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Key Points:

- Senegal's relatively high humidity year-round may favor relatively low meningitis incidence
- Meningitis seasonality may be influenced by dust, Harmattan wind, temperature, and humidity
- Saharan dust may affect the onset of the meningitis season through direct or indirect processes

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Temporal Relationships Between Saharan Dust Proxies, Climate, and Meningitis in Senegal

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Abstract The Harmattan, a dry, northeasterly trade wind, transports large quantities of Saharan dust over the Sahelian region during the dry season (December–March). Studies have shown that bacterial meningitis outbreaks in Sahelian regions show hyper-endemic to endemic levels during high-dust months. We examine the (a) seasonality and intraseasonal variability of dust, climate, and meningitis and the (b) quantitative relationships between various dust proxies with meningitis lags of 0–10 weeks in Senegal from 2012 to 2017. The results show that the onset of the meningitis season occurs in February, roughly 2 months after the dusty season has begun. The meningitis season peaks at the beginning of April, when northeasterly wind speeds and particulate matter (PM) are relatively high, and the meningitis season ends near the end of June, when temperature and humidity rise and northeasterly wind speeds decline. Furthermore, we find that Senegal's relatively high humidity year-round may help slow the transmission of the infection, contributing to a lower disease incidence than landlocked countries in the meningitis belt. Lastly, our results suggest the desert dust may have a significant impact on the onset to the peak of the meningitis season in Senegal, particularly at the 0–2 and 10-week lag, whether that be directly through biological processes or indirectly through changes in human behavior. PM and visibility, however, are not in phase with aerosol optical depth throughout the year and consequently show different relationships with meningitis. This study further exemplifies the critical need for more PM, meteorological, and meningitis measurements in West Africa to further resolve these relationships.

Plain Language Summary The World Health Organization has estimated that 7 million people are killed from air pollution every year, with low and middle-income countries having the highest exposure. West Africa is particularly vulnerable to elevated particulate matter (PM) emissions from Saharan dust intrusions during the dry season (December–March), which have been shown to cause cardiovascular and respiratory disease. We examine the relationship between climate, Saharan dust, and meningitis cases in Senegal from 2012 to 2017 using various dust proxies. We find that the onset of the disease occurs in February, roughly 2 months after the dusty season has begun. The disease peaks during the dry season when northeasterly wind speeds and PM are relatively high and declines as the temperature and humidity increase. We find that PM and visibility are not in phase with aerosol optical depth and thus, have different relationships with meningitis throughout the meningitis season. However, we suspect dust may have a significant effect on the upstart and peak of the meningitis season, whether that be biologically or through changes in human behavior. Lastly, relatively high humidity in Senegal year-round may favor fewer meningitis cases compared to landlocked countries in the meningitis belt.

1. Introduction

Meningococcal meningitis is observed globally, but the highest incidence occurs in the "Meningitis Belt," a sub-Saharan African region that stretches from Senegal to Ethiopia (Lapeyssonnie et al., 1963; Molesworth et al., 2002). Meningococcal meningitis is a serious infection in which the meninges that surround the brain and spinal cord become inflamed (WHO, 2022). If left untreated, meningococcal meningitis has a 50% mortality rate, so early antibiotic therapy is critical to saving lives (WHO, 2022). Historically, Neisseria meningitidis serogroup A (NmA) accounted for 80%–85% of meningitis epidemics in the meningitis belt (WHO, 2022). MenAfriVac, a group A conjugate vaccine developed specifically for Africa, was introduced to the meningitis belt in 2010, targeting people aged 1 to 29. As a result, meningitis incidence in vaccinated populations has decreased by 57%

(Trotter et al., 2017). Although the vaccine has been shown to reduce group A incidence by over 99% in fully vaccinated populations throughout the region (Trotter et al., 2017), serogroups such as W, X, and C continue to cause epidemics across the belt, with roughly 30,000 cases per year (Fernandez et al., 2019; WHO, 2022). An improved understanding of which factors impact meningitis outbreaks is necessary to prevent and control the spread of the disease.

Several studies have suggested that Saharan dust and climate have a significant impact on meningococcal meningitis incidence in West Africa (Agier et al., 2013; Jusot et al., 2017; Martiny & Chiapello, 2013; Mueller & Gessner, 2010; Sultan et al., 2005; Yaka et al., 2008). Mueller and Gessner (2010) found dust combined with dry air conditions weakens the mucous membrane, enabling the passage of bacteria into the blood more easily. The meningitis season typically occurs from February to May during the latter part of the dry season, which coincides with warm and dusty Harmattan trade winds (Adetunji et al., 1979). Agier et al. (2013), Martiny and Chiapello (2013), and Deroubaix et al. (2013) found a 0–2-week lag between dust peaks and elevated suspected meningitis cases, corresponding to the 0–2 week incubation period of the disease in Mali, Niger, and Burkina Faso. Mueller and Gessner (2010) suggested that hyper-endemic meningitis levels begin during the dry season and end abruptly with the start of the wet. Pandya et al. (2015) found that an average of 40% relative humidity or greater for several weeks would naturally end a meningitis epidemic with no vaccine. Jusot et al. (2017) and Ayanlade et al. (2020) found that high temperatures were a significant risk factor for meningitis in Niger and Nigeria. Overall, these studies showed that atmospheric factors like dust, Harmattan winds, temperature, and humidity may impact the seasonality of meningitis in West Africa.

The quantification of atmospheric dust is necessary to understand its affects on human health. However, air quality monitoring stations are almost nonexistent throughout Northern Africa where major dust sources exist (Petkova et al., 2013). As a result, the seasonality of mineral dust has more frequently been assessed through remote measures of aerosol optical depth (AOD) from sun photometers and satellites. AOD, however, may not be a good measure of surface dust due to the seasonal variability in dust altitude throughout the year (Yahi et al., 2013). During the winter, the dust remains below 2 km above sea level because the vertical mixing is weak. During the summer, however, the vertical mixing of dusty air is strong, and the dust stream is between 1 and 5 km (Tsamalis et al., 2013). Thus, the seasonal cycle of surface dust concentrations and AOD are not in phase throughout the year. For example, Drame et al. (2011) found the highest AOD during the summer months when the dust is elevated above the monsoon layer. Hence, finding a reliable relationship between AOD and surface pollution in West Africa remains a challenge.

Surface visibility observations at meteorological stations have also been used as a proxy for mineral dust throughout the Sahel (N'tchayi et al., 1994). Visibility is a common atmospheric measurement that can be used as a visual indicator of air quality (Kuo et al., 2013; Singh et al., 2020). Pauley et al. (1996) and Ogunjobi et al. (2012) showed dust storms strongly degrade visibility in the atmosphere. N'tchayi et al. (1994) and Goudie and Middleton (1992) showed that visibility has a pronounced seasonal cycle in the Sahel. Visibility measurements are useful because meteorological stations are much more frequent throughout northern Africa than sun photometers or air quality stations.

The focus of the study is on the country of Senegal, a coastal country in the western Sahel. Limited studies have linked Saharan dust to meningitis seasonality in West Africa, and of those studies, none have considered Senegal in their analysis. This may be because of the countries within the meningitis belt, Senegal is among the least afflicted (Figure 1). Low and often sporadic meningitis incidence in Senegal prompted this study in part because most previous research focused on countries with high meningitis incidence, such as Burkina Faso and Niger (Agier et al., 2013; Jusot et al., 2017; Martiny & Chiapello, 2013; Mueller & Gessner, 2010; Yaka et al., 2008). Despite a relatively low case count, we suspect dust may still influence meningitis incidence in Senegal since particulate matter (PM) concentrations in Dakar, the capital city with over 1 million people, have been shown to frequently exceed 425 μg/m^3, which is defined as hazardous by the Environmental Protection Agency (EPA) (Diokhane et al., 2016). High PM concentrations coupled with Senegal's coastal climate make this study unique since most prior work primarily considered landlocked countries within the meningitis belt.

The goal of this work is to provide the first statistical analysis of dust, climate, and meningitis in Senegal. More particularly, the first objective of this study is to determine temporal relationships, specifically the seasonality and intraseasonal variability, between dust, climate, and meningitis in Senegal from 2012 to 2017. The second objective of this work is to quantify and compare the statistical relationships between various dust proxies, including

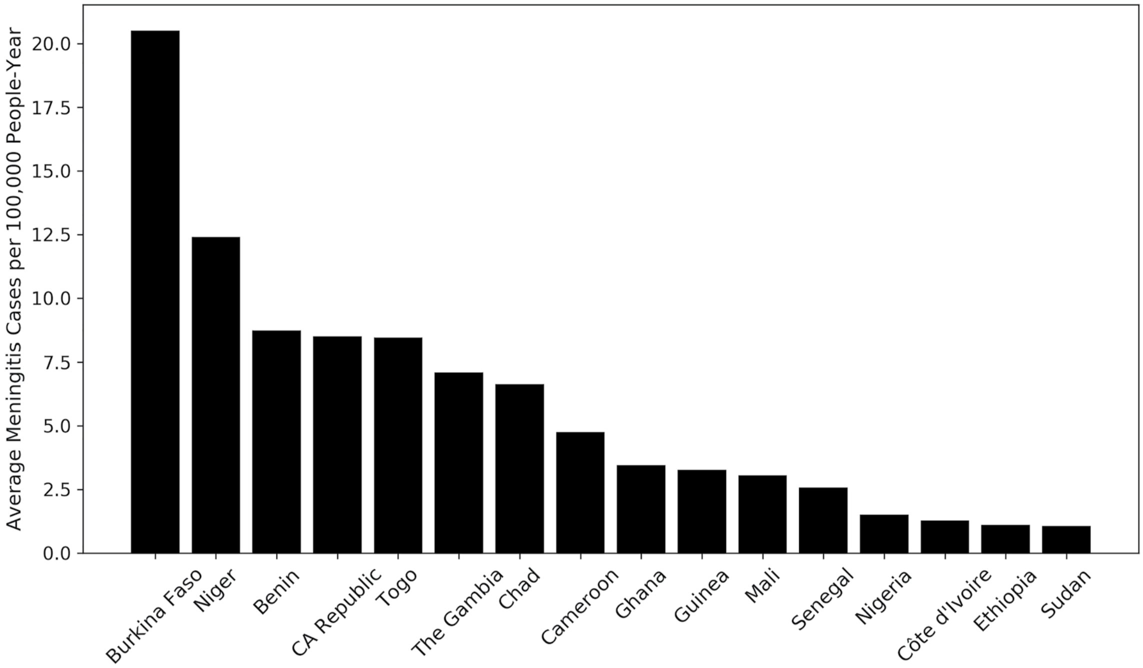

Figure 1. Average meningitis incidence per 100,000 people per year in Sub-Saharan African meningitis belt countries from 2012 to 2017.

PM observations, visibility, and indirect ground-based and satellite aerosol measurements, with meningitis lags of 0–10 weeks.

2. Data Description and Methodology

2.1. Epidemiological Data

Weekly meningitis reports were obtained from the World Health Organization (WHO) (https://www.who.int/publications/m) at the national scale (WHO, 2021). Bacterial samples were not collected for all reported cases. Of the bacterial samples collected, NmA was detected 5 times, representing 0.36% of sampled cases. The vast majority of samples reported were Cerebral Spinal Fluid negative, constituting 96% of sampled cases. The most common serogroups found were Neisseria meningitidis W135 and Streptococcus Pneumoniae (S. Pneum.), representing 2.2% and 1.8%, respectively.

No epidemics were reported in Senegal between 2012 and 2017.

2.2. Atmospheric Data

The observational data for this study include PM_{10} and $PM_{2.5}$ measurements, satellite and surface-based AOD, visibility, temperature, relative humidity, wind speed, and wind direction from 2012 to 2017. Hourly PM_{10} and $PM_{2.5}$ measurements were taken by the Centre de Gestion de la Qualit'e de l'Air (CGQA) in Dakar, Senegal (14.59°N, 17.5°W) with BAM-1020 continuous particle monitors (https://www.denv.gouv.sn/stations-cgqa/) (CGQA, 2018). Missing data and values above the maximum limit (1,000 μg/m^3) and below the minimum limit (0 μg/m^3) of the monitors were not considered. We produce weekly averages of PM_{10} and $PM_{2.5}$ using this data set. Additionally, AOD observations were utilized as a proxy for dust to supplement the lack of ground-based air quality monitoring stations throughout the country. Satellite-based AOD measurements were made by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Terra and Aqua satellites with the deep blue algorithm for land and sea at 550 nm. The deep blue algorithm screens out the pixels of contaminated clouds (https://giovanni.gsfc.nasa.gov/giovanni/) (MODIS, 2018). This data set includes daily means on a 1° × 1°grid. For comparison with countrywide meningitis data, AOD values were area-averaged over the spatial extent of Senegal using 29 grid points based on latitudinal and longitudinal location. For a ground- based

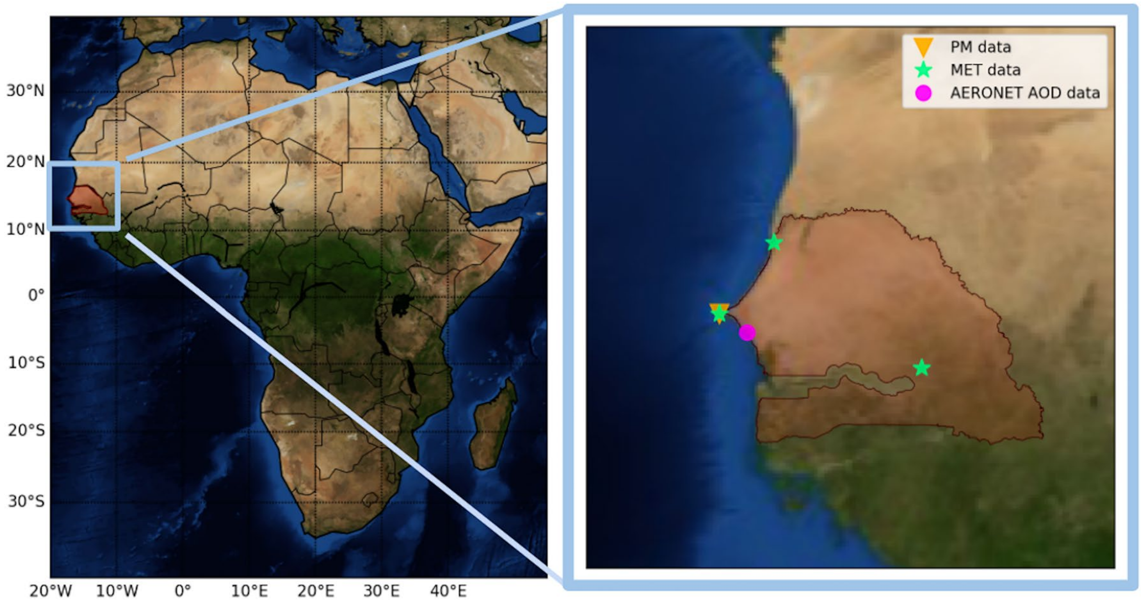

Figure 2. Point source particulate matter (orange triangle), Aerosol Robotic Network aerosol optical depth (magenta circle), and meteorological site (green star) locations used in this study from 2012 to 2017 in Senegal are shown.

perspective, sun photometer AOD measurements from the Aerosol Robotic Network (AERONET) site in Mbour, Senegal (14°N, 16°W), 80 km south of Dakar, were used (https://aeronet.gsfc.nasa.gov/) (AERONET, 2018). AERONET AOD of the highest quality control (Level 2.0) at 440 and 675 nm were utilized to interpolate AOD at 550 nm for comparison with MODIS AOD. Weekly averaged AERONET AOD was used in this study. Meteorological data were obtained from regional airports. Hourly data was provided by the Wyoming Weather Surface Observations database (http://weather.uwyo.edu/surface/) (UWYO, 2018). Weekly averages of meteorological data were produced and averaged across all sites in Senegal to account for national meningitis data.

All point source data sets used in this study are shown in Figure 2.

2.3. Typical Annual Cycle of Dust, Climate, and Meningitis

Temporal relationships between dust, climate, and meningitis were analyzed using the annual cycle of mean standardized weekly anomalies in PM_{10}, $PM_{2.5}$, AOD, visibility, temperature, relative humidity, wind speed, and meningitis. Sultan et al. (2005) developed this methodology to investigate the relationship between climate and meningitis epidemics in Mali. Even though Senegal is one of the least affected nations in the meningitis belt, this method allowed us to estimate the disease's usual seasonal cycle even when the number of annual cases were low. To show the typical annual cycle of climate and disease, we calculate the annual cycle of mean standardized weekly anomalies using Equation 1:

$$A(w) = \frac{\sum_{year1}^{year6}\left[\frac{x_y(w) - M_x}{\sigma_x}\right]}{N} \quad (1)$$

where $X_y(w)$ denotes a variable at a weekly time-step, and M_x and σ_x denote the mean and standard deviation of a variable over the 52 weeks of the year evaluated. The number of years considered is N, with *year*1 being 2012 and *year*6 being 2017, for a total of 6. Throughout the year, these anomalies are utilized to differentiate significant values in meningitis, dust, and meteorological variables.

3. Results

3.1. Annual Cycle of Dust, Climate, and Meningitis

Figure 3 shows the annual cycle of standardized mean weekly anomalies in meningitis, PM, AOD, N-NE wind speed, visibility, temperature, and relative humidity. To understand how dust and climate impact the seasonality and intra-seasonal variability of meningitis, we compare these variables together. As a supplement to these anomalies, we refer to Figure 4 for the mean and spread of the data.

We first analyze the dry season. We define the dry season when relative humidity anomalies are negative from the third week of November to the second week in May (Figure 3d). During the dry season, the first and most intense dust events occur in December, as shown by the highest positive PM_{10} and $PM_{2.5}$ anomalies (Figure 3a). Figures 4a and 4b show the highest mean weekly values of PM_{10} (513.1 μg/m^3) and $PM_{2.5}$ (184.4 μg/m^3) occur in December and are approximately 3.4 and 5.3 times the EPA standard, respectively. The onset of meningitis occurs the first week of February, indicating roughly a 2-month lag period between the onset of dust and the onset of meningitis. We observe simultaneous peaks of PM and meningitis during the second week of February and the first week of March. PM anomalies mostly become negative during the second week of April until the beginning of the dry season again in December.

Contrary to PM anomalies from December to February, AOD anomalies are primarily negative but become positive in March during the dry season (Figure 3b). Similar to PM, we observe simultaneous peaks in AOD during the second week of February and the first week of March. However, on average, the lowest AOD values occur during the dry season with minimum mean weekly values in December for MODIS (0.09) and January for AERONET (0.09) (Figures 4c and 4d). Temperature anomalies are mostly negative throughout the dry ason, excluding the last 2 weeks of November leading into the first week of December (Figure 3d). N-NE wind speeds are in phase with the disease (Figure 3c) with mean values of 4.28 m/s during the meningitis onset in February and 4.53 m/s during the meningitis peak April (Figure 4f). Visibility is generally reduced during most of the dry season with minimums during the first week of February and the first week of March, corresponding to peaks in PM, AOD, and meningitis (Figure 3c).

Now we analyze the humid season, which we define as the third week of May to the first week of November when relative humidity anomalies are positive (Figure 3d). During the humid season, the decreasing phase in meningitis occurs closely with the decreasing phase in wind speed and the increasing phase in temperature and humidity (Figures 3c and 3d). PM anomalies are negative and visibility anomalies are positive, indicating dust concentrations near the surface are relatively low (Figures 3a and 3c). Contrarily, AOD anomalies reach a peak during this period, particularly during the fourth week of June for both MODIS and AERONET when the meningitis season ends (Figure 3b). The increasing trend of AOD during the humid season is not in phase with the decreasing trend in meningitis. Thus, higher AOD values that occur in the humid season appear to not influence meningitis case variability, as the dust is lofted higher in the troposphere during the spring and summer months.

Pandya et al. (2015) found that an average weekly relative humidity of 40% or greater for several weeks would naturally end a meningitis epidemic with no vaccine in the meningitis belt. We explore if this relative humidity threshold may in part contribute to Senegal's low disease incidence compared to high disease burdened countries like Burkina Faso, for example, a country of similar geographical size (Burkina Faso: 170,379 km^2; Senegal: 122,231 km^2) and population size (Burkina Faso: 17 million in 2012 and 19 million in 2017; Senegal: 13 million in 2012 and 15 million in 2017) (WB, 2020). Figure 4e shows that the average monthly relative humidity always exceeds 40% in Senegal. Thus, compared to landlocked countries within the meningitis belt, high relative humidity year round may suppress meningitis incidence in the country. Although no epidemics were reported during our study period, epidemics have been reported in Senegal in prior years (Chippaux et al., 2007; Nicolas et al., 2000). An analysis of humidity and disease, particularly during epidemic years, is necessary to further understand the relationship between humidity and disease within the country.

3.2. Statistical Relationships Between Dust and Meningitis

To assess the quantitative relationship between dust and the disease, we compute Pearson correlations during two different periods: (a) the meningitis onset to meningitis peak (the first week of February to the first week of April), which we refer to as the P1 period and (b) the meningitis peak to the end of the meningitis season (the

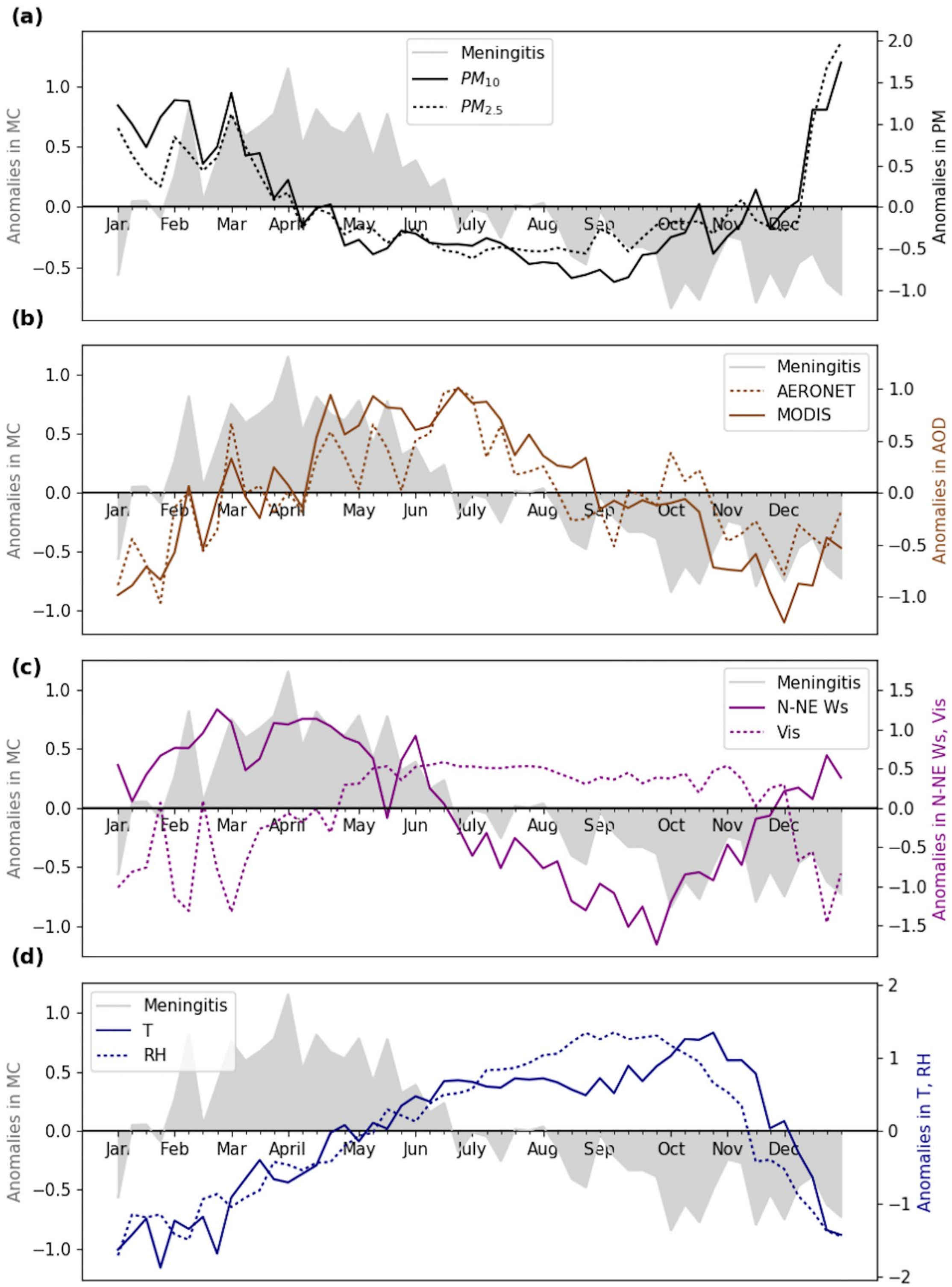

Figure 3. The annual cycle of mean weekly anomalies in meningitis (gray), PM_{10} (solidblack), $PM_{2.5}$ (dashed-black), Aeronet aerosol optical depth (AOD) (dashed-brown), and Moderate Resolution Imaging Spectroradiometer AOD (solid-brown), N-NE wind speed (solid-purple), visibility (dashed-purple), temperature (solid-blue), and relative humidity (dashed-blue) in Senegal from 2012 to 2017.

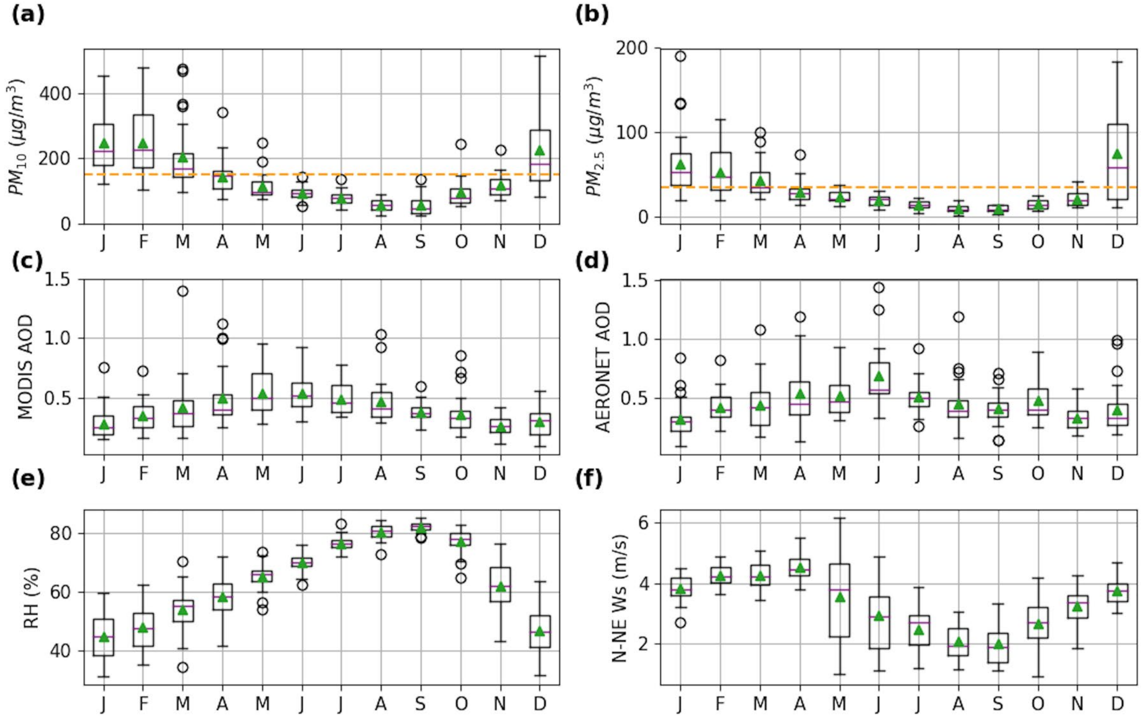

Figure 4. Box plot of mean weekly aerosol optical depth (AOD) (a), PM_{10} (b), $PM_{2.5}$ (c) Moderate Resolution Imaging Spectroradiometer AOD, (d) Aerosol Robotic Network AOD, (e) relative humidity, and (f) N-NE wind speed grouped by month with median (purple line), the lower 25th and upper 75th percentile (black box), mean (green triangle), the 10th and the 90th percentiles (black whiskers), and outliers (black circles) from 2012 to 2017 in Senegal. The orange-dashed line in (a) and (b) represent the Environmental Protection Agency daily standard for PM_{10} and $PM_{2.5}$.

second week of April to the third week of June), which we refer to as the P2 period. We explore lags of 0–2 weeks corresponding to the ∼2-week incubation period of the disease as well as lags of 8–10 weeks, corresponding to the ∼2-month lag between the onset of the dust and the onset of meningitis season.

Correlation coefficients and p-values for the P1 and P2 period are shown in Table 1. First, we evaluate the relationship between dust and meningitis during the P1 period. MODIS AOD and meningitis correlations are relatively high ($r = 0.53 - 0.73$), positive, and statistically significant at each lag, thereby suggesting that dust storms were associated with more meningitis cases during the period. The highest correlation occurred at the 1-week lag ($r = 0.73$, $p{-}value$ <0.01), and the lowest occurred at the 10-week lag ($r = 0.53$, $p - value$ <0.05). AERONET AOD and meningitis correlations were weaker which may be due to the sun photometer's point source nature and inability to capture the spatial variability of aerosols throughout the country corresponding to national meningitis data. However, relatively high, positive, and significant correlations occurred at the 0–2 week lag ($r = 0.50$–0.61), but correlations dropped and became in-significant at the 8 to 10-week lags ($r = 0.00$–0.12). Similar to MODIS, the highest AERONET and meningitis correlation occurred at the 1-week lag ($r = 0.61$, $p{-}value$ <0.05). Both relationships suggest that dust may be positively influencing meningitis incidence during the P1 period, particularly 0–2 weeks after exposure to a dust intrusion.

Compared with AOD, PM and visibility correlations with meningitis show contradictory results. During the P1 period, PM and meningitis correlations are negative, high, and statistically significant at the 0–2 week lag, thereby suggesting that meningitis cases decline during or after a dust intrusion. PM_{10} and meningitis correlation range from $r = -0.75$ to $r = -0.79$, with the highest correlation at the 0-week lag ($r = -0.79$, $p{-}value$ <0.01). $PM_{2.5}$ and meningitis correlations are just as strong, ranging from $r = -0.70$ to $r = -0.79$, with the highest correlation at the 0-week lag ($r = -0.79$, $p{-}value$ <0.01). However, as the lag time increases to 8–10 weeks, the relationship between PM and meningitis generally becomes positive. The correlation between PM_{10} and meningitis at the 10-week lag is $r = 0.71$ with a p-value <0.01 while the correlation between $PM_{2.5}$ and meningitis is weaker at $r = 0.42$ and lacks statistical significance. Similarly, visibility shows relatively high, positive, and statistically significant correlations with meningitis at the 0–2 week lag ($r = 0.59 - 0.64$), with the highest posi-

Table 1
Weekly Mean Dust Proxy and Meningitis Lagged Correlations in Senegal for Two Periods: P1 (Meningitis Onset to Peak) and P2 (Meningitis Peak to End of Meningitis Season)

	Lag-time	P1	P2
MODIS AOD	None	0.66[b]	−0.12
	1 week	0.73[a]	−0.14
	2 weeks	0.70[a]	−0.32
	8 weeks	0.61[b]	−0.32
	9 weeks	0.60[b]	−0.52
	10 weeks	0.53[b]	−0.52[c]
AERONET AOD	None	0.50[b]	−0.59[c]
	1 week	0.61[b]	−0.24
	2 weeks	0.57[b]	−0.49
	8 weeks	0.11	−0.34
	9 weeks	0.00	−0.34
	10 weeks	0.12	−0.24
PM_{10}	None	−0.79[a]	0.57[c]
	1 week	−0.74[a]	0.60[c]
	2 weeks	−0.75[a]	0.65[b]
	8 weeks	0.42	0.77[a]
	9 weeks	0.55[b]	0.75[a]
	10 weeks	0.74[a]	0.49
$PM_{2.5}$	None	−0.79[a]	0.68[b]
	1 week	−0.74[a]	0.68[b]
	2 weeks	−0.70[a]	0.68[b]
	8 weeks	−0.05	0.79[a]
	9 weeks	0.18	0.78[a]
	10 weeks	0.42	0.40
Visibility	None	0.64[b]	−0.71[b]
	1 week	0.52[c]	−0.62[b]
	2 weeks	0.59[b]	−0.74[a]
	8 weeks	−0.001	−0.67[b]
	9 weeks	−0.16	−0.51
	10 weeks	−0.47[c]	−0.27

Note. MODIS, Moderate Resolution Imaging Spectroradiometer. Simple correlation coefficients are denoted as:
[a]Significant correlation with P-value <0.01. [b]Significant correlation with P-value <0.05. [c]Significant correlation with P-value <0.10.

tive correlation at the 0-week lag ($r = 0.64$, $p{-}value <0.01$). At the 10-week lag, however, correlation becomes relatively high and negative ($r = -0.47$, $p{-}value <0.1$).

The results during the P1 period suggest that dust may be influencing the onset to peak of the meningitis season in Senegal, but the relationship remains unclear as meningitis correlations with different dust proxies yield significantly different results. The highest agreement among the dust proxies, including MODIS AOD ($r = 0.53$, $p{-}value <0.05$), AERONET AOD ($r = 0.11$), PM_{10} ($r = 0.74$, $p{-}value <0.01$), $PM_{2.5}$ ($r = 0.42$), and visibility ($r = -0.47$, $p{-}value <0.10$), occurs at the 10-week lag. Given the disease's ~2 week incubation period, it is unlikely that a Saharan dust event would have a direct effect on meningitis incidence 10 weeks after a dust intrusion. Other factors, such as changes in human behavior that promote the spread of the disease, may be influenced by changes in atmospheric variables during the dry season.

Now, we evaluate the relationship between each dust proxy and meningitis during the P2 period. For MODIS AOD, the correlation coefficients generally drop in comparison to the P1 period, become negative, and lack statistical significance ranging from $r = -0.12$ to $r = -0.52$, except for the 10-week lag ($r = -0.52$, $p{-}value <0.10$). Similarly, for AERONET AOD, correlations become negative and insignificant ranging from $r = -0.24$ to $r = -0.49$, excluding the 0-week lag ($r = -0.59$, $p{-}value <0.10$). We suspect this may be for two reasons: (a) after the end of March, surface PM concentrations decline, and the dust is lofted to higher altitudes in the troposphere. Thus, AOD measurements during the latter half of meningitis season do not accurately represent dust concentrations near the ground that impact air quality and health (Figures 3a and 3b), or (b) dust does not influence the meningitis case variability after the meningitis peaks, similar to what was found in Martiny and Chiapello (2013).

Unlike MODIS and AERONET AOD, PM and visibility correlations with meningitis during the P2 period are relatively high and mostly significant. The highest correlations of PM_{10} ($PM_{2.5}$) occur at the 8-week lag where $r = 0.77$ ($r = 0.79$). Visibility has the highest correlation with menigitis at the 2-week lag ($r = -0.74$). Contrary to AOD, this suggests that dust may influence meningitis case variability in the latter half of the meningitis season after the disease peaks.

4. Discussion and Conclusion

In this study, the impact of dust and climate on meningitis seasonality and intraseasonal variability was assessed in Senegal using a 6-year data set (2012–2017). Limited studies have assessed the impact of dust and climate on meningitis seasonality in West Africa, and to our knowledge, none of these studies included Senegal in their analysis. Figure 5 summarizes our findings of dust, climate, and meningitis seasonality in Senegal. The onset of the meningitis season occurs at the beginning of February during the heart of the dry season when Harmattan wind speeds are relatively high and AOD, humidity, temperature, and visibility are relatively low, roughly 2 months after dust onset has begun in December (Figure 5). The onset of the meningitis season occurs simultaneously with peaks in PM and AOD during the first week of February. Meningitis cases reach a maximum during the first week of April, following simultaneous PM, AOD, and meningitis peaks during the first week of March. Disease incidence begins to decline during the second week of April when the PM and N-NE wind speed anomalies generally decline. The end of the meningitis season occurs during the fourth week of June during the humid season, roughly 6 weeks after temperature and humidity anomalies become positive.

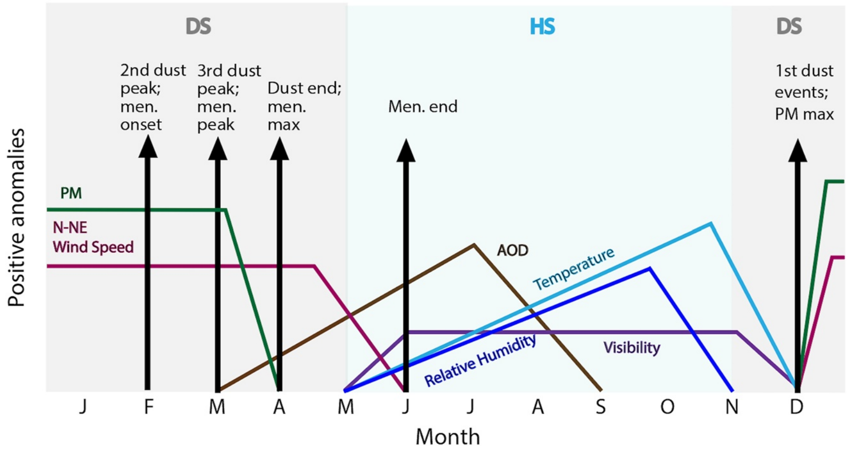

Figure 5. A summarizing schematic of dust, climate, and meningitis seasonality and intraseasonal variability in Senegal from 2012 to 2017. The gray background represents the dry season, denoted as "DS" from November to April. The light blue background represents the humid season, denoted as "HS" from May to October. The colored lines represent positive anomalies in dust proxies and meteorological variables. The black lines represent the intraseasonal variability of dust and meningitis. "Men. onset," "men. peak," "men. max," and "men. end" represent the onset, peak, maximum, and end of the meningitis season.

Furthermore, we find that throughout the year, Senegal always exceeds the mean monthly relative humidity threshold of 40% found in Pandya et al. (2015) to end a meningitis epidemic with no vaccine. A high relative humidity year-round may suppress meningitis incidence in Senegal compared to landlocked countries within the Sahel. Although often excluded from prior work, perhaps due to relatively low meningitis incidence, Senegal may be an interesting country to further examine since most people live near the coast where the climate is more moderate. To further understand the relationship between humidity and disease in Senegal, an analysis of humidity and disease is required, particularly during epidemic years when this 40% threshold can be evaluated by regional health districts.

Additionally, we find that AOD and meningitis correlations are positive and relatively high from the onset to the peak of the disease at the 0 to 10-week lag for MODIS and the 0–2 week lag for AERONET, suggesting the meningitis cases increase during or after a dust intrusion. The strongest correlation was found at the 0–2 week lag for both AOD measures, indicating that dust aerosols may be most strongly impacting health between 0–2 weeks of Saharan dust exposure, similar to what was found in Martiny and Chiapello (2013), Agier et al. (2013), and Deroubaix et al. (2013). However, PM and visibility correlations with meningitis show contradictory results. PM (visibility) show negative and high (positive and low) correlations with meningitis at the 0–2 week lag, indicating that an increase in dust emissions is associated with a decrease in meningitis infections. As the lag time increases to 10 weeks, PM (visibility) show relatively high and positive (negative) correlations with dust, although not all are statistically significant. Thus, the highest agreement among all dust proxies and meningitis occurs at the 10 weeklag. A 10-week lag indicates that indirect processes such as changes in human behavior during or after a dust storm may be influencing disease incidence, as this lag-time exceeds the meningitis incubation period of ∼2 weeks.

As previously shown, in this study, we use different dust proxies, most of which are remotely sensed. Indirect aerosol measurements may not produce representative estimates of surface conditions because air quality can be most accurately quantified through direct surface measurements, which are crucial for determining surface PM concentrations associated with disease outbreaks. PM measurements throughout most of West Africa, however, are scarce (Petkova et al., 2013). This study highlights the uncertainties associated with using AOD as a proxy for surface dust, particularly during the humid season when the meningitis cases decline. During the latter half of the meningitis season, correlation coefficients drop possibly because AOD estimates during the humid season do not appropriately estimate dust concentrations near the ground, since the dust is lofted high in the troposphere. AOD estimates were shown to peak during the summer, months after PM peaks, similar to what was found in Drame et al. (2011). Contrarily, PM (visibility) show relatively high and positive (negative) correlations with meningitis during the latter half of the meningitis season, suggesting that dust may impact disease incidence during this period.

A significant limitation of this study was the overall lack of both atmospheric and health data in Senegal. It is important to reiterate the different spatial scales of the dust proxies used in this study. PM and AERONET AOD data are point source measures near the coast and visibility data are averaged across three point source meteorological sites throughout the country. Even though Saharan dust storms would likely be detected by all instruments given their synoptic nature (Knippertz & Todd, 2010), MODIS is likely most suitable for comparison with national meningitis since it captures the spatial variability of aerosols throughout the country, particularly during the dry season when the dust is at the surface. Although we average across all available data sets to obtain a general understanding, the meteorological, dust, and health conditions vary throughout the country. Our findings suggest daily and district level PM, meteorological, and meningitis data are critical to resolving the relationship between dust, climate, and meningitis in Senegal.

To conclude, this study shows that atmospheric variables such as dust, Harmattan wind speed, relative humidity, and temperature may influence the seasonality and intraseasonal variability of meningitis in Senegal, despite the country's relatively low case count.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Weekly meningitis reports utilized in this study are publicly available at https://www.who.int/publications/m. MODIS AOD data are publicly available at https://giovanni.gsfc.nasa.gov/giovanni/. AERONET AOD data are publicly available at https://aeronet.gsfc.nasa.gov/. Other data used in this study are archived at https://doi.org/10.26207/dpab-2s17.

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