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Assessments for the impact of mineral dust on the meningitis incidence in West Africa

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HIGHLIGHTS

- ► Weak humidity is a necessary but not sufficient condition to impact on meningitis.
- ► Desert dust is closely linked to the onset and development of the disease.
- ► The mean dust/meningitis lead-time varies from 0 to 2 weeks.
- ► High humidity is a sufficient condition to stop the meningitis season.

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ABSTRACT

Recently, mineral dust has been suspected to be one of the important environmental risk factor for meningitis epidemics in West Africa. The current study is one of the first which relies on long-term robust aerosol measurements in the Sahel region to investigate the possible impact of mineral dust on meningitis cases (incidence). Sunphotometer measurements, which allow to derive aerosol and humidity parameters, i.e., aerosol optical thickness, Angström coefficient, and precipitable water, are combined with quantitative epidemiological data in Niger and Mali over the 2004–2009 AMMA (African Monsoon Multidisciplinary Analysis) program period. We analyse how the extremely high aerosol loads in this region may influence both the calendar (onset, peaks, end) and the intensity of meningitis. We highlight three distinct periods: (i) from November to December, beginning of the dry season, humidity is weak, there is no dust and no meningitis cases; (ii) from January to April, humidity is still weak, but high dust loads occur in the atmosphere and this is the meningitis season; (iii) from May to October, humidity is high and there is no meningitis anymore, in presence of dust or not, which flow anyway in higher altitudes. More specifically, the onset of the meningitis season is tightly related to mineral dust flowing close to the surface at the very beginning of the year. During the dry, and the most dusty season period, from February to April, each meningitis peak is preceded by a dust peak, with a 0–2 week lead-time. The importance (duration, intensity) of these meningitis peaks seems to be related to that of dust, suggesting that a cumulative effect in dust events may be important for the meningitis incidence. This is not the case for humidity, confirming the special contribution of dust at this period of the year. The end of the meningitis season, in May, coincides with a change in humidity conditions related to the West African Monsoon. These results, which are interpreted in the context of recent independent epidemiological studies on meningitis highlight, (i) the particular role of dust during the dry season (low humidity conditions) on the onset and the intra-seasonal variability of the meningitis season; (ii) the specific role of high humidity at the end of the meningitis season in two Sahelian countries particularly affected by the disease.

1. Introduction

Mineral dust, referred to as "dust" in the following, represents about 40% of global aerosol emissions from natural sources (Ramanathan et al., 2001), the Sahara–Sahel zone being the world's largest source. These aerosols have a number of impact on the environment, especially: (i) on climate, through their direct and indirect radiative forcing (Sokolik et al., 2001) (ii) on air quality and human health, notably through effects such as asthma attacks, serious breathing-related problems, or cardiovascular disease (Prospero et al., 2008).

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In West Africa, the bacterial meningitis (mainly meningococcal meningitis with bacteria *Neisseria meningitidis* with serogroups A (dominant), C, Y and W135) outbreaks are a major public health problem causing each year, according to World Health Organisation (2000), between 25 000 and 250 000 deaths throughout the "meningitis Belt" (Lapeyssonnie, 1963), which extends from Senegal to Ethiopia on a 10–15° North latitudinal band. The meningitis season, epidemic or not, occur from February to May, during the winter dry season dominated by warm and dry dust-laden winds coming from the North-East, the Harmattan winds (Adetunji et al., 1979). This extremely high air dryness combined to high dust load that persists over many weeks may contribute to host susceptibility, including physical damage to the mucosa to the point where the colonizing meningococci are more likely to invade the nasopharyngeal epithelium (Mueller and Gessner, 2010). Indeed, the bacteria *N. meningitidis* is a frequent colonizer of the human upper respiratory tract, its only known reservoir since a hundred years ago (Bratcher et al., 2012). A questionable but interesting assumption is that Saharan dust may also bring the iron (Zhu et al., 1997) required for growth to the bacteria *N. meningitidis* (Jordan and Saunders, 2009).

Some previous studies have shown the role of climate on meningitis in Sub-Saharan Africa (Greenwood et al., 1984), in Niger (de Chabalier et al., 2000), Mali (Sultan et al., 2005) and Burkina Faso (Yaka et al., 2008), although, up to now, the association of dust and meningitis epidemics has mainly been suggested (Molesworth et al., 2002). In the frame of the African Multidisciplinary Monsoon Analyses (AMMA) international program (Redelsberger et al., 2006), a first quantitative dust/meningitis analysis conducted in Niger (Jeanne et al., 2005) have highlighted a possible relationship between the dust levels, based on Infrared Difference Dust Index (IDDI) from METEOSAT (Legrand et al., 2001), and weekly epidemiological data sets at the district scale from 1995 to 2005. Moreover, Thomson et al. (2006) established statistical models at the district level in Burkina Faso, Niger, Mali and Togo, by considering the annual incidence in meningitis as the predictand and a set of societal, climate and environment variables, among which the Aerosol Index from TOMS (Torres et al., 1998), as predictors. Significant relationships were found for both estimates of rainfall and dust in the pre-, post- and epidemic season.

The objective of the current paper is to provide one of the first detailed analysis of the dust/meningitis statistical relationship in two countries in West Africa (Niger and Mali), based on referenced ground-based aerosol measurements and robust epidemiological data sets on a recent time period (2004–2009). The regional spatial scale is in agreement with the "bottom-up" approaches which consist in discriminating between local properties and potential large-scale effects on disease patterns (Guégan et al., 2005). The time period covers that of the AMMA program – phase 1, during which ground-based aerosol measurements have been reinforced (Marticorena et al., 2010), and which encompasses issues on the climate/health links in West Africa, especially climate/dust/meningitis relationships (Martiny et al., 2009). More specifically, our goal is to evaluate, based on basic statistical approaches, (i) if the calendar (onset, ending date) and the intra-seasonal variability of meningitis may be driven by that of dust; (ii) if the intensity of the meningitis season may depend on the atmospheric dust load.

2. Data and methods

2.1. AERONET data set

Our analysis relies on weekly Level 2 (highest quality level) Aerosol Optical Thickness at 440 nm (AOT_{440}), extracted from the Aerosol Robotic Network (AERONET/PHOTONS) database (Holben et al., 2001), which has been extensively used, especially in the AMMA context (e.g. Rajot et al., 2008; Tulet et al., 2008). We focus here on continuous Sunphotometer measurements available from 2004 to 2009 in Banizoumbou (Niger), and 2005 to 2009 in Cinzana (Mali). We use the weekly time-step, which is in agreement with that of the available epidemiological data set, and which enable to take into account, during a week, diversified situations of aerosol events, which are, given their spatio-temporal variability, representative of different scenarios that may occur at the country scale. At this time-step, in the Sahel, the agreement between AOT_{440} and concentrations of dust measured at ground level, i.e., particulate matter (PM_{10}), has been proved to be better than at the daily time-step: correlation coefficients between AOT and PM_{10} time series increase from 0.58 to 0.64 in Cinzana (Mali) and from 0.68 to 0.79 in Banizoumbou (Niger) (Deroubaix et al., in revision). This shows that the AOT_{440} is a satisfactory proxy for dust concentrations at the ground at a 1-week time-step.

The weekly Level 2 (highest quality level) Angström coefficient, aerosol spectral dependency between 440 and 870 nm ($\alpha_{440/870}$), has also been extracted from the AERONET/PHOTONS. $\alpha_{440/870}$ is an indicator of the aerosol size distribution. In typical Sahelian stations, high daily AOT_{440} (>1) are generally associated with dust particles with $\alpha_{440/870}$ close to 0, whereas daily AOT_{440} between 0 and 1 may be associated with a mixture of large dust and fine carbonaceous particles with greater $\alpha_{440/870}$ (Eck et al., 1999). At a weekly time-step, the threshold for high/low AOT_{440} will obviously be lower (see Section 3.1). The empirical threshold generally used to distinguish pure dust from dust mixed with other kind of aerosols, i.e. particles of smaller size is $\alpha_{440/870} = 0.5$ (Holben et al., 2001). In the following, a "high" $\alpha_{440/870}$ will refer to $\alpha_{440/870} > 0.5$ and a "low" $\alpha_{440/870}$ will refer to $\alpha_{440/870} < 0.5$.

Lastly the precipitable water, referred to as PW (cm), has also been extracted at a 1-week time-step from the AERONET/PHOTONS. PW is the total column water vapour amount and can be considered as a proxy for absolute humidity along the air column. Its value, derived from the irradiance measurements at 940 nm, 870 nm and 675 nm (Schmid et al., 2001), is independent from temperature. In this, PW is different from relative humidity which is a percentage of water vapour in the atmosphere at a given temperature. In the Sahel, humidity has a clear seasonal regime, with high values from May to October, period which includes the rainy season from June to September, and low values the rest of the time, i.e. during the dry season. Here, the humidity parameter is analysed jointly with AOT_{440} and $\alpha_{440/870}$.

2.2. WHO data set

The strength of our analysis is to cross well-known geophysical parameters with an epidemiological data set that is generally difficult to obtain and to analyse for non specialists. Thus, our study is one of the first using quantitative epidemiological data set to be crossed with aerosol parameters, based on robust ground-based measurements. This is in the frame of the AMMA program that a research team started working with such a methodology (Jeanne et al., 2005), and since then, a hard and long work has been devoted to settle collaborations with epidemiologists able to give some keys to interpret the epidemiological data. Thus, our analysis is based on the unique WHO meningitis surveillance data set over the African meningitis belt (WHO, 1998). Broutin et al. (2007) and Yaka et al. (2008) recently used a WHO database for the period 1939–1999 in Burkina Faso and Niger. However, since 2001, WHO, in close collaboration with WHO collaborating centres for meningitis, has supported the implementation of enhanced field surveillance in 14 countries of the meningitis belt. A regional team, based in Ouagadougou (Burkina Faso), produces weekly epidemiological reports.

Weekly number of cases in meningitis (incidence) used in the current analysis are extracted from this actualized data set on the common dust/meningitis data sets periods. Among the 14 countries of the Belt, the Sahelian West African sites that are the most affected by meningitis epidemics are Burkina Faso, Chad, Niger and Mali (Fig. 1). Given the lack of epidemiological and/or AERONET/PHOTONS data sets in Burkina Faso and Chad, we focused the analysis on Niger (period 2004–2009) and Mali (period 2005–2009). In Fig. 1, we observe that Niger records 28 000 cases (left *Y* axis) among which 1700 deaths (right *Y* axis). Mali is less affected with about 5700 cases and 300 deaths. Thus, for the recent time-period 2004–2009 considered, Niger and Mali are affected by the disease at different levels (Niger $>$ Mali). The total population in Niger and Mali being similar (between ~12.5 millions of inhabitants in 2004 to ~14.9 millions of inhabitants in 2009), the attack rate, which is defined as the annual incidence in meningitis divided by the total population multiplied by 100.000, is higher in Niger (on average 21) than in Mali (on average 5) on the period considered.

2.3. Methodology

The analysis is based on the comparisons between mean standardized annual regimes in AOT_{440} and in meningitis. This methodology was previously adopted by Sultan et al. (2005) to analyse the relationship between climate and meningitis epidemics in Mali.

For that purpose, we first standardized the annual regime in AOT_{440} for each year based on:

$$X_{\mathrm{i}}^{\mathrm{STAND}} = \frac{X_{\mathrm{i}} - M_{\mathrm{X}}}{\sigma_{\mathrm{X}}}, \tag{1}$$

where X_{i} is the AOT_{440} at a weekly time-step, M_{x} and σ_{x} the average and the standard deviation of AOT_{440} over the 52 weekly values for the year considered.

We then standardized the annual regime in meningitis for each year based on (1), with X_{i} the incidence in meningitis at a weekly time-step, M_{x} and σ_{x} the average and the standard deviation of the incidence in meningitis over the 54 weekly values for the year considered.

The average of the standardized annual regimes in AOT_{440} and meningitis are then computed as

$$A = \frac{\sum_{year1}^{year2} X_{\mathrm{i}}^{\mathrm{STAND}}}{N}, \tag{2}$$

with *year1* the year 2004 in Niger and the year 2005 in Mali, and *year2* the year 2009 in Niger and Mali. *N* is the number of years considering in the analysis for each country.

These standardized results, referred to as “anomalies”, are then analysed to identify the break points in the dust and meningitis annual regimes (onset, peak, and ending dates).

3. Results

3.1. Mean dust characteristics

The mean AOT_{440} and $\alpha_{440/870}$ annual regimes at a weekly time-step are presented in Niger and Mali in Fig. 2. We interpret the results regarding different possible configurations: high AOT_{440}/high $\alpha_{440/870}$, high AOT_{440}/low $\alpha_{440/870}$, low AOT_{440}/high $\alpha_{440/870}$, low AOT_{440}/low $\alpha_{440/870}$. High/low AOT_{440} is defined based on the averaged value of AOT on the site, i.e., 0.61 in Banizoumbou and 0.49 in Cinzana. High/low $\alpha_{440/870}$ is determined based on the empirical threshold of 0.5 (see Section 2.1). First, the annual regimes present similar characteristics for the two Sahelian sites highlighting 2 periods, the “high aerosol period” (Period 1) from January to the end of July (week 1 to week 28) and the “low aerosol” period (Period 2) from August to December (week 29 to week 52). Each period can be subdivided into two sub-periods: “1a”, “1b”, “2a” and “2b”. The mean characteristics of aerosols for these periods are summarized in Table 1. Period “1a” refers to the beginning of the year (weeks 1–4). High AOT_{440} (between 0.53 and 0.64) are associated with either high (0.51 for Banizoumbou) or low (0.40 for Cinzana) $\alpha_{440/870}$. This indicates that the aerosol load is generally important at this period, but that the aerosols detected are not compulsory dust. Indeed, in December and January in the Sahel, the AOT may be impacted by the presence of carbonaceous aerosols emitted from biomass burning (Smirnov et al., 2000; Ogunjobi et al., 2008). Fig. 2 shows that Banizoumbou may be impacted by these fine and absorbant aerosols as $\alpha_{440/870}$ is partly above 0.5. Period “1b” refers to the dust season, which covers about 6 months in this region, i.e. from February to July (weeks 5–28): very high AOT_{440} (between 0.62 and 0.75) are associated with low $\alpha_{440/870}$

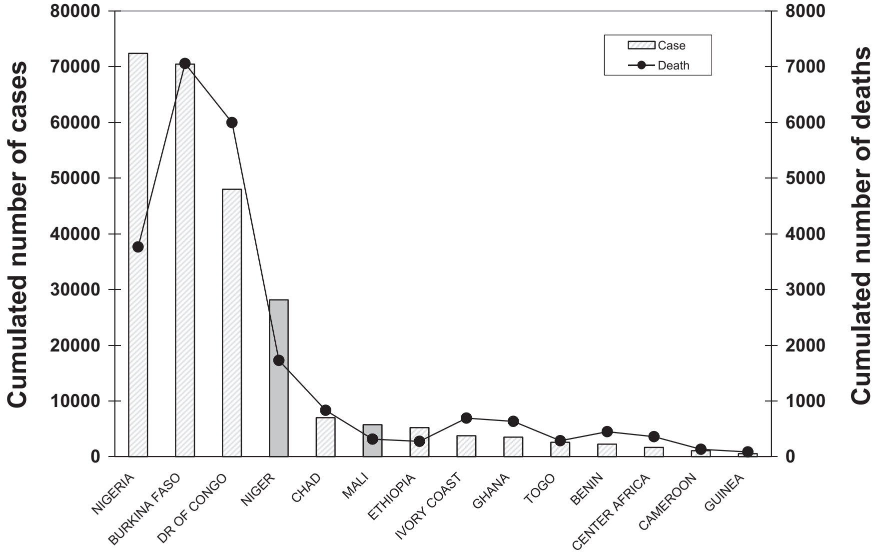

Fig. 1. Meningitis total incidence (left axis) and deaths (right axis) in 14 countries of the meningitis belt for the period 2004–2009 (World Health Organization data set).

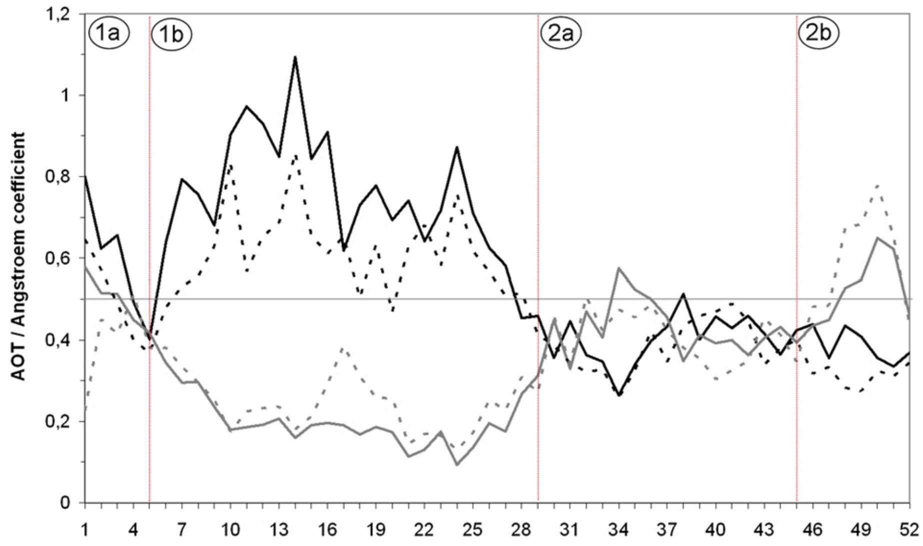

Fig. 2. AOT_{440} and $\alpha_{440/870}$ mean annual regimes in Niger and Mali. Black and grey curves stand for AOT_{440} and $\alpha_{440/870}$, respectively. Full lines stand for Banizoumbou (Niger). Dashed lines stand for Cinzana (Mali). The grey line at 0.5 indicates the empirical threshold for $\alpha_{440/870}$ that enables to distinguish pure dust from dust mixed with other type of aerosols.

(below 0.5), which is typical of the Sahelian sites as mentioned by Eck et al. (1999). The aerosols encountered are mainly purely dust, characterized by loads reaching extremely high levels during these months (standard deviation between 0.07 and 0.16).

Period 2a lasts from week 29 to week 44. Lower AOT_{440} (around 0.40) is associated with low $\alpha_{440/870}$ (below 0.5). The aerosol load is relatively low for the location. The period, from the end of July to the beginning of November, includes a part of the rainy season during which the atmosphere is progressively made clear: dust is still in the atmosphere at the beginning of the rainy season (generally in mid-June) but they start a decreasing phase. Period "2b" refers to the end of the year (weeks 45–52). Low AOT_{440} (below 0.40) is associated with high $\alpha_{440/870}$ (above 0.5). This indicates the influence of smaller particles, most probably biomass burning aerosols known to be encountered in the Sahel at the end and at the beginning of the year (see Period "1a"). Thus, both aerosol parameters present a clear seasonal regime that we roughly know how to explain, and the two Sahelian sites present some similar characteristics for the different periods. However, aerosol loads are systematically higher in Banizoumbou than in Cinzana for each period. This may be due to the proximity with the most important source for dust over the entire globe, the Bodélé depression in Chad (Prospero et al., 2002; Washington et al., 2003).

3.2. Dust/meningitis relationships

3.2.1. Calendar

Fig. 3 presents the mean anomalies in meningitis and AOT_{440} superimposed with those of the PW in Niger and Mali. As a first step, the AOT_{440} and PW mean annual regimes are jointly analysed. Three configurations clearly appear. From January to mid-April (week 1 to week 16 in Niger and week 1 to week 15 in Mali), PW anomalies are negative and we are in the "high aerosol" period: this configuration is referred to as DS1 (Dry Season 1). DS1 covers the whole Period 1a and the first part of Period 1b of Fig. 2. From mid-April to October (week 17 to week 43 in Niger week 16 to week 43 in Mali), PW anomalies are positive, with high levels of aerosols at the beginning of this configuration (around week 28, which is consistent with Fig. 2) and then low levels of aerosols: this configuration is referred to as HS (Humid Season). HS covers the second part of Period 1b and the whole Period 2a of Fig. 2. From November to December (week 44 to week 52), PW anomalies are negative, there are low levels of aerosols: this configuration is referred to as DS2 (Dry Season 2). DS2 corresponds to the whole Period 2b of Fig. 2. These periods are represented in Fig. 4 that is further commented in Section 4. In terms of meningitis, DS1 is the period during which the onset and the maximum peak date of the season occur, HS is the period during which the ending of the season occur. During DS2, anomalies in meningitis cases are all negative.

We first focus on DS1 and the onset of the meningitis season. The mean onset date of the dust season falls in week 1 in Mali and week 2 in Niger. The mean onset date of the meningitis season falls in week 3 in Mali, thus 2 weeks later. In Niger, we notice an increase in the meningitis incidence from week 4 to week 5 (about two weeks later) but the anomalies are not positive yet, so this date can not be considered as the onset of the meningitis season. In order to explain these differences between the two countries, we examine the Angström properties. The value of the Angström coefficient is different at the beginning of the year in Niger and Mali (Period 1a of Fig. 2). In Niger, $\alpha_{440/870}$ is above 0.5 whereas in Mali, $\alpha_{440/870}$ is below 0.5. This probably indicates a different type of aerosols in the two countries at this specific period of the year, with mainly large dust in Mali possibly moving close to the surface, and a mixture of biomass burning and dust in Niger moving both close to the surface and mostly in the high levels due to their small size. This could explain that in Mali the increase in the meningitis cases after the increase in dust load is more clearly noticeable.

We focus now on DS1 and on the variability of the occurrence of the meningitis peaks. In Niger, four aerosol peaks are observed during DS1, in weeks 7, 11, 14, and 16. We detect peaks in the meningitis regime in weeks 8, 11, 14, and 17. In Mali, two aerosol peaks are

Table 1
Mean characteristics of aerosols derived from AERONET/PHOTONS sunphotometer measurements in Banizoumbou (Bani., Niger 2004–2009) and Cinzana (Cinz., Mali 2005–2009). The averaged values of the aerosol optical thickness at 440 nm and Angström coefficients (440/870 nm) are indicated in bold, the standard deviations in italic. The four different time periods are reported in Fig. 2.

Periods		"High aerosol" period				"Low aerosol" period			
Sub-periods		1a W1–4		1b W5–28		2a W29–44		2b W45–52	
Bani.	AOT_{440}	**0.64**	*0.11*	**0.75**	*0.16*	**0.40**	*0.06*	**0.39**	*0.04*
	$\alpha_{440/870}$	**0.51**	*0.05*	**0.20**	*0.07*	**0.42**	*0.07*	**0.51**	*0.09*
Cinz.	AOT_{440}	**0.53**	*0.09*	**0.62**	*0.12*	**0.40**	*0.07*	**0.34**	*0.05*
	$\alpha_{440/870}$	**0.40**	*0.11*	**0.25**	*0.07*	**0.40**	*0.07*	**0.57**	*0.14*

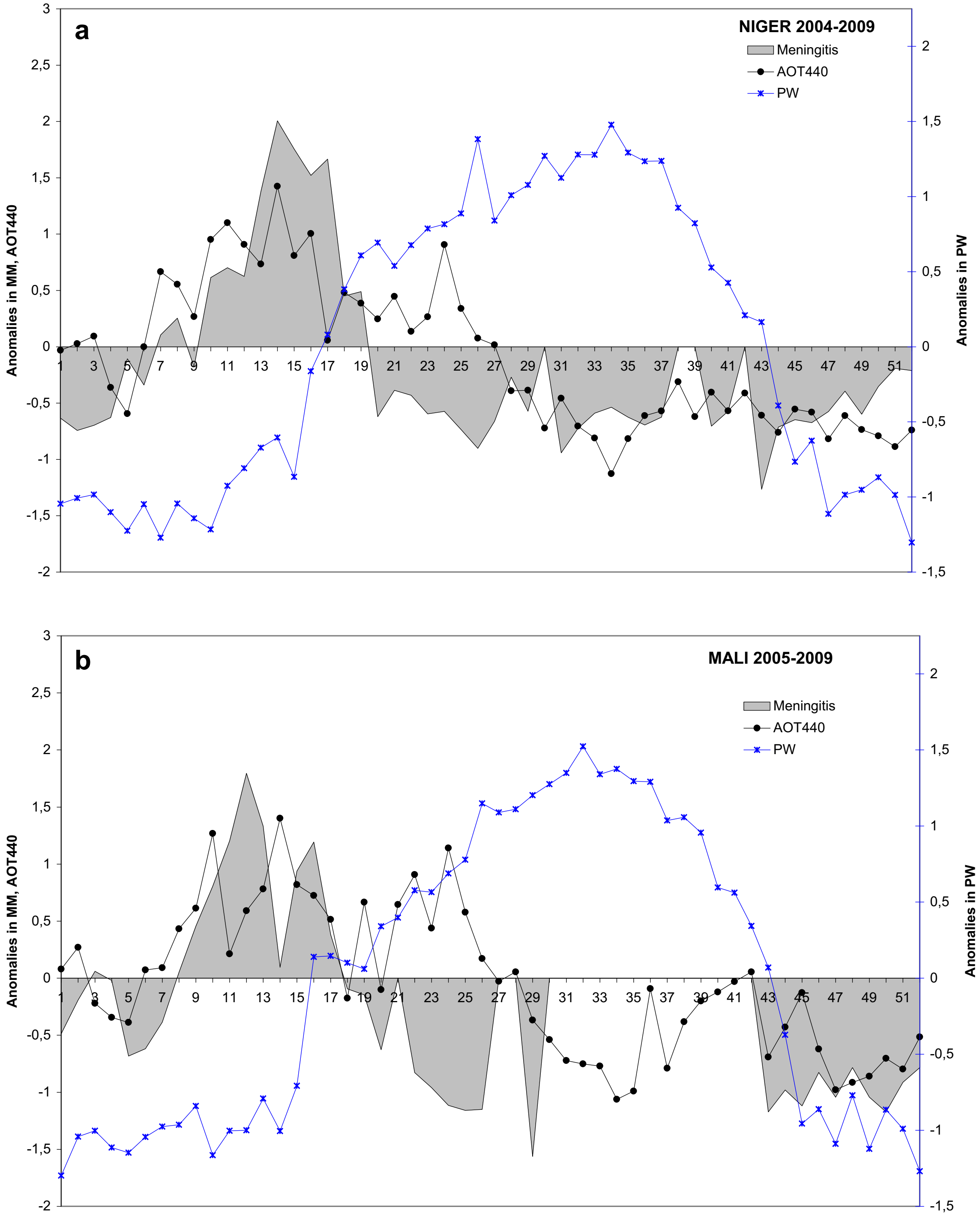

Fig. 3. Comparison between mean annual regimes in meningitis (grey) and AOT$_{440}$ (black) with superimposition of the precipitable water vapor anomalies (blue) in: a) Niger; b) Mali. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

observed during DS1, in weeks 10 and 14. We detect peaks in the meningitis regime in weeks 12 and 16. Thus, during DS1, when the aerosols are dust ($\alpha_{440/870} < 0.5$), each meningitis peak is preceded by an aerosol peak, with a varying lead-time from 0 to 2 weeks. So, our data set shows that when the heart of the dust season has started, i.e. from week 5 (Period 1b of Fig. 2), until the establishment of the HS conditions (around week 16), dust and meningitis peaks follow more or less closely. Both meningitis cases and aerosol loads reach their maximum values during this 12-week period, which encompasses February, March, and a part of the April months.

We now focus on HS, the “humid” season and the ending of the meningitis season. On the one hand, HS starts (anomalies become positive) in week 16 in Mali, and week 17 in Niger. On the other hand, the decreasing phase in meningitis cases starts in week 16 in Mali, and week 17 in Niger. Thus, the end of the meningitis season in both countries coincides with the beginning of the “humid” season. In Mali and Niger, the end of the meningitis season occurs less than 3 weeks after the start of the meningitis decreasing phase, i.e. relatively quickly. In Mali, the meningitis season ends in week 18, and in Niger in week 20. We note that during the decreasing

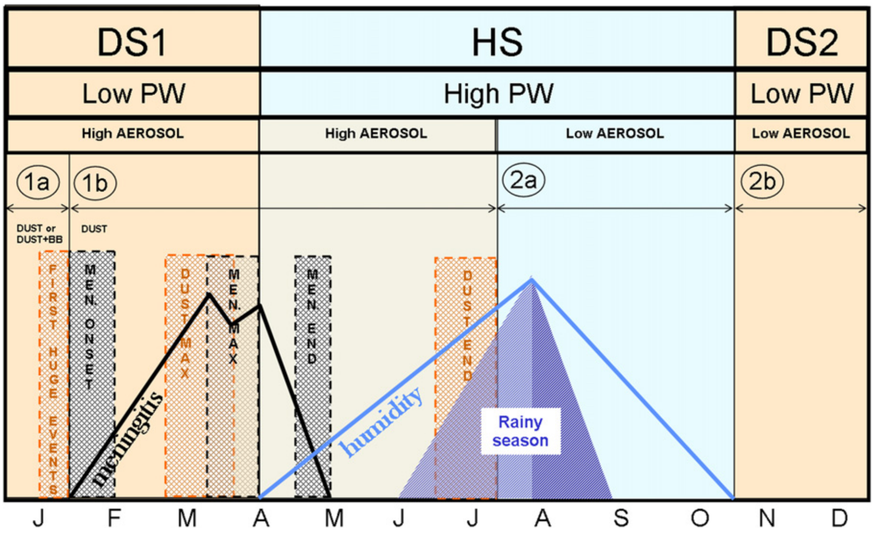

Fig. 4. Conceptual scheme of the dust/meningitis relationship in Niger and Mali. On the (*X*) axis are represented the months. DS1, HS and DS2 stand for "Dry Season 1" (roughly January to mid-April), "Humid Season" (roughly mid-April to end-October) and "Dry Season 2" (roughly end-October to end-December) defined in Section 3.2.1. DS1 corresponds to low PW and high aerosol loads. DS2 corresponds to low PW and low aerosol loads. HS corresponds to high PW and is divided into two sub-periods: one "high aerosol" and one "low aerosol" periods. Periods 1a, 1b, 2a and 2b as defined in Section 3.1 are also represented. Period 1a corresponds to a "high aerosol" period with two possible aerosol configurations: dust or dust + biomass burning. Period 1b corresponds a "high aerosol" with a purely dust atmosphere. Periods 2a and 2b correspond to "low aerosol" periods. The black line represents the positive anomalies of the meningitis incidence. The blue line indicates the positive anomalies of the humidity. The rainy season is also indicated for information. The black "MEN. ONSET", "MEN. MAX" and "MEN. END" boxes stand for the beginning, the maximum and the end of the meningitis regime, respectively. The orange boxes represent the important moments of the dust season. *Note: the boxes have been elaborated using the calendars observed both in Niger and Mali.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phase in meningitis, the aerosols, dust here, still seems to find an echo in the meningitis incidence. In Mali, no aerosol peak is observed during the decreasing phase (between week 16 and week 18) and no increase in the meningitis incidence is observed. However, in Niger, an aerosol event occurs in week 18, which seems to imply a slight increase in the meningitis incidence one week later. Note that the peak in meningitis is of minor intensity compared to the ones occurring during DS1. After the establishment of persistent humid conditions (week 17 in Niger and week 16 in Mali), other aerosol events may occur, but there is no increase in the meningitis incidence anymore. This is the case in Niger in weeks 21 and 24 and in Mali in weeks 19, 22 and 24, where we observe an increase in AOT_{440}.

As a summary, this analysis shows that from February to mid-April, which coincides with the first half of the dust season (Period 1b of Fig. 2) and dry conditions (DS1), dust and meningitis peaks occur closely. The decreasing phase of the meningitis season occurs when humidity starts to increase, i.e. during HS. Humidity does not increase abruptly although the cases in meningitis decrease rapidly, in one week or two. Dust events that continue to occur during the second half of the dust season, i.e. from mid-April to July (week 26), associated with humid conditions (HS) appear to have mostly no echo in the meningitis cases variability, the season of meningitis being ended during the May month, between weeks 18 (Mali) and 20 (Niger).

3.2.2. *Intensity*

The mean AOT_{440} of the DS1 period is 0.77 in Niger, and 0.60 in Mali for the respective time-periods (Table 2). Although these mean AOT_{440} values are not strictly comparable as the years considered are not exactly the same, they enable a first assessment of the dusty degree of each country for the respective periods. The minimum AOT_{440} of the mean annual regime are nearly similar in the 2 countries (0.26 in Niger and Mali), whereas the maximum AOT_{440} values of the mean annual regime reach 1.09 in Niger and 0.87 in Mali. For the 2 countries, the maximum AOT_{440} occur during DS1 in week 14 (Fig. 2). Moreover, the minimum AOT_{440} values during the dry season are always greater than the minimum AOT_{440} during the whole year (0.40 in Niger and 0.41 in Mali). Overall, Table 1 shows that Niger experienced more dust for the period 2004–2009 than Mali for the period 2005–2009. As previously shown in Fig. 1 it is noteworthy that the cumulated meningitis incidence is 6-times more important in Niger than in Mali (Table 1). If there is a quantitative relationship between dust and meningitis, this result suggests that there is a threshold phenomenon as the AOT_{440} is not 6-times more important in Niger than in Mali.

In order to accurately investigate the mineral dust/meningitis quantitative relationship, we computed the simple correlation coefficients between the evolution of weekly mean AOT_{440} and that of weekly mean meningitis incidence considering different lead-times (from none to 2 weeks as 2 weeks correspond to the maximum mean lead-time observed) and three distinct time-periods: (i) from week 1 to the mean ending date in the meningitis regimes: W1–W20 in Niger and W1–W18 in Mali (ii) DS1: W1–W16

Table 2
Analysis of the AOT_{440}/meningitis relationships: mean AOT_{440} and incidence characteristics and simple correlation coefficients between the weekly AOT_{440} and weekly incidence time-series considering different lead-times (from none to 2 weeks) and three distinct periods (meningitis onset to maximum peak date: "C_1 column", DS1 period: "C_2 column", and meningitis onset to ending date: "C_3 column").

Country	Mean AOT_{440}	Cumulated incidence	Simple correlation coefficients			
			Lead-time	C_1	C_2	C_3
Niger	0.77[a]	18 000	None	**0.80**[1]	**0.79**[1]	**0.70**[1]
			1 week	**0.78**[1]	**0.77**[1]	**0.73**[1]
			2 weeks	**0.78**[1]	**0.77**[1]	**0.74**[1]
Mali	0.60[a]	3000	None	**0.52**[3]	0.42	**0.45**[3]
			1 week	0.41	0.42	**0.45**[3]
			2 weeks	0.39	**0.47**[3]	**0.48**[2]

[1] Significant correlation with $P\text{-value} < 0.01$; [2] Significant correlation with $P\text{-value} < 0.05$; [3] Significant correlation with $P\text{-value} < 0.10$.

[a] These values are computed for the DS1 period (January to mid-April).

in Niger and W1–W15 in Mali; (iii) from week 1 to the maximum peak date in the meningitis regimes: W1–W14 in Niger and W1–W12 in Mali. The results are summarized in Table 2. In Niger, the correlations are all significantly high ($\sim$0.7–0.8, *P*-value < 0.01), whatever the lead-time and the period considered, with slightly higher correlations (0.78–0.80) when considering the onset-maximum peak date period (C_1 column). This highlights that the dust load (AOT_{440}) may influence the variability in the incidence in meningitis, specifically during the increasing phase of the epidemics, with a lead-time varying from 0 to 2 weeks. In Mali, the quantitative relationship between dust and meningitis is not that clear: the correlations are weaker than in Niger ($\sim$0.4–0.5, *P*-value < 0.10 or 0.05), and they are not all significant. The main result in Mali is that the correlation coefficients between dust and meningitis are all found significant considering the meningitis season (C_3 column), with a slightly more significant result (*P*-value < 0.05) for a 2-week lead-time.

4. Discussion

The pattern for dust meningitis links shown by the analysis of quantitative Sunphotometer atmospheric measurements and epidemiological data set in the Sahel is summarized by a conceptual scheme (Fig. 4), where the three important periods of the year, DS1, HS and DS2, are represented as well as their characteristics. Periods 1a, 1b, 2a and 2b are also designed in order to distinct, within the "high aerosol" period, the Period 1a, which experiences dust or dust/biomass aerosol events, and the Period 1b, which experiences pure dusty atmosphere. The meningitis mean regime is also represented, based on the calendars observed in both Niger and Mali. The mean calendar of the dust regime is indicated, as well as that of the humidity evolution, including the rainy season.

The onset of the meningitis season (end-January/mid-February) occurs in the heart of the dry season, and is preceded by the first dust events of the dry season (Fig. 4). The recent AMMA results, based on analysis of West African LIDAR measurements have highlighted that at the beginning of the year, the dust particles are mainly found in low altitude (Léon et al., 2009; Cavalieri et al., 2010). Another important point is that the onset of the meningitis season seems to be influenced by the aerosol type. Indeed, in Mali, the meningitis onset date occurs one week after the aerosol event. In Niger, we note an increase in the meningitis incidence two weeks after the aerosol event, but it seems that this increase is not important enough to be a real start of the meningitis season (anomalies are still negative, Fig. 3): this may be due to the occurrence of mixed dust and biomass burning in the atmosphere. The epidemiological explanation may be as follows: both dust and biomass burning aerosols are breathed by populations, but dust being larger particles, they enter and mainly stop in the upper respiratory tract, location of the *N. meningitidis* bacteria susceptible to be carried by healthy people. The inhalation of aerosols combined to extremely dry air conditions, fragilizes the ORL mucous membranes, and the passage of the bacteria from the nasopharyngeal epithelium into the blood. The infection of the meninges depends then on the host susceptibility. Mueller and Gessner (2010) suggest that the persistent dry and dusty climate would increase by 10–100 the invasiveness of the bacteria. This may be due the immuno-compromised character of the host, favoured by dry conditions in Africa (Virji, 2009).

The intra-seasonal variability of the meningitis incidence seems to be driven by that of dust: each peak (increase and decrease) observed in the weekly meningitis incidence is preceded by or coincident with a dust peak from the onset to the end of the meningitis season (Fig. 3). Based on the Angström coefficients that are always well below 0.5 in Niger and Mali during the meningitis season, it can be concluded that the aerosols are mainly dust. This favours our assumption according to which dust flowing close to the surface, combined with low humidity conditions, may play a role on meningitis. The mean lead-time between the dust and meningitis peaks varies between 0 and 2 weeks. This lead-time is consistent with the recent results highlighted by Agier et al. (2013), i.e. a lead-time between aerosol and meningitis incidence of 1,56 weeks. The authors conducted wavelet analyses to find periodicities in a historical 10-year meningitis, climate and aerosol data sets at the district level in Niger. Moreover, and this is an important element, the 0–2-week lead-time is consistent with the knowledge in bacteriology, i.e., the incubation period for the meningitis disease usually varies between 1 and 14 days (Stephens et al., 2007). The fact that *N. meningitidis* can be hold by hosts without any symptoms (healthy carrier state) does not facilitate the evaluation of this incubation period. However, Tzeng and Stephens (2000) showed that, in 70% of individuals, carriage is brief (days or weeks), transient or infrequent, and, on average for these individuals, the acquisition of the disease varies between 1 and 14 days.

The decreasing phase of the meningitis season is quick (less than one month in April/May) compared to its increasing phase (a bit more than 2 months from end-January/mid-February to end-March/early-April). This result is summarized in Fig. 4 with the meningitis regime representation (black line). Fig. 4 also illustrated that the decreasing phase is associated to the beginning of the HS period. Indeed, since the anomalies in humidity are positive, the meningitis incidence starts decreasing (Fig. 3). Jeanne et al. (2005) previously showed that the end of the meningitis season coincided with a change in the wind direction. Thus, the decreasing phase of the meningitis season seems to be triggered by the arrival of the Monsoon indicated by the change in the wind direction that comes from the South-East direction, and brings fresher and wetter air masses. This result is consistent with meningitis epidemics occurring elsewhere in the world, notably in India, where epidemics of meningococcal disease show similar characteristics as those of epidemic meningococcal A disease in Africa (Sinclair et al., 2010). There, the increase in monthly cases in meningitis occur during the dry season and falls with the onset of the Monsoon. The University Corporation for Atmospheric Research evokes the hypothesis of a threshold in relative humidity of 40% (Seefeldt et al., 2012) above which there is no case in meningitis anymore. Our results confirm this interpretation even though we did not analyse the relative humidity but the PW parameter that does not depend on temperature.

The current study suggests the quantitative relationship between dust loads and meningitis incidence exists. However, we obtain less clear results in Mali than in Niger (Table 2) probably attributed to the methodology used. Indeed, through the computation of the correlation coefficients between dust and meningitis time-series, we try to measure the statistical relationship between data sets containing peaks which seem to be phased. For this reason, the correlation coefficients will be low: (i) when the dust and meningitis peaks are not phased, or (ii) when there are few peaks in the time-series. This leads to assume that, as each dust peak is followed by one in meningitis few weeks later during the meningitis season, the weaker dust loads/meningitis incidence correlations in Mali compared to Niger may be explained by the fact that Mali experiences less dust peaks on average than Niger during the meningitis season (Fig. 3). Thus, the number of dust peaks occurring in the season may be important for the meningitis incidence. Moreover, the intensity of the dust peaks (duration and amplitude) seems to impact on that of meningitis (Fig. 3). These two elements suggest that the importance of the meningitis season may be linked to a cumulative effect of important dust events. Yaka et al. (2008) show that the intensity of the epidemics in Burkina Faso is linked to a specific reinforcement of the Harmattan winds in October, i.e. several months before the onset of the epidemics. The assumption the authors propose is that dry conditions may favour early cases in meningitis in autumn. These conditions could combine with the dusty conditions in winter to impact on the intensity of the epidemics.

At last, the specific contribution of mineral dust compared to dry conditions on meningitis incidence is clearly highlighted in the current analysis. The onset and development of the meningitis season occur in low humidity conditions, more than 3 months after the dry season has started, but closely follow the first dust events of the year, generally located at low altitude (Fig. 4). This points out the combined impacts of dust and humidity on meningitis incidence but also suggests that their respective influence differ. It is noticeable in a recent study conducted in Niger by Agier et al. (2013) who explored the relationships between the seasonality of meningitis, dust and climate variables based on wavelet and phase analysis at the district level. They conclude to a strong spatial consistency in the lead-time between dust and meningitis, although this lead-time has been noticed to be temporally changing. This highlights the special contribution of dust on meningitis in the dry season, and reinforces the confidence in dust forcing on meningitis seasonality. It is also important to mention here that at the end of the meningitis season (April–May), when the climate conditions change (pressure, humidity, wind) as the Monsoon arrives, dust has been shown to be located in higher levels of the atmosphere (Léon et al., 2009). Thus, the decreasing phase of the meningitis incidence may also be due to the decrease in dust at the surface that occurs at the same time as the increase in humidity.

5. Conclusions

Our joint analysis of mean annual dust and meningitis regimes in Niger and Mali constitutes one of the first inter-compared quantitative approach in the field, relying on recent pluriannual aerosol measurements acquired in the AMMA context and WHO meningitis data sets (2004–2009) in two countries affected by meningitis epidemics. Our analysis, which enables to test some new hypotheses based on recent epidemiological literature, highlights that, for two countries of West Africa, desert dust may have a significant impact on the meningitis season, especially on its onset and intra-seasonal variability, and humidity a determinant role on its end.

The onset of the meningitis season (end-January/mid-February) occurs in the heart of the dry season, in low humidity conditions, more than 3 months after the dry season has started, and coincides with the occurrence of dust arrival. This may be due to their high load close to the surface but also to their large size. Indeed, at this period of the year, dust enters and mainly stops in the upper respiratory tract, where the meningococcal bacteria has been shown to be located (Bratcher et al., 2012). Dust combined with extremely dry air conditions tends to fragilize the mucous membrane favouring the passage of the bacteria into the blood (Mueller and Gessner, 2010). The specific importance of dust is noticeable during the meningitis season, where each peak in meningitis incidence is preceded by a dust peak, with a 0–2-week lead-time (this is not the case for PW for instance, as shown in the current paper). This result has also recently been highlighted at the district level in Niger (Agier et al., 2013). Moreover, this lead-time corresponds to the incubation time of the bacteria (Stephens et al., 2007). The end of the meningitis season (early April to mid-May) seems to be related to a change in humidity and the arrival of the African Monsoon (Sinclair et al., 2010). Note that in April–May dust events may still occur in the region, but they mainly flow in higher altitudes. As a summary, weak humidity is a necessary but not sufficient condition to impact on the onset and evolution of the meningitis season (dust is required) whereas high humidity is a sufficient condition to stop the meningitis season. Our study finally suggests that the intensity of the meningitis season may be linked to a cumulative effect of important dust events. However, further investigation is required to highlight the quantitative relationship between dust loads and meningitis incidence, and some questions remain open, as for instance: what combined climate and environmental conditions, and with which calendar, may favour huge and early epidemics in West Africa? What is the precise role of dust on the meningitis development, apart from a mechanical assumption of fragilization of the upper respiratory tract: do they have specific characteristics that favour the passage of the bacteria into the blood? The fully successful interpretation of the results will have to be conducted with our epidemiologist partners, thanks to the frame of the MERIT (The Meningitis Environmental Risk Information Technologies) international program sponsored by WHO since 2007.

Until these research issues are fully resolved, it could be possible to concretize an important step forward in the elaboration of early warning system for meningitis risks, by the use of mineral dust loads as a new input in existing operational meningitis forecasting models, actually solely based on climate (Yaka et al., 2008; Martiny et al., 2012). This requires the consolidation of the dust/meningitis statistical results, notably through the use of confirmed meningitis incidence time-series at the district spatial scale provided by local Health centres in the African countries, and long-term surface aerosol concentrations data sets in Africa that could be modelled, for instance based on CHIMERE, already used for dust modelling in Africa (Menut et al., 2009) or for health impact studies in other part of the world (Valari and Menut, 2010).

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