrations as high as during the dry season and responsible for the high monthly mean concentrations observed in May–June [*Marticorena et al*., 2010]. The lower monthly mean dust concentrations are recorded from August to September, in coincidence with the highest monthly precipitation [*Kaly et al*., 2015].

In M'Bour, the instrumentation is installed on the terrace of a building of the geophysical station of the French Institut de Recherche pour le Développement (IRD), facing the Atlantic Ocean. The site of Cinzana (Mali), 40 km east southeast of Segou, is embedded 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 latter sites, specific installations have been built up, including solar panels in order to make the stations autonomous (Figure 1).

All three stations are managed by local technicians trained by a the French technical staff to apply the same experimental protocols. Instrumentation has been selected to be simple of use and maintenance and for their capability to resist to severe dust and meteorological conditions. The three stations are fully operational since January 2006.

2.2. Aerosol Concentrations Measurements and Meteorological Parameters

Dust concentration measurements are performed at 6.5 m above the ground level in Banizoumbou and Cinzana and at 10 m high in M'Bour. Meteorological measurements are performed at the same level than the dust concentration measurements at Banizoumbou and M'Bour, but in Cinzana, they are made at 2.3 m from the ground level.

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. 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 1 h sampling time. The filter of the instrument is changed around 2 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).

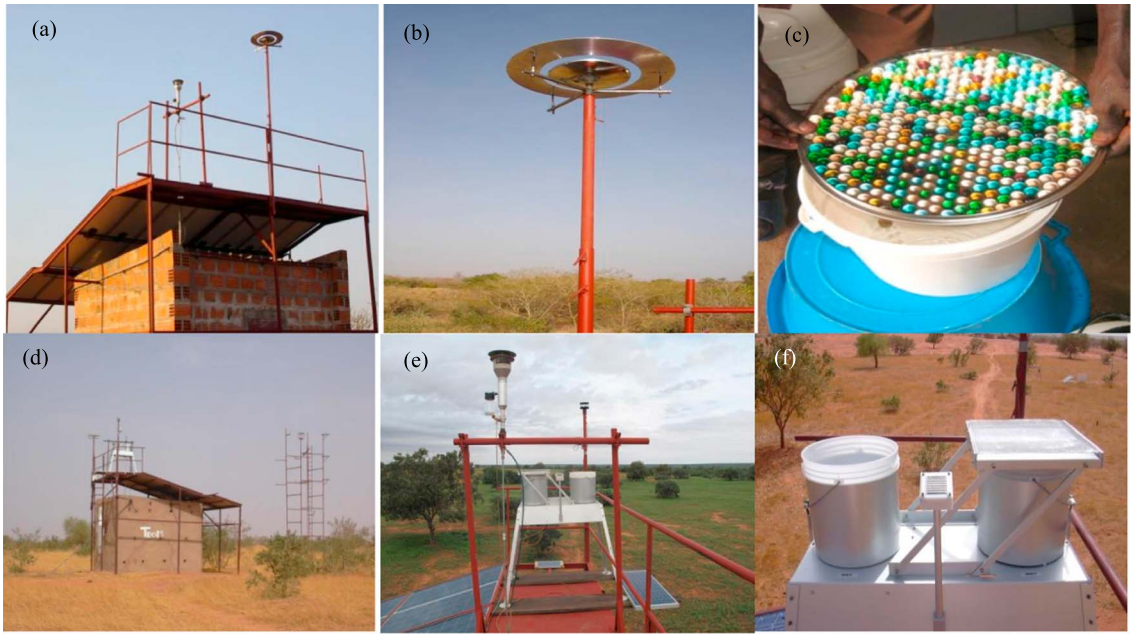


Figure 2. (a and b) Total deposition passive collector at Cinzana station (Mali) and (c) view of the collecting frisbee full of marbles and (d–f) MTX collector at Banizoumbou station (Niger).

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 Gill, temperature, and relative humidity using a 50Y or HMP50 or HMP60 Vaisala sensor and precipitation with an ARG100 tipping bucket rain gauge. Data acquisition uses a CR200 data logger.

2.3. Deposition Measurements

Different collectors are commercially available to sample wet deposition. However, there is no international reference instrument or procedure to sample total and dry deposition [*Goossens*, 2010]. Total and dry deposition collectors are generally passive collectors consisting in containers of different shapes (rectangular, bowl, cylinder, funnel,…). The shape is a critical factor since it can induce directional differences in the efficiency of the collector [*Sow et al*., 2006]. The collectors can be filled with material (water, marble, synthetic turf,…) to avoid the resuspension of dust by wind or the ejection by splash during intense rainfall. Several wind tunnel studies have attempted to estimate or intercompare the efficiency of the different collectors [e.g., *Hall et al*., 1993; *Goossens and Offer*, 1999; *Sow et al*., 2006]. Some authors also investigated the dependence of the collection efficiency with particle size [*Goossens*, 2007].

Goossens and Rajot [2008] have intercompared the capabilities of several collectors of dry deposition in natural conditions at Banizoumbou. The tested collectors included some of the most widely used: the MDCO (marble dust collector [*Ganor* 1975]) and the CAPYR (Capteur Pyramidal [*Orange et al*., 1990]) and the frisbee shape collector [*Hall and Waters*, 1986]. The authors found that the deposition fluxes measured using these different samplers were very similar despite their differences in shape and in material filling the collectors.

2.3.1. Collectors

In the SDT stations, total deposition is sampled with a passive collector of an inverted "frisbee" shape [*Hall and Waters*, 1986], equipped with a flow deflector ring, as tested by *Wiggs et al*. [2002]. The sampler consists of a circular stainless steel collecting bowl (30 cm in diameter and 3.6 cm deep), surrounded by an aerodynamically shaped aluminum deflector ring with an inner diameter of 38.4 cm and outer diameter of 64.0 cm (Figures 2a and 2b). At 1 cm from the edge of the collecting bowl, a hole, 1 cm in diameter, facilitates the collection of the deposits. During the rainy season it is connected via a hose to a bucket to collect the wet deposition and prevent water overflow during precipitation events. The collector is filled with marble (Figure 2c) to avoid the remobilization of the deposited dust during dry deposition events and to limit the

loss by splashing during intense precipitation events. This collector has been selected based on wind tunnel experiments that have shown that it has the highest efficiency for dry deposition collection and a comparable efficiency whatever the particles size [*Sow et al*., 2006]. Compared to a water surface, the sampling efficiency of this collector remains higher than 50% at low wind velocity (2 m s^{-1} in the wind tunnel) but decrease when the wind velocity increases [*Sow et al*., 2006]. The collectors are located on the roof of the local building at the same height than the PM_{10} inlet.

Wet deposition is collected using a passive MTX ARS 1010 automatic deposition sampler (MTX Italia SPA, Modane, Italy). This collector has been widely used for many years, especially to investigate nutrients and metals deposition in different environmental conditions [e.g., *Fuzzi et al*., 1997; *Azimia et al*., 2003, *de Vicente et al*., 2012; *López-García et al*., 2013]. The collector is located on the roof of the local building, slightly lower than the total deposition collector (Figures 2a and 2d). It is made of two buckets (30 cm diameter) and is equipped with a humidity sensor that activates an aluminum lid to cover or uncover the buckets. In this study, the collector was used to sample only wet deposition.

It must be noted that the two collectors have different efficiencies and sampling duration. Indeed, as a consequence, in some cases, wet deposits appear as almost equal or even higher than the total deposits including the wet deposition events.

2.3.2. Recovery of Dust Deposits

The collection procedure is similar for both total and wet deposition and is composed of three stages. In the first stage, the collectors are rinsed with a large amount of water (several liters). The amount of water is lower for wet deposition samples than for total deposition samples due to the presence of precipitation and because a larger amount of water is required to wash the total deposition collector and the marbles. The second stage is a decantation period, of at least 6 h, after which the excess water is siphoned. The sample is then transferred in a beaker for a second sedimentation stage. The sample is finally transferred in a pre-weighted small container and dried in an oven at 70°C until complete water evaporation. The container with the dry material is weighted three times with a balance having a precision of 0.0001 g. For the whole data set, the maximum standard deviation associated with the weighting is 0.0002 g.

The collection is made with the water locally available at each station. To estimate the possible contamination due to the precipitation of soluble components present in the water during the drying procedure, laboratory blanks have been made at each site, by analyzing the water used for collection without exposure in the field. The median value of the blanks is 0.0031 ± 0.0024 g in Niger for 35 samples and 0.0004 ± 0.0002 g in Mali for 27 samples. These values represent a negligible mass compared to the minimum mass weighted for the collected samples (>0.03 g). In M'Bour (Senegal), the blanks are much higher: 0.0182 ± 0.0015 g for 27 samples. To account for this contamination, these blank median values have been systematically subtracted to the measured deposited masses.

2.3.3. Sampling

The sampling schedule for total deposition is 1 week, while individual precipitation events are collected for wet deposition. Except for the opening and closing of the wet deposition collector, the whole sampling procedure is manual. As a result, the sampling schedule was in a few cases not strictly respected, since the operators have had occasionally impediments for technical or personal reasons. The identification of the precipitation events also relies on local operators: they go and recover the wet deposition samples at the end of each precipitation they observe. As a consequence, in some few cases wet deposition samples can be composed of several precipitation events, but all being collected during precipitation periods only.

Since 2006, 363 total deposition samples have been collected in Banizoumbou, 356 in Cinzana, and 344 in M'Bour. From 2006 to 2012, 180 wet deposition samples have been collected in Banizoumbou, 305 in Cinzana, and 144 in M'Bour.

The number of weekly total deposition samples collected by year from 2006 to 2012 (Table 1) is of the order of 50, i.e., close to the number of weeks per year. The number of wet samples differs from one station to the other: the highest number of wet samples (39 to 54 samples per year) is recorded for Cinzana due to the higher frequency of precipitation events. The lowest number of wet deposition samples (15 to 30 depending on the year) is recorded in M'Bour. It must be noted that there is no wet deposition samples in Banizoumbou in 2006 due to an instrument failure and a low number of samples in 2012 in M'Bour where deposition sampling stopped in September.

Table 1. Number of Total and Wet Deposition Samples Collected From 2006 to 2012 at the Three Stations

	M'Bour (Senegal)		Cinzana (Mali)		Banizoumbou (Niger)	
	Total	Wet	Total	Wet	Total	Wet
2006	52	30	50	47	49	-
2007	52	25	49	40	53	24
2008	52	20	52	39	52	33
2009	52	15	52	54	52	30
2010	52	18	51	49	53	26
2011	52	26	51	40	52	30
2012	32	10	51	36	52	37
Total	344	144	356	305	363	180

2.3.4. Computation of the Deposition Fluxes

The mass collected with the MTX sampler allows to determine the deposition fluxes associated specifically with wet deposition, here after referred to wet-only (WO) deposition fluxes. The total deposition fluxes (TOT) were computed based on the mass collected weekly all along the year using the total deposition collector. By excluding samples during which precipitation has been recorded, it is possible to estimate the minimum deposition fluxes due to dry deposition only (DO). The DO fluxes do not strictly correspond to the entire dry deposition fluxes because by discarding the samples for which precipitation events occurred during the week of sampling, we also excluded the part of this week during which dry deposition has contributed to the measured total deposition fluxes.

Daily deposition fluxes, F, are computed by dividing the collected mass, M, by the surface of the collector, S_{coll}, divided by the duration of the sampling, $T_{sampling}$.

$$F = \frac{M}{S_{coll} T_{Sampling}} \qquad \left(\mathrm{g\,m^{-2}d^{-1}}\right) \tag{1}$$

Both for total and wet deposition collectors, the sampling duration (expressed in days) is computed as the difference between the date of installation of a clean collector and the date of collection of a deposition sample. For wet deposition samples, in Banizoumbou the sampling duration ranges from 1 to 20 days for 90% of the data, with a median duration of 4 days. The median duration is 3 days in Cinzana and 6 days in M'Bour. In both stations, the sampling duration for wet deposition ranges from 1 to 14 days for 90% of the data.

Precipitation is monitored with a 5 min time step, which allows the estimation of its duration, T_{precip}. A more precise computation of the wet deposition flux (WO_p) can thus be provided based on equation (1) but using the precipitation duration T_{precip} instead of the sampling duration $T_{sampling}$. In this case, the wet deposition flux is expressed in $\mathrm{g\,m^{-2}\,min^{-1}}$ to be consistent with the typical durations of the precipitation events.

Monthly and annual deposition fluxes were determined by summing the deposits collected respectively during each month and during each year. When a sampling period is overlapping 2 months or 2 years, the computed deposit was apportioned as a function of the number of sampling days within each month or each year.

2.3.5. Consistency of the Measurements

A way to evaluate the reliability of the measurements is to compare the TOT fluxes estimated directly from the total deposition measurements to the sum of the DO and WO fluxes (Table 2). As already mentioned, the DO fluxes do not represent the totality of the dry deposition, so the difference between TOT and (DO + WO) is expected to be positive and to represent the dry deposition fluxes collected by the total deposition collector during the sampling duration with wet deposition.

In Banizoumbou, the 6 years average sum (DO + WO) is $119\,\mathrm{g\,m^{-2}\,yr^{-1}}$, while the 7 year average TOT is $133\,\mathrm{g\,m^{-2}\,yr^{-1}}$. The 6 years average difference is $14\,\mathrm{g\,m^{-2}\,yr^{-1}}$, which represents about 10% of the collected total deposition. The annual differences are positive (from 6 to $48\,\mathrm{g\,m^{-2}\,yr^{-1}}$) except in 2010 where the WO fluxes exceed the TOT fluxes by 13%. In Cinzana, the 7 years average sum (DO + WO) is $115\,\mathrm{g\,m^{-2}\,yr^{-1}}$, while the 7 years average TOT $119\,\mathrm{g\,m^{-2}\,yr^{-1}}$. The average difference is less than 4%, but the year to year variability is larger (noted the 48% difference observed for 2012). At this station, the difference between (DO + WO) and TOT is often negative (3 years over 7). Negative differences between (DO + WO) and TOT can be explained by a lower efficiency of wet deposition sampling with by the total deposition collector in cases of intense

Table 2. Annual Total (TOT), Dry Only (DO) and Wet-Only (WO) Deposition Fluxes Measured at the Three Sahelian Stations From 2006 to 2012 and Annual Means and Standard Deviations for the 7 Years of Sampling, Sum of Dry Only and Wet-Only Deposition Fluxes (DO + WO), Differences Between the Total Deposition and the Sum of Dry Only and Wet-Only Deposition (TOT − (DO + WO)) and Percentage of Difference to Total Deposition (%) (TOT − (DO + WO)/TOT) and Ratio of Wet Only to Total Deposition Fluxes (% WO/TOT)

Annual Deposition Fluxes ($g\,m^{-2}\,yr^{-1}$)

	2006	2007	2008	2009	2010	2011	2012	Mean	STD
				Banizoumbou (Niger)					
Total (TOT)	126.4	93.6	155.7	159.2	112.5	103.8	183.1	133.5	33.1
Dry only (DO)	31.4	38.8	52.8	35.2	82.9	35.9	39.4	45.2	17.9
Wet only (WO)	-	38.0	83.9	117.6	44.7	51.2	96.7	72.0	32.1
DO + WO	-	76.8	136.7	152.8	127.6	87.0	136	119.5	30.4
(TOT − (DO + WO))	-	16.7	18.9	6.42	-15.1	16.7	48.1	15.1	20.1
% (TOT − (DO + WO)/TOT)	-	18	12	4	-13	16	26	10.4	13.7
% WO/TOT	-	41	54	74	40	49	53	51.7	12.4
				Cinzana (Mali)					
Total (TOT)	104.5	109.5	131.6	125.5	75.3	159.9	129.5	119.4	26.4
Dry only (DO)	31.0	25.0	20.9	66.2	40.6	31.0	37.5	36.0	14.9
Wet only (WO)	57.8	51.4	80.6	67.3	70.8	117.0	107.4	78.9	24.7
DO + WO	88.8	76.4	101.5	133.4	111.4	147.9	145.0	114.9	28.0
(Total − (DO + WO))	15.7	33.1	30.1	−7.9	−36.1	12.0	−15.5	4.5	25.3
% (Total − (DO + WO)/TOT)	15	30	23	−6.3	−48	7.5	−12	1.3	26.4
% WO/TOT	55	47	61	54	94	73	83	66.7	17.2
				M'Bour (Senegal)					
Total (TOT)	84.5	79.1	100.1	91.7	102.1	97.0	-	92.4	9.1
Dry only (DO)	38.9	56.1	57.6	83.6	87.3	67.4	-	65.1	18.4
Wet only (WO)	9.7	4.7	6.4	4.8	8.9	6.5	-	6.8	2.0
DO + WO	48.0	60.8	64.1	88.4	96.2	73.9	-	71.9	18.0
(TOT − (DO + WO))	36.5	18.3	36.1	2.3	6.0	23.1	-	20.53	14.3
% (TOT − (DO + WO)/TOT)	46	23	36	4	6	24	-	22.6	15.8
% WO/TOT	11	6	6	5	9	7	-	7.4	2.3

precipitation events and by the resuspension of deposited dust by the strong winds preceding such intense precipitation. In M'Bour, the 6 years average sum (DO + WO) is $72\,g\,m^{-2}\,yr^{-1}$ and the 6 years average TOT $92\,g\,m^{-2}\,yr^{-1}$. The annual differences between (DO + WO) and TOT are always positive and represent 22% of the total in average. Globally, the estimated TOT and (DO + WO) are consistent, suggesting that uncertainties on the total deposition fluxes do not exceed 50%, the maximum negative difference. The median difference between the estimated deposition fluxes derived from the two types of collection for the three stations and for the 7 years is 15%, and these differences are lower than 25% for 75% of the annual estimations.

3. Deposition Fluxes

3.1. Annual Deposition Fluxes

3.1.1. Total Deposition (TOT)

Over the three stations and the 7 years of sampling, annual TOTs vary from 75 to $183\,g\,m^{-2}\,yr^{-1}$ (Table 2). The average total deposition fluxes are higher in Niger ($133 \pm 33\,g\,m^{-2}\,yr^{-1}$) than in Mali ($119 \pm 26\,g\,m^{-2}\,yr^{-1}$) and Senegal ($92 \pm 9\,g\,m^{-2}\,yr^{-1}$). This spatial pattern is consistent with the observed PM_{10} concentrations [*Marticorena et al.*, 2010]: over the 7 years, the mean annual PM_{10} concentration is $157\,\mu g\,m^{-3}$ in Banizoumbou, $115\,\mu g\,m^{-3}$ in Cinzana, and $105\,\mu g\,m^{-3}$ in M'Bour. The interannual variability of the annual TOT is relatively low: the coefficient of variation, CV, is 25% in Niger, 22% in Mali, and 9% in Senegal.

These annual deposition fluxes can be compared to other direct measurements of deposition fluxes of mineral dust performed using passive collectors (i.e., dust traps). *Drees et al.* [1993] have monitored dust deposition in Sadoré and Chikal, respectively, 40 km south east and 160 km northeast from Niamey (Niger) from 1985 to 1989. The measured annual total deposition fluxes range from $164\,g\,m^{-2}\,yr^{-1}$ to $212\,g\,m^{-2}\,yr^{-1}$. In Sadoré also, *Herrmann* [1996] measured from 1992 to 1994 an average deposition flux of $95.3\,g\,m^{-2}\,yr^{-1}$. The dust deposition fluxes measured in Banizoumbou by *Rajot* [2001] from 1996 to 1998 were respectively 73, 97, and $128\,g\,m^{-2}\,yr^{-1}$. There is about a factor of 2 between the measurements

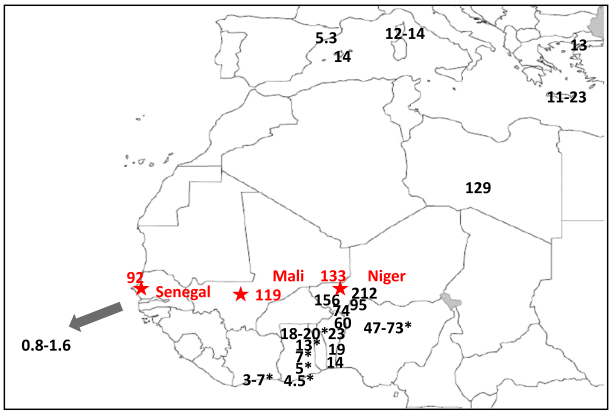


Figure 3. Deposition fluxes (in $g\,m^{-2}\,yr^{-1}$) measured by passive deposition collectors inside and close to the north of Africa: Senegal, Mali, and Niger (this work, in red); Niger [*Drees et al.*, 1993; *Herrmann*, 1996; *Rajot*, 2001]; Libya [*O'Hara* et al., 2006], Ghana [*Breuning-Madsen et al.*, 2015]. Asterisks denote dry season only; Nigeria [*Møberg et al.*, 1991], dry season only; Ivory Coast [*Stoorvogel et al.*, 1997], dry season only; Mediterranean basin: Spain [*Avila et al.*, 1997]; Balearic Islands [*Fiol et al.*, 2005]; Corsica [*Bergametti et al.*, 1989; *Loye-Pilot et al.*, 1986]; Turkey [*Kubilay et al.*, 2000]; Kriti [*Mattson and Nihlen*, 1996]; Barbados [*Prospero et al.*, 2010].

performed by *Drees et al.* [1993] and those from *Herrmann* [1996] and *Rajot* [2001]. However, the period 1985–1989 corresponding to Drees et al.'s measurements was one of the dustiest in the Sahel [*N'Tchayi Mbourou et al.*, 1994, 1997]. With annual deposition fluxes ranging from 93 to 183 $g\,m^{-2}$, our measurements are consistent with the deposition fluxes previously measured in Niger.

Few other measurements of dust deposition have been performed in the North of Africa: dust deposition has been monitored during 1 year (June 2000 to May 2001) in east, central, and southeast Libya [*O'Hara et al.*, 2006]. The average annual deposition flux measured and averaged over 24 sampling sites is 129 $g\,m^{-2}\,yr^{-1}$. Additional measurements are available downwind of the Sahel, where the Harmattan flux transports mineral dust during the dry season. *Herrmann* [1996] measured dust deposition along a north-south transect from Niger to Benin. From the northernmost location (Ouallam, Niger) to the southernmost location (Houéto, Benin), the average deposition fluxes range from 156 to 14 $g\,m^{2}\,yr^{-1}$.

Measurements of annual deposition mineral dust have been performed at further distance of the Saharan desert, in particular in the Mediterranean Basin. Annual deposition flux in the Mediterranean basin can be estimated to tens of $g\,m^{-2}\,yr^{-1}$, i.e., 1 order of magnitude lower than the deposition flux over the north of Africa. Annual wet deposition flux of mineral dust has been estimated after long-range transport across the Atlantic Ocean (Florida) to about 1 $g\,m^{-2}\,yr^{-1}$ [*Prospero et al.*, 2010].

All these measurements (Figure 3) show a strong decrease of the deposition fluxes over distances of the order of 1000 km. This suggests that a major part of the dust emitted from a given source is deposited at relatively short distance downwind. Mineral dust emitted in the Sahara and the Sahel is thus massively deposited on the African continent downwind of the main dust sources. The decrease is more than 1 order of magnitude from the Sahara to the Mediterranean basin and the Gulf of Guinea and 2 orders of magnitude after crossing the Atlantic Ocean.

3.1.2. Wet Deposition

The annual wet deposition fluxes exhibit higher variability than the total deposition both in space and in time (Table 2). The annual wet deposition fluxes range from 4.7 to 117.6 $g\,m^{-2}\,yr^{-1}$. The lowest annual mean wet deposition flux over the sampling period is recorded in Senegal (6.8 $g\,m^{-2}\,yr^{-1}$). This is 1 order of magnitude lower than the mean annual wet deposition measured in Mali and Niger (78.9 and 72.0 $g\,m^{-2}\,yr^{-1}$).

Such a variability cannot be explained by differences in the 7 year average annual precipitation: they are comparable in Banizoumbou (505 $mm\,yr^{-1}$) and M'Bour (593 $mm\,yr^{-1}$) and much higher in Cinzana (776 $mm\,yr^{-1}$). Similarly, there is no coincidence between the annual wet deposition fluxes and the annual precipitation measured from 2006 to 2012 at each station (Table 3).

When examining the ratio of wet to total deposition (Table 2), it appears that the contribution of WO to TOT differs at the three stations. The largest contribution of WO to TOT is measured in Mali (66.7% in average, from 47 to 94% over the 7 years). WO represents about 52% in average of the TOT in Niger, with annual contributions ranging from 40 to 74%. In Senegal, the proportion of WO to TOT is very low in comparison, ranging from 5 to 11% over the 7 years. These results show that despite comparable annual TOT fluxes, the three stations exhibit very different relative contributions of wet and dry deposition.

Table 3. Annual Wet Deposition Fluxes (g m^{-2} yr^{-1}) and Annual Precipitation (mm yr^{-1}) at the Three Sahelian Stations From 2006 to 2012

	Banizoumbou		Cinzana		M'Bour	
	Wet	Precipitation	Wet	Precipitation	Wet	Precipitation
2006	-	533	57.8	717	9.7	559
2007	38.0	471	51.4	911	4.7	383
2008	83.9	698	80.6	722	6.4	590
2009	117.6	307	67.3	765	4.8	764
2010	44.7	371	70.8	860	8.9	779
2011	51.2	349	117.0	493	6.5	486
2012	96.7	807	107.4	941	-	-

3.1.3. Dry Deposition

The mean annual DO fluxes in Niger and Mali are respectively 45.2 and 36 g m^{-2} yr^{-1}, i.e., much lower than the WO fluxes (Table 2). The annual DOs have similar variability than the WOs at these stations. The CV is 39% in Banizoumbou and 41% in Mali. Annual DO fluxes are, most of the time, higher in M'Bour than at the two other stations: they range from 39 to 87 g m^{-2} yr^{-1}, against 31 to 83 g m^{-2} yr^{-1} in Banizoumbou and 25 to 66 g m^{-2} yr^{-1} in Cinzana. In Senegal, the 6 years average DO flux is 1 order of magnitude higher than the WO fluxes, with a comparable variability (CV = 28%).

The DO fluxes can be compared to deposition fluxes measured during the dry season in several countries of West Africa. Harmattan dust deposition was collected from November 1984 to March 1985 in six locations in the North of Nigeria [*Møberg et al.*, 1991]. The deposition fluxes range from 47 g m^{-2} to 73 g m^{-2} with an average flux of 58 g m^{-2} yr^{-1}. In Ghana, deposition fluxes have been monitored at four locations along a north to south gradient (11–6°N) during the dry seasons 2000 to 2003, i.e., the seasons during which the region is submitted to the Harmattan flux [*Breuning-Madsen and Adwazi*, 2005]. The highest deposition fluxes are measured in North Ghana, with average deposition fluxes of 42 g m^{-2} yr^{-1}, while the deposition flux is much lower in the southern location (~12 g m^{-2} yr^{-1}). More recently, *Breuning-Madsen et al.* [2015] estimated the average deposition fluxes averaged from 2002 to 2006 over the same spatial gradient to slightly lower values: 18.3 g m^{-2} yr^{-1} in the north of Ghana to 5 g m^{-2} yr^{-1} in the south. This latter value is consistent with the dust deposition fluxes (3.3 to 7.6 g m^{-2} yr^{-1}) measured during the dry season 1990–1991 in the south-west of Ivory Coast [*Stoorvogel et al.*, 1997]. The DO fluxes measured in our stations are thus consistent with the deposition fluxes gradient previously measured in the dry season in West Africa.

3.2. Seasonal Pattern

3.2.1. Mean Pattern

The multiannual average monthly fluxes for TOT, WO, and DO have been computed for each station (Tables 4, 5, and 6). At Cinzana, all measurements are averaged over the period 2006–2012. Because there was no wet

Table 4. Monthly Average Total Deposition Fluxes (TOT) and Associated Standard Deviations From 2007 to 2012 in Banizoumbou, From 2006 to 2012 in Cinzana and From 2006 to 2011 in M'Bour

	Banizoumbou		Cinzana		M'Bour	
	Mean (g m^{-2})	STD (g m^{-2})	Mean (g m^{-2})	STD (g m^{-2})	Mean (g m^{-2})	STD (g m^{-2})
Jan	4.5	1.8	3.9	1.1	7.6	1.9
Feb	4.6	0.7	4.4	1.8	8.7	1.9
Mar	8.0	1.8	6.3	2.3	12.7	4.0
Apr	8.4	3.4	6.9	2.2	11.0	5.3
May	20.0	10.4	22.5	10.5	11.1	3.3
Jun	43.7	24.2	37.8	27.8	12.8	4.0
Jul	18.1	6.8	21.5	10.1	7.1	2.8
Aug	10.6	7.6	7.0	3.9	3.4	09
Sep	4.4	1.5	2.5	1.3	3.4	0.8
Oct	4.1	0.8	1.9	0.9	4.5	1.8
Nov	3.8	1.8	2.3	0.8	6.8	2.8
Dec	3.4	0.4	2.6	0.4	6.3	1.2

Table 5. Monthly Average Wet Deposition Fluxes (WO) and Associated Standard Deviations From 2007 to 2012 in Banizoumbou, From 2006 to 2012 in Cinzana and From 2006 to 2011 in M'Bour

	Banizoumbou		Cinzana		M'Bour	
	Mean (g m^{-2})	STD (g m^{-2})	Mean (g m^{-2})	STD (g m^{-2})	Mean (g m^{-2})	STD (g m^{-2})
Jan	0.0	0.0	0.1	0.2	0.0	0.0
Feb	0.0	0.0	0.1	0.1	0.0	0.0
Mar	0.1	0.2	0.6	0.6	01	0.2
Apr	1.2	1.6	2.4	3.1	0.7	1.7
May	15.1	10.9	14.5	11.2	0.3	0.9
Jun	33.1	21.2	29.7	24.8	0.7	0.8
Jul	12.1	4.7	18.7	6.9	1.8	0.9
Aug	7.0	3.4	8.0	4.5	2.2	0.9
Sep	3.2	2.5	3.2	2.3	1.7	0.3
Oct	0.3	0.2	1.6	1.5	0.5	0.5
Nov	0.0	0.0	0.1	0.2	0.0	0.0
Dec	0.0	0.0	0.1	0.2	0,0	0,0

deposition measurements in 2006 in Banizoumbou, the data reported on these tables and on Figure 4 only concern the period 2007 to 2012. Similarly, since the total and wet deposition measurements were stopped in September 2012 in M'Bour, the data reported for this station correspond to the period 2006 to 2011. The average seasonal cycle of the deposition fluxes can be compared with the seasonal cycle of the PM_{10} concentrations and the precipitation (Figure 4).

3.2.1.1. Banizoumbou (Niger) and Cinzana (Mali)

At these two stations, the total deposition fluxes exhibit a clear seasonal cycle, with maximum in June and minima observed in September to December. At the period during which highest deposition fluxes are measured (from May to July), most of the deposition is due to wet deposition (Table 5).

This seasonal cycle of the total deposition fluxes is phased neither with the seasonal cycle of the PM_{10} concentration nor with that of precipitation. The PM_{10} monthly mean concentrations exhibits a clear seasonal cycle, with maximum occurring during the dry season, most frequently in March, and minimum during the wet season [*Marticorena et al*,. 2010, *Kaly et al*., 2015]. These authors have shown that the high concentrations recorded during the dry season is due to massive transport of Saharan dust that takes place close to the surface. High monthly concentrations are also recorded at the beginning of the wet season (June) due to local Sahelian dust emissions mobilized by high surface winds associated with the passage of mesoscale convective systems [*Marticorena et al*., 2010]. After June, the PM_{10} concentrations progressively decrease due to the combination of less intense local dust emissions and more frequent scavenging of the suspended dust by precipitation, the minimum PM_{10} concentrations being recorded in August [*Marticorena et al*., 2010]. This corresponds to the maximum of precipitation, which then decreases until October.

Table 6. Monthly Average Dry Only Deposition Fluxes (DO) and Associated Standard Deviation From 2007 to 2012 in Banizoumbou, From 2006 to 2012 in Cinzana and From 2006 to 2011 in M'Bour

	Banizoumbou		Cinzana		M'Bour	
	Mean (g m^{-2})	STD (g m^{-2})	Mean (g m^{-2})	STD (g m^{-2})	Mean (g m^{-2})	STD (g m^{-2})
Jan	4.5	1.8	3.7	0.9	7.6	1.9
Feb	4.2	0.7	4.4	1.8	7.1	1.6
Mar	7.7	2.2	5.2	1.9	10.4	4.0
Apr	6.9	3.8	5.0	1.2	10.2	4.7
May	5.5	5.9	9.4	10.1	9.4	4.2
Jun	1.7	4.6	1.9	4.2	7.7	6.4
Jul	2.8	5.5	0.2	0.5	1.4	1.6
Aug	0.7	1.6	0.3	0.8	0.0	0.1
Sep	1.2	1.2	0.2	0.3	0.1	0.3
Oct	3.0	1.1	1.1	0.9	2.3	2.2
Nov	3.7	1.8	2.1	0.9	4.8	4.2
Dec	3.2	0.3	2.6	0.4	4,8	3.1

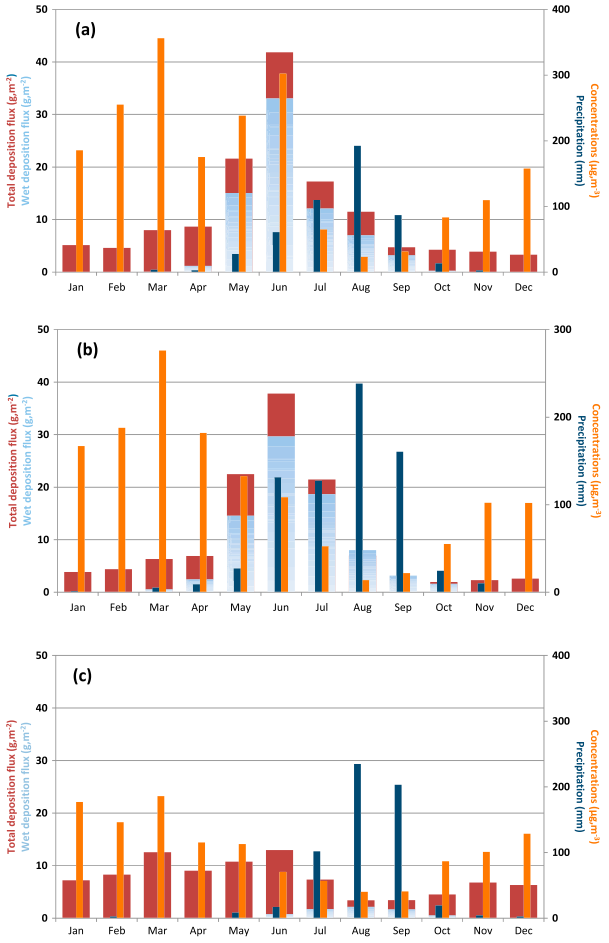


Figure 4. Monthly total (brown large bar) and wet (superimposed light blue large bar) deposition fluxes, PM_{10} monthly concentrations (orange thin bar), and monthly precipitation (dark blue thin bar) averaged (a) from 2007 to 2012 in Banizoumbou, (b) from 2006 to 2012 in Cinzana, and (c) from 2006 to 2011 in M'Bour.

The maximum of total deposition flux is thus recorded 3 months after the monthly maximum in PM_{10} concentrations and 2 months before the maximum of precipitation. It results from an optimum combination between PM_{10} concentrations and precipitation in June when the PM_{10} concentrations are still high and precipitation starts to be significant. The monthly average deposition fluxes from April to July represent 61% in average of the annual deposition flux in Banizoumbou. This is consistent with the deposition measurements performed by *Drees et al.* [1993] which showed that deposition fluxes collected from 15 April to 15 July from 1985 to 1989 in Chikal (Niger) represent 55% of the annual averaged deposition flux. A similar average ratio (63%) is obtained for the deposition fluxes recorded from May to October 1992 to 1994 in Sadoré [*Herrmann*, 1996].

Monthly wet deposition fluxes are comparable in Banizoumbou and Cinzana from May to July, despite differences in the monthly PM_{10} concentrations and precipitation (higher PM_{10} concentrations in Banizoumbou but higher precipitation in Cinzana), suggesting that these two factors probably compensate each other (Table 5). At the monthly scale, the contribution of wet deposition to the total deposition fluxes differs between the two stations. It is dominant (66 to 77%) from May to September in Banizoumbou and from May to October in Cinzana (65 to 100%).

The monthly DO are comparable at the two stations but slightly higher in Banizoumbou in the dry season (Table 6). They exhibit a seasonal cycle with maximum in March in Banizoumbou, consistent with the maximum of the monthly PM_{10} concentrations. In Cinzana, the maximum DO is recorded in May, but with a very large standard deviation due to an extremely high DO in 2009 (28.4 g m^{-2}). In May the monthly mean DO and its standard deviation in Cinzana are almost twice higher than in Banizoumbou.

These results point out that wet deposition is the dominant contributor to total deposition in Banizoumbou and Cinzana. Dry deposition is obviously the dominant deposition process during the dry season, but it is still a significant contributor to total deposition at the early stage of the wet season (April–May).

3.2.1.2. M'Bour (Senegal)

In M'Bour, the seasonal cycle is not as well marked as at the two other stations. The monthly TOT are lower than at the two other stations (Figure 4) and range from 13 g m^{-2} in June to 0.8 in September. The highest monthly deposition fluxes are recorded earlier, i.e., from March to June. The monthly mean WOs are also much lower and do not exceed 2 g m^{-2}.

As in Banizoumbou and Cinzana, the highest monthly PM_{10} mean concentrations are recorded from December to April, i.e., during the dry season. Even if precipitation events are occasionally recorded from

in April, in M'Bour the wet season occurs slightly later than in Banizoumbou and Cinzana, and the period with precipitation is not as homogeneously distributed from May to September.

During the summer months (June–August), the surface PM_{10} concentrations are low because at this period, most of Saharan dust transport takes place at high altitude in Senegal [*Léon et al*., 2009]. In addition, no significant dust emission by local convective activity is recorded at this station. [*Marticorena et al*., 2010; *Kaly et al*., 2015]. These two factors explain why deposition fluxes in M'Bour are not as high as those recorded at the two other stations during summer.

Even if WO fluxes during the wet season are much lower in M'Bour than in Cinzana and Banizoumbou, they can be the major contributor to TOT at the monthly scale. In August and September, WO deposition fluxes represent 50 to 65% of TOT. However, these months are those for which TOT is the lowest of the year. During the period corresponding to highest mean monthly TOT (from May to June), the contribution of WO is not dominant (6 to 25%). Thus, the contribution of WO to TOT (6 to 65%) is significantly lower in M'Bour than in Niger and Mali, and the period during which WO is the major contributor to TOT occurs later in the year than at the two other stations.

On the opposite, dry deposition is more intense during the dry season (from November to April) and at the early stage of the wet season (May–June) in M'Bour than in Cinzana and Banizoumbou (Table 6). From October to June, where DO is the main contributor to TOT, the DO fluxes measured in M'Bour are twice higher than in Banizoumbou and Cinzana.

Dry deposition is by far the main driver of dust deposition in M'Bour (>90%; Table 2). This leads to a smoother seasonal cycle of total deposition than in Banizoumbou and Cinzana. The minimum total deposition is observed when the contribution of wet deposition is maximum, presumably due to the low dust concentrations measured at the surface at this period of the year.

3.2.2. Interannual Variability

The monthly TOTs averaged over the whole sampling period exhibit a moderate interannual variability: whatever the type of deposition flux, the standard deviation remains in the same order of magnitude than the mean (Tables 4–6).

Figure 5 shows that in Banizoumbou, the same seasonal cycle of TOT persists along the 7 years of observations. Except in 2007, this maximum occurs in June, i.e., at the beginning of the wet season and is associated with the highest WO. The monthly TOT recorded in June range from 16 g m^{-2} in 2007 to 80 g m^{-2} in 2012 and the monthly WO from 8 in 2007 to 70 g m^{-2} in 2009. The highest TOT is recorded in June 2012 and is associated with the highest monthly mean PM_{10} concentration recorded during the 7 years (487 μg m^{-3}, i.e., about 70% higher than the 7 years monthly average of 290 μg m^{-3}). The monthly precipitation (84 mm) is also higher than the 7 years average precipitation (58 mm). On the opposite, two of the years with the lowest annual deposition (2007, 2010) are characterized by the lowest contribution of WO to TOT and by low relative contributions of the deposition recorded in June to the annual deposition (<20%). The variability of the deposition recorded in June drives mainly the interannual variability of the annual deposition fluxes, especially through the relative contribution of WO to TOT.

The situation is similar in Cinzana: the general pattern of the seasonal cycle is the same every year, but the maximum of the monthly TOT varies from year to year from 11 g m^{-2} in June 2010 to 94 g m^{-2} in June 2011. The monthly TOT recorded in June 2011 is the highest monthly flux recorded during the 7 years at the three stations, and it represents 59% of the TOT measured in 2011. It is associated with the highest monthly recorded WO (78 g m^{-2}). The years with the highest TOT (2008, 2011, and 2012) have contribution of WO to TOT higher than 60%, with a contribution of the deposition recorded in June higher than 30% of the annual deposition. Symmetrically, the years having the lowest annual deposition fluxes (2006, 2007, 2010) are characterized by lower contributions of the deposition occurring in June (<20%). For these three years, the monthly deposition fluxes are more spread over the wet seasons than for the years having high deposition fluxes.

The variability of the maximum monthly TOT is linked to the variability of WO even if no unambiguous relationship between the monthly TOT and WO and the monthly precipitation and PM_{10} concentration can be established. The high monthly TOT and DO recorded in the beginning of the wet season—June—seem to correspond to specific combination of precipitation and PM_{10} concentration.

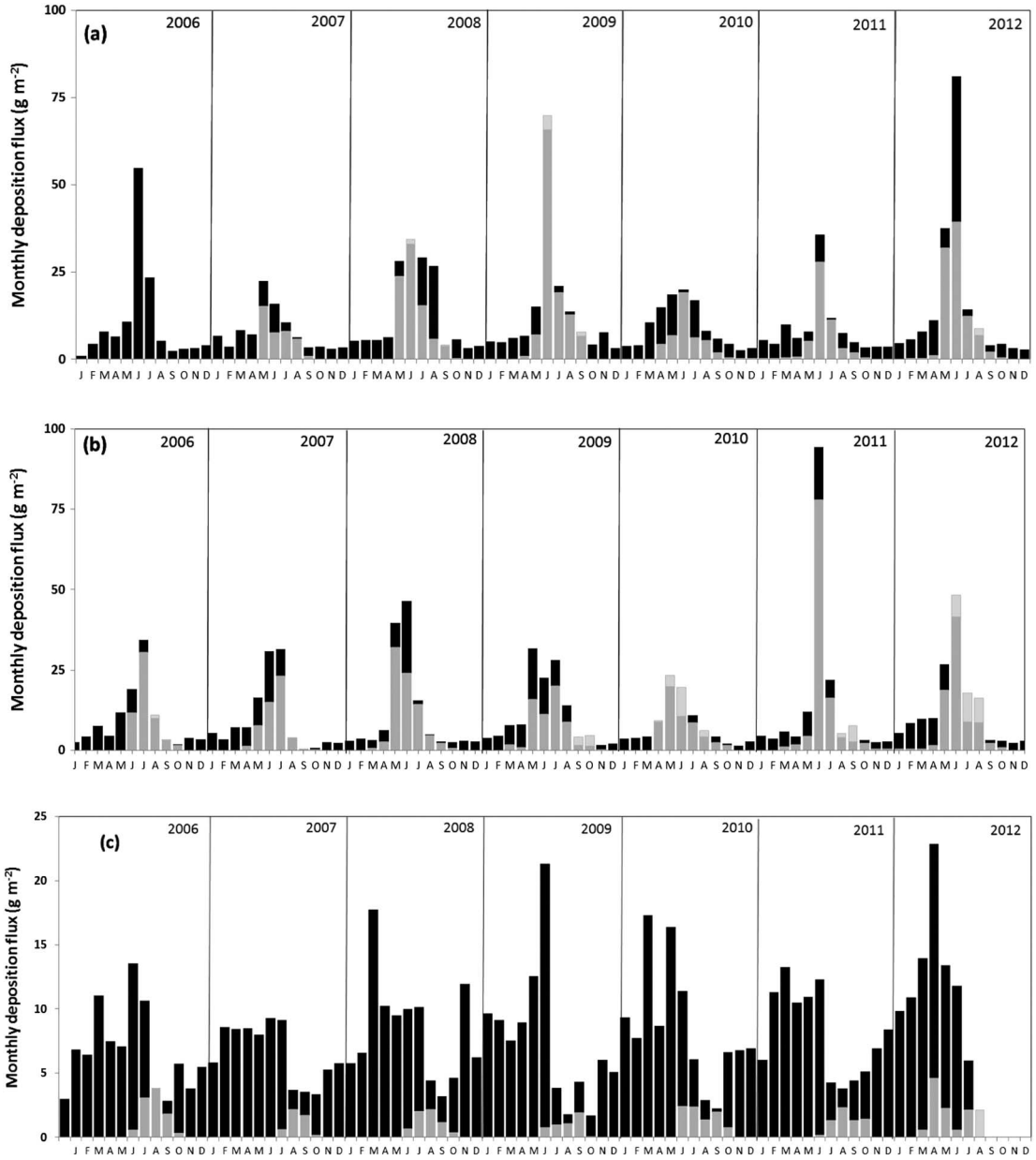


Figure 5. Monthly total (black) and wet (grey) deposition fluxes from 2006 to 2012 in (a) Banizoumbou (Niger), (b) Cinzana (Mali), and (c) M'Bour (Senegal) (no measurements of the wet fluxes for Banizoumbou in 2006).

In M'Bour, as mentioned above, the interannual variability of the total deposition (9%) is much lower than at the two other stations (25 and 22%) and not any no shift in the seasonal cycle for a specific year can be identified. The monthly TOT exceeding the 7 years monthly average are equally distributed in the wet and the dry seasons. Dry deposition is responsible for the highest monthly depositions fluxes. Thus, we specially examined the possible coincidence between high monthly deposition fluxes and high monthly dust concentrations. The monthly fluxes higher than the 75th percentile appear as almost always associated with monthly PM_{10} concentrations higher than the 75th percentile of the monthly concentrations. This strongly suggests that unusually high dust concentration are responsible for exceptionally high deposition fluxes in the dry season at M'Bour.

As a conclusion, in Banizoumbou and Cinzana, the year to year variability of the total deposition is mainly due to changes in the contribution of the wet deposition events occurring at the beginning of the wet season (June). In M'Bour, the interannual variability is low and depends on dry deposition events associated with extremely large dust concentrations. Such events can occur both in the dry and in the wet season.

3.3. Weekly Total and Individual Wet Deposition Fluxes

The analysis of the deposition fluxes at the finer scale (weekly, deposition event, precipitation event) allows to confirm and refine the conclusions drawn from the average values.

3.3.1. Time Series of Deposition Fluxes

Individual TOT and WO fluxes have been plotted with the PM_{10} concentrations and precipitation respectively averaged and cumulated during the deposition sampling period from January 2006 to December 2012 (Figure 6).

The weekly total deposition fluxes range over four orders of magnitude (0.001 to 10 g m^{-2} d^{-1}). Despite of the variability of the deposition fluxes from one event to the other, the seasonal pattern of the deposition fluxes is well marked at the three stations. During the dry season (October to May), at the three stations, the total deposition fluxes increase progressively, consistently with the increase of the mean dust concentration. However, in Banizoumbou and Cinzana, they do not reach their maximum at the maximum of concentration. The TOT fluxes tends to increase until May, while the mean PM_{10} concentrations increase until March–April, where they reach their seasonal maximum and then decrease until August. At these two stations, the highest TOT are recorded at the beginning of the monsoon season (June) and the lowest at the end of the wet season. They are clearly associated with wet deposition, as demonstrated by the coincidence of TOT and WO events. The high concentrations recorded at this period in Banizoumbou and Cinzana has been attributed to local dust emissions due to the passage of mesoscale convective systems (MCS) [*Marticorena et al*., 2010]. After the maximum, the deposition fluxes decrease progressively to reach a minimum in September, i.e., 2 months later than the mean PM_{10} concentration minimum. The fact that deposition fluxes remains significant while surface concentrations are at their minimum suggests that precipitation occurring at the end of the rainy season can wash out dust transported at high altitude rather than locally emitted dust. In Cinzana the minimum TOT and the minimum concentration are better phased and occur respectively at the end of August and the beginning of September. However, the variability of the WO from one sample to the other is very high: very low WO can be recorded at the beginning of the rainy season where the highest WO and TOT are also measured. This can be explained by the higher frequency of wet deposition events at this station (36 to 54 per year) compared to the other stations (26 to 37 in Banizoumbou and 15 to 30 in M'Bour), which leads to shorter delay between two successive precipitation events in Cinzana (3 days in average; less than 2 days in 32% of the cases) than in the other stations (4 days in average in Banizoumbou and 5.8 in M'bour and less than 2 days in 17 and 19% of the cases, respectively).

In M'Bour, the seasonal cycle of the total deposition flux is quite well phased with the seasonal cycle of the PM_{10} concentrations. The range of TOT and WO is not as large as at the two other stations (only 2 orders of magnitude, from 0.1 to 1 g m^{-2} d^{-1}). Precipitation is less frequent and less intense than at the two other stations, and the number of WO events is also lower. The minimum of the deposition fluxes and of the concentrations is recorded at the end of August and coincide with the maximum of precipitation. In fact, the main difference between M'Bour and the other station is the absence of intense WO event and high PM_{10} concentrations at the beginning of the wet seasons.

Marticorena et al. [2010] noted that the mean daily PM_{10} concentration computed at the beginning of the wet season was largely influenced by the occurrence of short-duration pulses of extremely high concentrations due to local emission by MCSs. To clearly highlight the occurrence of such events, the maximum 5 min PM_{10} concentration recorded during the deposition sampling period has been extracted and compared to the mean PM_{10} concentration (Figure 7). In Banizoumbou and Cinzana, the seasonal cycle of the 5 min maximum PM_{10} concentration is different from the one of the mean PM_{10} concentration. This is clearly highlighted by the difference between the sliding averages of the mean and maximum PM_{10} concentrations. Compared to the mean concentrations, the peaks of the maximum concentration are shifted toward the beginning of the wet season (May–June). The maximum concentrations at this period are 1 or 2 orders of magnitude higher than the maximum concentrations recorded in the dry season. This clearly highlights the extremely high dust concentrations due to local dust emissions by convective systems. Such behavior is not observed in M'Bour: the maximum of the PM_{10} concentration is not as marked and is more phased with the mean PM_{10} concentrations. Except for occasional events, no intense of the PM_{10} concentrations and no intense precipitation and thus no intense TOT or WO events are recorded at the beginning of the wet season. This suggests that in M'Bour, the dust atmospheric content and deposition fluxes are not affected by local interactions between mineral dust and MCSs

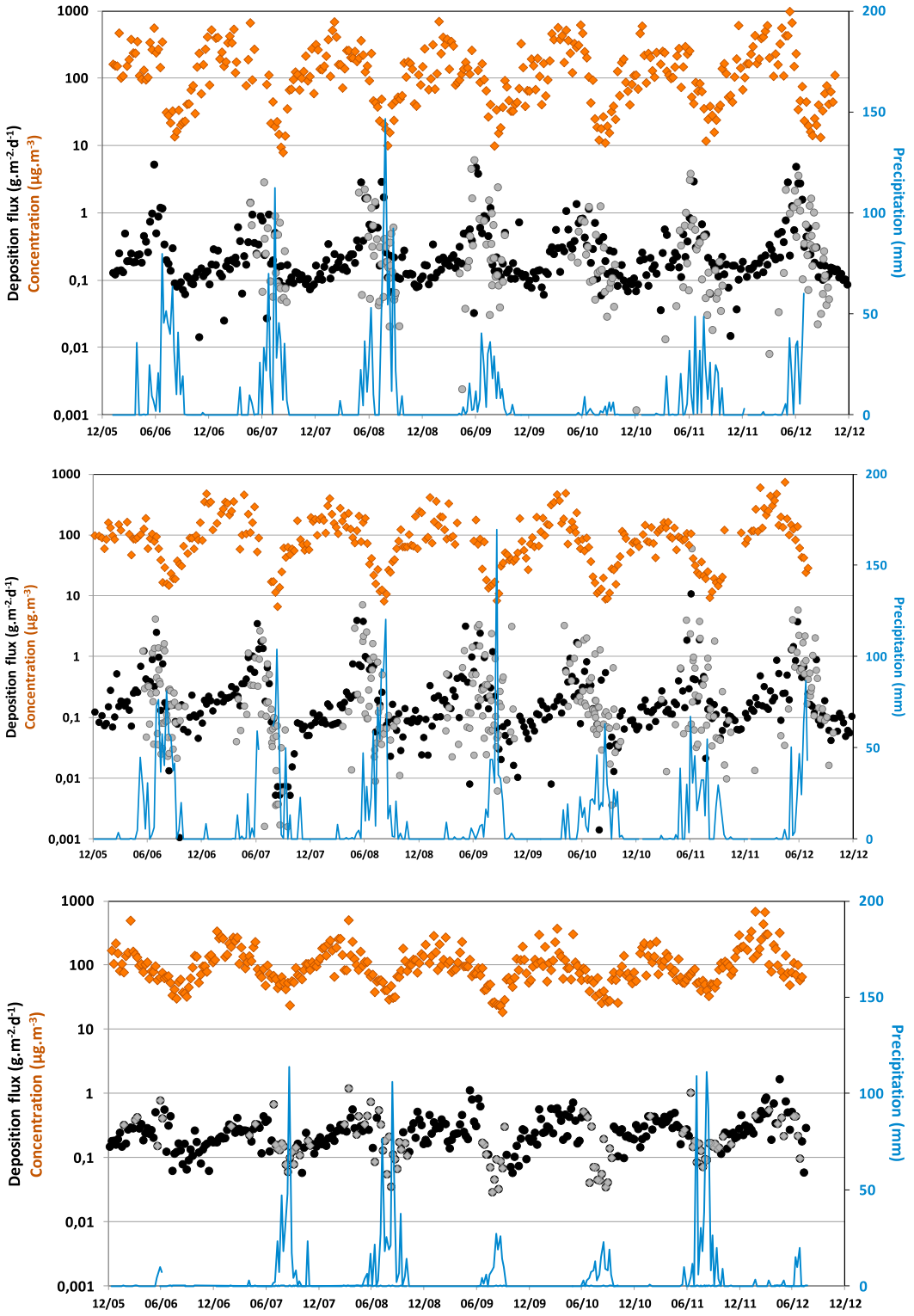


Figure 6. Total (black dots) and wet (grey dots) deposition fluxes and PM_{10} concentrations (orange diamonds) and precipitation (blue line) respectively averaged and cumulated over the sampling period of the depositions fluxes from January 2006 to December 2012 at the three stations of the SDT (top: Banizoumbou, middle: Cinzana, bottom: M'Bour).

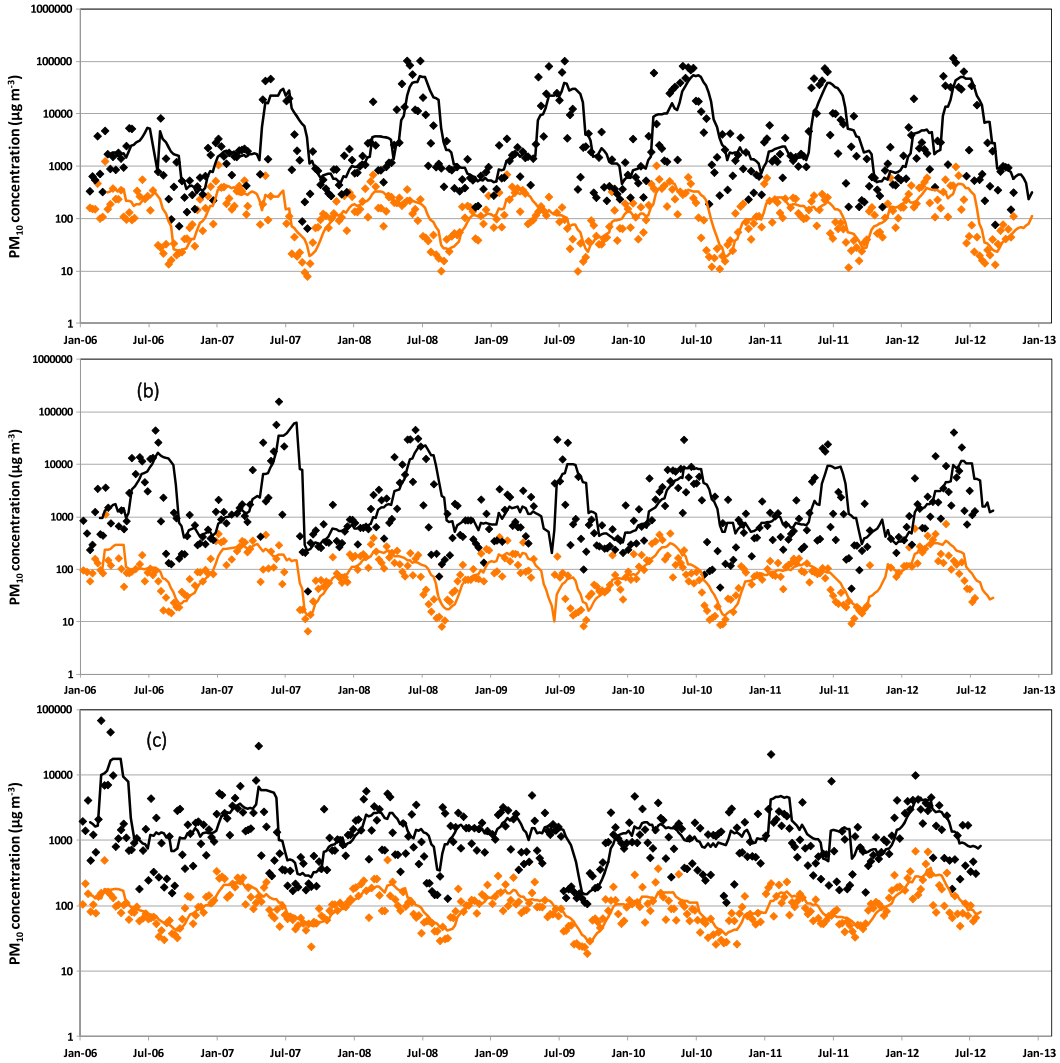


Figure 7. Mean (orange) and maximum (black) PM_{10} concentration over the sampling duration of the total depositions fluxes from January 2006 to December 2012 in (a) Banizoumbou (Niger), (b) Cinzana (Mali), and (c) M'Bour (Senegal). The lines correspond to a sliding averaged performed over eight successive data, i.e., about 8 weeks.

(i.e., no local dust emission by the high surface winds associated with the passage of the MCSs and less frequent precipitation events), while such events are responsible for the most intense deposition events at the two other stations.

3.3.2. Wet Deposition at the Precipitation Scale

To investigate the factors that determine the intensity of wet deposition, we specifically examined the variability of the wet deposition fluxes computed as a function of the precipitation duration, WO_p, during the wet seasons. It must be noted that in a few cases, wet deposition samples (with non-negligible mass) have been collected for which no precipitation has been recorded in the rain gauge. Since the detection limit of the rain gauge is 0.2 mm, to compute the WO_p in these cases, we assumed a precipitation amount below the detection limit (0.1 mm) and a precipitation duration of 5 min, i.e., the time step of acquisition. The mean WO_p, the mean PM_{10} concentration, mean precipitation cumulated during the deposition events, and mean date of occurrence have been computed by classes of wet deposition fluxes (Table 7). The individual WO_p deposition fluxes ranging over several orders of magnitude (from 10^{-7} to 10^{-1} g m^{-2} min^{-1}), the WO_p classes have been defined to properly samples the whole range of measured WO_p, especially in Banizoumbou and Cinzana. However, the WO_ps in M'Bour are much lower than at the two other stations, which require more classes in the lower range.

Table 7. Classes of Wet Deposition Fluxes Computed as a Function of the Precipitation Duration (WO_p), Number of Samples by Classes, Mean Wet Deposition Fluxes, Mean Precipitation Duration, Mean Precipitation Cumulated During the Deposition Events, Mean PM_{10} Concentration, and Mean Date of Occurrence of the Samples in Each Class

Classes of WO_p ($g\,m^{-2}\,min^{-1}$)	Number of Samples	WO_p ($g\,m^{-2}\,min^{-1}$)	Precipitation Duration (min)	Precipitation Amount (mm)	PM_{10} Concentration ($\mu g\,m^{-2}$)	Date in the Year (dd-mm)
			Banizoumbou			
0–5E-05	10	3.25E-05	199	28.0	25	21-Aug
5E-05–1E-04	10	6.89E-05	208	29.6	19	22-Aug
1E-04–2.5E-04	21	1.75E-04	136	22.4	82	10-Aug
2.5E-04–5E-04	30	4.92E-04	95	22.3	61	30-Jul
5E-04–1E-03	12	7.53E-04	87	22.8	95	26-Jul
1E-03–5E-03	29	2.65E-03	40	7.2	215	16-Jul
5E-03–1E-02	27	7.54E-03	21	3.9	151	27-Jun
1E-02–1E-01	22	2.77E-02	12	5.3	142	28-Jun
1E-01–5E-01	3	2.18E-01	5	0.1	177	30-May
			Cinzana			
0–5E-05	33	2.62E-05	194	29.3	13	22-Aug
5E-05–1E-04	22	7.11E-05	111	19.9	21	27-Aug
1E-04–2.5 E-04	45	1.61E-04	95	16.0	35	7-Aug
2.5E-04–5E-04	31	3.61E-04	112	21.1	53	2-Aug
5E-04–1E-03	32	7.20E-04	81	12.2	56	22-Jul
1E-03–5E-03	67	2.66E-03	28	5.3	66	5-Jul
5E-03–1E-02	25	7.22E-03	19	4.2	145	12-Jun
1E-02–1E-01	19	3.18E-02	13	2.9	101	3-Jul
1E-01–5E-01	2	1.22E-01	5	0.1	93	20-May
			M'Bour			
0-1E-06	31	5.07E-07	204	26.9	48	24-Aug
1E-06–5E-06	41	2.79E-06	73	11.7	50	10-Aug
5E-06–1E-05	10	6.93E-06	47	13.1	47	10-Aug
1E-05–5E-05	20	2.40E-05	26	6.6	58	13-Aug
5E-05–5E-05	3	6.88E-05	7	2.4	57	11-Aug
>1E-04	4	1.76E-04	6	1.6	89	16-Jun

At the three stations, both the mean precipitation amount and the precipitation duration range over 1 order of magnitude and decrease from the lowest to the highest flux classes. The mean precipitation cumulated during the deposition events ranges from 30 mm for the lower flux classes to a few millimeters and their mean duration from 3–4 h to about ~10 min. The mean precipitation amount and duration are well correlated at the three stations (R^2 from 0.84 to 0.97). In Banizoumbou and Cinzana, the highest flux class corresponds to cases where default values of 0.1 mm and 5 min have been assigned to precipitation amount and duration. The highest WO_ps are associated with the lowest mean precipitation with a similar dependence on the precipitation amount in Banizoumbou and Cinzana (Figure 8). In M'Bour, there is also a trend of increase of WO_p when precipitation decreases, but for the same precipitation amount, WO_p is 1 to 2 orders of magnitude lower than at the two other stations. There is also a link between WO_p and the PM_{10} concentration, especially in Banizoumbou and Cinzana: the higher the mean concentration is, the higher the wet deposition flux is (Figure 9). The link is not as clear in M'Bour, mainly because the range of the mean PM_{10} concentration is very limited compared to the other stations (89 to 47 $\mu g\,m^{-3}$ in M'Bour, compared to 215 to 19 $\mu g\,m^{-3}$ in Banizoumbou; Table 7). The PM_{10} concentrations decrease from June to August, while the precipitation increases during the same period. Consistently, the mean WO_p decreases as a function of the mean date of occurrence of the deposition event in the year in Banizoumbou and Cinzana (Figure 10). The situation is different in M'Bour. Except for the highest

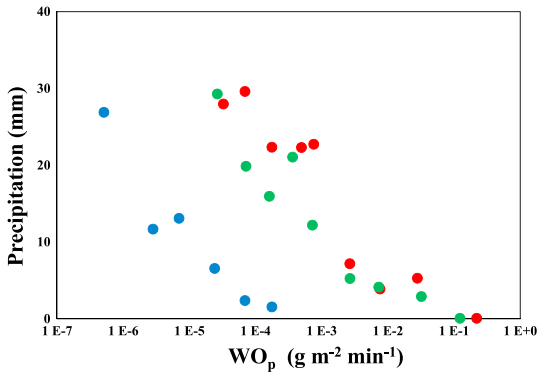


Figure 8. Mean precipitation associated with the WOp as a function of the mean WO_p computed by classes of WO_p samples for Banizoumbou (red), Cinzana (green), and M'Bour (blue).

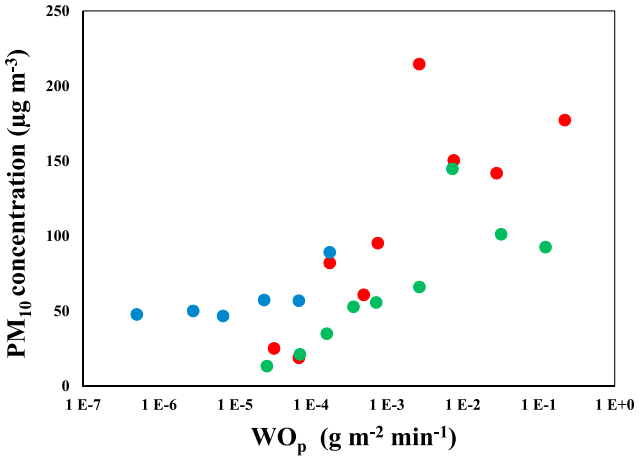


Figure 9. Mean PM_{10} concentration associated with the WO_p samples as a function of the mean WO_p computed by classes of WOp for Banizoumbou (red), Cinzana (green), and M'Bour (blue).

flux class ($>10^{-4}$ g m^{-2} min^{-1}), which represents less than 5% of the samples, the mean dates of occurrence of the other classes range between the beginning and the end of August. This suggests indicates once again that the main difference between M'Bour and the two other stations is the absence of wet deposition events associated with high dust concentrations at the beginning of the rainy season.

3.3.3. Intense Deposition Events

3.3.3.1. An Exceptional Wet Deposition Events Associated With a Convective System

The highest individual deposition flux measured at the three stations since the deployment of the measurements in 2006, was sampled in Cinzana (Mali) from 14 to 21 June 2011. The total deposition flux measured during this period was 75.8 g m^{-2}. During the same time period, 3 samples of wet deposition were collected between 14–16, 16–20, and 20 and 21 June, corresponding to a cumulative deposition flux of 65.7 g m^{-2}. The last sample corresponds to a wet deposition flux of 60.8 g m^{-2}, i.e., more than 90% of the wet deposition measured during this week. This single event represents 80% of monthly dust deposit in June and 47% of the annual deposit in 2011.

Thus, this weekly total deposition sample mainly results from a wet deposition event that occurred between 20 and 21 June. The 5 min PM_{10} concentration, maximum wind velocity, and precipitation recorded from 17h30 to 21h30 on 20 June 2011 are reported in Figure 11. At 18h50, the maximum surface wind speed suddenly increases from 5 m s^{-1} up to more than 10 m s^{-1}, while the PM_{10} concentration raised from 69 up to 24,700 µg m^{-3}. Both the wind speed and the PM_{10} concentration decrease when precipitation starts at 19h10. At this time the PM_{10} concentration is still as high as 15,000 µg m^{-3} but it decreases rapidly during the precipitation to finally reach values lower than 30 µg m^{-3} when precipitation stops.

Such extremely high PM_{10} concentrations have been recorded during other deposition events at this station. As an example, during the same month of June 2011, PM_{10} concentrations as high as 20,700 µg m^{-3} have been measured on 5 June but no precipitation was recorded at that time. As a result, the total deposition flux for the sample including this dust event (13.3 g m^{-2}) is about 5 times lower than that measured for the 20 June event.

3.3.3.2. Dry Deposition Intense Events

We focus here on the most intense total deposition events for which no precipitation was recorded (DO). Those events correspond to deposition fluxes higher than the 95th percentile of the measured DO (Table 8).

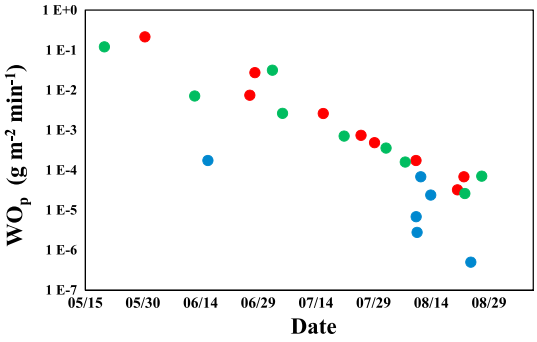


Figure 10. Mean WO_p computed by classes of WO_p as a function of the mean date of occurrence in the year for Banizoumbou (red), Cinzana (green), and M'Bour (blue).

As an example, in Banizoumbou, among the 12 events higher than the 95th percentile (>0.568 g m^{-2} d^{-1}) of the DO, nine are recorded between April and July; i.e., during the period when convective activity starts. Even if no precipitation is measured at the station, the temporal evolution of the PM_{10} concentration and the wind velocity are similar to the behavior illustrated in Figure 11, i.e., the typical signature of the passage of a convective system producing local dust emissions. The high deposition rates associated with these events suggest that a large fraction of the local dust emission is also locally deposited, even without local wet scavenging. The situation is similar in Cinzana, with 7 of

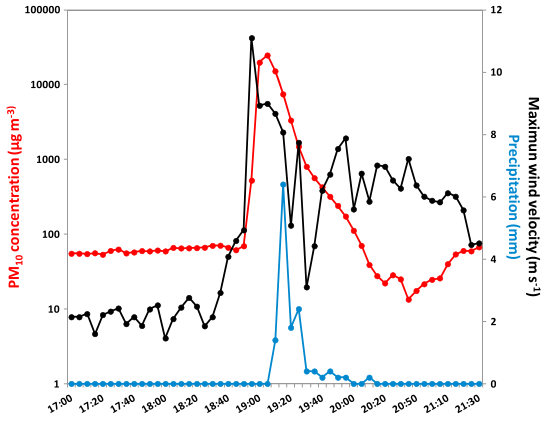


Figure 11. The 5 min mean PM_{10} concentrations, 5 min maximum wind velocity, and 5 min cumulated precipitation recorded on the evening of 20 June 2011 in Cinzana (Mali).

the 11 DO higher than the 95th percentile (0.403 g m^{-2} d^{-1}) being recorded between May and June. In both stations, these DO events associated with convective activity are well identified by a large difference between the mean and the maximum concentrations measured during the deposition sampling period (Table 8).

In M'Bour, among the 13 deposition fluxes higher than the 95th percentile (0.581 g m^{-2} d^{-1}), only two events are recorded in June and six in May. But the examination of the concentration and wind pattern does not allow to associate unambiguously these events with "convective-like" events. Indeed, the duration of the increase in the concentration and the length of the period with high concentrations are longer than for the typical convective events observed at the two other stations. In M'Bour, *Marticorena et al.* [2010] observed that relatively short duration (of the order of 1 day) Saharan dust transport events are frequently observed. As a matter of fact, the dry deposition events recorded in May in M'Bour are more frequently associated with such transport events. They are responsible for more than half of the deposition events higher than the 95th percentile recorded from April to June in M'Bour. As an example, the highest dry deposition flux (1.69 g m^{-2} d^{-1}) recorded in M'Bour from 27 April to 4 May 2012 is associated with a short-duration Saharan dust transport event that occurs from 28 to 30 April. During these 2 days, the PM_{10} concentrations remained higher than 500 µg m^{-3} and reached a maximum of 2090 µg m^{-3} on 29 April.

In Banizoumbou and Cinzana, in addition to the high DO events recorded in the transition period between the Harmattan and the monsoon regime, high DO events are also recorded during the late winter and the beginning of spring, the period during which the mean monthly dust concentrations are the highest (Figure 4). An example of such intense transport event is given by the continental dust storm that took place from 7 to 10 March 2006 over the North Africa and the Sahel [e.g., *Slingo et al.*, 2006; *Marticorena et al.*, 2010]. The DO flux (0.50 g m^{-2} d^{-1}) is among the 10% highest values recorded in Banizoumbou and the fourth most intense DO flux (0.52 g m^{-2} d^{-1}) recorded in Cinzana. Such large DO are generally recorded between February and April at the three stations. They are associated with high PM_{10} concentrations and high aerosol optical depths. Both in Cinzana and Banizoumbou slightly lower but still high DO fluxes (~0.30 g m^{-2} d^{-1}) are also recorded at the end of January. From January to April, the dust transported from the Sahara to the Sahel is confined in very shallow surface layers [i.e., *Léon et al.*, 2009; *Cavalieri et al.*, 2010], producing high surface dust concentrations but moderate AODs. This situation does not favor the long-range transport of dust but may enhance the efficiency of dry deposition.

4. Parameters Controlling the Deposition Fluxes

4.1. Dry Deposition

Knowing the deposition velocity V_d, the downward dry deposition flux of particles, F_{dry}, can be computed as a function of the concentration of the considered particle in the air [C_{air}]:

$$F_{dry} = V_d[C_{air}] \quad (2)$$

From this relationship, for a given particle size, the dry deposition flux is expected to be linearly correlated with the concentration. Conversely, the ratio between the deposition flux and the concentration should provide an estimation of the deposition velocity.

One of the limitations to test this relationship from our measurements is that the deposition flux measurements are cumulated over the whole dust size distribution, while the atmospheric particulate concentration is measured only for particles having a diameter smaller than 10 µm. Moreover, as mentioned in the experimental section, it is difficult for deposition collectors to mimic the surface properties and this can impact the

Table 8. Date, Total Deposition Flux, Mean PM_{10} Concentration, and Maximum 5 min PM_{10} Concentration for the Deposition Fluxes Higher Than the 95th Percentile at the Three Stations of the SDT

Date	Deposition Flux ($g\,m^{-2}\,d^{1}$)	C_{mean} ($\mu g\,m^{-3}$)	C_{max} ($\mu g\,m^{-3}$)
	Banizoumbou (Niger)		
29-Apr-10	0.571	368	29,355
17-Mar-11	0.575	254	1,299
20-Jul-12	0.602	45	14,942
18-Jul-08	0.609	38	1,035
29-Mar-07	0.620	443	15,343
29-Jul-10	0.717	25	8,268
13-Nov-09	0.732	71	422
11-Jun-10	0.819	625	75,136
17-Jun-10	0.832	471	69,699
22-Apr-10	1.077	523	25,008
11-Jul-08	1.307	44	9,762
27-May-10	1.369	291	82,916
	Cinzana (Mali)		
6-May-11	0.404	94	4,794
24-Apr-09	0.442	160	1,630
8-May-09	0.476	-	-
14-May-10	0.477	167	3,638
4-Feb-12	0.488	608	5,566
27-Mar-09	0.498	333	3,223
4-May-12	0.501	187	3,053
10-Mar-06	0.526	1135	3,688
6-Apr-12	0.531	146	1,934
23-Apr-10	0.600	492	4,912
7-May-10	0.945	124	7,467
	M'Bour (Senegal)		
10-May-10	0.584	61	1,622
01-Mar-10	0.586	85	547
22-Mar-10	0.597	375	3,798
30-Jun-09	0.638	70	1,627
10-Apr-12	0.707	208	3,478
16-May-10	0.732	307	1,831
21-May-12	0.762	143	518
11-Mar-12	0.805	678	2,875
01-Jun-09	0.819	68	1,424
23-Jun-09	0.841	91	1,461
15-Mar-12	0.875	306	3,438
25-May-09	1.136	123	2,668
30-Apr-12	1.693	322	2,422

dry deposition measurements. However, DO flux is mainly driven by sedimentation which limits this uncertainty. Despite these limitations, we examined the relationship between the individual deposition fluxes and the dust concentration and derived a "bulk" dry deposition velocity.

For the three stations, Table 9 reports (i) the correlation coefficients, *R*, between the deposition fluxes and the mean PM_{10} concentrations measured during dry deposition sampling periods, and (ii) the annual and monthly mean and median deposition velocities (except for the rainy season, where several months are grouped to obtain a number of DO samples comparable to the other months). The correlation for the whole period are quite low (0.26 to 0.41) but significant regarding the number of data (166 to 239). Higher correlation coefficients are obtained for the middle and end of the dry season (January–April), with the highest *R* values of 0.72 and 0.77 obtained for January in respectively Banizoumbou and Cinzana. A high level of correlation is also obtained in Cinzana for the period of June to September, but for a limited number of observations. In M'Bour, the highest correlation coefficients are obtained in March (0.63) and April (0.82). The correlations are thus significant and high in the dry season, i.e., the periods during which the dust concentrations are high.

At the monthly scale, the mean deposition velocities estimated for the months for which the correlation is significant range from 0.98 $cm\,s^{-1}$ to 2.93 $cm\,s^{-1}$ in Banizoumbou, 0.93 $cm\,s^{-1}$ to 9.29 $cm\,s^{-1}$ in Cinzana,

Table 9. Number of Dry Only (DO) Deposition Data, Correlation Coefficients Between DO and Mean PM_{10} Concentration, Mean and Standard Deviation, Median, and 25th and 75th Percentiles of the Estimated Dry Deposition Velocity at the Yearly and Monthly Time Scale (Except in Summer Where Several Months Have Been Grouped to Get a Sufficient Number of Data) at the Three Stations of the SDT[a]

Banizoumbou (Niger)							
			Deposition Velocity ($cm\ s^{-1}$)				
Period	Nb	*R*	Mean	STD	Median	25th Percentile	75th Percentile
Year	218	0.26	2.7	5.4	1.3	0.8	8.8
Jan	26	0.72	1.0	0.5	1.0	0.7	1.3
Feb	27	0.52	1.0	0.6	0.9	0.6	1.2
Mar	23	0.48	1.1	0.8	1.6	0.9	2.1
Apr	23	0.62	1.6	0.8	1.6	0.9	2.1
May	14	0.71	2.8	1.9	2.2	1.6	3.5
Jun–Jul	*10*	*0.42*	*15.4*	*14.0*	*9.9*	*3.4*	*29.3*
Aug	*10*	*-0.43*	*16.5*	*4.0*	*3.4*	*2.6*	*6.7*
Sep	*10*	*−0.49*	*4.8*	*4.1*	*3.4*	*2.0*	*6.7*
Oct	24	0.50	2.1	1.2	1.7	1.3	2.9
Nov	*25*	*-0.16*	*2.0*	*2.4*	*1.1*	*0.8*	*2.4*
Dec	25	0.45	1.1	0.8	0.8	0.5	1.4
Cinzana (Mali)							
			Deposition Velocity ($cm\ s^{-1}$)				
Period	Nb	*R*	Mean	STD	Median	25th Percentile	75th Percentile
Year	166	0.29	1.8	2.4	1.2	0.8	5.1
Jan	27	0.77	1.1	0.4	1.1	0.8	1.4
Feb	*25*	*0.29*	*1.2*	*0.6*	*1.1*	*0.8*	*1.4*
Mar	25	0.65	0.9	0.5	0.7	0.6	1.3
Apr	18	0.50	1.7	1.0	1.4	1.0	2.0
May	*15*	*0.26*	*4.2*	*2.5*	*3.6*	*2.7*	*4.6*
Jun–Sep	7	0.96	9.3	6.7	9.5	5.4	9.9
Oct	*8*	*0.36*	*1.1*	*0.8*	*1.0*	*0.5*	*1.8*
Nov	*15*	*0.19*	*1.3*	*0.7*	*1.3*	*0.9*	*1.6*
Dec	25	0.55	1.1	0.5	1.1	0.7	1.4
M'Bour (Senegal)							
			Deposition Velocity ($cm\ s^{-1}$)				
Period	Nb	*R*	Mean	STD	Median	25th Percentile	75th Percentile
Year	239	0.41	3.1	2.1	2.6	1.7	7.8
Jan	*29*	*0.23*	*1.8*	*1.0*	*1.5*	*1.1*	*2.1*
Feb	*24*	*0.24*	*2.7*	*1.3*	*2.5*	*1.6*	*3.2*
Mar	29	0.63	2.7	1.5	2.2	1.5	3.3
Apr	27	0.82	3.3	1.0	2.8	2.7	3.5
May	*24*	*0.36*	*4.5*	*2.6*	*3.5*	*2.8*	*5.7*
Jun	*19*	*0.32*	*6.3*	*3.1*	*5.8*	*4.4*	*8.1*
Jul–Sep	*19*	*0.39*	*4.1*	*2.7*	*3.2*	*2.3*	*5.0*
Oct	19	0.48	2.4	1.3	2.0	1.5	2.7
Nov	*25*	*0.04*	*2.6*	*1.4*	*2.4*	*1.6*	*3.3*
Dec	*24*	*0.21*	*2.1*	*1.4*	*1.7*	*1.3*	*2.6*

[a]Values in italics correspond to nonsignificant correlations according to the number of data for a confidence level of 0.05.

and 1.82 $m\ s^{-1}$ to 4.48 $cm\ s^{-1}$ in M'Bour. At the three stations, the estimated DO velocities are lower in the dry season and can reach much higher values in the rainy season, in agreement with the difference in the transport time of the dust at these two periods. This range of deposition velocity (1–10 $cm\ s^{-1}$) is comparable to the deposition velocities that can be computed from different deposition models [e.g., *Slinn and Slinn*,1980] for particle sizes ranging from about 5 to 30 μm, i.e., a size range typical of the coarse fraction of mineral dust. The bias induced by the fact that the measured concentration is for PM_{10} particles only can be roughly estimated considering the fraction of the total mass that the PM_{10} fraction represents. During a Saharan dust episode in July 2002, both the total suspended particle (TSP) and the PM_{10} concentrations have been measured in the Canary Islands [*Alastuey et al*., 2005]. From the measurements performed in the free troposphere (Izana Observatory), i.e., in the Saharan dust layer, the ratio of PM_{10}/TSP was of the order

of 50%. Assuming a PM_{10}/TSP ratio ranging from 25 to 75%, the range of estimated deposition velocities (1–10 cm s^{-1}) would be shifted to lower values: (0.25–2.5 cm s^{-1}) for a ratio of 25% and (0.75–7.5 cm s^{-1}) for a ratio of 75% and thus leading to smaller size ranges, respectively (4–15 μm) and (6–29 μm).

These results show that at the first order, the DO fluxes are driven, by the dust concentrations. Several other factors can be responsible for a part of the variability of the estimated dry deposition velocities. In M'Bour, for example, mineral dust is transported close to the surface in winter and spring and at high altitude in the Saharan Air Layer during summer [*Léon et al*., 2009]. Such a seasonality in the altitude of transport can significantly impact the dust size distribution of the deposited dust. For example, *Ratmeyer et al*. [1999] explained the coarsening of the mineral dust deposited in oceanic dust trap near the Cape Verde Islands in summer compared to spring by the settling of the coarser dust particles out of the Saharan Air Layer.

4.2. Wet Deposition

Wet deposition includes all depositional processes by which aerosol are removed from the atmosphere due to the presence of liquid water, i.e., mainly cloud, snow, and fog. Two main processes are generally distinguished: the in-cloud scavenging corresponds to the scavenging of aerosol particles acting as condensation nuclei or colliding preexisting cloud droplets or ice crystals inside the cloud and the below-cloud scavenging which corresponds to the impaction of aerosol particles by the falling droplets. Both processes depend on the characteristics of the precipitation (amount, type, intensity) and on the properties of the scavenged particles (composition, size). Even if our measurements do not allow to investigate in detail the processes by which mineral dust is scavenged by wet deposition, they can help in quantifying the bulk efficiency of the involved processes. The dimensionless "scavenging ratio" or "washout factor," *S*, provides an estimation of this efficiency [e.g., *Buat-Ménard and Duce*, 1986]. It is defined as the ratio of the concentration in the air, C_{air}, and in the precipitation, C_{precip}, of a scavenged specie, multiplied by the air density, ρ:

$$S = \frac{[C_{precip}]}{[C_{air}]}\rho \tag{3}$$

S can be computed from the deposition flux, *F*, the precipitation rate, *P*, and the concentration in the air, as described by *Duce et al*. [1991]:

$$S = \frac{F\rho}{p\ C_{air}} \tag{4}$$

Equation (4) was applied to our measurements, with a conversion factor to estimate the mass of the precipitation from the measurement of precipitation in millimeters (10^{-3} g m^{-2} mm^{-1}), as in *Duce et al*. [1991]. The scavenging ratios have been computed for each station based on the WO_p and the precipitation rate during the precipitation events. As illustrated in Figure 8, wet deposition is mainly associated with convective systems that produce local dust emissions and thus a sudden and strong increase in the dust concentration just before the precipitation starts. In such condition, the mean concentration during the sampling period may not be the most appropriate value to estimate the dust concentration used for estimating the scavenging efficiency. Regarding the typical pattern of increase of the dust concentration during the passage of convective system (see Figures 9 and 10), the maximum concentration during the sampling period may be more representative of the amount of dust available to be washed out by precipitation. We thus computed two different scavenging ratios (S_{Cmean} and S_{Cmax}) using respectively the mean PM_{10} concentration and the maximum PM_{10} concentration measured during the sampling period. The median, 25th and 75th percentiles and the range of *S* estimated at the three stations for all available measurements are reported in Table 10.

The median S_{Cmean} at the three stations ranges from 667 to 2150, while the median S_{Cmax} ranges from 55 to 142. Beside the differences between the absolute values of S_{Cmax} and S_{Cmean}, each of these estimations of *S* exhibits a very large range. In both case, the range between the maximum and the minimum exceeds several orders of magnitude but the range between the 25th and 75th percentiles is of only one order of magnitude. In Banizoumbou, the 25th and 75th percentiles range from 807 to 6428 for S_{Cmean} and from 11 to 190 for S_{Cmax}. In Cinzana, the 25th and 75th percentiles for S_{Cmean} are almost similar to those of Banizoumbou (868 to 6449) but 2 to 4 times higher for S_{Cmax} (44 to 378). In M'Bour, the 25th and 75th percentiles for S_{Cmean} are lower (216 to 1593) than at the two other stations, and the 25th and 75th percentiles for S_{Cmax} have intermediate values (28 to 268).

Table 10. Minimum, 25th Percentile, Median, 75th Percentile, and Maximum Scavenging Coefficients Estimated From the Mean (S_{Cmean}) and the Maximum (S_{Cmax}) PM_{10} Concentration Recorded During the Deposition Sampling Duration and Number of Data for the Stations of Banizoumbou (Niger), Cinzana (Mali), and M'Bour (Senegal) From 2006 to 2012

	Banizoumbou (Niger)		Cinzana (Mali)		M'Bour (Senegal)	
Scavenging Coefficients	S_{Cmean}	S_{Cmax}	S_{Cmean}	S_{Cmax}	S_{Cmean}	S_{Cmax}
Minimum	15	0.16	17	1	13	2
25th Percentile	807	11	868	44	216	28
Median	1,817	55	2,150	142	667	83
75th Percentile	6,428	190	6,449	378	1593	268
Maximum	277,663	42,011	237,942	15,309	119,668	7,290
Number	107	107	225	225	100	100

These ranges of *S* can be compared with the estimations of scavenging ratios available in the literature. Based on measurements of different trace elements in rain and in aerosol particles collected in the tropical Pacific Ocean, *Buat-Ménard and Duce*, [1986] estimated scavenging coefficients ranging from 300 to 1200, depending on the elements, with a value of the order of 500 to 1000 for elements commonly associated with mineral dust (Al, Fe, Ca). They compared their estimation, corresponding to the remote marine regions, to values reported for measurements performed in Florida (USA) that range from about 100 to 1200, with values higher than 1000 for Al and Ca. *Duce et al*. [1991] recommended a range of 200 to 2000 as the most reliable range for *S* for mineral dust. Based on these recommendations, scavenging ratios have been used to compute dust deposition in 3-D models. *Tegen and Fung* [1994] used a value of 750. *Jung and Shao* [2006] tested a value of 500 to compare different wet deposition schemes. This range fits quite well to the median S_{Cmean} (~600 to 2000) computed with the mean PM_{10} concentrations, while the median S_{Cmax} are slightly lower (55–142). The better agreement obtained with the mean concentration could be due to the fact that the scavenging ratios reported in the literature are estimated using the mean concentration during the events or more precisely "bulk concentrations" measured on aerosol and rain samples collected with comparable sampling durations. Compared to the range of S recommended by *Duce et al*. [1991], our estimations spread over a much larger range. This can be explained by the fact that both the atmospheric dust concentrations and the deposited mass in our measurements span also over a much larger range than the one used to estimate *S* in the literature, which mainly correspond to remote regions or regions of long-range transport of mineral dust.

Considering the numerous processes involved in wet deposition of aerosol, including in-cloud and below-cloud processes, *S* is expected to be affected by aerosols and precipitation characteristics (particle size, physical and chemical form, cloud properties including droplet size and temperature, and cloud type). But because scavenging ratios are generally determined from bulk measurements, only their dependence with more integrated parameters has been investigated. For example, information on elementary composition or particle size allows to investigate the scavenging ratios for different aerosol types and sizes [*Buat-Ménard and Duce*, 1986; *Jaffrezo and Colin*, 1988]. Relationships between the precipitation amount or precipitation rates have also been investigated, especially when sequential precipitation collectors have been used [*Asman*, 1980; *Jaffrezo et al*., 1990].

From our data set, only the dependence of S with the dust concentration, the precipitation amount (in mm) and the precipitation rate (in mm min^{-1}) can be investigated. Whatever the station, neither S_{Cmean} nor S_{Cmax} were found significantly correlated with the dust concentration or the precipitation rates. All the computed S_{Cmean} have been plotted against precipitation amount on Figure 12. The same figures obtained with Scmean and Sc max at the three stations are given in Figure A1. There is clear trend of decrease of S_{Cmean} with the precipitation amount. Such a decreasing trend has been interpreted as due to the dilution of the dust concentration during the precipitation and sustained by measurements with sequential precipitation sampling [*Jaffrezo et al*., 1990]. This dilution effect suggests that most of the dust present in the atmosphere is scavenged during the first minutes of the precipitation events as observed in Niger by *Desboeufs et al*. [2010]. When the precipitation lasts longer, there is no more dust to be washed out and the scavenging is less efficient. This is consistent with the results shown in Table 7 which underlined that the highest wet deposition fluxes are not necessarily associated with the highest precipitation amount. This clearly suggests that precipitation occurrence is more critical than precipitation amount for wet scavenging of mineral dust in the Sahel.

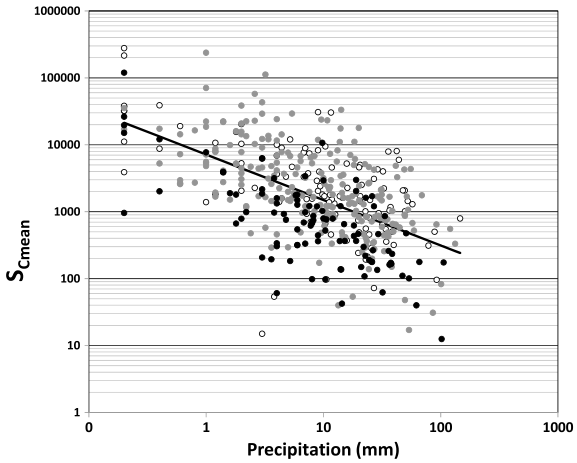


Figure 12. Scavenging ratio S_{Cmean} computed as a function of the mean PM_{10} concentration measured during the wet deposition sampling period in Banizoumbou (white dots), Cinzana (grey dots), and M'Bour (black dots) from 2006 to 2012. The solid black line corresponds to the linear regression between $\log_{10}(S_{Cmean})$ and $\log_{10}(\text{Precip})$ ($(\log_{10}(S) = a \cdot \log_{10}(P) + b)$, with $a = -0.68$ and $b = 3.85$; $R = 0.58$; $n = 432$).

5. Conclusions

This paper has reported the results of the first long-term (2006–2012) monitoring of mineral dust deposition in West Africa. The data collected during this period allowed to investigate the variability of dust deposition at time scales ranging from the event to the multiannual scale. The measurements of total and wet deposition fluxes also permit to estimate the contribution of the wet deposition to the total deposition fluxes.

The mean annual total deposition fluxes range from 92 to 133 g m^{-2} yr^{-1}, with an east to west decreasing gradient, consistent with the gradient of the PM_{10} concentration. Nevertheless, there is no direct link between the mean annual PM_{10} concentration and the annual deposition. In average, wet deposition represents 67% of the annual total deposition in Cinzana (Mali), 52% in Banizoumbou (Niger), but only 8% in M'Bour (Senegal).

The deposition fluxes exhibit a strong seasonal cycle in Banizoumbou and Cinzana. This seasonal cycle is characterized by a maximum that occurs later than the maximum of PM_{10} concentration and sooner than the maximum of precipitation. This means that high fluxes require both sufficiently high atmospheric concentrations and the occurrence of precipitation.

Monthly fluxes from 2006 to 2012 show that wet deposition is the main factor controlling the variability in the stations of Mali and Niger. The monthly dust deposition fluxes during the dry season are much lower and less variable than the deposition fluxes associated with precipitation during the rainy season. The seasonal cycle is not so marked in M'Bour where dry deposition dominates the monthly deposition almost all along the year. This is partly explained by the fact that precipitation occurs later at M'Bour than at the other stations, at a period of time where the dust concentrations are low in the surface layer.

Individual deposition fluxes, collected with a nearly weekly time step, range over several orders of magnitude (0.001 to 10 g m^{-2} d^{-1}). Total deposition fluxes in dry conditions are generally lower than in wet condition. Wet deposition is responsible for the most extreme deposition fluxes recorded at the three stations. The most intense wet deposition events are observed at the beginning of the rainy season. They are associated with the passage of convective systems producing intense local dust emissions that can be largely and immediately washed out by following precipitation. The very low contribution of wet deposition in M'Bour is thus mainly due to the fact that such convective events are less frequently observed than at the two other stations. In the dry season, and at the three stations, the highest deposition fluxes are associated with large-scale Saharan dust transport events that are responsible for the highest monthly mean PM_{10} concentrations recorded from January to April.

The weekly deposition fluxes measured over the three stations do not allow to perform detailed studies on deposition processes. However, the main drivers of the total deposition fluxes can be identified using the additional measurements performed at the station (especially PM_{10} concentrations, precipitation, and wind velocity). Significant relationships have been found between the deposition fluxes measured in dry conditions (DO) and the PM_{10} surface concentrations averaged over the sampling duration. From these measurements, estimations of the dry deposition velocity are provided and are found consistent with the deposition velocities theoretically estimated for micron and supermicron particle sizes. This suggests that the variability of the dry deposition fluxes is primarily driven by the variability of the PM_{10} concentration. To better understand wet deposition (WO) processes, scavenging ratios have been computed to quantify the efficiency of the wet deposition processes regarding the PM_{10} concentration and the precipitation amount. Significant

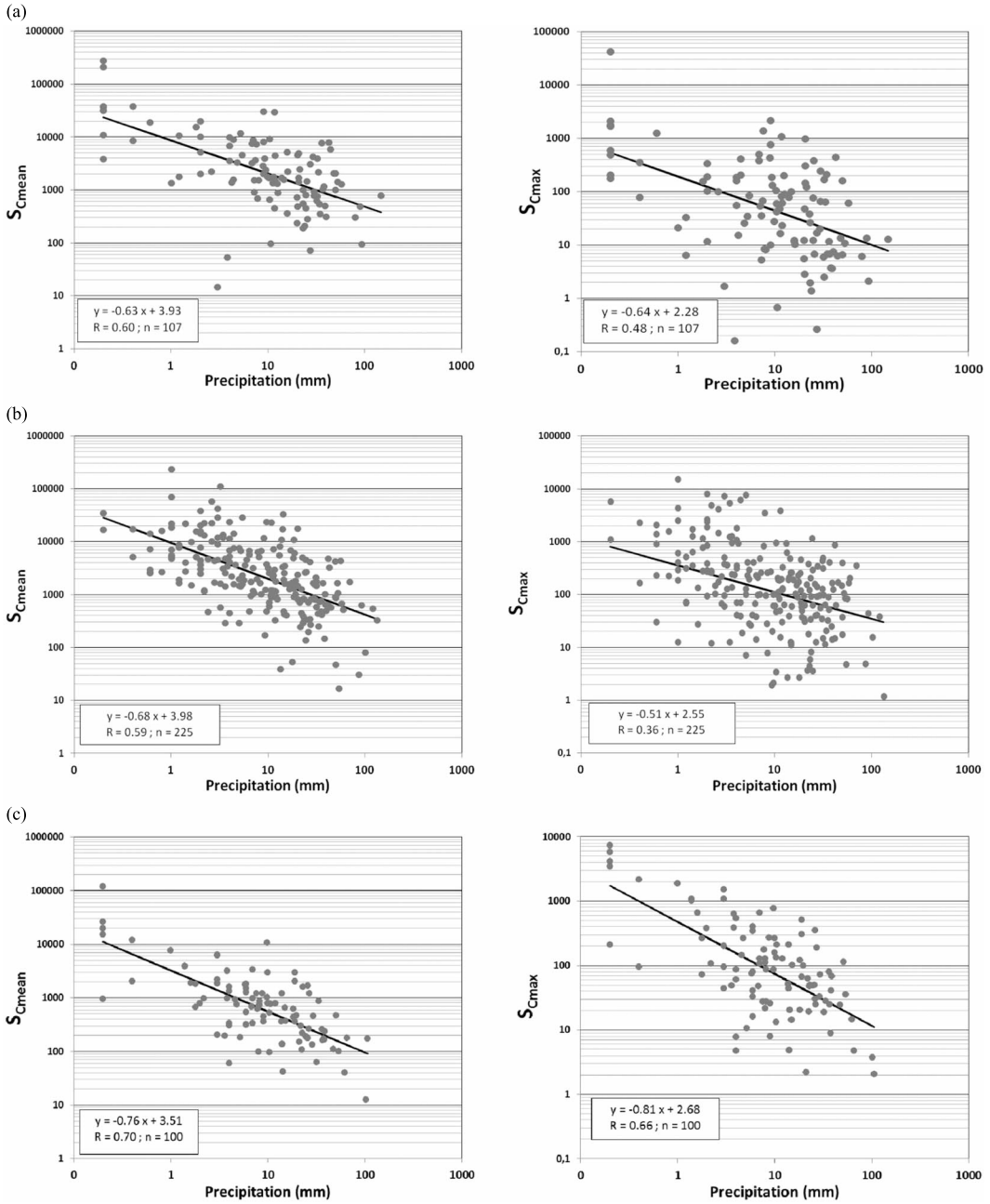


Figure A1. Scavenging ratios computed as a function on the mean S_{Cmean} and the maximum S_{Cmax} PM_{10} concentrations measured during the wet deposition sampling period in (a) Banizoumbou, (b) Cinzana, and (c) M'Bour from 2006 to 2012. The solid black lines corresponds to the best linear regression between $\log_{10}(S_{Cmean})$ and $\log_{10}$(Precip).

anticorrelation have been found between the scavenging ratios and the precipitation amounts. This relation confirms that whatever the dust concentration, the atmospheric dust load is efficiently washed out, whatever the precipitation amount. This suggests that most of the dust is washed out at the beginning of the precipitation and that longer precipitation does not increase the efficiency of the process. Like for dry deposition, similar relationships have been obtained at the three stations suggesting that similar processes take place at the regional scale over the Sahel. From these results, the spatial and temporal variability of the individual deposition fluxes appears as mainly driven by the variability of the PM_{10} concentration and the variability of precipitation occurrence.

This quantification of the deposition fluxes in the Sahel at the regional scale, the identification of their seasonal patterns and of the parameters that control, at the first order, the intensity of the deposition fluxes, improve our knowledge on the mineral dust cycle. This deposition data set and the additional measured parameters also offer a unique opportunity to test the capability of the 3-D models of the mineral dust cycle to correctly reproduce deposition fluxes in the Sahelian region, i.e., close to the source regions. From a methodological point of view, reproducing simultaneously the surface dust concentration, the aerosol optical depth, the deposition fluxes, and in particular the ratio of wet to total deposition, appears as extremely challenging for dust models. This would represent a huge step forward for the improvement of 3-D dust models. Estimating how much of the dust emitted from the Sahara-Sahel arid regions is really transported toward the Atlantic Ocean and how much is effectively deposited on the path of the dust over soils of more humid regions and oceanic surface waters is a key issue to estimate their biogeochemical impact. The quantification of the deposition fluxes as reported in this study could be a significant contribution to this question.

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Erratum

In the originally published version of this article Figures 8 and 9 were inadvertently identical. This error has since been corrected and this version may be considered the authoritative record.