

Analysis of the Rainfall Series in Benin from 1952 to 2007 by the Functional Data Method

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Abstract

This paper explores the use of functional data analysis to study the rainfall regime in Benin, utilizing daily data from six synoptic stations. It identifies three distinct periods: a wet phase (1952-1970), a dry phase (1971-1990), and a recovery phase (from 1991). The findings also reveal a rainfall distribution characterized by a decreasing gradient in the south and an increasing gradient in the north.

Keywords

Rainfall, Functional Data, Synoptic Stations, Benin

1. Introduction

The rainfall regime in West Africa has undergone changes since the early 1970s [1] [2]. These changes in rainfall patterns have been manifested since 1966 mainly in Senegal, Guinea-Bissau, Guinea, Mali, Burkina Faso and northern Benin [1]. The period 1950-1968 was qualified as a wet period while the period 1969-1970 is considered as a deficit period [3].

Several research have been carried out in Benin to better understand the rainfall regime. For example, a study of the agricultural region of Ina (North Benin) revealed that the monsoon began to withdraw early from 1970 [4]. Farmers noticed that the rains decrease and become irregular causing an unusual deviation of the seasons and changes in temperature and wind speed [5]. A study of January rainfall in Bohicon, Cotonou, Kandi, Natitingou, Parakou and Savè highlighted two categories of cities: The first, consisting of Bohicon, Cotonou and Savè, is characterized by substantial rainfall due to the presence of the sea, lakes and lagoons while the second (Kandi, Natitingou and Parakou) is distinguished by the low

rainfall recorded since this month coincides with the period of harmattan [6]. In Benin, we have a spatio-temporal variation in rainfall patterns in the periphery of the Park W transboundary biosphere reserve over the period 1965-2010 [7]. All the above research used classical laws, it appears clearly that the climate in Benin has experienced many variations since the 1950s. In addition, rainfall data have been widely used to study the climate.

The present work, whose main objective is to resume the various existing works by using the new methods of statistics that is the Functional Data Analysis (FDA), will look at the study environment, data and methods used for data analysis in Section 2. The results obtained will be presented in Section 3 followed by the discussion in Section 4 and Section 5 will be devoted to the conclusion.

2. Materials and Methods

2.1. Study Area

This study was conducted in Benin through our six (6) synoptic stations located in Kandi, Natitingou, Parakou, Savè, Bohicon and Cotonou. Located in the inter-tropical zone between parallels $6^{\circ}10'$ and $12^{\circ}25'$ North latitude and $0^{\circ}45'$ and $3^{\circ}55'$ East longitude, Benin is a West African country bordered by Burkina Faso and Niger to the North, the Atlantic Ocean to the South, Nigeria to the East and Togo to the West. **Figure 1** shows the geographical location of each synoptic station.

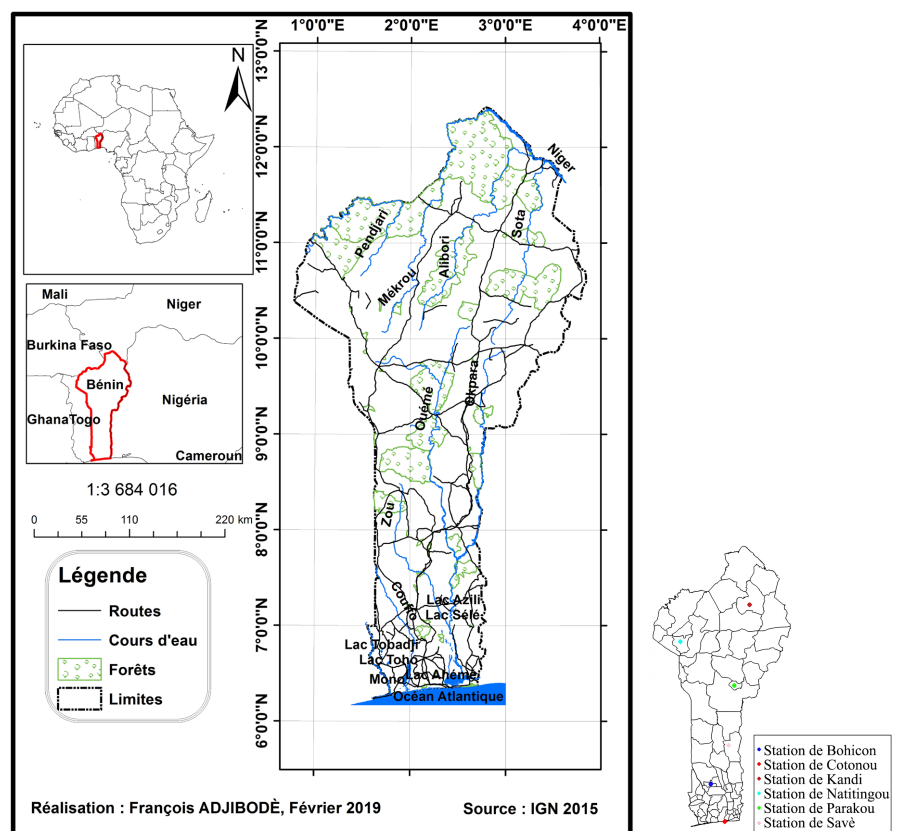


Figure 1. Map of Benin with its different rivers and the six synoptic stations.

Table 1 shows that the stations of Savè, Parakou, Natitingou and Kandi and that of Cotonou airport are older than that of Bohicon.

Table 1. Characteristics of the synoptic stations studied [8].

	Station	Latitude (North)	Longitude (East)	Altitude (m)	Date opened
1	Cotonou aéroport	06°21	02°26	005	1922
2	Bohicon	07°10	02°04	166	1940
3	Savè	07°59	02°26	198	1921
4	Parakou	09°21	02°36	392	1921
5	Natitingou	10°19	01°23	460	1921
6	Kandi	11°08	02°56	290	1921

2.2. Data Used

The daily precipitation data used are measurements taken at the six (6) synoptic stations. They are collected by Météo Benin in Cotonou.

2.3. Functional Data Method

In this section, we will provide a very short summary of the functional PCA (fpca).

Let $X_{(s,t)}$ be a spatial point process that is observed on $W = D \otimes T$, where $D \subset \mathbb{R}^2$ is a spatial domain and T is a temporal domain.

For a fixed point s , $X_{(s,t)}$ of L^2 (set of second-order processes) can be considered as a Gaussian process T , and therefore by the Karhunen-Loève standard expansion. For more details; see [9] [10]

$$X_{(s,t)} = \mu(s) + \sum_{j=1}^p \xi_j(s) \rho_j(t), \tag{1}$$

where $\mu(s) = \mathbf{E}\{X_{(s,t)}\} = \frac{1}{T} \sum_{t=1}^T X_{(t,s)}$, $\rho_j(\cdot)$ are orthonormal functions, and $\xi_j(\cdot)$ are independent Gaussian random vectors [11]. We assume that $\xi_j(s)$ is a random vector of mean zero and variance λ_j and whose covariance function is given,

$$C_j(s_1, s_2) = cov(\xi_j(s_1), \xi_j(s_2)) \text{ for } j = 1, 2, \dots, p.$$

The functions $\rho_j(\cdot)$ are called the proper functions of the X process. We suppose that $\rho_j(\cdot)$ are kept in descending order of λ_j 's $\lambda_1 > \lambda_2 > \dots > \lambda_p > 0$. The number of principal components p can be infinite in theory, but is often considered finite for practical considerations after having set the percentage of variance to be explained [10]. Smoothing is an essential step for the fpca.

Suppose that the functional data $Y(t_i)$ with $i \in \{1, \dots, n\}$ are obtained according to the model

$$Y(t_i) = X(t_i) + \varepsilon(t_i) \tag{2}$$

where $X(t_i)$ and $\varepsilon(t_i)$, representing the original signal and the error respectively.

We use the 2 to do the smoothing [12]. In the present work, we have chosen for convenience reasons, the approach that uses the Nadaraya-Watson estimation defined by:

$$\hat{x}(t_j) = \sum_{i=1}^n S_j(t_i) y(t_i) \quad (3)$$

with $S_j(t_i)$ [13] the weighting coefficient defined by:

$$S_j(t_i) = \frac{K\left(\frac{t_i - t_j}{h}\right)}{\sum_{k=1}^n K\left(\frac{t_k - t_j}{h}\right)} \quad (4)$$

with h the smoothing window, $n = 60$, $1 \leq i, j \leq n$ and K a kernel.

We have used the Gaussian kernel because it is more adapted to Nadaraya-Watson's estimator:

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right), \quad x \in \mathbb{R}. \quad (5)$$

and used the function `min.np()` of the package `fda.usc` [13] of the software R [14] to perform the data smoothing.

2.4. Methodology

We first performed multivariate analysis (PCA) just to understand the structure of the data and then analyzed the variability of the monthly mean rainfall by synoptic station. This last analysis was carried out in two steps, namely: 1) the evolution of the series of monthly mean rainfall and 2) the classification of the months according to the intensity of rainfall.

3. Results

The results below were obtained from daily average rainfall at Benin's six synoptic stations.

3.1. Multivariate Analysis

Referring to [15] (Table 2 and Figure 2), it is very difficult here to reduce the number of principal components since the eigenvalues of the four (04) eigenvectors are all close to 1. It is therefore deduced that this method reveals the limits of classical exploitation and analysis techniques, and imposes the development and then the implementation of new tools, adapted to this profusion of data.

Table 2. Table of explained variances.

	Shareholders' Equity	Percentage of Variance	Cumulative Percentage of Variance
comp 1	1.93	32.12	32.12

Continued

comp 2	1.20	19.94	52.07
comp 3	0.81	13.55	65.61
comp 4	0.73	12.22	77.83
comp 5	0.67	11.13	88.96
comp 6	0.66	11.04	100.00

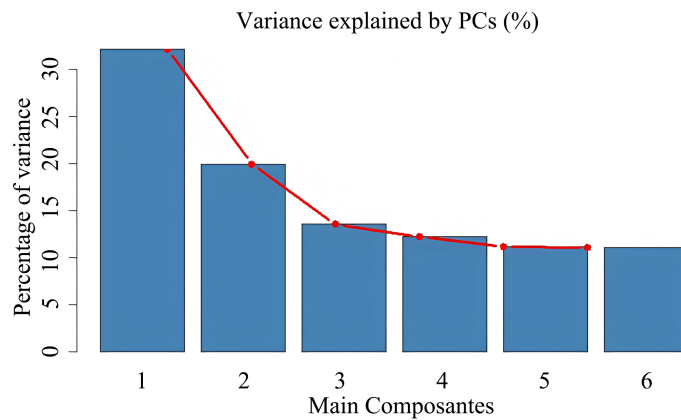


Figure 2. Strip diagram of the main components.

Nevertheless, we take the liberty of drawing the correlation circle by projecting the data from the synoptic stations on the first two main components. The analysis of Figure 3 allows us to say that by just deciding to explain 52.07% of the total variance, we have two large groups of synoptic stations that govern the rainfall situation in Benin namely the group (Cotonou, Bohicon and Savè) and the group (Parakou, Kandi and Natitingou). Within each group, there are two subgroups, the first having Cotonou and Bohicon on one side and Savè on the other. Similarly, Kandi and Natitingou form a subgroup associated with Parakou with a similarity between the Savè and Parakou stations, *i.e.*, the two groups are in the same direction on the first principal component and virtually equal in absolute value on the second principal component. To better understand this underlying information, we will analyze the data using the functional data method.

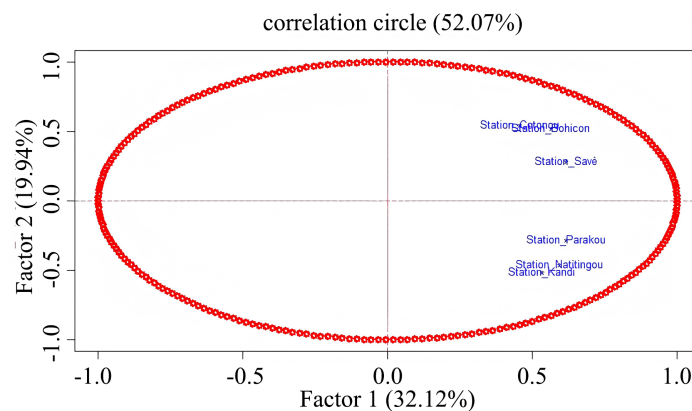


Figure 3. Correlation circle between mean daily precipitation for synoptic stations.

3.2. Functional Data Analysis

3.2.1. Parakou Synoptic Station

Figure 4 shows the average monthly rainfall series for the synoptic station of Parakou. Analysis of this graph reveals that rainfall in Parakou has varied from one year to the next since 1952 to 2007 and each month has a non-zero humidity, which confirms the work of [6]. It is marked by a high frequency of rainfall especially during the months of June, July, August and September and medium frequency during the months of April, May and October. These months represent the wettest months. The other months of the year are marked by low frequency rainfall.

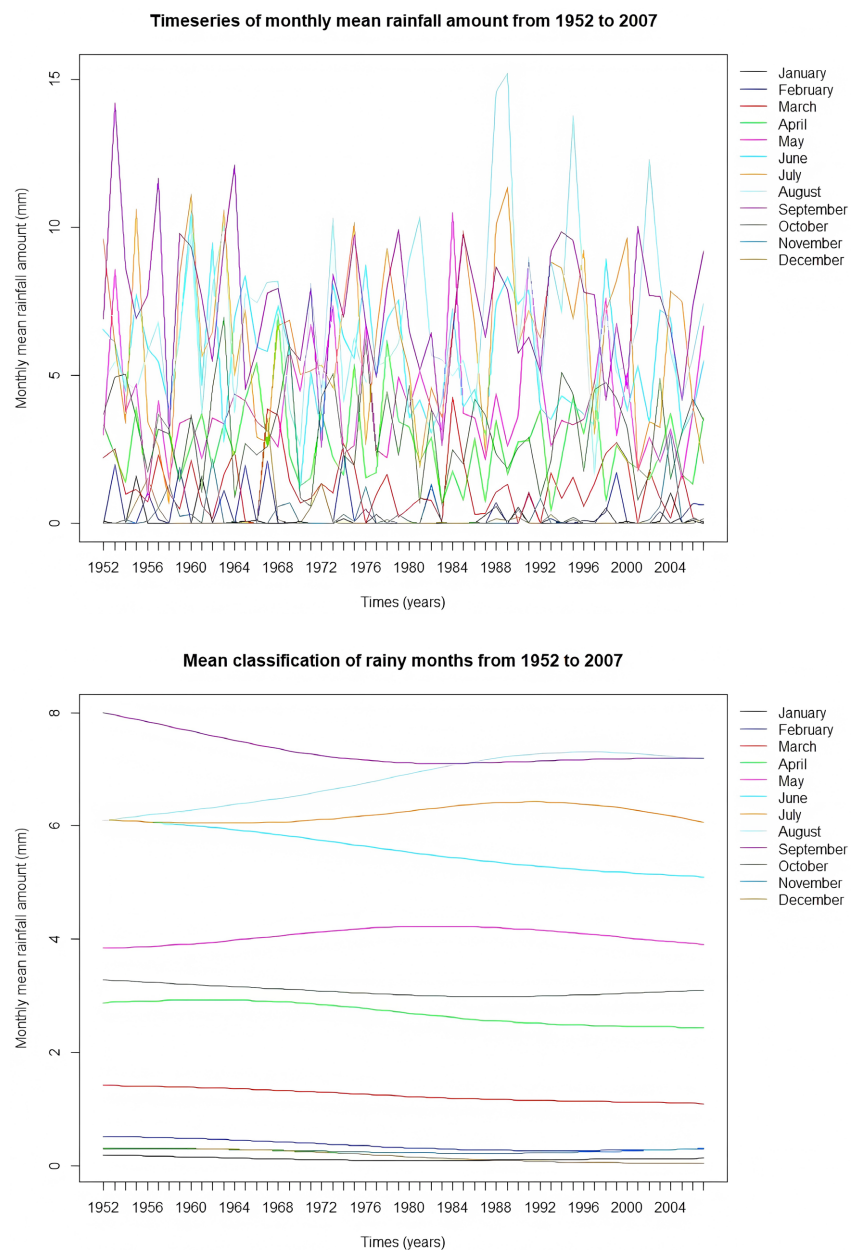


Figure 4. Average monthly rainfall series and classification of rainy months in Parakou.

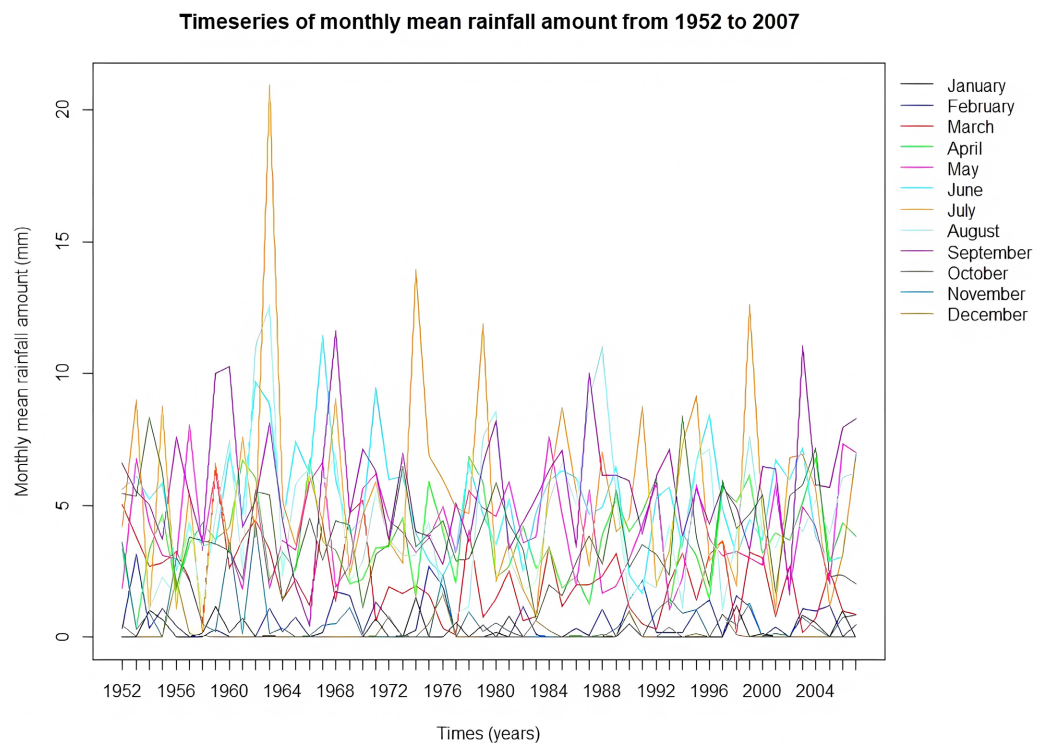
Figure 4 shows a ranking of the wettest and least wet months. It can be seen that the wettest month in Parakou was September until the end of 1979, followed by August and July and June. This indicates that rainfall intensity increases from June to September, and that precipitation is heaviest during these months. The months with average rainfall are May, October, April and March in that order. The months with low rainfall are November, December, February and January. Despite this very long rainy period, Parakou is marked by a dry period from December to February. This last period coincides well with the harmattan period in the north and the dry season.

Furthermore, examination of **Figure 4** reveals that the evolution of average monthly rainfall is marked by three periods:

- 1) The wet period covering the years 1952 to 1970;
- 2) Dry period from 1971 to 1990;
- 3) Rainfall recovery beginning in 1991.

3.2.2. Savè Synoptic Station

Figure 5 shows the curves of the monthly rainfall series for the synoptic station of Savè. Analysis of this graph reveals that average monthly rainfall in Savè varies from one year to the next and from one month to the next from 1952 to 2007. The area covered by this station is characterized by seven (07) months of heavy rainfall that are difficult to characterize (April, May, June, July, August, September, October) and one month of average rainfall (March) and four (04) months of low rainfall (November, December, January, February) of which only January is less rainy.



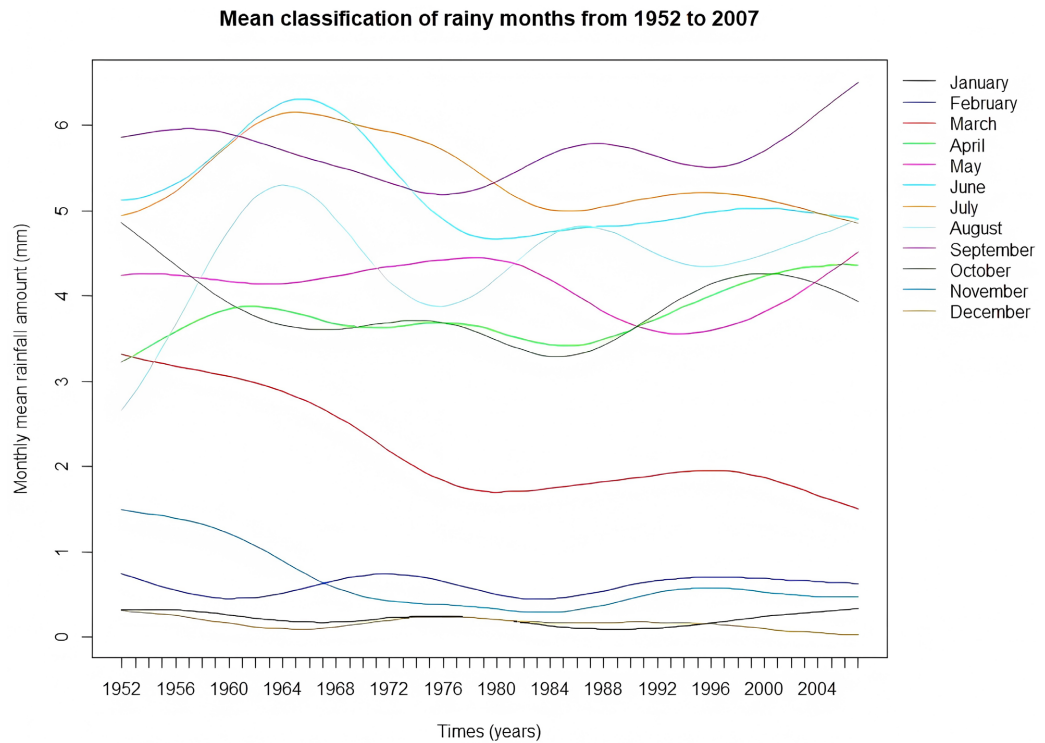


Figure 5. Average monthly rainfall series and classification of rainy months in Savè.

It allows to say that the synoptic station of Savè is watered all year long and with a high quantity of water.

3.2.3. Cotonou Synoptic Station

Figure 6 shows the average monthly rainfall series for the Cotonou synoptic station. Its analysis shows that from 1952 to 2007, the average monthly rainfall of Cotonou varies from one year to another. We note that the Cotonou synoptic station is characterized by three types of rainfall: the highest in June with a large amount of precipitation, the average in the months of April, May, July, September and October and the lowest in the months of March, August, November, December, January and February. The analysis of the two figures shows us that all the months are watered, even January is characterised by a few drops of precipitation, which allows us to say that the ground covered by this synoptic station is permanently wet. It can be seen that in general it rains every month in Cotonou with variable rainfall intensity. This could justify the cases of flooding recorded during this period.

3.2.4. Bohicon Synoptic Station

Figure 7 allows us to see the classification and evolution of rainy months in Bohicon from 1952 to 2007. We see that it rains in the area every month with a variable amount of water. From this graph, we note that since 2007 and until today the area of Bohicon is characterized by (03) three major rainy periods during the year: The first, characterized by a large amount of water is observed during the months

of April, May, June, July, August, September and October; the second, during which the area receives an average amount of water is obtained during the month of March, the last observed during the months of November, December, January and February is the weakest in the area with a significant rainfall. This analysis allows us to say that the area covered by the synoptic station of Bohicon is a permanently watered area even during the dry season.

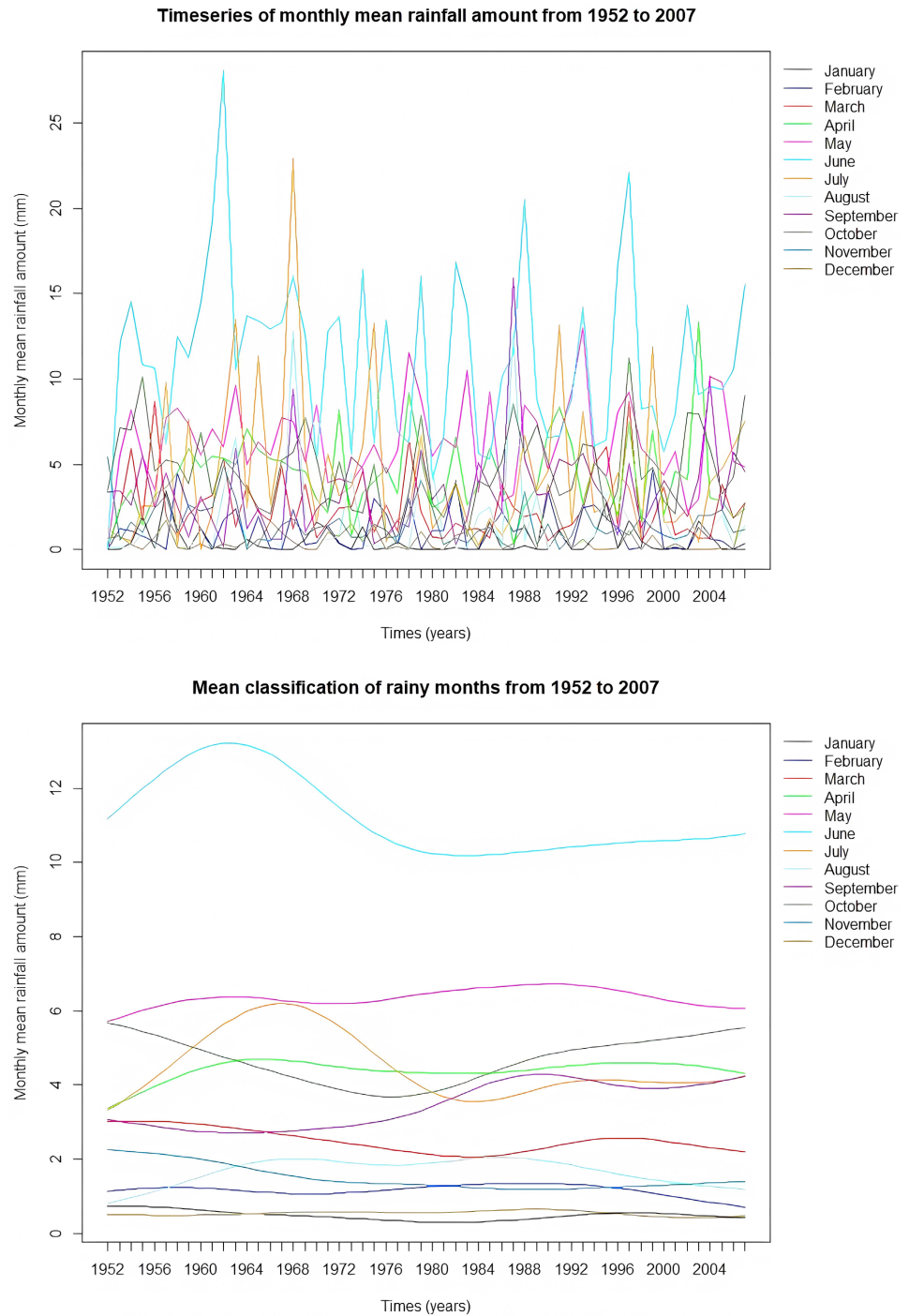


Figure 6. Average monthly rainfall series and classification of rainy months in Cotonou.

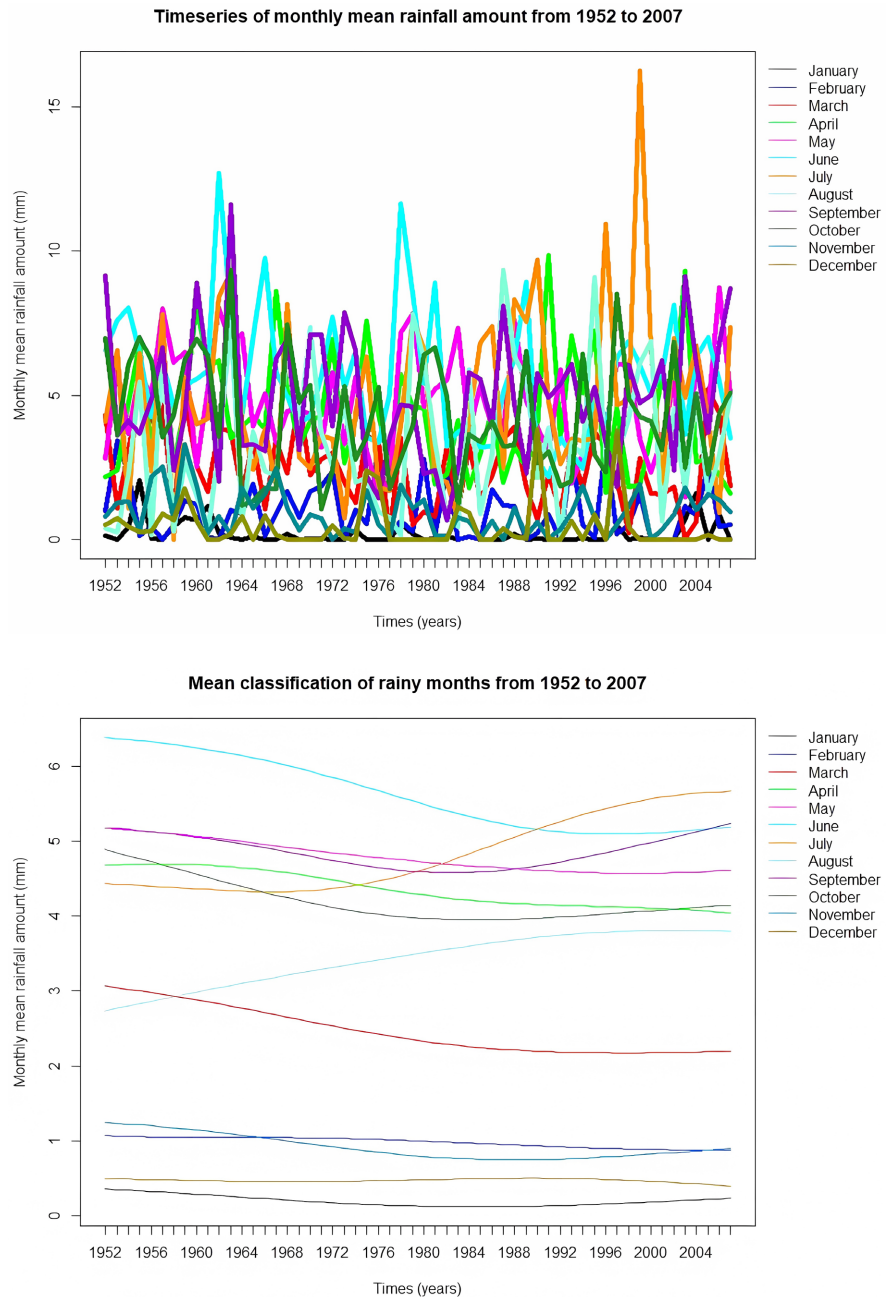


Figure 7. Bohicon monthly average precipitation series and classification of rainy months.

3.2.5. Kandi Synoptic Station

Figure 8 shows the classification of wet months in Kandi from 1952 to 2007. This area is characterized by two major rainy periods over the entire study period, interspersed with a month of rainfall resumption during the month of May. The month of April is characterized here by a month of rainfall announcement while that of October announces the disappearance of rainfall in the area. The months of June, July, August and September are months of heavy rainfall in the area and correspond to the period of the main crop season. November, December, January, February and March are characterized by periods of low rainfall. It also coincides

with the dry period and is influenced by the harmattan, which puts us in agreement with Chabi and others who revealed in [6] that even the month of January has wet days throughout Benin.

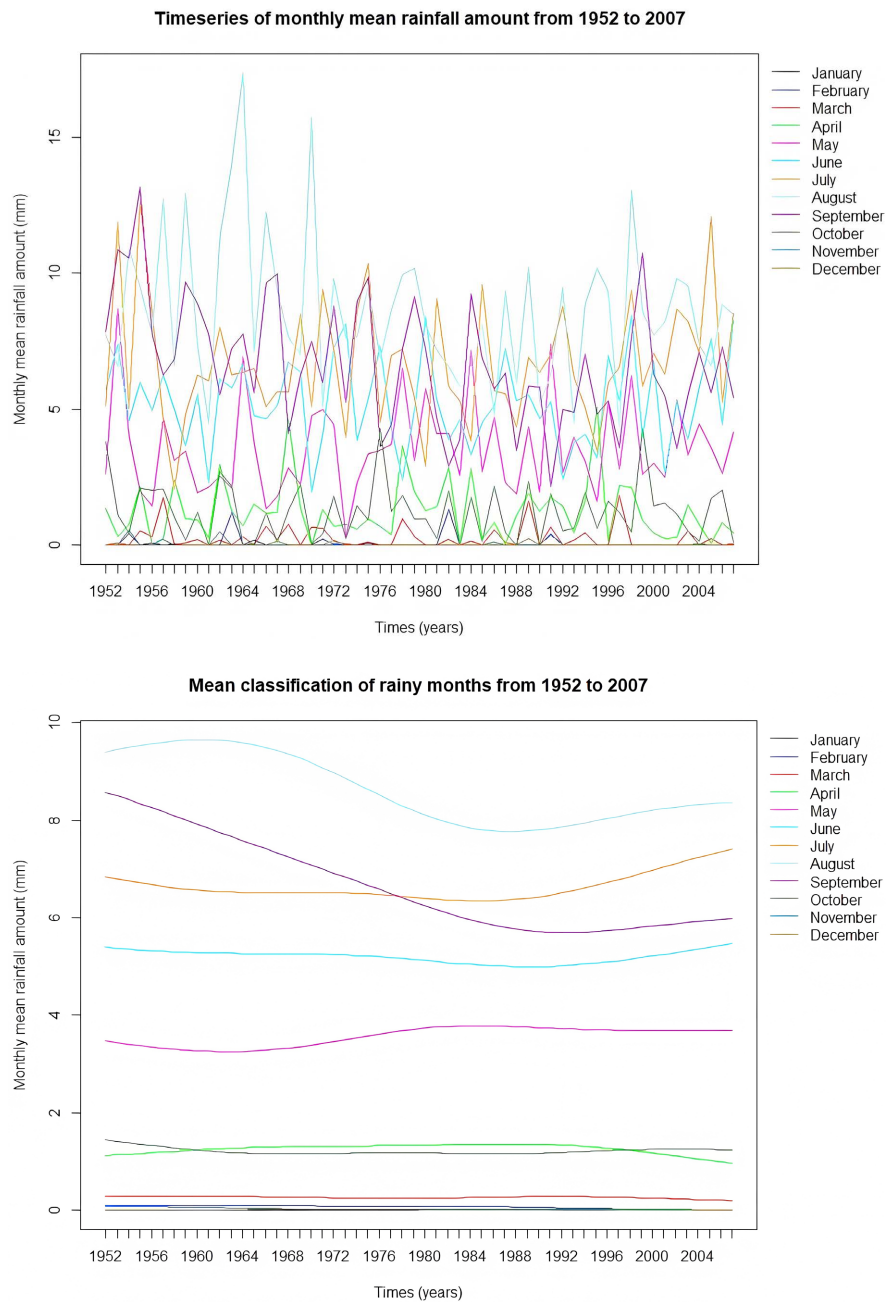


Figure 8. Kandi monthly average precipitation series and classification of rainy months.

3.2.6. Natitingou Synoptic Station

Figure 9 shows the classification of rainy months in Natitingou from 1952 to 2007. Here we can clearly see the two different seasons characteristic of northern Benin (one rainy and one dry). The rainy season extends over seven months from April to October, with heavy rainfall in July, August and September. The dry season

runs from November to March and is sometimes characterised by low rainfall, coinciding with the start of the dry season and the harmattan. which puts us in agreement with [6]. who revealed that even the month of January has wet days throughout Benin.

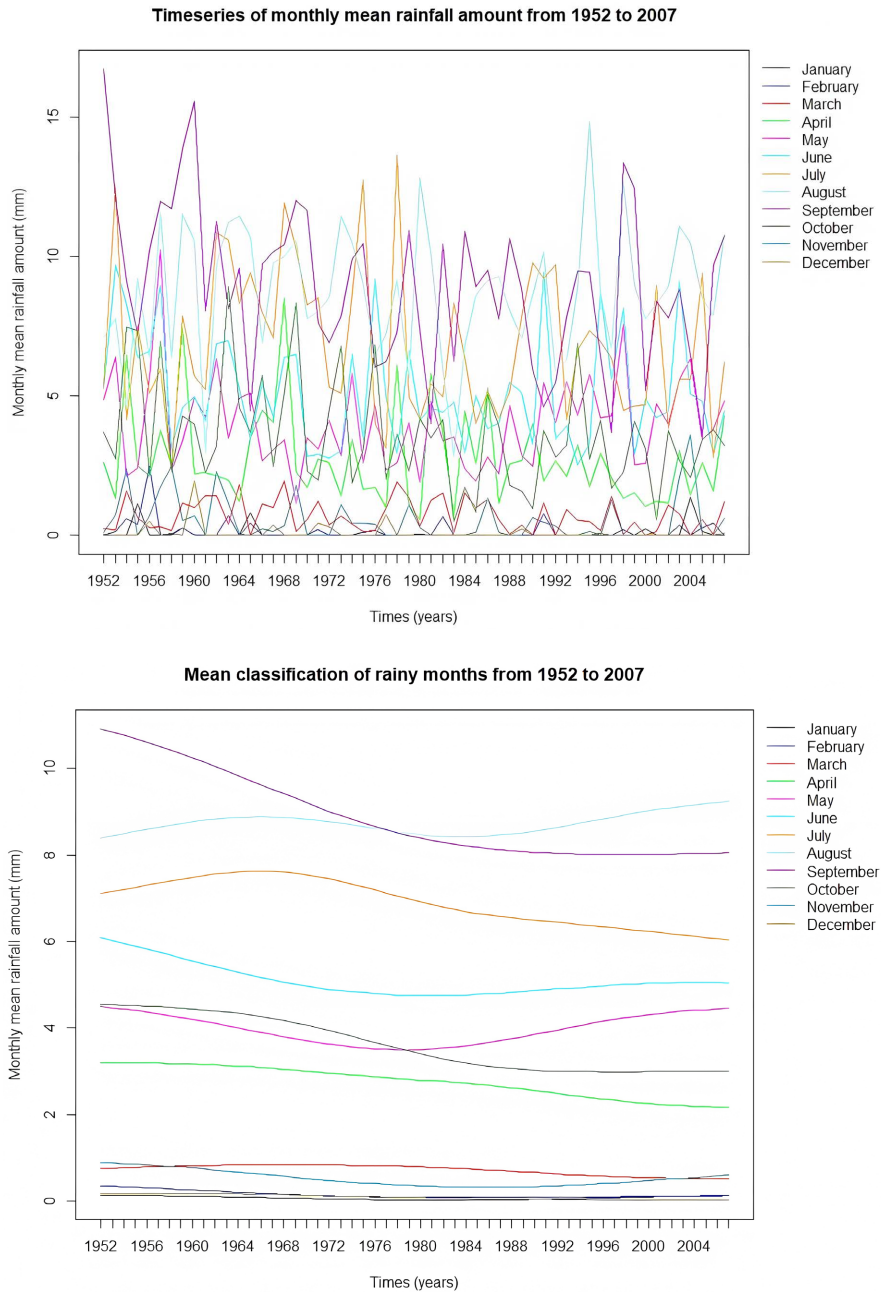


Figure 9. Natitingou monthly average precipitation series and classification of rainy months.

4. Discussion

The three periods of the rainfall regime (the wet period from 1952 to 1970; the dry period from 1970 to 1990 and the resumption of precipitation in 1990) mentioned

in previous work [1] [2] [16], have been highlighted and this in a monthly manner on all synoptic stations. This work puts us in agreement with [6] on the fact that the month of January receives more and more rainfall almost everywhere in the country nowadays. This work allows us to note that the areas covered by the synoptic stations of Savè and Bohicon are watered much more permanently over all the months of the year and that Cotonou has more rainy months which makes it permanently wet. This same work confirms that throughout the country, June is the rainiest month.

The results allow us to identify the different types of climate in Benin and present the situation of the 6 synoptic stations of this study. The stations of Cotonou and Bohicon represent the sub-equatorial climate, Savè the transitional climate, Parakou the southern Sudanese climate, Kandi and Natitingou the Sudanese climate. It also allows us to say, contrary to previous studies, that we have two rainfall directions in Benin: a decreasing gradient direction (south-north) for the southern stations (Cotonou-Bohicon-Savè) and an increasing gradient direction (north-south) for the northern stations (Kandi-Natitingou-Parakou). The increasing gradient direction allows us to say that rainfall converges towards the synoptic station of Savè, which gives Savè a transitional climate, and to see that it is the most watered area of the country, from the same graphs, we can see that the rains are unevenly distributed over the whole territory from North to South.

The analysis of **Figure 5** allows us to say that since about 1992, the hilly region has been receiving rain every month, which means that this region has been watered a lot since 1992. It emerges from this analysis that the center is an area that should be taken seriously in flood management in Benin since Benin's rivers have a north-south direction.

5. Conclusions

The functional data analysis (FDA) method is used in the present study to evaluate the variability of precipitation. This method allows us to take into account both the temporal dimension and the spatial correlations, in contrast to the analysis by traditional methods.

This work has also allowed us to:

Show that there is a zone of convergence of rainfall in Benin and that this zone is the center and is watered every month and all year.

To show also that we can define in a local way the moments of high season and those of low season.

The stations in Cotonou and Bohicon represent the sub-equatorial climate, Savè the transitional climate, Parakou the southern Sudanian climate, and Kandi and Natitingou the Sudanian climate, which is influenced by the Atacora mountain range.

The new data analysis techniques (FDA) also make it possible to highlight the three rainfall regimes of Benin and allow us to better quantify the level of water collected per month and per year at the synoptic stations.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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