Impact of Climate Factors in Modeling and Predicting the Transmission of Meningitis in Africa: The Case of Burkina Faso

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Abstract

Background Meningitis is a major cause of morbidity in the world. Previous studies showed that climate factors influence the occurrence of meningitis. A multiple linear regression model was developed to forecast meningitis cases in Burkina Faso using climate factors. However, the multivariate linear regression model based on times series data may produce fallacious results given the autocorrelation of errors.

Aims The aim of the study is to develop a model to quantify the effect of climate factors on meningitis cases, and then predict the expected weekly incidences of meningitis for each district.

Data and methods The weekly cases of meningitis come from the Ministry of Health and covers the period 2005-2017. Climate data were collected daily in 10 meteorological stations from 2005 to 2017 and were provided by the national meteorological Agency of Burkina Faso. An ARIMAX and a multivariate linear regression model were estimated separately for each district.

Results The multivariate linear model is inappropriate to model the number of meningitis cases due to autocorrelation of errors. With the ARIMAX Model, Temperature is significantly associated with an increase of meningitis cases in 3 of 10 districts, while relative humidity is significantly associated with a decrease of meningitis cases in 3 of the 10 districts. The effect of wind speed and precipitation is not significant at the 5% level in all 10 districts. The prediction of meningitis cases with 8 test observations provides an average absolute error ranging from 0.99 in Boromo and Bogandé to 7.22 in the district of Ouagadougou.

Conclusion The ARIMAX model is more appropriate than the multivariate linear model to analyze the dynamics of meningitis cases. Climatic factors such as temperature and relative humidity have a significant influence on the occurrence of meningitis in Burkina Faso; the temperature influences it positively and the relative humidity influences it negatively.

1-introduction

According to the World Health Organization (WHO), meningitis is a serious infection of the thin membranes that surround the brain and spinal cord. It is most often caused by an infection (bacterial, viral or fungal).

Different bacteria can cause meningitis. Neisseria meningitidis is most likely to cause major epidemics. Twelve serogroups of Neisseria meningitidis have been identified, and six of them are known to cause epidemics (A, B, C, W135, X and Y). The geographical distribution and the epidemic potential vary from one serogroup to another.

This bacterial infection is a major cause of morbidity and mortality in the world: about 500,000 cases are reported each year, with a fatality rate of about 10% (Maiden and Caugant, 2006). Half of the cases occur in sub-Saharan Africa during the dry season, in an area called the "meningitis belt” where meningococcal meningitis is endemic and "epidemic" (Lapeyssonnie, 1963).

Studies carried out in epidemiology and climatology since the mid-twentieth century have demonstrated the existence of a spatial and temporal concordance of meningitis epidemics with the dry season (Lapeysonnie, 1963; Greenwood et al., 1984, Cheesbrough et al. 1995; Besancenot et al 1997; Molesworth et al. 2002). Meningitis epidemics generally begin in February and disappear in May. The Sudano-Sahelian part of Africa is subject to the alternation of a dry season in winter, dominated by harmattan winds, and a wet season that starts in the spring to reach its peak in summer with the establishment of the monsoon. The typical climatic context of winter in subtropical latitudes provides favorable conditions for the development of meningitis: whereas drought and strong, dust-laden winds can stimulate meningococcal invasion by directly damaging the mucosal barrier or inhibiting surface immune defenses, spring moisture and Guinean latitudes significantly reduce the incidence of meningitis (Chippaux et al., 2002).

The work of Sultan et al. (2005) in Mali have statistically shown ($r = 0.92$) that the start of meningitis epidemics coincided with maximum winter in the middle of February. This period is characterized by a strongest harmattan and a lowest humidity.

The launch of the African Monsoon Multidisciplinary Analysis Program (AMMA) in 2002 (Redelsperger et al., 2006) has led to unprecedented progress in understanding the climate-meningitis relationship. Around a multidisciplinary approach led by the Climatology Research Center (CRC), pilot of the group climate-health at the French level of the program, and since recently in collaboration with the World Health Organization (WHO), new ways of investigation to better understand the climate - environment - meningitis relationship have been updated.

More recently, (Martiny and Chiapello,2013) used weekly WHO censuses of meningitis-related cases and deaths in Niger, Mali and Burkina Faso for the period 2004–2009 as well as moisture data from AERONET, the network of photometric measurements. The results of this study in Niger show that the increase in humidity is associated with a reduction in the number of cases over the same period, and then signs the cessation of the seasonal cycle of meningitis (whether the years are epidemic or not). The results obtained in Burkina Faso and Mali are also similar.

However, the mechanisms responsible for the start, cessation and intensity of these outbreaks are not accurately identified yet. Many studies have shown the relationship between climatic factors and the occurrence of meningitis, but few have established predictive models for meningitis cases.

It is in this context that this study will focus on providing predictions of meningitis cases to address a possible failure of the surveillance system and consequently to plan the stock of vaccines for controlling the disease.

We suggest the use of the ARIMAX model (Box-Tiao, 1975) or Auto Regressive Integrated Moving Average with eXegenous variables, to evaluate the impact of climatic factors on the occurrence of meningitis. ARIMAX is an extension of the ARIMA model (Box-Jenkins, 1970), popular in econometric analysis (Unkel et al., 2012), which includes independent variables as explanatory variables and combines regression and ARIMA model (C. Imai et al, 2015).

Pascal Yaka et al. (2008) developed a forecasting model using climatic factors, but this multivariate linear regression model can produce misleading or fallacious/invalid results given the auto-correlation inherent in time series (fallacious regression / spurious regression).

The main difference between the formal ARIMAX modeling and the widely used multiple regression modeling is that the ARIMAX modeling rigorously meets six statistical assumptions underlying the multiple regression model. Since the ARIMAX modeling process is much more complex than that of the multiple regression, it discourages model builders to use it.

One of the assumptions related to that of a multiple linear regression requires, inter alia, that the residuals are not auto-correlated (The auto-correlation is the correlation of a time series with its lags. When the residuals are auto-correlated, this means that the current value depends on the previous ones). Violation of these assumptions generates inefficient results.

It is in this context we propose to build an ARIMAX model for predicting the incidence of meningitis for the coming years. We will also build a second multiple linear regression model, the results of which will be compared to that of the ARIMAX model, in order to compare the performances of these models.

2-research Objectives And Hypothesis

2.1. Aim

Estimate the expected incidences of meningitis by epidemiological week and by district, using known or predicted climatic factors.

2.2. Objectives

1) Determine the correlation between climatic factors and the transmission dynamics of meningitis;

2) Modeling the transmission dynamics of meningitis taking into account climatic factors;

3) Recommend the best model to explain and predict the transmission dynamics of meningitis;

4) Estimate the number of expected meningitis cases in the case the surveillance system fails;

5) Predict possible epidemics of meningitis.

2.3. Research hypotheses

i.
The transmission dynamics of meningitis is correlated with climatic factors;
ii.
There is over-dispersion and auto-correlation for the series of cases of meningitis;
iii.
The ARIMAX model is better than the multiple linear regression model to establish the relationship and predictions of the incidence of meningitis.

3-materials And Methods

3.1. Study design

This is a retrospective study based on data from meningitis and climate registered in 10 health districts out of the 70 that exist in Burkina Faso. These districts are: Bobo-Dioulasso, Bogandé, Boromo, Dédougou, Dori, Fada N'Gourma, Gaoua, Ouagadougou, Ouahigouya and Po (Figure 1). Data are collected weekly and cover the period 2005-2017. These districts were included in the study because they host weather stations that report climatic parameters each day.

3.2. Meningitis data

The meningitis weekly data are surveillance data obtained from the Ministry of Health. These data come from the different health facilities of the country, and are centralized at district level before being transmitted to central database. An official request was sent to the Ministry of Health to obtain these data and permission to use them for the study.

3.3. Climate data

The climate data were collected daily through weather stations in the ten health districts of the study. The data were obtained from the National Agency of Meteorology and covers the same period as the meningitis data (2005-2017). Climatic variables are: minimum temperature, average temperature, maximum temperature, relative humidity, rainfall, and wind speed.

3.4. Data processing

The daily climate data were aggregated on a weekly basis using the mean function for all variables except for rainfall where total function was used. The weeks of aggregation are consistent with epidemiological weeks used for meningitis surveillance. The series of meningitis cases and climatic parameters were merged to obtain a database containing both meningitis cases and climatic variables by district.

3.5. ARIMAX modeling methods

The ARIMAX model is an extension of the ARIMA (Auto Regressive Integrated-Moving Average) that takes into account exogenous variables when the past values of the series are insufficient to explain its present and future values. The estimation of the ARIMAX model is implemented in two phases: (1) An estimation of the ARIMA model using the Box-Jenkins approach, then (2) a multiple regression taking into account the exogenous variables.

The estimation of the ARIMAX model is based on the following assumptions:

- H1: The series is stationary;

- H2: Errors are not auto-correlated;

- H3: The coefficient associated with the exogenous variable is significant;

- H4: There is no significant multi-collinearity between exogenous variables ;

- H5: There is a causal relationship (in the sense of Granger) between and ;

The estimation algorithm of the ARIMAX model follows 8 (eight) steps:

1. Test the stationarity of the series and exogenous variables , then eventually differentiate the series to make them stationary. Augmented Dickey-Fuller and Philip Perron's Tests are appropriate to test the stationarity of series;
2. Test the causality between the variable and the exogenous variables using Granger's causality test ;

iii. Determine the sign of the effect of the exogenous variables on the dependent variable using an analysis of the correlation matrix ;

1. Determine the number of lags p and q of the AR and MA components using the correlograms (ACF and PACF);
2. Estimate the ARIMAX regression using lags p and q, then add the exogenous variables;
3. Test residual auto correlation using the LJung-Box test;

vii. Repeat steps iv, v, and vi until the residuals are non-auto correlated and the exogenous variables are significant;

viii. Keep the final model that meets basic assumptions and with the smallest information criterion such as AIC and BIC.

The model was implemented independently in each of the 10 districts where dependent variable is the weekly meningitis cases and exogenous variables are maximum temperature, relative humidity, rainfall and wind speed.

The variables were visualized to identify missing values, outliers and the possible presence of seasonality and trend. Missing values were imputed using the average of the neighboring points.

Since the three temperature variables (minimum, mean and maximum) are strongly correlated, the one having significant Granger causality with the number of meningitis cases (maximum temperature) was chosen to avoid multi-collinearity between exogenous variables.

The last 8 observations in the series were excluded from the ARIMAX model estimate and then used as a test sample to assess the quality of the prediction of the number of meningitis cases. The model was estimated using the forecast package of the R software.

Fig 1. Study area

4-results

4.1 Summary of variables

The distribution and quality of the data were assessed by calculating the minimum, the median, the average, the maximum and the number of missing values for each variable. A total of 676 weekly observations were collected for each district over the period 2005 to 2017, giving a total of 6,760 observations for the 10 districts. The maximum temperature varies from 23.8 to 44.8, with an average of 35.43. The average wind speed is 3.9 km/h, and the average relative humidity is 49.7%. Wind speed has 7% missing values in 7 of the 10 districts (Table 1).

4.2 Evolution of the number of meningitis cases by district

The data were visualized to detect possible outliers, seasonality and trend. The weekly meningitis cases fluctuated over the period 2005-2017 for each district with peaks observed for some weeks. The district of Ouagadougou recorded 1,828 cases of meningitis in March 2007. For the district of Bobo-Dioulasso, the peak were recorded in March 2006 with 407 cases of meningitis (Figure 2a, Figure 2b). The figures indicates a variation in the evolution of meningitis cases by district and no clear trend over the period of the study. Also, the increases in the number of meningitis cases are observed in the months of March and April of each year.

Table 1. Descriptive statistics of variables of interest

Figure 2a. Number of meningitis cases reported between 2005 and 2007

Figure 2b. Number of meningitis cases reported between 2005 and 2007

4.3 Correlation and Granger causality between variables

The correlation matrix was computed to identify the possible sign of the effect of climatic factors on the number of meningitis cases and the presence of multi-collinearity among climatic factors. Table 2 presents the correlation coefficients between the number of meningitis cases and the lag values of climatic factors, as well as the results of the Granger causality test for each of the 10 health districts.

Temperature is positively correlated with the number of meningitis cases in all 10 health districts. (). Wind speed is also positively correlated with the number of meningitis cases in 3 of the 10 health districts namely Ouahigouya, Bobo-Dioulasso and Ouagadougou. The correlation is however low. (). The correlation is also significant for the current values and some lagged values of temperature and wind speed. For relative humidity and rainfall, the correlation with meningitis cases is negative for the 10 districts.

The Granger causality test indicates whether past and present climatic factors predict the number of meningitis cases significantly. The last column of Table 2 shows statistical test and the associated p-value with the null hypothesis (no causality). Temperature is causal factor of meningitis cases in 6 of the 10 districts (. The relative humidity is another causal factor in 7 of the 10 districts. However, rainfall and wind speed are also causal factors in only on district, respectively Po and Ouagadougou.

Thus, temperature and wind speed are positively correlated with the number of meningitis cases, while rainfall and relative humidity are negatively correlated to this variable. These 4 climatic factors have a Granger causal effect on the number of meningitis cases in at least one health district. Simultaneous consideration of these factors in ARIMAX modeling will provide the adjusted effect of each factor.

Table 2. Autocorrelation coefficients between the number of meningitis cases and climatic factors, Granger causality by district

4.4 Results of Linear Models and ARIMAX

The stationarity tests of Augmented Dickey-Fuller and Philip Perron on the series provide no evidence of unit root for each of the 10 districts (This property of the series being satisfied; the model can be estimated with the level series (not differentiated).

Table 3 shows a comparison between the linear and ARIMAX models for each district. The results suggest that ARIMAX models are valid whereas the linear models are not. Indeed, the null hypotheses of the Portementeau residuals autocorrelation test (white noise) are all rejected for the linear models, but are not rejected for the ARIMAX models. Therefore, residuals of ARIMAX models are not autocorrelated. In addition, the AIC and BIC criteria derived from the models of each district are lower for the ARIMAX models compared to those of the linear models. This results in higher performances of ARIMAX models compared to linear models.

Table 4 shows the estimated coefficients of the ARIMAX model associated with the autoregressive (AR) components, Moving Average (MA) and exogenous variables. The best model selected for the Bobo-Dioulasso district is an ARIMAX model (3, 0, 4) where temperature is the only significant exogenous variable. Residuals auto-correlation test (LJung-Box) shown in the last column of the table validates the model. The parameters of the ARIMAX model vary by district and the only significant exogenous variables are temperature and relative humidity. Temperature is significant in 4 of the 10 districts (and the relative humidity is significant in 3 of the 10 districts. In some districts such as Bogandé and Boromo, no exogenous variable is significant, but the final model for the district of Po has two significant exogenous variables.

The real values of meningitis cases for the last 8 observations and those predicted by the model in each district are presented in Table 5. The number of recorded cases of meningitis on the 45th week of 2017 for the District of Bogandé is 0 and the value predicted by the model is 0.3. The mean absolute error of the 8 predicted values is 0.99, which means that the predicted values deviate by plus or minus 1 case for Bogandé district. For the district of Ouagadougou, the value observed for the same period as before is 4 cases and the predicted one is 11.2. The mean absolute error of the 8 values predicted for Ouagadougou is 7.22. Among the 10 districts, the models for Bogandé and Boromo have a relatively high quality of prediction, while those of Ouagadougou and Bobo-Dioulasso have a poor quality of prediction.

Table 3. Parameters of linear multivariate and ARIMAX models of weekly meningitis cases and their performance

Table 4. ARIMAX parameters of weekly meningitis cases and their performance

Table 5. Actual and predicted meningitis cases of the last 8 weeks of 2017

5-discussion

In his study, we modeled the occurrence of meningitis cases taking into account climatic factors using an ARIMAX model and a multivariate linear model. The residuals auto-correlation in the series suggests that the multivariate linear model may produce fallacious results regarding the effect of climatic factors on the occurrence of meningitis. It is therefore, unappropriated to model the effect of climatic factors on the occurrence of meningitis.

ARIMAX models for the districts of Bogandé, Boromo, Dori and Fada have no significant climatic factors, whereas the districts of Bobo-Dioulasso, Dédougou, Gaoua, Ouagadougou, Ouahigouya and Po models have climatic factors significantly associated with occurrence of meningitis cases. The climatic factors that have a significant effect are the maximum temperature and the relative humidity. Indeed, an increase in maximum temperature is associated with an increase in meningitis cases for Bobo-Dioulasso, Ouagadougou, Ouahigouya and Po, while an increase in relative humidity is associated with a decrease in meningitis cases for Dédougou, Gaoua and Po.

Results about effect of humidity are similar to those of other studies mentioned in the introduction. Indeed, "the humidity of spring and Guinean latitudes considerably reduces the incidence of meningitis (Chippaux et al., 2002). The results of Martin's and Chiapello's (2012) Nigerian study, which used weekly

WHO data, also showed that the increase in humidity is associated with a decrease in the number of meningitis cases. Other studies like that of Sultan B et al (2004) on Mali showed a relationship between meningitis cases and wind speed. However, the effect of wind speed was not significant in this study. In addition, this variable contained several missing values and was therefore taken into account in the modeling of 3 of the 10 districts.

Few studies have pointed temperature as a risk factor for meningitis even though our study has shown it. However, the fact that its effect is significantly positive in 4 of the 10 districts provides strong evidence to conclude that temperature is a risk factor for the increase in the number of meningitis cases.

The quality of prediction based on the ARIMAX model is relatively better for 8 of the 10 districts, but relatively poor for the districts of Ouagadougou and Bobo-Dioulasso. The poor quality of the prediction can be potentially explained by the high frequency of zero cases of meningitis in the data (40%).

Note, however, that the available data both clinical and climatic does not allow a precise analysis of correlations because other climatic parameters (such as vegetation index normalized difference, the wind direction, Carlos data: concentration of surface dust) are potential explanatory factors for the occurrence of meningitis. In fact, the occurrence and spread of meningitis epidemics is multifactorial (Mbaye et al., 2004, Sultan et al., 2004, and Jackou-Boulama et al., 2005). It would then be appropriate to use a systemic approach which, beyond climate, would take into account the virulent strain, the receptive population, the environment and the living conditions. The absence of these parameters in the modeling reduce explanatory and predictive power of the model. Future studies may take these parameters into account if they are available to better refine the effect of climatic factors on the occurrence of meningitis, and thus, build more robust predictive models.

It should also be noted that the meningitis surveillance data used in this study are data from suspected and unconfirmed cases of meningitis, and this could therefore have an effect on the quality of the models, especially the lack of control over the case definitions by some health workers due to a lack of training on Integrated Disease Surveillance and Response (IDSR) can lead them to diagnose false suspected cases of meningitis like other diseases.

For the specific case of the cities of Ouagadougou and Bobo-Dioulasso, which are not limited to a single district, the cumulation of data from all the districts of each of these two cities has been made because the climatic factors were calculated for each city and not for a given district. Elsewhere each city corresponded to a district.

In addition to this, it should be emphasized that the aggregate meningitis data does not give indications on the districts of origin of the patients but on the reporting districts, which can also impact the quality of the models when one knows that there are movements of people from one district to another. These different aspects may have influenced the quality of our models and the results we have obtained.

6-conclusion

The purpose of this study was to develop models to predict the meningitis weekly cases. We used an ARIMAX modeling approach that resulted in models without climate variables for some districts but mostly models using relative humidity and / or maximum temperature as exogenous variables for other cities (districts).

Results show that the decrease in relative humidity and the increase in temperatures are favorable conditions for the occurrence of meningitis epidemics in some cities in Burkina Faso. Strong correlations that are both negative (humidity) and positive (temperature) suggest that monitoring these parameters may contribute to the establishment of a warning system for meningitis epidemics at the local level.

Taking climate variables into account improves the power of the model to predict the number of meningitis cases. Our results therefore suggest that the predictive power increases when adding climate variables in the model.

This first study in Burkina Faso in the field of meningitis pathology hopes to stimulate other interests for further studies. To do this, meningitis surveillance must continue and even be strengthened, in order to better participate in the international effort to fight against the pathology.

7-declarations

Ethics approval and consent to participate

This study did not require ethics committee approval because no individual data was used. Only district level aggregated data was used. We obtained the authorization of the Ministry of Health for the use of meningitis data as well as the meteorology department authorization for the use of climate data.

Consent for publication

All authors consent for publication of the manuscript.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

Conflicts that the editors consider relevant to the content of the manuscript will be disclosed by all authors.

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Authors' contributions

IY and LO collected surveillance and laboratory data.

OO collected and cleaned climate data.

BB cleaned and merged surveillance and climate data.

SS and BB did the statistical analysis.

HT supervised data management and drafted the manuscript.

SS designed the methodology and developed the protocol.

AE, JM and RN assisted with funding acquisition.

All authors contributed in manuscript review.

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