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Atmospheric Dust, Early Cases, and Localized Meningitis Epidemics in the African Meningitis Belt: An Analysis Using High Spatial Resolution Data

Maxime Woringer,[1†] Nadège Martiny,[2] Souleymane Porgho,[3] Brice W. Bicaba,[3] Avner Bar-Hen,[4] and Judith E. Mueller[5,6]

[1]École Normale Supérieure (ENS), Paris, France
[2]UMR6282 BIOGEOSCIENCES, University of Burgundy, Dijon, France
[3]Direction de la lutte contre la maladie, Ministry of Health, Ouagadougou, Burkina Faso
[4]Conservatoire national d'arts et métiers (CNAM), Paris, France
[5]French School of Public Health (EHESP), Sorbonne Paris Cité, Paris, France
[6]Institut Pasteur, Paris, France

Background: Bacterial meningitis causes a high burden of disease in the African meningitis belt, with regular seasonal hyperendemicity and sporadic short, but intense, localized epidemics during the late dry season occurring at a small spatial scale [i.e., below the district level, in individual health centers (HCs)]. In addition, epidemic waves with larger geographic extent occur every 7–10 y. Although atmospheric dust load is thought to be an essential factor for hyperendemicity, its role for localized epidemics remains hypothetic.

Objectives: Our goal was to evaluate the association of localized meningitis epidemics in HC catchment areas with the dust load and the occurrence of cases in the same population early in the dry season.

Methods: We compiled weekly reported cases of suspected bacterial meningitis at the HC resolution for 14 districts of Burkina Faso for the period 2004–2014. Using logistic regression, we evaluated the association of epidemic HC-weeks with atmospheric dust [approximated by the aerosol optical thickness (AOT) satellite product] and with the observation of early meningitis cases during October–December.

Results: Although AOT was strongly associated with epidemic HC-weeks in crude analyses across all HC-weeks during the meningitis season [odds ratio (OR) = 6.82; 95% CI: 4.90, 9.50], the association was no longer apparent when controlling for calendar week (OR = 0.92; 95% CI: 0.60, 1.50). The number of early meningitis cases reported during October–December was associated with epidemic HC-weeks in the same HC catchment area during January–May of the following year (OR for each additional early case = 1.14; 95% CI: 1.06, 1.21).

Conclusions: Spatial variations of atmospheric dust load do not seem to be a factor in the occurrence of localized meningitis epidemics, and the factor triggering them remains to be identified. The pathophysiological mechanism linking early cases to localized epidemics is not understood, but their occurrence and number of early cases could be an indicator for epidemic risk. https://doi.org/10.1289/EHP2752

Introduction

Bacterial meningitis affects tens of thousands of people every year, with a case fatality rate of >10% (WHO 2014). The majority of these cases occur in the African meningitis belt, an area characterized by a single long dry season with intense dust events (Lapeyssonnie 1963; Molesworth et al. 2002) that spans sub-Saharan Africa from Senegal to Ethiopia. In this region, bacterial meningitis exhibits a complex epidemiological pattern. During the rainy season (June–September), endemic meningitis cases occur at a rate that is similar to those of other areas of the world. However, during the late dry season (January–May) the incidence of meningitis due to *Neisseria meningitidis* (meningococcal meningitis) and *Streptococcus pneumoniae* increases 10- to 100-fold throughout the meningitis belt. In addition, localized epidemics of meningococcal meningitis with incidence rates that imply an additional 10- to 100-fold increase may occur within smaller areas (Tall et al. 2012). Finally, epidemic waves that cover larger geographic areas occur every 7–10 y, with some variation in the specific regions affected by each periodic wave (Lapeyssonnie 1963). Although the introduction of a meningococcal serogoup A conjugate vaccine in 2010 appears to have eliminated serogroup A meningitis epidemics in the meningitis belt countries (Diomandé et al. 2015), epidemics due to other serogroups (W, X, and C) continue to occur (Xie et al. 2013; Kretz et al. 2016). A better understanding of the factors that contribute to ongoing meningitis outbreaks is needed to more effectively control them and to optimize future vaccination strategies.

No widely accepted explanation for the meningococcal epidemiology exists today (Agier et al. 2017). A hypothetical explanatory model that combines factors at different time scales and spatial scales has been proposed (Mueller and Gessner 2010). These factors are low relative humidity (typically below 20% during the late dry season) and exposure to atmospheric dust through the Harmattan winds for hyperendemic seasonality of meningitis incidences (Savory et al. 2006; Yaka et al. 2008; Martiny and Chiapello 2013; Agier et al. 2012; García-Pando et al. 2014; Deroubaix et al. 2013), coinfections for localized outbreaks and genetic variations of meningococcal strains for epidemic waves. Furthermore, exposure to domestic smoke (Hodgson et al. 2001; Mueller et al. 2011) has been found to increase individual risk of bacterial meningitis. Several of these factors can be seen in analogy to indoor smoke and environmental dust as risk factors of pneumonia and other respiratory morbidity (Gordon et al. 2014; Trianti et al. 2017). In addition, ecological studies suggest that the occurrence of cases during the early dry season (before January) is associated with the risk of subsequent epidemics during January–May (Yaka et al. 2008; Paireau et al. 2014; García-Pando et al. 2014).

A considerable body of evidence based on weekly or monthly meningitis surveillance data at the national or district level thus supports the essential role of environmental factors in the seasonality of epidemic meningitis. However, it is unclear so far whether the environment accounts only for seasonal hyperendemicity or also for the occurrence of localized epidemics and of epidemic

Address correspondence to J.E. Mueller, 20 ave. George Sand, 93210 La Plaine St Denis, France. Telephone: 33 2-99-02-24-32. Email: judith.mueller@ehesp.fr

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†The current affiliation of M.W. is the Institut Pasteur, Paris, France.

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waves. Such questions require a distinction between seasonality and epidemic events (and their respective onset) that needs to be based on high-resolution data that allow identification of individual localized epidemics. Findings from two recent studies suggested that the use of case counts at the health center (HC) level facilitates research on the spatial and temporal dynamics of localized meningococcal meningitis epidemics (Tall et al. 2012; Paireau et al. 2014). An individual HC is the smallest administrative health division in most countries of the meningitis belt and comprises primary health posts, hospitals, and clinics. For the present analysis, we used high-resolution case-count data to estimate associations of localized meningitis epidemics with dust load and the occurrence of early cases (reported during October–December).

Methods

Compilation of Surveillance Data at High Spatial and Temporal Resolution

We used surveillance data collected during 2004–2014 for 14 health districts, including 7 districts in the Hauts Bassins region, Dédougou district in the Boucle du Mouhoun region (both regions are in Western Burkina Faso), 5 districts in the Nord region, and the Boulas district in the Centre-Nord region (Figure 1). As a group, these districts accounted for 20% of the country surface and 3.7 million inhabitants (22% of the population of Burkina Faso in 2012). In collaboration with the Direction de la Lutte contre la Maladie (DLM) of Burkina Faso, we retrieved weekly case counts from district officers for all individual HCs in each district and evaluated the compiled data to identify duplicate reports and confirm consistency as previously described (Tall et al. 2012). Suspected cases of bacterial meningitis were reported based on clinical criteria, without laboratory confirmation. Thus, in addition to cases of meningococcal meningitis cases caused by *Neisseria meningitidis*, the case counts included other forms of bacterial meningitis (primarily cases due to *Streptococcus pneumoniae*) and conditions presenting with similar symptoms (e.g., encephalitis and, in young children, malaria). Informed consent was not required because the analysis was based on routine surveillance data. Approval for the project was provided by the Burkina Faso Ministry of Health.

In order to determine weekly incidence rates for individual HCs, we first had to define catchment areas and estimate associated population sizes for each HC catchment area during each calendar year. Numbers of HCs within each district varied over time. We obtained district-level shapefiles from the Ministry of Health, and geolocated individual HCs within districts using sanitary maps for 2007 and 2010 (http://cns.bf/spip.php?article42), and spatial databases provided by the Direction des Statistiques Sectorielles that were supplemented by additional information from Nominatim-OpenStreetMaps (https://nominatim.openstreetmap.org), GeoNames (http://www.geonames.org), and Google Maps (https://www.google.com/maps) when needed (e.g., to geolocate new HCs that began reporting after 2010 or were missing in the database). We then divided each district into preliminary HC catchment areas for each study year by generating a Voronoi partition with individual HCs as the centroids of each cell. Large numbers of private HCs in urban areas resulted in small catchment areas that could not be assigned to a reference population. We therefore merged preliminary HC catchment areas whose centroids were closer than 2.5 km to provide coherent partitioning in urban areas without compromising the spatial structure of rural areas (see Figure S1). In total, the aggregation of 456 preliminary HC catchment areas resulted in 362 final HC catchment areas. Of these, 337 included only one HC (i.e., no aggregation was required), whereas the aggregated HC catchment areas included 240 individual HCs. From this point forward, we use "HC catchment areas" to refer to the HC catchment areas defined after aggregation for each year during the study period. Case counts reported during each calendar week ($n = 1–52$, beginning with the first week in January) by all HCs included within a catchment area were summed to generate HC-week data, which along with annual population estimates for each HC catchment area (provided by the health authorities of each district) were used to convert case counts to incidence rates for each HC-week. Missing population data for individual HC-years (calendar years beginning in January and ending in December) were extrapolated from previous years assuming a 3% yearly growth rate. HC-weeks and years were defined according to calendar weeks and years.

To validate our HC-week data, we summed HC-week case counts into district-week case counts and compared them to the number of cases per week for each district reported by the Ministry of Health to the World Health Organization (WHO) in the national report. The absolute difference between district-week case counts for our data versus the national report was ≤ 2 cases for 84% of all district weeks (2,307 of 2,745) and ≤ 5 cases for 93%, with a median error of 0. When we summed our annual population estimates for all HC catchment areas within each

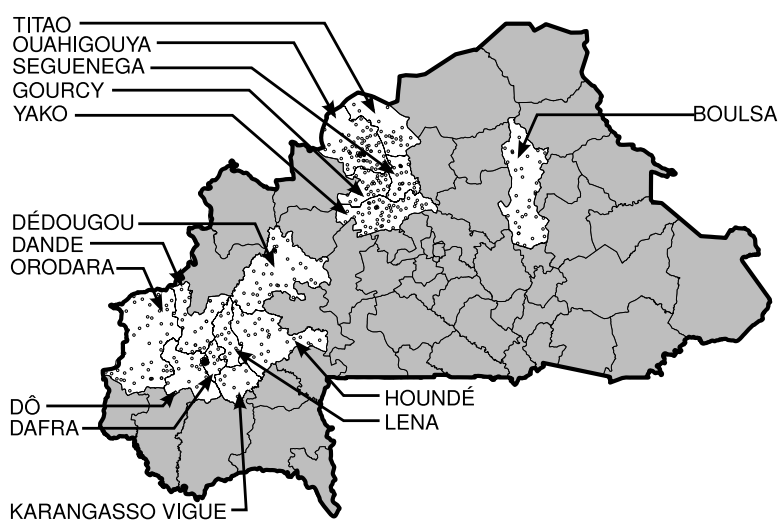

Figure 1. Map of Burkina Faso showing the limits of the health regions and health districts, 2010. Areas in white are districts included in the present analysis, with geolocalization of 456 health centers (HCs; gray dots). HCs created between 2010 and 2014 were also included.

district, 89% of our estimated district-year populations were within $\pm 2.5\%$ of the population size in the national report for each district year, and 94% were within $\pm 5\%$ for the 98 district years with data available for this comparison.

Definition of Localized Epidemic Clusters and Early Cases

Bacterial meningitis epidemic events in the African meningitis belt are typically defined using the current WHO guideline of ≥ 10 cases/week per 100,000 inhabitants for populations of 30,000–100,000 inhabitants (WHO 2014). There is no standard for defining epidemic events at the HC level, but previous studies in Burkina Faso (Tall et al. 2012) and Niger (Maïnassara et al. 2016) used 75 and 20 cases/week per 100,000 inhabitants for ≥ 2 weeks, respectively. Both studies used a receiver operator curve (ROC) to define the optimal threshold and gold standards for annual incidence rates based on "known epidemic" seasons (July year N to June year N + 1) and on seasons with incidence rates above the 95th percentile. To avoid false positive signals in HC with small reference populations (in which a single weekly case could meet the threshold of 75 cases/100,000), Tall et al. (2012) also required a minimum of 5 cases/week per HC, which, however, reduced sensitivity. For the present analysis, we expanded the approach by Tall et al. (2012) assuming that for a given HC, the number of cases follows a binomial distribution of parameters N (the HC population) and p (the actual unobserved incidence). We used a binomial test to assess whether each observed weekly HC incidence rate was significantly above the given epidemic threshold and counted as localized epidemic only the HC-weeks in which the test yielded a $p < 0.05$. This definition thus avoided false signals due to imprecise incidence estimate in small HC populations. As the gold standard for epidemics at the HC level, we used observations above the 95th percentile of all annual HC incidences. The eventually retained threshold corresponded to 40 weekly cases per 100,000 and yielded, with population size adjustment, a sensitivity of 86.0% and specificity of 98.4% (see Figure S2). Each HC-week was thus classified as epidemic or nonepidemic.

Early cases of suspected meningitis cases were reported during the early weeks of each dry season (weeks 40–52 in October–December of the previous year), that is, just before or at the beginning of a given dry season. To minimize potential reporting bias, HCs not reporting any cases during January–May (1,450 of 2,848 HC-years) were excluded from analyses of the association between early cases and epidemic HC-weeks.

Dust Load

Ground-level dust measurements are rarely available for sub-Saharan Africa. However, during January–March, most of the aerosols encountered in the Sahel region (which includes most of the African meningitis belt) are mineral dusts flowing close to the surface (Léon et al. 2009). We used the Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue Aerosol Optical Thickness (AOT) product (collection 6), derived at the 550-nm band and validated in North Africa (Sayer et al. 2013) over 10 sites, among which 7 were located in the African meningitis belt. The AOT is a key variable for health impact studies because it is a proxy for the aerosol concentrations of particulate matter with an aerodynamic diameter ≤ 10 μm (PM_{10}) at the surface during the dry season in the African meningitis belt (Deroubaix et al. 2013).

These data sets were processed on a 10×10 km grid on a daily time step. We subsampled the database on a 1×1 km grid and averaged values over all pixels located in a given HC catchment area for all days within each calendar week to derive a single AOT value per HC-week. AOT values of 0–0.5 represent low dust levels, and AOT values >1.5 represent very high dust levels (Martiny and Chiapello 2013; Eck et al. 1999). In our data set, weekly AOT values ranged from 0 to 2.2. For each calendar week (Monday to Sunday) for which meningitis data was reported, we averaged AOT values over the same period. 1-d lag AOT values were defined by averaging AOT value on a 7-d window shifted 1 d ahead of the meningitis calendar week (Sunday to Saturday). Higher lags were defined similarly. We obtained complete information on meningitis incidence and AOT data for 94,867 of the 188,240 theoretically available HC-weeks.

Statistical Analyses

To evaluate the association between epidemic HC-weeks and either the dust load (per 1-unit increase in AOT) or early cases (per 1-unit increase in number of early cases), we used a case–control design. For each epidemic observation, five nonepidemic control observations were selected through survivor sampling. Effects were estimated using binomial regressions (generalized linear models) and are reported as odds ratios (ORs, the exponentiated coefficients) and 95% confidence intervals (CIs). Several complementary analyses were conducted on the role of AOT. In a first step, all nonepidemic HC-weeks during January–April (meningitis season) were included in the control sampling. In a second step, to isolate the hypothetical effect of spatial AOT variations on occurrence of localized epidemics and to control for the already documented temporal relation between the risk of meningitis epidemics and AOT, we sampled control HC-weeks from the pool of nonepidemic HC-weeks according to the calendar week distribution of epidemic HC-weeks. In a third step, to control for impact of epidemic waves, the same was done according to the calendar week and year distribution of epidemic HC-weeks. To assess a hypothetical time lag in the association between AOT and localized epidemics, we generated shifted profiles of AOT with respect to epidemic HC-weeks. We used average AOT values for the period from 8 to 1 d prior to the first day of the epidemic HC-week. We varied this lag between -30 d and 20 d with a 1-d resolution. Negative values mean that AOT preceded the epidemic HC-week. Positive values were included as an internal control.

In the analysis of the association between localized epidemics and early cases, we explored a hypothetical role of AOT as a confounder by adjusting for AOT as observed in a given HC on the first day of the calendar week of the first early case. In sensitivity analyses, we excluded data from the 2005–2006 season (July 2005 to June 2006), during which a particularly high number of localized epidemics was observed and which thus dominated the results. The explanatory factor for epidemic waves is unknown (evidence pointing to meningococcal strain variations) and could be independent from the factor causing localized epidemics. All analyses were performed using R (version 3.3.1; R Development Core Team).

Results

The database included 129,342 HC-weeks or 2,475 HC-years, with 15,344 suspected meningitis cases mapped at the HC level. Weekly incidence rates (per 100,000 inhabitants) for the entire study area of the 14 health districts peaked during March each year at ≤ 5 cases during 2004, 2005, and 2009–2014 and at 30, 10, and 8 cases, respectively, during 2006–2008 (Figure 2). The median area of HC catchment areas was 124 km^2 with a median radius of 11 km (computed as the square root of the area). The database allowed us to map localized epidemic events to individual HC catchment areas (Figure 3).

Among 3,934 high-AOT episodes (HC-weeks with average AOT >1.0), 96 epidemic HC-weeks were observed. For all HC-weeks taken together, AOT values correlated with meningitis

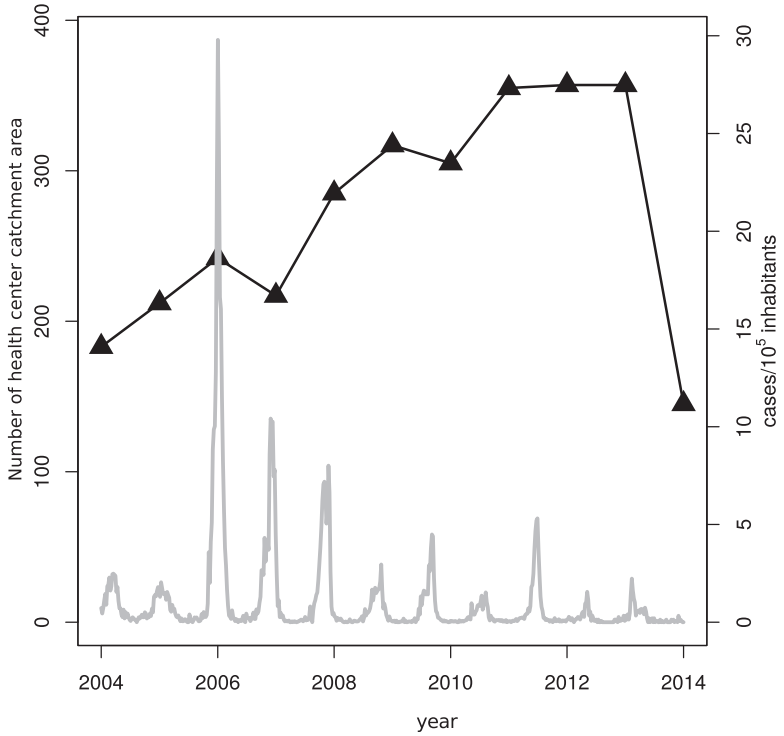

Figure 2. Weekly incidence rates of suspected meningitis cases (per 100,000 inhabitants) estimated for the entire study area of 14 health districts, 2004–2014 and numbers of health center catchment areas (during each year). The gray curve represents the estimated weekly incidence over the 10-year study period. The black curve represents the evolution of the number of health centers over time.

incidence (Figure 4) and showed strong association with the occurrence of epidemic HC-weeks (OR = 6.82; 95% CI: 4.90, 9.50) (Table 1). However, when controlling for calendar week, or both calendar week and year, no association was found between AOT and localized epidemics (OR controlling for calendar week and year = 1.12; 95% CI: 0.70, 1.80) (Table 1). Including a 5-d lag for AOT levels did not substantially change these results (Table 1, Figure 5).

Among the 15,344 suspected meningitis cases reported during the study period, 471 (3%) were classified as early cases because they were reported in October–December [including 53 (11% of all early cases) that occurred in an HC that subsequently experienced a localized epidemic during January–May of the same dry season]. Each additional early case reported by an HC was associated with a significantly increased likelihood of a subsequent localized epidemic in the same HC (OR for each additional early case = 1.14; 95% CI: 1.06, 1.21) (Table 2). Adjusting for AOT during the same week when the first early cases were reported or excluding the data of the 2005–2006 season did not substantially change the result (Table 2).

Discussion

In this ecological analysis of high-resolution surveillance data of suspected bacterial meningitis from Burkina Faso, encompassing over one-fifth of the country's population and a period of over a decade, we found that dust load was not associated with the occurrence of localized meningitis epidemics if analyses were controlled for the common seasonality of dust load and meningitis incidences. Furthermore, we found a significant association between the number of early meningitis cases observed during October–December prior to a meningitis season and the risk of a subsequent localized epidemic. This association was not explained by dust load at the time of occurrence of early cases, and it persisted if analyses were restricted to meningitis seasons outside the 2005–2006 epidemic wave.

The absence of an association between AOT and localized epidemics after controlling for calendar week suggests that dust during the dry season (for which AOT is a proxy) is not a sufficient cause of meningitis epidemics. This is consistent with the hypothetical model presented by Mueller and Gessner (2010), who proposed that environmental factors (e.g., dust, low humidity) drive the seasonal transition from endemic meningitis to a hyperendemic state by facilitating invasive infection among residents already colonized by meningococci. However, although this transition is believed to be a necessary condition for epidemics to occur, the model proposes that nonenvironmental factors (such as viral respiratory infections) drive the transition from hyperendemicity to localized epidemics. Therefore, according to the model, environmental conditions associated with the dry season are likely to be necessary, but not sufficient, for localized meningitis epidemics to occur. In Burkina Faso during the meningitis season, the dust load is mostly governed by regional-scale Harmattan winds, which lead to a spatially homogeneous AOT across larger areas (Marticorena et al. 2010). This spatial homogeneity likely explains why AOT was not associated with localized epidemics within HC catchment areas. Paireau et al. (2014) reported that aerosols were not associated with annual meningitis incidence rates in Niger, but their analysis relied on a monthly semi-empirical absorption aerosol index (AAI) on a $1^\circ \times 1.25^\circ$ latitude–longitude grid that could not be used to evaluate the potential links with localized epidemic events. We have proposed that coinfections, possibly of the respiratory tract, may explain the surge in asymptomatic nasopharyngeal carriage of meningococci observed during localized epidemics (Koutangni et al. 2015). Consistent with this, in a previous study using the same data base as in the present report, we found a strong association between high respiratory infection incidences and localized epidemics (Mueller et al. 2017).

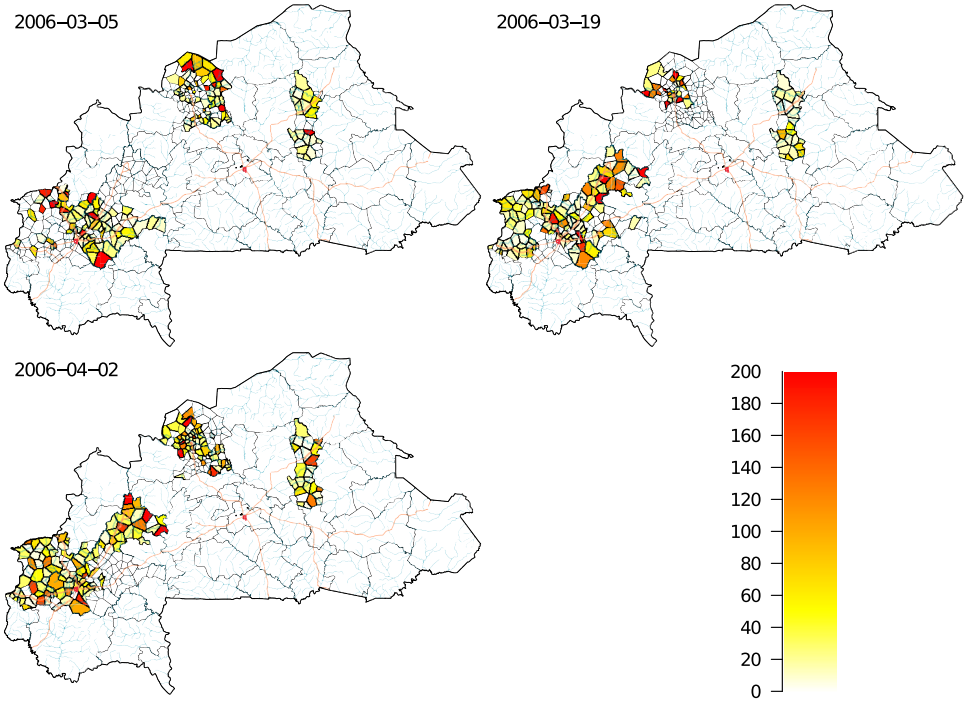

Figure 3. Map of weekly incidence rates of suspected meningitis cases (per 100,000 inhabitants) reported during 3 selected weeks during 2006 in individual health centers (HCs) of 14 health districts in Burkina Faso. The selected weeks started on 5 March, 19 March, and 2 April 2006. The bold black lines represent the borders of the health district. The fine black lines within the study area represent the borders of the HC catchment areas. Color shades (yellow to red) indicate weekly incidence levels in HCs (0 to >200 cases per 100,000 inhabitants).

Nonetheless, our results suggest that the association between dust (as indicated by AOT) and meningitis incidence rates, which also has been reported by several previous studies (Martiny and Chiapello 2013; Agier et al. 2012; García-Pando et al. 2014), is apparent even at the level of individual HCs. An effect of dust on the risk of invasive disease among asymptomatic carriers is supported

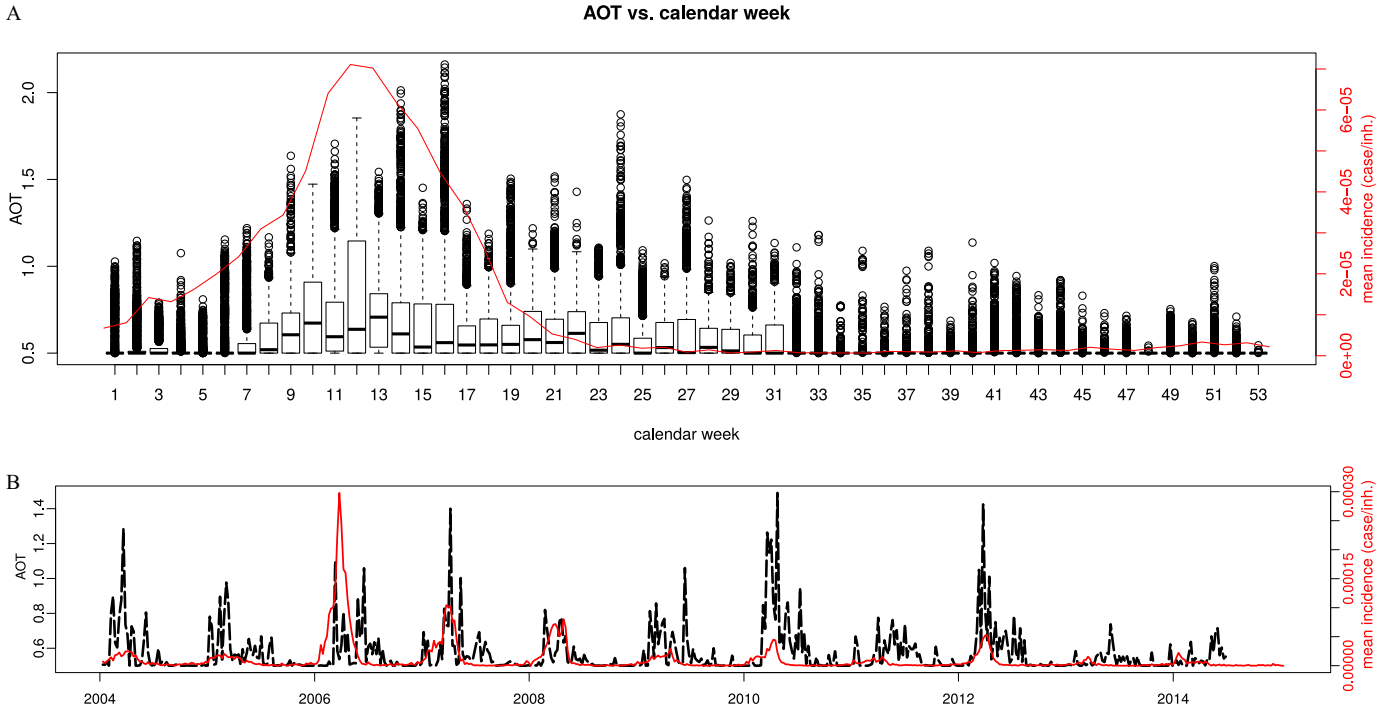

Figure 4. Temporal variation in aerosol optical thickness (AOT) and meningitis incidence rates at the health center (HC) level in the study area, 2004–2014. (*A*) Distribution of average AOT (black box-and-whiskers plots) and meningitis incidence rates (solid red line) over the entire study area according to calendar week. The upper and lower extents of each box indicate the 75th and 25th percentiles, respectively, the lines within each box indicate the median values. The lower (upper) whiskers indicate the first (third) quartile minus (plus) 1.5 times the interquartile range. Outlier observations outside this range are indicated as dots. Meningitis weekly incidences are the average per calendar week over the study period. (*B*) Weekly means of meningitis incidence (solid red line) and average AOT (dashed black line), averaged over the study area.

Table 1. Association between the occurrence of a localized meningitis epidemic during a health center (HC)–week and aerosol optical thickness (AOT). Burkina Faso, 2004–2014.

	No lag[b]		5-d lag[c]	
Control sampling strategy[a]	OR (95% CI)	*p*-Value	OR (95% CI)	*p*-Value
Crude	6.82 (4.90, 9.50)	<0.001	7.01 (5.10, 9.60)	<0.001
According to calendar week distribution	0.92 (0.60, 1.50)	0.73	0.83 (0.50, 1.30)	0.41
According to calendar week and year distribution	1.12 (0.70, 1.80)	0.65	1.16 (0.70, 1.80)	0.51

Note: ORs and 95% CIs were generated using binomial regression, per unit increase of AOT (range 0–2.2). Seasonal and secular trends were controlled for by sampling control observations according to the distribution of calendar weeks (and years). AOT, aerosol optical thickness; CI, confidence interval; OR, odds ratio.
[a]Crude models compared all epidemic HC-weeks to all nonepidemic HC-weeks during January–April (the period when the epidemics occurred); models controlling for calendar week compared epidemic HC-weeks to a randomly drawn sample of nonepidemic HC-weeks with the same distribution of calendar weeks, regardless of year; models controlling for calendar week and year compared epidemic HC-weeks to a randomly drawn sample of nonepidemic HC-weeks with the same distribution of calendar weeks and years.
[b]ORs for a 1-unit increase in weekly average AOT during the epidemic HC-week (defined as a calendar week).
[c]ORs for a 1-unit increase in 7-d average AOT 5 d before the start of the calendar week classed as epidemic.

by available surveillance and carriage data (Koutangni et al. 2015). Although a pathophysiological mechanism to explain such an effect is uncertain, proposed mechanisms include mechanical damage to the mucosal barrier or mucosal inflammation leading to altered host–pathogen interactions. A preliminary analysis of dust transported by the Harmattan winds and collected in Dédougou (Burkina Faso) indicated a majority of very small-sized particles (<100 nm) (Martiny et al. 2015), which may be more consistent with an effect via nasopharyngeal inflammation rather than mechanical damage, although the effects of dust on the mucosal barrier might also vary depending on humidity at the time of exposure. In addition, a mechanism involving direct bacterial invasion of the meninges along the olfactory structures, thus bypassing the blood stream, has been discussed (Mueller and Gessner 2010; Filippidis and Fountas 2009; Sjölinder and Jonsson 2010).

A link between the occurrence of meningitis cases early during the dry season and an increased number of cases during the subsequent dry season has been described by several studies at the national (Yaka et al. 2008), district (Agier et al. 2012; García-Pando et al. 2014), and HC level (Paireau et al. 2014). Proposed explanations for this association are that early cases are an indicator of a longer meningitis season (resulting in a proportional increase in cases), a consequence of an extreme climatic condition that contributes to risk (e.g., higher dust exposures early in the season), or a consequence of early exposures to nonenvironmental risk factors (Paireau et al. 2014). Our results suggest that it is not only the number of cases, but also the occurrence of a localized epidemic that is related to early cases, thus weakening the first explanation. In our analysis, the association between early cases and subsequent localized epidemics in the same HC catchment areas was not affected by adjustment for AOT levels when the first early case was reported, thus weakening the second explanation. Overall, the association with early cases may thus be the result of a complex epidemiological mechanism including further risk factors. However, this argumentation is limited by the fact that the AOT–dust link is based on several assumptions that are not met outside the period of January–April (see below).

Our finding of an association between the occurrence of early cases and subsequent localized epidemics within the same HC catchment area supports the recommendation by the WHO that the

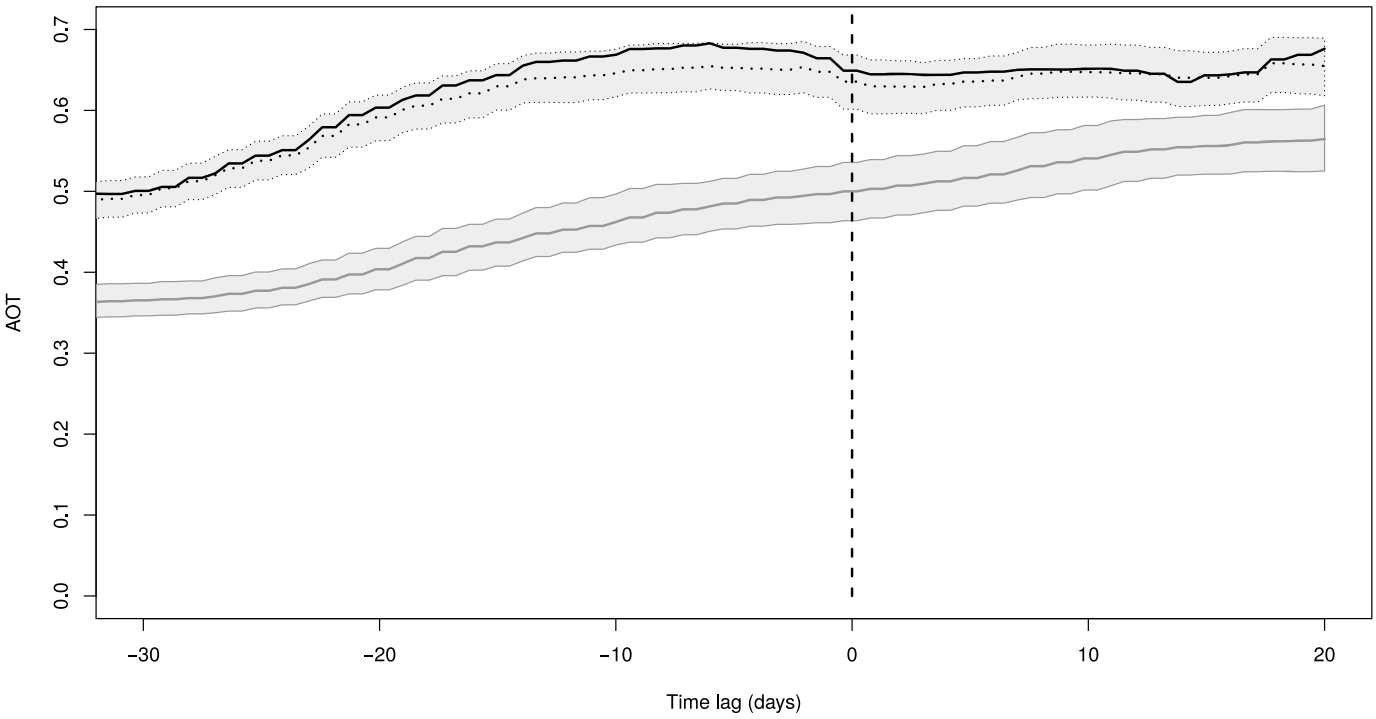

Figure 5. Aerosol optical thickness (AOT) values before and after onset of localized meningitis events in 14 health districts of Burkina Faso, 2004–2014. The solid black line represents the mean AOT over the 292 epidemic health center (HC)–weeks, aligned to the onset of the localized epidemic. The dotted black line and shading represent the mean AOT and 95% confidence interval (CI) in nonepidemic HC-weeks sampled according to the distribution of calendar weeks among epidemic HC-weeks. The full gray line and shading represent the mean AOT and 95% CI in all nonepidemic HC-weeks observed during January–April. The curves are smoothed with a 7-d rectangular kernel. Negative time lags mean that AOT was assessed before the epidemic HC-week.

Table 2. Association between occurrence of a localized meningitis epidemic in a health center (HC) and early cases of suspected meningitis reported by the HC during weeks 40–52 (October–December) of the previous calendar year.

	All years		Excluding 2005–2006[a]	
Model	OR (95% CI)	*p*-Value	OR (95% CI)	*p*-Value
Crude	1.14 (1.06, 1.21)	<0.001	1.20 (1.10, 1.30)	<0.001
Adjusted for AOT	1.15 (1.06, 1.23)	<0.001	1.22 (1.12, 1.33)	<0.001

Note: ORs and 95% CIs were generated using binomial regression, per unit increase in number of early cases. Adjustment was done for AOT on the first day of the calendar week of the first early case. AOT, aerosol optical thickness; CI, confidence interval; OR, odds ratio.
[a]Excluding early cases and epidemic HC-weeks during July 2005 through June 2006, as this meningitis season was a major epidemic wave with possibly additional specific factors explaining high incidences.

incidence of early cases at the national level be considered a warning sign of an increased risk of large epidemics later in the meningitis season (WHO 2014). However, there were relatively few early cases reported during October–December 2005, before the great 2006 epidemic wave. The role of early cases as a warning sign may therefore be more important for localized epidemics.

Cross-validation with aggregated data sets indicated strong agreement between our database and corresponding WHO data, with an absolute difference in case counts of ≤ 5 cases for 93% of HC-weeks and district-level populations within 5% of the reference population for 94% of district-years. Thus, our data set appears to be a reliable data source for mapping localized meningitis epidemics. However, there are several limitations to our analysis. First, underreporting of meningitis cases is likely in the context of limited health care resources in Burkina Faso, and our cross-validation technique cannot account for it. In addition, we used suspected case data, which included other meningitis etiologies (in particular, *Streptococcus pneumoniae*), encephalitis, and other diseases with similar clinical presentation (in particular, malaria in young children). Second, in the absence of a more precise map, each point of the district was associated with the nearest HC catchment area within the district. This may have led to the misclassification of the catchment area (and thus the AOT) for some cases, which would be expected to weaken associations. However, the impact of this misclassification was likely to have been small given that the median HC catchment area was approximately 120 km^2, and the AOT data were sampled on a 10×10 km pixel grid (100 km^2) so that small errors in HC catchment area classifications were likely to affect the same AOT pixel. In addition, dust waves usually span large regions and are spatially homogenous, resulting in high spatial autocorrelation. Therefore, the true AOT values were likely to have been the same as the AOT values for misclassified catchment areas.

Another limitation lies in the use of AOT, which measures the overall amount of aerosols in the atmospheric column without taking into account the altitude of the dust. It therefore can be interpreted only as a proxy for the ground-level dust load. However, over the January–April period, most of the aerosols are found to be around ground level (Léon et al. 2009; Cavalieri et al. 2010), where they can act as a potential meningitis risk factor. In addition, during January–April, the quantity of aerosols is dominated by dust particles; whereas outside this period, wood fire smoke contributes the most to aerosol particulates (Deroubaix et al. 2013). Before January, dust levels are usually very low, hampering the analysis power. After March, the aerosols are a mixture between ground-level dust and dust located at higher altitudes. In conclusion, within the January–April window, the validity of AOT as a proxy measure of surface dust is good, but AOT can still be influenced by topographic variability and other local factors. Further studies should consider taking into account additional predictors, including other remotely sensed aerosol products, the Angström coefficient (which provides indications of the type of particles), and relative humidity. The 10×10 km spatial resolution of the Deep Blue AOT was consistent with the size of the HC catchment areas (median radius 11 km) in our database, lending strength to our analysis.

Conclusion

We used surveillance data collected at the HC-week level to investigate the potential effect of atmospheric dust on bacterial meningitis epidemics. Although dust load was associated with the likelihood of a localized epidemic at the HC level, the association was not apparent when controlling for calendar week, which suggests that other local-scale factors may be responsible for triggering localized epidemics. The incidence of cases during the early dry season may be an indicator of the presence of such a factor, although underlying mechanisms are likely to be complex.

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The data supporting the findings of this study are the property of the Direction de la lutte contre la maladie (DLM), Ministry of Health of Burkina Faso (surveillance data) and the TELEDM project (dust data). Restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. However, data related to the present work are deposited on an online platform and can be obtained upon reasonable request and with permission of owners. For this purpose, please contact corresponding author J.E.M. Full analysis scripts are available online at https://github.com/MaximeMaW/MeningitisDustDynamics.

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