UNDER PEER REVIEW

Design of a climate model for forecasting and alerting meningitis epidemics in Burkina Faso.

Abstract

In this paper we are interested in the impact of climatic factors on the meningitis epidemic. To do this, we analyze data from 1990 to 2020 on climatic factors and on the number of reported cases and deaths from meningitis. The aim is to propose a mathematical model of the meningitis epidemic according to these climatic factors.

AMS subject classification: 03C30 , 03C50.
Keywords: Meningitis epidemic, climatic factors, multilinear regression, climatic model.

I- Introduction

Sometimes called cerebrospinal fever or cerebrospinal meningitis, meningitis probably emerges as a new infection in Africa more than 100 years ago [5] . Started in Ghana in 1906 , an epidemic spread rapidly into the French colonies' territories. Since then, outbreaks of meningitis have become frequent in West Africa. The meningitis belt spans almost the entire width of the African continent from Senegal in the West all the way to Sudan and Ethiopia in the East. Several studies have shown that meningitis is a seasonal disease and depends on climatic factors such as temperature, humidity level, wind speed, rainfall and dust load. With mortality rate around 8% to 12% in Sub-Saharan Africa, meningitis is a public health problem and negatively impacts development efforts of sub-Saharan countries in Africa. In Burkina Faso particularly, meningitis causes epidemics almost every year and kills many people. In recent years, several authors have been interested in meningitis disease. In 2016, L. Dembélé et al. [3] studied the use of climatic factors for the surveillance of meningitis/ malaria occurrences in Bamako. Two years later in 2018, J. K. K. ASMOAH et al.[1] studied mathematical modelling of bacterial meningitis transmission dynamics with Control Measures. In 2018, K. DEMBELE et[2] studied Design and evaluation of a climate model for prediction and early warning of meningococcal meningitis epidemics in Mali. In his thesis in 2020, T. KOUTANGNI [8] studied modelling bacterial meningitis in the African meningitis belt for the evaluation of preventive vaccination. Recently in his thesis in 2023, P. M. NIANE [9] studied modeling of bacterial meningitis in the Environment-Climate-Society interface using a multi-agent approach: application case in Senegal. Modeling and simulation. Our work consists of designing a mathematical model that uses climatic factors (temperature, humidity level, wind speed, rainfall) as input data to predict meningitis epidemics in Burkina Faso. More precisely, we make use of the least squares method, to propose two models based on multiple linear regression, which give the number of declared cases and the number of deaths from meningitis. The rest of the paper is organized as follows. The second section is devoted to data analysis and processing. In the third section we are interested in modeling the impact of climatic factors on the evolution of meningitis. Using the alienor method, we discuss climatic conditions for zero cases of meningitis in the fourth section. In the fifth section we provide a summary of our outcomes, discuss their importance for public health policy and propose guidelines for future meningitis disease management efforts. Throughout the remainder of the paper, we will use patients, death, mortality, temperature, humidity, wind and rainfall instead of number of cases, number of deaths, temperature average, relative humidity rate average, wind speed average, and rainfall average.

II- Data analysis and processing

1- Data analysis

To carry out this work, we needed data on meningitis epidemics which we obtained from the epidemic surveillance service of Health Ministry and climatic data which we obtained from the meteorological services and the geographical institute of Burkina Faso. These data cover the period 1990 to 2020 and are summarized in the following table.

Year	$Number\ of\ cases$	$Number\ of\ death$	$Mortality$	$Humidity$	$Temperature$	$Wind$	$Rainfall$
1990	8360	150	2%	43, 15	28, 29	2, 3	601, 57
1991	8195	124	2%	49, 59	27, 55	2, 21	786, 69
1992	9837	140	1%	44, 87	27, 42	2, 37	649, 24
1993	34599	224	1%	45, 66	28, 2	2, 33	637, 11
1994	4598	321	7%	49, 71	27, 29	2, 27	870, 18
1995	11696	251	2%	49, 81	27, 52	2, 29	729, 43
1996	42967	436	10%	46, 34	28, 52	2, 25	673, 2
1997	22298	2460	11%	48, 31	27, 75	2, 24	733, 42
1998	5695	894	16%	47, 65	26, 82	2, 3	831.84
1999	3231	655	20%	48, 7	27, 61	2, 2	830, 33
2020	4085	841	21%	43, 76	27, 99	2, 29	665, 17
2021	13641	1937	14%	42, 74	28, 89	2, 31	644, 53
2002	14455	1743	12%	40, 69	28, 71	2, 37	534, 29
2003	8675	1363	16%	48, 77	28, 35	2, 15	845, 1
2004	6386	1149	18%	46, 3	28, 25	2.21	647.49
2005	3625	751	21%	47.02	28, 49	2.23	703.33
2006	19162	1677	9%	46, 33	28, 08	2, 26	720, 8
2007	21188	1973	9%	48, 51	27, 67	2, 33	754, 97
2008	10425	1114	11%	46.73	27, 45	2, 33	793, 7
2009	4878	693	14%	50, 78	27, 94	2, 16	808, 87
2010	6837	989	14%	53, 54	27, 7	2, 15	925, 92
2011	3984	649	16%	51, 35	27, 52	2, 17	693, 13
2012	7025	739	11%	53, 22	27, 25	2, 25	931, 84
2013	2984	367	12%	51, 36	27, 69	2, 18	815, 37
2014	3633	397	11%	4, .36	28, 01	2, 2	792, 74
2015	3053	288	9%	49, 57	27, 36	2, 25	904, 08
2016	2761	290	11%	50, 87	27, 77	2, 21	870, 46
2017	2707	209	8%	47, 82	27, 99	2, 17	772, 71
2018	2514	171	7%	51, 91	27, 65	2, 19	894, 67
2019	1865	130	7%	51, 37	27, 67	2, 17	902, 43
2020	1845	126	7%	53, 26	27, 45	2, 27	953, 8

Table 1: data on the number of cases and deaths of meningitis and some climatic factors

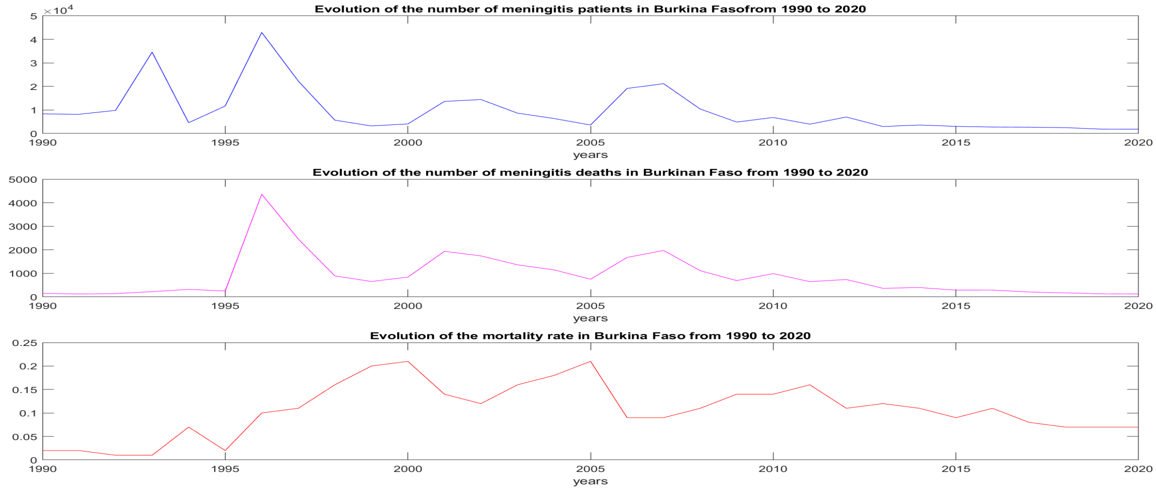

Figure 1: Evolution of meningitis disease in Burkina Faso from 1990 to 2020.

The spikes are mainly observed over the period 1993 – 1997. During these years, meningitis epidemics caused a very large number of illnesses and deaths. This led the Ministry of Health to put in place policies to combat this disease through vaccination campaigns and patient care. From 2006 we see that the mortality rate, the number of cases and the number of death are globally decreasing. This proves that control policies produce results and that they must be maintained and strengthened. To clearly observe the strength of the link between variables (Number of cases, Number of death, Mortality, Temperature, Humidity, Wind, Rainfall), we construct the graph of Pearson correlation matrix. To measure the correlation between different variables. We calculate Pearson's linear coefficient. We denote by $var1$, $var2$, $var3$, $var4$, $var5$ and $var6$ the vectors representing respectively the number of cases, the number of deaths, the temperature, the relative humidity rate, the wind speed and the rainfall.

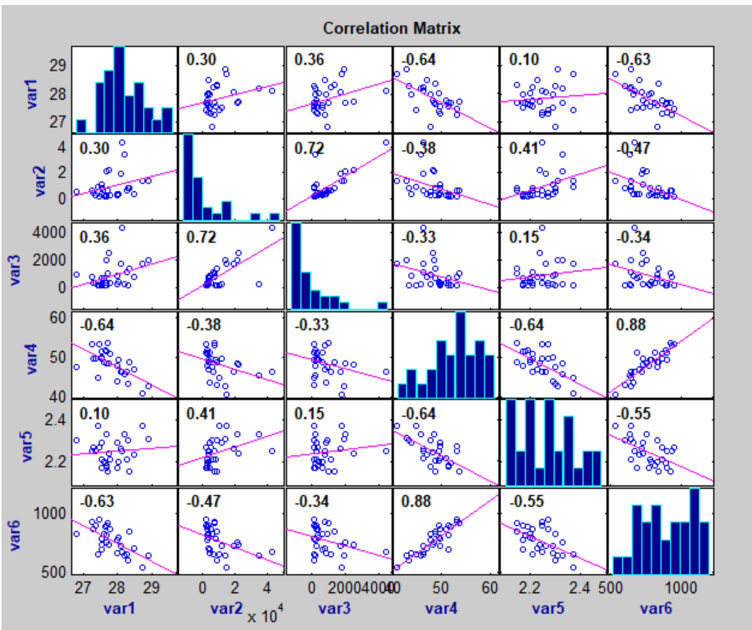

Figure 2: The Pearson's correlation matrix graph.

In the correlation matrix we note a linear adjustment between the variables taken two by two. This means that there exists a linear interdependence between the variables. This leads us to say that the number of cases of meningitis depend linearly on climatic factors. As well as the number of deaths due to meningitis. This justifies the choice of multilinear regression model to describe the number of cases and the number of deaths from meningitis as a function of these climatic factors. In the sequel the climatic factors temperature, relative humidity rate, wind speed and rainfall correspond respectively to the vectors x_1, x_2, x_3 and x_4.

2- Data normalization: Method Min-Max Scaling

The data on environmental factors collected are not on the same scale and do not have the same units. This can influence the multi-linear model that we want to build. To minimize the impact of certain factors on the model due to their large or small values, we chose to normalize the data. This normalization by the Min-Max Scaling method will allow us to have all values between 0 and 1 while retaining the linear relationship between the original variables. The determination of the new data is obtained using the formula:

$$X_{new} = \frac{X - min(X)}{max(X) - min(X)}.[6] \tag{1}$$

With:
X_{new}: The new value from the normalalized results;
X : Old value;
$max(X)$: Maximum value in the dataset;
$min(X)$: Minimum value in the dataset.

By applying (1), we obtain the normalized data given by the matrix X, y_1 and y_2.

$X =$

Number of observations	Temperature	Relative humidity rate	Wind speed	Rainfall
1	0, 7101	0, 1914	0, 6818	0, 1603
1	0, 3526	0, 6926	0, 2727	0, 6016
1	0, 2898	0, 3252	1	0, 2740
1	0, 6666	0, 3867	0, 8181	0, 2450
1	0, 2270	0, 7019	0, 5454	0, 8006
1	0, 3381	0, 7097	0, 6363	0, 4651
1	0, 8212	0, 4356	0, 4545	0, 3311
1	0, 4492	0, 5929	0, 4090	0, 4746
1	0	0, 5416	0, 6818	0, 7092
1	0, 3816	0, 6233	0, 2272	0, 7056
1	0, 5652	0, 2389	0, 6363	0, 3119
1	1	0, 1595	0, 7272	0, 2627
1	0, 91301	0	1	0
1	0, 7391	0, 6287	0	0, 7408
1	0, 6908	0, 4365	0, 2727	0, 2698
1	0, 8067	0, 4926	0, 3636	0, 4029
1	0, 6086	0, 4389	0, 500	0, 4445
1	0, 4106	0, 6085	0, 8181	0, 5260
1	0, 3043	0, 4700	0, 8181	0, 6183
1	0, 5410	0, 7852	0, 0445	0, 6545
1	0, 4251	1	0	0, 9335
1	0, 3381	0, 8253	0, 0909	0, 3786
1	0, 2077	0, 9750	0, 4545	0, 9476
1	0, 4202	0, 8303	0, 1363	0, 6700
1	0, 5748	0, 6747	0, 2272	0, 6160
1	0, 2608	0, 6910	0, 4545	0, 8814
1	0, 4589	0, 7922	0, 2727	0, 8013
1	0, 5652	0, 5548	0, 0909	0, 5683
1	0, 4009	0, 8731	0, 1818	0, 8590
1	0, 4106	0, 8311	0, 0909	0, 8775
1	0, 3043	0, 9782	0, 5454	1

; $y_1 =$

Number of cases
0, 1584
0, 1544
0, 1943
0, 7965
0, 0669
0, 2395
1
0, 4973
0, 0936
0, 0337
0, 0544
0, 2868
0, 3066
0, 1660
0, 1104
0, 0432
0, 4211
0, 4703
0, 2086
0, 0737
0, 1213
0, 0520
0, 1259
0, 0276
0, 0434
0, 0293
0, 0222
0, 0209
0, 0162
0.0004
0

and $y_2 =$

Number of deaths
0, 0111
0
0.0068
0, 0428
0, 0843
0, 0543
0, 1335
1
0, 3296
0, 2273
0, 3069
0, 7761
0, 6930
0, 5303
0, 4387
0, 2684
0, 6648
0, 7915
0, 4238
0, 2435
0, 3702
0, 2247
0, 2632
0, 1040
0, 1168
0, 0702
0, 0710
0, 0363
0, 0201
0, 0025
0.0008

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III. Climatic model of the meningitis prediction.

1-Model description

The equation of multi linear regression is :

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \epsilon. \tag{2}$$

where :

- y is the dependent variable,

- $x_1, \cdots, x_n$ are the independent variables,
- β_0, β_1, $\cdots$, β_n are coefficients to be determined ,
- ϵ is the error

In our case, we have two dependent variables which are the number of cases y_1 and number of deaths y_2. The independent variables are temperature, humidity, wind and rainfall denoted by x_1, x_2, x_3 and x_4 respectively. The coefficients β_0,β_1, β_2, β_3 and β_4 are chosen to minimize the square of the error ϵ:

$$min \sum \epsilon^2 \Leftrightarrow \frac{\partial}{\partial \beta_i}\left[min \sum \epsilon^2\right] = 0. \tag{3}$$

2-Multi linear climatic model of meningitis epidemics.

Now, with our climatic factors, the number of cases is given by:

$$y_1 = \beta_{1.0} + \beta_{1.1}x_1 + \beta_{1.2}x_2 + \beta_{1.3}x_3 + \beta_{1.4}x_4 + \epsilon_1. \tag{4}$$

and that of deaths by:

$$y_2 = \beta_{2.0} + \beta_{2.1}x_1 + \beta_{2.2}x_2 + \beta_{2.3}x_3 + \beta_{2.4}x_4 + \epsilon_2. \tag{5}$$

The matrix expression of equations (3) and (4) is:

$$Y_i = X\beta_i + \epsilon_i; \quad i = \overline{1,2} \tag{6}$$

with,

$$Y_i = \begin{pmatrix} y_i^1 \\ . \\ . \\ . \\ y_i^p \end{pmatrix}; X = \begin{pmatrix} 1 & x_1^1 & x_2^1 & x_3^1 & x_4^1 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ 1 & x_1^p & x_2^p & x_3^p & x_4^p \end{pmatrix}; \quad \beta_i = \begin{pmatrix} \beta_{i.0} \\ \beta_{i.1} \\ \beta_{i.2} \\ \beta_{i.3} \\ \beta_{i.4} \end{pmatrix}; \quad \epsilon_i = \begin{pmatrix} \epsilon_i^1 \\ . \\ . \\ . \\ \epsilon_i^p \end{pmatrix}.$$

So

$$\begin{pmatrix} y_i^1 \\ . \\ . \\ . \\ y_i^p \end{pmatrix} = \begin{pmatrix} 1 & x_1^1 & x_2^1 & x_3^1 & x_4^1 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ 1 & x_1^p & x_2^p & x_3^p & x_4^p \end{pmatrix} . \begin{pmatrix} \beta_{i.0} \\ \beta_{i.1} \\ \beta_{i.2} \\ \beta_{i.3} \\ \beta_{i.4} \end{pmatrix} + \begin{pmatrix} \epsilon_i^1 \\ . \\ . \\ . \\ \epsilon_i^p \end{pmatrix}; \quad i = \overline{1,2}$$

where, for $1 \leq j \leq p$; $i = \overline{1,2}$.

- y_i^j represents the $j-th$ observed value of y_i;
- x_1^j represents the $j-th$ observed value of temperature;
- x_2^j represents the $j-th$ observed value of humidity;
- x_3^j represents the $j-th$ observed value of wind;
- x_4^j represents the $j-th$ observed value of rainfall;

- ϵ_i^j represents the error.

Using equations (3) and (6) we prove that the estimator $\widehat{\beta_i}$ of the coefficients is given by:

$$\widehat{\beta_i} = (X^{'}.X)^{-1}.X^{'}.Y_i; \quad i = \overline{1,2}. \tag{7}$$

where $X^{'}$ is the transposed matrix of X and X^{-1} the inverse of matrix X.

After some calculations we abstain $det(X'.X) = 26,007 \neq 0$ therefore matrix $(X'.X)$ is invertible and we have:

$$(X'.X) = \begin{pmatrix} 31 & 15,1812 & 18,4885 & 13,4524 & 17,531 \\ 15,1821 & 8,9611 & 8,0268 & 6,6770 & 7,4737 \\ 18,4885 & 8,0268 & 12,9071 & 6,5826 & 12,15 \\ 13,4524 & 6,6770 & 6,5826 & 8,4450 & 6,4144 \\ 17,5317 & 7,4737 & 12,15 & 6,4144 & 11,9417 \end{pmatrix}; (X'.X)^{-1} = \begin{pmatrix} 3,2286 & -2,0304 & -2,1257 & -1,5007 & -0,5003 \\ -2,0304 & 1,6641 & 1,0575 & 0,7407 & 0,4656 \\ -2,1257 & 1,0575 & 3,4377 & 1,1139 & -1,6371 \\ -1,5007 & 0,7407 & 1,1139 & 0,0043 & 0,0669 \\ -0,5003 & 0,4656 & -1,6371 & 0,0669 & 2,1566 \end{pmatrix}$$

It follows that,

$$\beta_{1.i} = (X'.X)^{-1}.X'.y_1 = \begin{pmatrix} -0,4045 \\ 0,4954 \\ 0,6327 \\ 0,4703 \\ -0,409 \end{pmatrix} \quad \text{and} \quad \beta_{2.i} = (X'.X)^{-1}.X'.y_2 = \begin{pmatrix} 0,096 \\ 0,3464 \\ -0,2001 \\ 0,1294 \\ 0,1157 \end{pmatrix}$$

From the general form of multi linear model we deduce that the number of cases and the number of deaths are respectively.

$$\boxed{\widehat{y_1} = -0,4045 + 0,4954x_1 + 0,6327x_2 + 0,4703x_3 - 0,409x_4}$$

and

$$\boxed{\widehat{y_2} = 0,096 + 0,3464x_1 - 0,2001x_2 + 0,1294x_3 + 0,1157x_4}.$$

An analysis of mathematical models shows that the climatic factors studied have more impact on the number of cases than on the number of menigitis deaths. This is materialized by the fact that for each factor taken individually, its coefficient (in absolute value) in the number of cases model is greater than in the number of deaths model. According to the model of number of cases, the climatic factor rainfall has negative coefficient $(-0,4090)$. Which shows that rainfall contributes to slowing the spread of meningitis. However, temperature, humidity and wind are the climatic factors that favor meningitis disease because their impacts in the number of cases model are represented by positive coefficients $(0,4954;\ 0,6327;$ and $0,4703$ respectively). This last observation reinforces the hypothesis according to which these climatic factors are the main vectors for the spread of meningococcus within the population. When the weather is favorable, the meningococcus already present in the throat or nasal passages multiplies more easily and enters the bloodstream through the small tears inside the nasal passages. Also meningococcus is transported more easily from a sick person to a healthy person thanks to the movement of the wind following coughing or spitting.

In order to have an overall idea of the quality of the multi-linear adjustment we estimate R^2 the determination coefficient which is the square of the correlation coefficient R. With the data we obtain $R^2 = 0,7382$ and $R^2 = 0,5568$ for the number of cases and the number of death respectively.

For the number of meningitis cases, we have $0,7 < R_1^2 < 0,9$. Which means that the fit is pretty good. Which corroborates that meningitis disease is indeed a seasonal disease. For the number of deaths, we have $0,5 < R_2^2 < 0,7$. Which means that the fit is acceptable. So, we can conclude that these climatic factors are determining in the spread of meningitis in Burkina Faso. Indeed, when a individual is affected by meningitis, climatic factors are not decisive for his recovery or death but rather the quality of medical care.

3. Climatic conditions for zero case of meningitis

- Alienor's Method.

The Alienor method is a method based on approaching the space $\mathbb{R}^n$ by $\mathbb{R}$ using reductive transformations. Method proposed by Yves Cherruault and Arthur Guillez, it consists of reducing an optimization problem with several variables to an optimization problem with one variable. the first reductive transformation uses the Archimedes spiral. This first step consists of a transformation into polar coordinates. [7, 10]

$$\begin{cases} x = rcos(\theta) = h_1(\theta) \\ y = rsin(\theta) = h_2(\theta) \end{cases}$$

The two parameters r and θ are connected by the Archimedes spiral

$$r = a\theta \ . \ [7,\ 10]$$

$$tels \quad que \quad \begin{cases} a \geq 0 \\ a \quad fix\acute{e} \quad tend \quad vers \quad z\acute{e}ro \\ r = \sqrt{x^2 + y^2} \end{cases}$$

For n variables, the generalization is done by connecting the variables two by two by the spiral of angle θ_i, θ_i a real.

$$x_i = h_i(\theta), i = 1, \cdots, n.$$

In our model, we have four variables x_i, $i = 1, \cdots, 4$. We connect our four variables by the following graph:

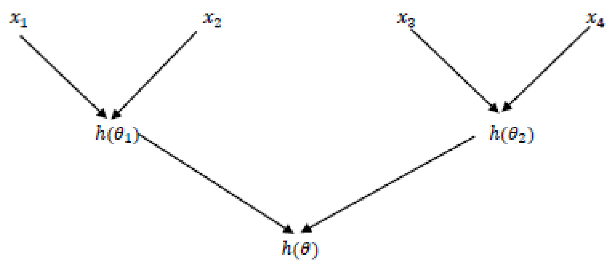

Figure 3: Alienor method for four variables

Setting,

$$x_1 = a\theta_1 cos(\theta_1),\ x_2 = a\theta_1 sin(\theta_1)\ ,\ x_3 = a\theta_2 cos(\theta_2) \text{ and } x_4 = a\theta_2 sin(\theta_2)$$

A follows that,

$$\theta_1 = a\theta cos(\theta) \text{ et } \theta_2 = a\theta sin(\theta).$$

By successive substitution we obtain:

$$\begin{cases} x_1 = h_1(\theta) = a^2\theta cos\theta cos(a\theta cos\theta) \\ x_2 = h_2(\theta) = a^2\theta cos\theta sin(a\theta cos\theta) \\ x_3 = h_3(\theta) = a^2\theta sin\theta cos(a\theta sin\theta) \\ x_4 = h_4(\theta) = a^2\theta sin\theta sin(a\theta sin\theta) \end{cases},$$

We then obtain a function $h(\theta) = (h_1(\theta), h_1(\theta), h_3(\theta), h_4(\theta))$. This new function obtained is equivalent to the function $f(x_1, x_2, x_3, x_4)$. The graph of $h(\theta)$ is given by:

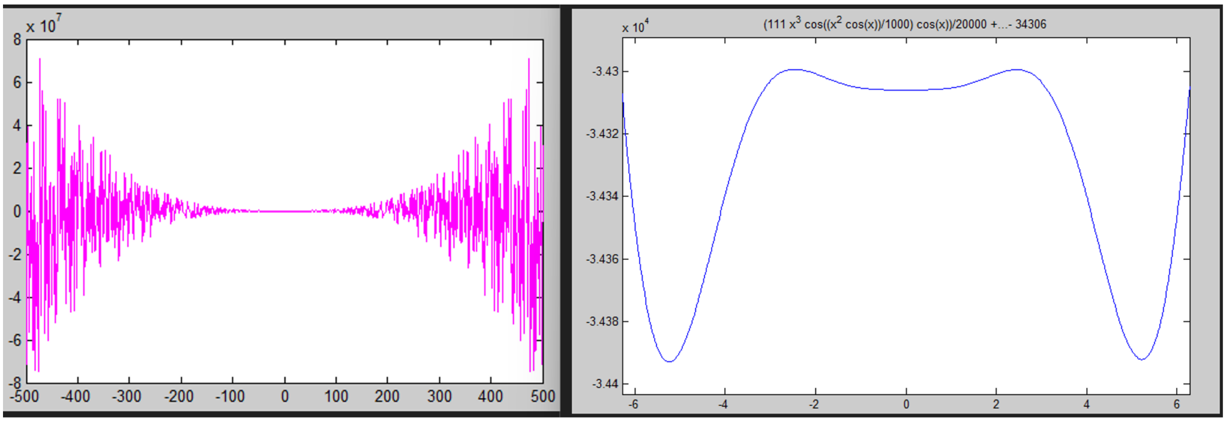

Figure 4: The graph of h and visualization of the local minima of the function of h.

We notice that the graph seen in the two-dimensional plane has oscillations better visible than in the hyperplane. The variables x_i, $i = \overline{1,4}$ being continuous trigonometric functions, the oscillations are therefore easily justified on the graph. We notice that a large part of the graph translated by its central part is that of a linear function. This linearity reflects the multi-linearity between the number of meningitis cases and the climatic factors. This corroborates the curve of the previous f function. The oscillations show a strong correlation and dependence between all climatic factors and the number of cases of meningitis reported over the last thirty years in Burkina Faso.
We are looking for the value of θ^* which minimizes $h(\theta)$:

$$h(\theta^*) = Glob.min \quad h(\theta). \; [7]$$

In our case, we are looking for the smallest positive minimum of $h(\theta^*)$ given the specific nature of our model which reflects the number of people declared with meningitis. It follows that a negative number of $h(\theta^*)$ for a value of θ, $(\theta \in \mathbb{R})$ is not significant at search but rather a zero number would be more reasonable. That is to say we will search for θ^* such that $h(\theta^*) = 0$.
Thus we visualize the set of minima of the function $\theta \mapsto h(\theta)$.
According to graph (right figure 4), h achieves its minimum at point $\theta = -5,2404$ and this is equal to $h(\theta) = -3,4393.10^4$.

Since we are looking for the positive minimum to translate the reality of our model, then the minimum found does not correspond to what we are looking for because it is negative $h(\theta) < 0$.
Consequently by programming on Matlab software, we search for the value of θ^* such that,

$$h(\theta^*) = 0.$$

We obtain:

$$\underline{\theta^* = -226,972.}$$

We deduce values of the variables x_1^*, x_2^*, x_3^* and x_4^* in which $h(\theta)$ reaches its minimum.

$$\begin{cases} x_1^* = h_1(\theta^*) = 13,223 \\ x_2^* = h_2(\theta^*) = 3,774 \\ x_3^* = h_3(\theta^*) = 0,9432 \\ x_4^* = h_4(\theta^*) = 0,475 \end{cases}$$

The function h reaches its minimum at point $(x_1^*, x_2^*, x_3^*, x_4^*)$. Therefore, without any preventive fight against meningitis, the minimum number of reported cases of meningitis is reaches at point $(x_1^*, x_2^*, x_3^*, x_4^*)$. These climatic conditions are almost impossible to achieve in Burkina Faso. It is necessary to put in place an effective meningitis prevention policy if we want to reduce the number of cases.

IV. Summary, discussion and conclusion

In this paper a mathematical multi linear models has been developed to predict the number of cases and the number of deaths due to meningitis. A mathematical analysis shows the effectiveness of these models. We show that the climatic conditions for zero cases of meningitis are practically impossible. So, to eradicate meningitis we must put in place effective prevention and care policies for patients .

The coefficients

$$\frac{\partial \widehat{y}_1}{\partial x_i} = \beta_{1.i} \text{ et } \frac{\partial \widehat{y}_2}{\partial x_i} = \beta_{2.i},$$

represent the impact of the climatic factors x_i on the number of cases and the number of deaths respectively. When the coefficient is positive, this means that the corresponding variable promotes the disease. On the other hand, when the coefficient is negative, this means that the corresponding variable slows down the progression of the disease. From coefficients we can conclude that climatic factors such as temperature, humidity and wind favor the spread of the meningitis disease and therefore contribute to increase the number of cases. These climatic factors as described correspond to the period between November and April. It is also during this period that meningitis appears in Burkina Faso and more generally in the African Meningitis Belt.

The population should be made aware of important role played temperature, humidity and wind in the transmission of meningitis. For example, encourage the population to wear a mask (nose mask) and to use shea butter in their nostrils.

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