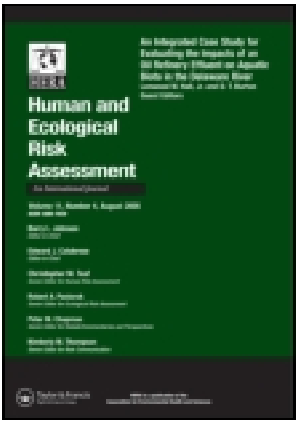

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Saharan Dust Impacts on Air Quality: What Are the Potential Health Risks in West Africa?

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ENVIRONMENTAL FATE ARTICLES

Saharan Dust Impacts on Air Quality: What Are the Potential Health Risks in West Africa?

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ABSTRACT
Despite the proximity of the Sahara, very few studies about dust impact on air quality and human health have been conducted in West Africa. The lack of data is a major constraint on our understanding of the impacts on human health in this area. We analyzed PM_{10} concentrations and horizontal visibility recorded in four West African stations. The pollution levels often exceed the standards defined by many countries/regulatory authorities and have been associated with serious health risks outside Africa. Over the Sahelian stations, 45.6% of the days between November 2006 and March 2007 were likely to impact human health and the studied Sudanian population was exposed to potential health effects every 5 days.

Key Words: dust, PM_{10}, air quality, AQI, health, West Africa.

INTRODUCTION

The impact of desert dust on air quality and human health is receiving increasing attention from the scientific community (de Longueville *et al*. 2010). The total amount of dust emitted globally is estimated to be between 1018 Tg year^{-1} (Miller *et al*. 2004) and 3000 Tg year^{-1} (Engelstaedter *et al*. 2006; Tegen and Fung 1994).

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Winds from the nine principal desert sources transport large amounts of dust around the world (Prospero *et al*. 2002; Tanaka and Chiba 2006).

The Sahara and its surroundings are responsible for between 600 and 900 Tg of atmospheric dust every year (Callot *et al*. 2000; D'Almeida 1986; Marticorena *et al*. 1997). In the literature, three main trajectories of Saharan dust are distinguished (Middleton and Goudie 2001). The first crosses the Atlantic Ocean to the United States, the Caribbean, and South America (Chiapello *et al*. 1995; Kellogg *et al*. 2004); the second carries dust to the western Mediterranean and Europe (Kellogg *et al*. 2004; Perez *et al*. 2008); the third transports dust to the eastern Mediterranean and the Middle East (Kubilay *et al*. 2003; Middleton *et al*. 2008). With a few rare exceptions, only recently has there been any research focus on desert dust and movement around the African continent (Resch *et al*. 2007). According to D'Almeida (1986), 60% of the total particles from the Sahara are transported to the Gulf of Guinea by northeasterly trade winds.

Regions of the world in the path of dust-laden wind record increased ambient air dust concentrations that re-associated with deteriorations in air quality and the strong possibility of negative impacts on human health (Engelstaedter *et al.* 2006; Kellogg *et al.* 2004; Ozer *et al.* 2005). The main constituents of Saharan dust particles are clays, minerals (especially iron, but also copper and zinc), and quartz (Linares *et al.* 2010). Coarse particles are more likely to be deposited in the bronchial passages and thereby affect respiratory conditions such as asthma, chronic obstructive pulmonary disease, and pneumonia (Sandstrom and Forsberg 2008). In contrast, fine particles seem more likely to reach the alveoli and lead to cardiovascular events (Sandstrom and Forsberg 2008). Saharan dust also carries large amounts of pollens and microorganisms such as bacteria and fungi, as well as related protein and lipid components (Griffin 2007; Kellogg and Griffin 2006). Finally, particulate matter may contain endotoxins, which are components of the bacterial wall and could cause respiratory and systemic inflammatory responses and can exacerbate lung disease (Sanstrom and Forsberg 2008).

Over the past 20 years, many studies have been conducted to better understand the impacts of dust emanating from deserts in Asia on air quality and health in several Asian regions (de Longueville *et al.* 2010). The Sahara emits about 50% of the total global burden of desert dust into the atmosphere (Ginoux *et al.* 2004; Washington *et al.* 2003), but impacts of Saharan dust on air quality and human health are substantially less studied. A search of the ISI Web of Knowledge database in January 1999–December 2011 revealed 15 studies with quantitative results on Saharan dust impacts on health (Appendix, adapted from de Longueville *et al.* 2013). No impact study has been published to date on West Africa despite its proximity to the main source of dust and its location with regard to the dominant winds (de Longueville *et al.* 2013).

The first aim of the present article was to provide further quantitative information on Saharan dust levels in some West African regions. The second aim was to speculate on the potential health effects of Saharan dust exposures of the Sahelian[1] and Sudanian populations.

[1]Editor's note: Sahelian refers to the Sahel, which is the ecoclimatic and biogeographic zone of transition between the Sahara desert in the north and the Sudanian savannas in the

Figure 1. Location of the three rural Sahelian stations (M'Bour, Cinzana, Banizoumbou) with PM_{10} data and the Sudanian station (Kandi) with visibility data.

DATA SOURCE AND METHODS

Data were collected from four stations recording air quality in West Africa (see Figure 1). This allowed the calculation of yearly mean, seasonal mean, maximum monthly mean, maximum daily mean and number of days recorded with respiratory particulates or particulate matter less than 10 μm in aerodynamic diameter (PM_{10}) concentrations above defined standards. These calculated values were compared with defined air quality standards and used to speculate on the exposure of the population to air pollution and the potential health effects.

Data

Daily concentrations of Particulate Matter smaller than 10 μm (PM_{10}) expressed in $\mu g.m^{-3}$, recorded between January 2006 and December 2007 in three rural Sahelian stations located at Banizoumbou (Niger, 13.54 N, 2.66 E), Cinzana (Mali, 13.28° N, 5.93° W), and M'Bour (Senegal, 14.39° N, 16.96° W) were used. Atmospheric PM_{10} concentrations were measured using a Tapered Element Oscillating Microbalance (TEOM 1400A from Thermo Scientific) equipped with a PM_{10} inlet (following the procedures outlined in Marticorena *et al.* 2010). Dust concentration measurements were performed at 6.5 m above the ground level at Cinzana and Banizoumbou and at 9.5 m at M'Bour (Marticorena *et al.* 2010). Thanks to a set of precautions taken

south. It is the semidesert south fringe of the Sahara desert and stretches from Mauritana to Chad (Wikipedia 2012).

during data acquisition (see Marticorena *et al.* 2010 for more information), we can say that the measured PM_{10} levels can be largely attributable to the Saharan dust. These data were recorded within the framework of the international African Monsoon Multidisciplinary Analysis (AMMA) program at these three stations comprising the so-called "Sahelian Dust Transect."

In addition, in order to extend the study area, hourly horizontal visibility data for the 2003–2004, 2004–2005, 2005–2006, 2006–2007 dry seasons (November to March[2]) provided by National Meteorology Office of Benin recorded in the rural environment of Kandi (Benin, 11.13 N, 2.94 E) were used. Several authors have proposed that there is a relationship between horizontal visibility and air quality indicators (Total Suspended Particulates, PM_{10} concentrations) (Bertrand 1976; d'Almeida 1986; Ben Mohamed *et al.* 1992). The fraction of PM_{10} is approximately 70% of the Total Suspended Particulates (TSP) in the clouds' dust transported over long distances (Viana *et al.* 2002). Because it is the only method of linking horizontal visibility and PM_{10} concentrations, the equation of D'Almeida (1986) was applied for this study:

$$C = 914.06 \times VV^{-0.73} + 19.03$$

where C is the PM_{10} concentration in $\mu g.m^{-3}$ and VV is the horizontal visibility in km. The equation was based on more than 200 observations of horizontal visibility ranging from 200 meters to 40 km collected in 1981 and 1982 in 11 synoptic stations distributed mainly south of the Sahara. This relationship has been previously described and applied to assess air quality degradation in Niamey (Niger) and Nouakchott (Mauritania) (Ozer 2004; Ozer *et al.* 2006).

There are many strengths to these data. The recording stations are well distributed throughout the sub-region (Figure 1), in the path of dust-laden winds, and located in different climatic zones (Lebel and Ali 2009). Both Banizoumbou and M'Bour are located between the 500 and 700 $mm.yr^{-1}$ isohyets while Cinzana is located between the 700 and 900 $mm.yr^{-1}$ isohyets (Marticorena *et al.* 2010). We refer to these three stations as "Sahelian" for the rest of this text, in line with the nomenclature of AMMA. By definition, the Sahelian zone is characterized by annual rainfall between 300 and 500 mm and the vegetation is dominated by grass and shrub savanna (Bellefontaine *et al.* 1997). The mean annual precipitation in Kandi, which we refer to here as "Sudanian" station, reaches 1000 mm. The Sudanian zone recorded annually rainfall between 900 and 1200 mm. Tree savanna, dry dense forest gallery forest, and woodland are the main vegetations found in this climatic zone (Bellefontaine *et al.* 1997). Because stations are located in a rural environment, they avoid as much as possible the influence of urban pollution sources. However they are also in inhabited regions,[3] otherwise the study of populations' exposure to dust would not make any sense. Daily data were available from all stations, with data

[2]Strictly speaking the dry season lasts longer in these regions of West Africa but analyses focused on these five months of dry season because data collected in Kandi (Benin) are only for these months.

[3]For instance, in Niger, total population exceeded 15.10^6 inhabitants in 2010. While population density is relatively weak (12 $inh.km^{-2}$), spatial repartition is very mixed: more than 75% of the population live in the southern part of the territory (Heinrigs and Perret 2006).

Table 1. USEPA Air Quality Index (AQI), associated 24-h PM_{10} concentration, and health effects (USEPA 1999).

AQI Category	AQI Values	PM_{10} (μg.m^{-3})	Health effects
Good	0–50	0–54	None
Moderate	51–100	55–154	None
Unhealthy for sensitive groups	101–150	155–254	Increasing likelihood of respiratory symptoms and aggravation of lung disease, such as asthma
Unhealthy	151–200	255–354	Increasing likelihood of respiratory symptoms and aggravation of lung disease, such as asthma; possible respiratory effects in general population
Very unhealthy	201–300	355–424	Significant increase in respiratory symptoms and aggravation of lung disease, such as asthma; increasing likelihood of respiratory effects in general population
Hazardous	>300	>424	Serious risk of respiratory symptoms and aggravation of lung disease, such as asthma; respiratory effects likely in general population

throughout the year for the Sahelian stations (Banizoumbou, M'Bour, and Cinzana) and for several months for the Sudanian station (Kandi). Finally, the study period was recent and predominantly the same for the different stations (Table 2).

From these direct and indirect PM_{10} concentration datasets, a set of reference values were calculated for each of the four stations: yearly mean, seasonal mean, maximum monthly mean, maximum daily mean, and number of days recorded PM_{10} concentrations greater than defined standards. This allowed a comparison between the stations and a simple assessment of the PM_{10} concentrations in the four zones. The spatio-temporal variations were highlighted.

Air Quality Standards

The World Health Organization (WHO), the U.S. Environmental Protection Agency (USEPA), and the European Commission (EC) have defined air quality standards based on PM_{10} concentrations. For the WHO these are defined as 20 μg.m^{-3}

Table 2. Synthesis of the PM_{10} reference values relating to the four studied stations.

PM_{10} reference values	Banizoumbou Niger 2006–2007 12 months/year	Cinzana Mali 2006–2007 12 months/year	M'Bour Sénégal 2006–2007 12 months/year	Kandi Benin 2003–2007 5 months/year
Yearly mean ($\mu g.m^{-3}$)	187	129	108	—
Seasonal mean ($\mu g.m^{-3}$)	260	204	176	141
Maximum monthly mean ($\mu g.m^{-3}$) (year)	561	352	262	—
Maximum monthly mean ($\mu g.m^{-3}$) (dry season)	561	352	262	422
Maximum daily mean ($\mu g.m^{-3}$) (year)	4024	2503	1605	—
Maximum daily mean ($\mu g.m^{-3}$) (dry season)	2714	2503	1605	3172
Number of days with PM_{10} concentration >50 $\mu g.m^{-3}$ (by year)	237	237	287	—
Number of days with PM_{10} concentration >50 $\mu g.m^{-3}$ (by dry season)	134	138	148	35

and 50 $\mu g.m^{-3}$ for the annual mean and 24-h mean concentration, respectively (WHO 2006). For the USEPA the acceptable annual mean value of PM_{10} is 50 $\mu g.m^{-3}$ and the 24-h PM_{10} concentration should not exceed 150 $\mu g.m^{-3}$ more than once per year on average over 3 years (USEPA 2006). In Europe, Directive 2008/50/EC on air quality laid down standards (EU Air Quality Limit Values—EU AQLV) with 40 $\mu g.m^{-3}$ as the limit value for the annual level and for the 24-h level and 50 $\mu g.m^{-3}$ of PM_{10} should not be exceeded more than 35 times per year (EU 2008).

Through literature review, an international survey, and querying an international legal database, 80 countries were identified that had standards based on 24-h PM_{10} concentrations (Vahlsing and Smith 2012). Based on these data, overall the average standard for 24-h PM_{10} concentration was calculated to be 95 $\mu g.m^{-3}$. There was a disproportionate lack of information relating to African countries. In West Africa, only Ghana and Senegal have standards with limit values of 70 and 260 $\mu g.m^{-3}$, respectively. A recent compilation of air quality regulations around the world shows that no criteria exist in West Africa relating to maximum annual level (de Longueville *et al.* 2010).

Potential Health Effects

The USEPA developed the Air Quality Index (AQI) as a tool to provide timely and easy-to-understand information on local air quality and whether it poses a health concern (USEPA 1999) (Table 1). The AQI scale is divided into six categories, each corresponding to a different level of health concern. The two first AQI categories (good and moderate, PM_{10} concentration <155 $\mu g.m^{-3}$) are defined as having no impact on health, while the last AQI category (hazardous, PM_{10} concentration >424 $\mu g.m^{-3}$) is defined as associated with a serious risk of respiratory symptoms and aggravation of lung disease, such as asthma and with respiratory effects likely to impact the general population (Ozer *et al.* 2006). Three intermediate AQI categories are defined with increasing potential health effects. In the present study, PM_{10} concentration values from the four studied stations were systematically compared with this scale to assess the West African population's exposure to air pollution and to speculate on the potential health effects.[4]

RESULTS AND DISCUSSION

Dust Impacts on Air Quality

PM_{10} concentrations recorded at the four stations included in this study frequently exceeded by a large margin any of the major regulatory criteria governing air quality described here. Given the wide geographic spread, this finding is concerning as it implies that a large area of West Africa is subject to high concentrations of atmospheric dust that may have severe impacts on human health. It seems likely that change in land use through anthropogenic pressures, natural climatic variability,

[4]The intensity and type of health impacts depend on the grain-size distribution and the chemical composition of particles (Nel 2005). In the absence of this information, we considered the PM_{10} concentrations in a comprehensive manner in this study, bearing in mind that differences could exist.

and global warming (Goudie 2009) are three factors all now combining to increase dust formation (Ozer *et al.* 2006). It is reasonable to assume that if these factors continue to be accentuated, the amount of dust entering the atmosphere in the region could worsen. There is therefore an urgent need to better quantify impacts of desert dust on air quality and health. To date, in the countries examined here only Senegal has installed equipment to monitor air quality (including measures of PM_{10} concentrations). Since 2010, five stations record daily air quality in Dakar. Nevertheless this should only be viewed as a first step, as monitoring is restricted only to Senegal and not more broadly in the sub-region.

PM_{10} reference values, comparison between stations

Shown in Table 2 are the results of the different PM_{10} reference values calculated for each of the four study stations. Of the three Sahelian stations, Banizoumbou (Niger) was the most exposed to Saharan dust (187 μg.m^{-3}) based on yearly PM_{10} concentration. Lower values were recorded at M'Bour (Senegal) but PM_{10} concentration remained high in absolute terms (108 μg.m^{-3}). Cinzana (Mali) occupied an intermediate position. These trends also hold true for seasonal mean, maximum monthly, and daily mean PM_{10} concentrations throughout the year. This can probably be explained by the relative location of these stations compared to the dust source and dust trajectories.

In terms of number of days with PM_{10} concentrations greater than 50 μg.m^{-3} (WHO standard), M'Bour recorded the highest values (287 and 148 days by year and by dry season, respectively) and Banizoumbou the lowest values of the three Sahelian stations (237 and 134 days by year and by dry season, respectively) for the 2006–2007 period. With a full year of data for these stations, it is possible to observe what happens in the dry season compared to the rest of the year. Seasonal means are higher than yearly means by about 35%. For all the stations, maximum monthly mean was recorded during the dry season (January 2007). This was also true for maximum daily mean recorded at Cinzana, M'Bour, and Banizoumbou, where the absolute maximum daily concentration (4024 μg.m^{-3}) was recorded on April 2, 2007. These comparisons confirm that the dry season is more impacted by dust events (Figures 2 and 3).

While it is difficult to compare the data from Kandi with the other stations because the data sources are different, the overall trends appear to differ from the other three stations. Seasonal means (141 μg.m^{-3}), while raised, were lower than those observed at the Sahelian stations. This is perhaps due to the less arid character of this zone. However, maximum monthly PM_{10} concentrations (422 μg.m^{-3}) and maximum daily PM_{10} concentrations (3172 μg.m^{-3}) over the entire period (2003–2007) followed a similar trend to that observed at the three other stations. But for a stricter comparison (exactly on same period of time), between November 2006 and March 2007, the maximum monthly mean PM_{10} concentration calculated at Kandi was 382 μg.m^{-3} (in January 2007) and the maximum daily mean was 1535 μg.m^{-3} recorded on January 3, 2007. The number of days with a PM_{10} concentration less than 50 μg.m^{-3} was sharply lower than the values obtained for the other stations.

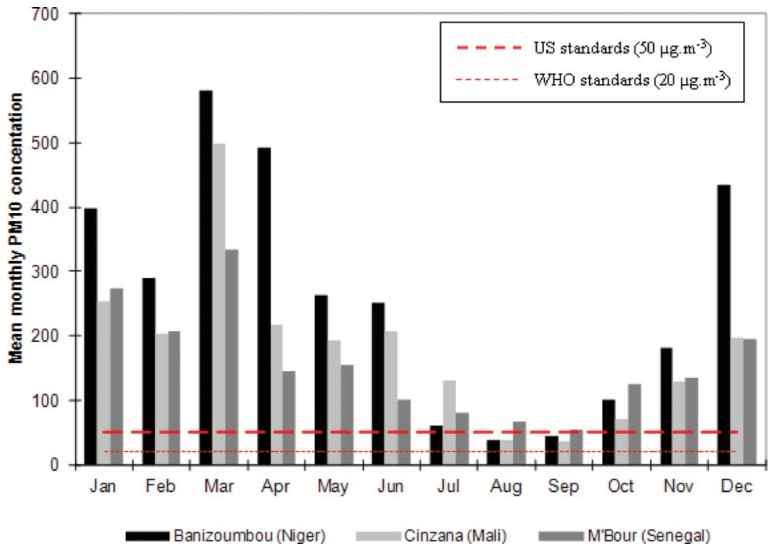

Figure 2. Intra-annual variability of monthly PM_{10} concentration ($\mu g.m^{-3}$) (2006–2007) in three Sahelian stations (source of data: Sahelian Dust Transect; AMMA). (Color figure available online.)

Annual and monthly PM_{10} concentrations

It is clear that levels of PM_{10} concentrations recorded in these four stations are substantially higher than those that would be permissible under the standards defined by the WHO and the United States (and thus Europe because of intermediate standard). The mean yearly PM_{10} concentration exceeds the least stringent standard (US standard, $PM_{10} < 50\ \mu g.m^{-3}$) in the three Sahelian stations and the mean seasonal PM_{10} concentration recorded in Kandi suggests that this is the case for this part of the Sudanian zone. Monthly PM_{10} concentrations exceeded 20 $\mu g.m^{-3}$ (WHO standard) each month of the year at all the stations (refer to Figure 2). Even the threshold of 50 $\mu g.m^{-3}$ was exceeded 10 months a year at Banizoumbou and Cinzana, and year-long at M'Bour. In March, during which the highest PM_{10} concentrations were recorded, the PM_{10} levels were 7 to 12 times higher than the U.S. standard and 17 to 29 times higher than the WHO standard, depending on the station. The highest levels were recorded in Banizoumbou (561 $\mu g.m^{-3}$, in March 2007).

Yearly and monthly PM_{10} concentrations observed in the four stations were in the same order of magnitude as observed in the few previously reported studies. These studies reported a yearly PM_{10} concentration of 108 $\mu g.m^{-3}$ in Nouakchott (Mauritania) in 2000 with a maximum monthly PM_{10} concentration of 344 $\mu g.m^{-3}$ in February of that year (Ozer *et al.* 2006). In Niamey (Niger), the yearly PM_{10} concentration reached 67 $\mu g.m^{-3}$ in 2003 and months in which the northern trade winds (Harmattan) were prevalent were characterized by monthly PM_{10} concentrations that were about 160 to 200 $\mu g.m^{-3}$ (Ozer 2005). Annual PM_{10} concentrations reached 245 $\mu g.m^{-3}$ in Gouré (Niger) in 1984 with a maximum monthly PM_{10} concentration greater than 900 $\mu g.m^{-3}$ in January (Ozer *et al.* 2005).

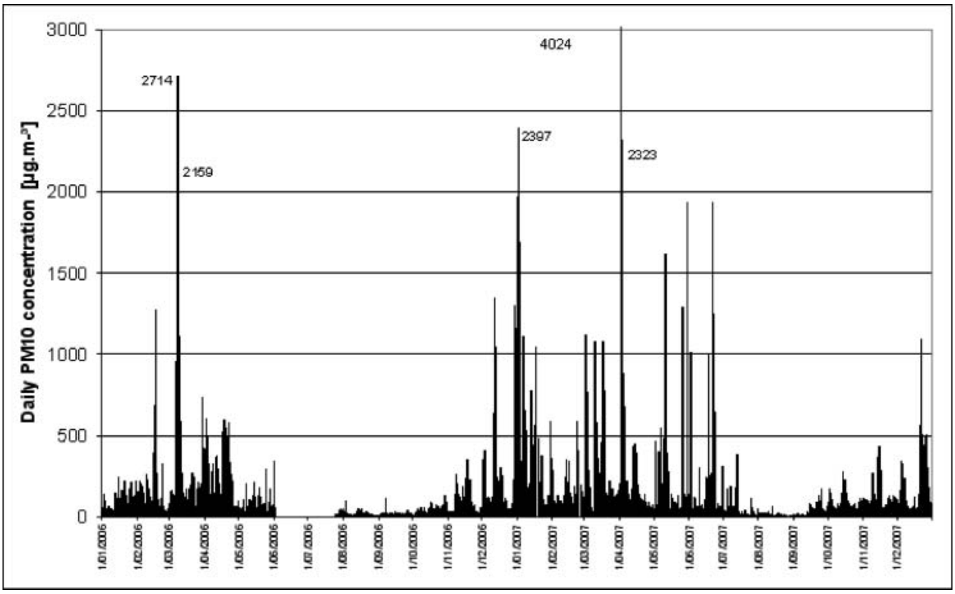

Figure 3. Daily PM_{10} concentration ($\mu g.m^{-3}$) between January 2006 and December 2007 at Banizoumbou (Niger) (source of data: Sahelian Dust Transect; AMMA).

Daily PM_{10} concentrations

Variations of daily PM_{10} concentrations recorded during this study ranged from between 1 and 4024 $\mu g.m^{-3}$ (the lower value was recorded on August 27, 2007 the higher on April 2, 2007) in Banizoumbou (Figure 3). The 25th, 50th, and 75th percentiles of the entire series were 44, 89, and 190 $\mu g.m^{-3}$. For the duration of the study, there were at least 30 days per year where a PM_{10} concentration greater than 500 $\mu g.m^{-3}$ was recorded: in Europe, the regulatory threshold is a maximum of 50 $\mu g.m^{-3}$, one-tenth of the amount recorded here (EU 2008). At Banizoumbou this EU threshold was exceeded for 202 days in 2006 and 271 days in 2007 (Figure 3). The mean value over 24-h exceeded the U.S.-defined standards (150 $\mu g.m^{-3}$) for more than 30% of the days of the year. Between four and eight times as many dust events were recorded at the Banizoumbou station compared to data published previously (Lee *et al.* 2007, 2008; Middleton *et al.* 2008; Monteil 2008; Park *et al.* 2005). To provide further context to the severity of the impact in air quality, a level regarded as "severely hazardous" of 600 $\mu g.m^{-3}$ recorded during a dust episode in Seoul in 2002 (Hwang *et al.* 2008) was recorded 14 times in 2006 and 27 times in 2007 at Banizoumbou. The standard defined by the Senegalese authorities (24-h PM_{10} concentrations <260 $\mu g.m^{-3}$) was exceeded for 45 days a year in M'Bour (6% of the year) and 29 days between November 2006 and March 2007 (19%).

Based on visibility data, our data appear consistent with that observed in some other areas of the Sahel. For example, an extreme daily PM_{10} concentration of 1942 $\mu g.m^{-3}$ was recorded at Nouakchott (Mauritania) on January 28, 2000 (Ozer *et al.* 2006). In Mali, a daily atmospheric dust concentration of 13,735 μg.m^{-3} and 3139 μg.m^{-3} was measured during two consecutive days (April 27 and 28, 1990) during a dense dust haze reducing visibility to less than 100 m (Gillies *et al.* 1996).

Potential Dust Impacts on Human Health

Impact studies on human health would be meaningless in uninhabited areas. Study stations for this study were located in a rural environment but in populated parts of the countries (Heinrigs and Perret 2006). African populations are particularly vulnerable to health concerns because of the structure of the population (50–57% are less than 20 years old and only 10% are more than 50 years old) associated with low income in most countries (Chaulet 1989). Moreover, the living conditions expose people to many diseases (mainly malaria, pneumonia, and diarrhea) and access to healthcare remains very limited (Black *et al.* 2003; Peters *et al.* 2008). Often, malnutrition further reduces their resistance (Rice *et al.* 2000).

Comparison with USEPA-AQI

In terms of the USEPA-AQI, on average over the three Sahelian stations between November 2006 and March 2007, 30 days (20%) may be considered as "unhealthy for sensitive groups," 14 days (9.6%) as "unhealthy," 8 days (5.3%) as "very unhealthy," and 17 days (11.6%) may be qualified as "hazardous"; 45.6% of the days during this period were therefore likely to impact human health because of the high abundance of mineral dust processes. The population of Banizoumbou is the most exposed with more than 50% of the days with potential adverse health effects (Figure 4). Together, the two categories with the most important health effects (associated with PM_{10} concentration >355 μg.m^{-3}) account for 25% of the total; 21% of the days are associated with the most serious risks (*i.e.*, PM_{10} concentration >424 μg.m^{-3}). Elevated dust concentrations were observed for the other two Sahelian stations for about the same number of days, although there were fewer days with the most severe gradings. The situation in Kandi was less severe. A total of 29 days (19.2%) were therefore likely to impact human health but 18 days (11.9%) may be qualified as hazardous. Inter-season variations were important (Figure 5). On the basis of PM_{10} estimations, during the dry season 2005–2006, the population of this region was almost 5 times less exposed to health risks due to dust than during the dry season 2003–2004. But the trend of the distribution between the classes remained the same: the dominance of the more extreme categories, namely "good" and "hazardous." In summary, when air degradation occurs, it is likely to have a significant impact on health.

Comparison with results in specific literature

Thirteen of the 15 published studies (ID 1 to ID 13) describing the impact of Saharan dust on human health mentioned a significant increase of mortality/morbidity (hospital admissions) in relation to dust events or air quality deterioration

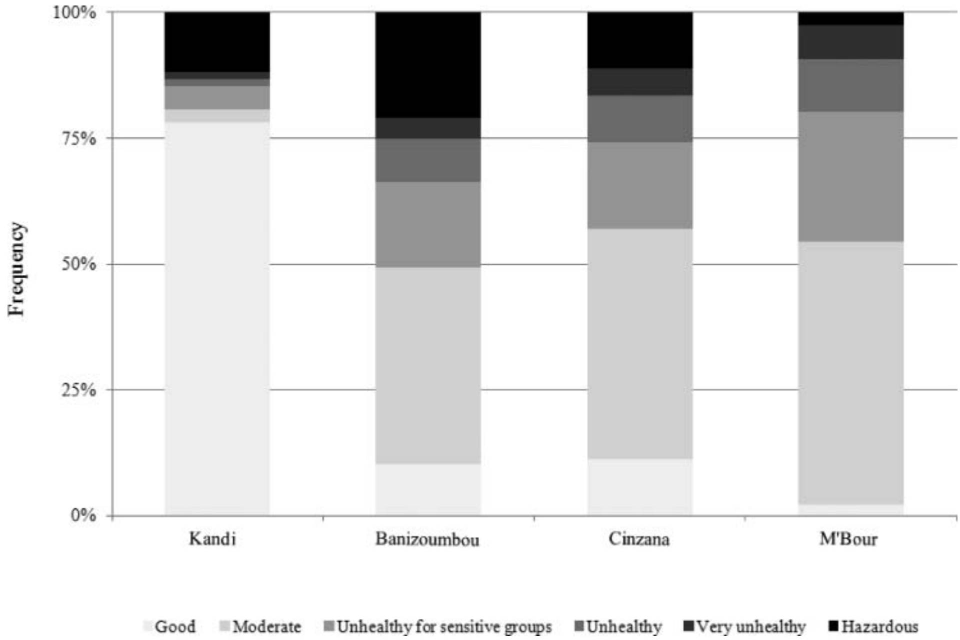

Figure 4. Distribution of the number of days belonging in the different USEPA Air Quality Index categories in the four study stations during the dry season 2006–2007.

(Appendix). A number of adverse health effects have been associated with desert dust including respiratory diseases (among others asthma and pneumonia), cardiovascular diseases (ischemic heart disease, cerebrovascular disease), cardiopulmonary diseases (chronic obstructive pulmonary disease), and more rarely, conjunctivitis and allergic rhinitis (de Longueville *et al.* 2013). Meningitis has also been associated with desert dust events (Sultan *et al.* 2005; Thomson *et al.* 2006).

In one study in Cyprus in which a dust event was defined as a day with at least one hour with a PM_{10} concentration greater than 100 $\mu g.m^{-3}$, an increase of 4.8% and 10.4% of hospital admissions for all-causes and cardiovascular causes, respectively, was observed (Middleton *et al.* 2008). In another study in which a dust event was defined as a daily concentration of 85 $\mu g.m^{-3}$, there was a significant increase in the number of paediatric admissions for up to 7 days following the peak of dust cover (Monteil 2008). In Barcelona, Spain, an 8.4% increase daily mortality per 10 $\mu g.m^{-3}$ increase in $PM_{10-2.5}$ during Saharan dust days has been observed (PM_{10} concentration at a reference remote rural monitoring site reached at least 50% of the PM_{10} concentration at the urban sampling site in Barcelona) (Perez *et al.* 2008). A 10 $\mu g.m^{-3}$ increase in PM_{10} concentration in Athens, Greece, was associated with a 2.54% increase in the number of paediatric asthma hospital admissions (Samoli *et al.* 2011a).

However, these cited levels of PM_{10} concentration are only a fraction of those observed in this study in Sahelian and Sudanian zones described here. It seems likely that these substantially higher dust concentrations would have more important

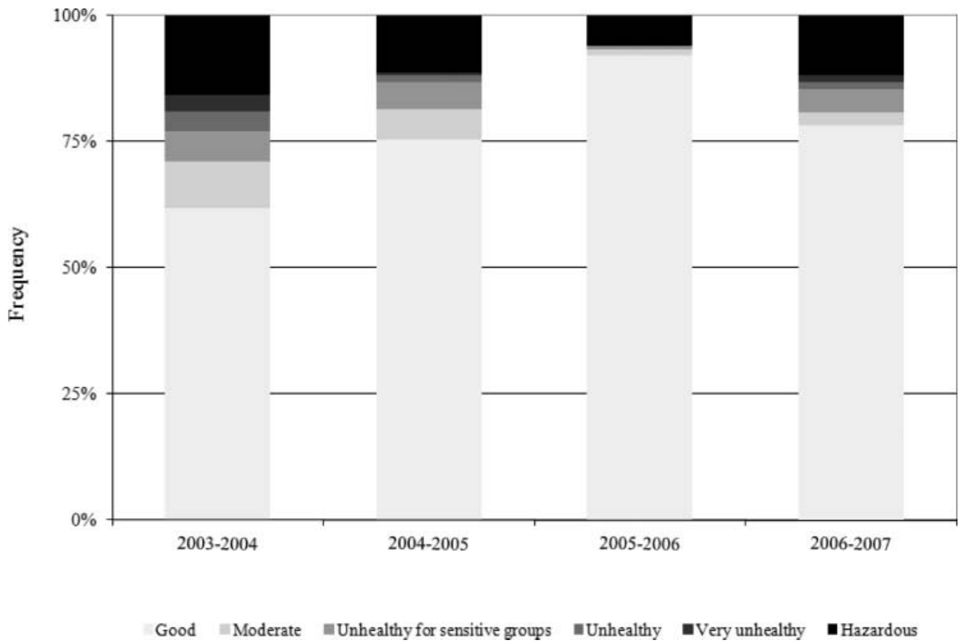

Figure 5. Average distribution of the number of days belonging in the different USEPA Air Quality Index categories in Kandi during dry season between 2003 and 2007.

impacts on human health. Some studies carried out in Asia make reference to very high levels of PM_{10} concentrations with significant health effects. For instance, daily PM_{10} concentrations greater than 300 μg.m^{-3} observed in Minqin, China, were significantly associated (lag of 3 days) with total hospitalizations due to respiratory illness (Meng and Lu 2007). During a dust episode in 2002, daily PM_{10} concentration in Seoul exceeded 600 μg.m^{-3}. The rate of emergency department visits increased by 9.4% for atopic asthma and 15.2% for visits of persons aged 65 years and older during this period (Hwang *et al.* 2008). Nevertheless while these PM_{10} levels are higher than those previously discussed in Europe, they are still lower than those observed during this study in West African regions. However, in the absence of comprehensive health data, it is difficult to quantify the health effects in the countries investigated here.

CONCLUSION

Whether based on daily, monthly, seasonal, or annual PM_{10} concentrations measured in the four West African stations, the dust concentrations were far higher than air quality standards defined by the European Union, United States, and WHO. The results presented here have the unique advantage that they comprise data compiled from direct measurements in West African stations and cross-sectional analysis in a set of stations spread in the region. These results are a first quantitative assessment of the importance of PM_{10} concentrations in West Africa, and these findings lead one to suppose that the Saharan dust has adverse health effects on the Sahelian and Sudanian populations. On the basis of PM_{10} concentrations, the population of Banizoumbou (Niger) seems to be the most exposed to air pollution while the population of Kandi (Benin) appears to be the least exposed of the four studied zones. Our results should encourage the extent of air quality monitoring in this African sub-region and the collection of health data to assess the real impacts of Saharan dust on health. All evidence now suggests that the effects will be amplified in coming years and that the African populations that will remain the most exposed are the most vulnerable.

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APPENDIX

Table A1. Published studies about Saharan dust impacts on human health.

ID	Reference	Time & place	Health outcomes, target population, data source	Dust event definition	Main findings
1	Gdalevich *et al.* 2009	2006–2008 Israel	The number of emergency department (ED) visits for acute cardio-respiratory conditions at a regional medical center	Use of continuous air quality monitoring carried out by the Israel Ministry of Environmental Protection	Mean cardio-respiratory ED patient load on Saharan Dust Days (SDD) was 32.67 ± 11.39 visits, compared to a mean of 29.07 ± 5.33 on matched control days ($P = 0.04$). This represents a relative increase of 12.4% over the expected patient load
2	Gyan *et al.* 2005	May 2001–May 2002 Island of Trinidad Caribbean	Patients aged 15 years and under who attended the Paediatric Priority Care Facility for asthma of the Wendy Fitzwilliam Children's Hospital	A reduction in visibility equal to or less than 15 km (+ reddish – brown color)	There was an association between increased paediatric asthma admissions and increased Saharan dust cover. A deterioration of visibility due to Saharan dust cover increases a daily admission rate of 7.8 patients to 9.25

3	Jimenez *et al.* 2010	2003–2005 Madrid, Spain	Daily mortality due to: all organic causes except accidents; circulatory causes; and respiratory causes provided by the Madrid Regional Inland Revenue Department	According to data from the Directorate-General for Environmental Quality & Assessment at the Ministry for the Environment and Rural & Marine Habitats	On Saharan dust days, a significant statistical association was detected between PM_{10} and mortality for all 3 causes analysed
4	Lopez-Villarrubia *et al.* 2010	2000–2004 Two Canary Island Cities	Daily death (all-cause, heart and respiratory diseases) reports from the Mortality Register of the Canary Islands Regional Authority	Air pollution data were obtained from the Air Quality Network	$PM_{2.5}$ was clearly associated with heart disease mortality and $PM_{10-2.5}$ with respiratory mortality
5	Mallone *et al.* 2011	2001–2004 Rome, Italy	80,423 residents ≥35 years of age who died within the city from natural causes. Data were obtained from the Regional Register of Causes of Deaths	Saharan dust days were defined by combining LIght Detection And Ranging (LIDAR) observations and analyses from operational models	Evidence of effects of $PM_{2.5-10}$ and PM_{10} on natural and cause-specific mortality, with stronger estimated effects on cardiac mortality during Saharan dust outbreaks

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Table A1. Published studies about Saharan dust impacts on human health. *(Continued)*

ID	Reference	Time & place	Health outcomes, target population, data source	Dust event definition	Main findings
6	Maté *et al.* 2010	2003–2005 Madrid, Spain	Daily mortality due to diseases of the circulatory system in the city of Madrid during the study period. The data were furnished by the Madrid Regional Revenue Authority		A linear relationship was observed between $PM_{2.5}$ levels and mortality due to diseases of the circulatory system. For every increase of 10 $\mu g.m^{-3}$ in daily mean $PM_{2.5}$ concentration, for overall circulatory mortality, associations were established at lags 2 and 6, with Relative Risk (RR) of 1.022 (1.005–1.039) and 1.025 (1.007–1.043), respectively
7	Middleton *et al.* 2008	January 1995–December 2004 Nicosia, Cyprus	Cardiovascular and respiratory admissions. Data from the two public hospitals in Nicosia. The daily volume of all-cause admissions in the same period was obtained from the Cyprus Statistical Services	Days with at least 1 hourly PM_{10} concentration higher than 150 $\mu g.m^{-3}$ recorded at Nicosia Central or higher than 100 $\mu g.m^{-3}$ at the rural station	+0.9% all-causes and +1.2% cardiovascular admissions per 10 $\mu g.m^{-3}$ PM_{10}; +4.8% all-causes and +10.4% cardiovascular admissions on dust storm days

8	Monteil 2008	March 2003 Trinidad, Caribbean	Clinical Paediatric Asthma Admissions.Several data source (primary care facilities and hospital)	Daily PM_{10} concentrations greater than 85 $\mu g.m^{-3}$	Significant increase in the number of pediatric admissions for up to 7 days from the peak of dust cover
9	Nastos *et al.* 2011	March 22–23, 2008 Crete Island, Greece	Daily counts of admissions for cardiovascular and respiratory syndromes obtained from the two main hospitals in Heraklion during March–April 2008	High dust concentration (>250 $\mu g.m^{-3}$)	The respiratory admissions were 3-fold than the mean daily admissions on the same day of the emergence of the Saharan dust episode (key day). The admissions concerning the cardiovascular syndromes did not appear any significant change
10	Perez *et al.* 2008	March 2003–December 2004 Barcelona, Spain	Deaths from external causes (including injury, poisoning, and accidents) were not included. Data from the Barcelona mortality registry (24,850 deaths)	PM_{10} concentration at a reference remote rural monitoring site reached at least 50% of the PM_{10} concentration at the urban sampling site in Barcelona	+8.4% daily mortality per 10 $\mu g.m^{-3}$ $PM_{10-2.5}$ during Saharan dust days

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Table A1. Published studies about Saharan dust impacts on human health. *(Continued)*

ID	Reference	Time & place	Health outcomes, target population, data source	Dust event definition	Main findings
11	Samoli *et al.* 2011a	2001–2004 Athens, Greece	Daily time-series data provided by the children's hospitals. All children admitted with the diagnosis of "asthma" "asthmatic bronchitis" or "wheezy bronchitis" aged 0–14 years, living in the greater Athens area were included	Dust days using back-trajectory analysis in combination with a data driven criterion, based on high particle concentrations provided by the fixed monitoring sites	A 10 $\mu g.m^{-3}$ increase in PM_{10} was associated with a 2.54% increase (95% confidence interval (CI): 0.06%, 5.08%) in the number of paediatric asthma hospital admissions. Statistically significant PM_{10} effects were higher during winter and during desert dust days
12	Tobias *et al.* 2011	2003–2005 Madrid, Spain	All-cause natural daily mortality (except deaths from external causes provided by the Madrid's mortality registry)		Evidence of stronger adverse health effects of $PM_{10–2.5}$ during Saharan dust outbreaks. During Saharan dust days, an increase of 10 mg/m3 of $PM_{10–2.5}$ raised total mortality by 2.8% compared with 0.6% during non-dust days (P-value for interaction = 0.0165)

13	Zauli Sajani *et al.* 2011	August 2002–December 2006 Emilia-Romagna, Italy	Residents in the six main of the central-western part of the Emilia-Romagna region who died during the study period	Two SDD definitions were used: 1/all SDD regardless of the intensity of the transport phenomenon. 2/ a subset of "strong" SDD characterised by coarse particle number concentrations higher than 0.25 particles/cm^3, that is, the 90th percentile of coarse particle distribution	Evidence of increased respiratory mortality for people aged 75 or older on SDD. Respiratory mortality increased by 22.0% (95% CI 4.0% to 43.1%) on the SDD in the whole year model and by 33.9% (8.4% to 65.4%) in the hot season model. Effects attenuated for natural and cardiovascular mortality with ORs of 1.042 (95% CI 0.992 to 1.095) and 1.043 (95% CI 0.969 to 1.122), respectively
14	Prospero *et al.* 2008	1996–1997 Caribbean	Daily attendance asthma of paediatric patients (7158 cases in 1996 and 8584 in 1997). Data from the asthma clinic in Barbados	Peaks in dust concentration, some approaching or exceeding 100 $\mu g.m^{-3}$	No obvious relationship although there may be more subtle linkages between dust and asthma
15	Samoli *et al.* 2011b	2001–2006 Athens, Greece	The daily counts of all-cause mortality excluding deaths from external causes, cardiovascular mortality and respiratory mortality obtained from the Greek National Statistical Service	The PM_{10} median concentration from this monitoring station was 66.8 $\mu g.m^{-3}$ during desert dust events and 52.0$\mu g.m^{-3}$ for the rest of the days	The particles' effects were significantly higher during non-desert dust days