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Rainfall Variability and Trends in West Africa

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Abstract

Rainfall variability associated with climate change has enormous impacts on ecosystems, agriculture and people in West Africa but few studies have been devoted to it. Monthly rainfall data from 1901 to 2013, provided by the Global Precipitation Climatology Center dataset, were analyzed using segmentation and empirical modal decomposition (EMD) methods to increase our knowledge on past and recent spatio-temporal rainfall trends and their impacts on the West African region. The results obtained showed that the peak of rainfall during the short rainy season is observed in September in Côte d'Ivoire, Ghana and Liberia. The temporal variability of this rainfall is marked by several breakpoints whose durations range from 2 to 70 years. The periods of change in the rainfall regime, characterized by the appearance of breakpoints, vary from one country to another and are of unequal duration. The main breakpoint appears after 1960. Periods of relative or normal increase or decrease in precipitation are observed before and after 1960. The long-term variability of this rainfall is characterized by a decrease in the amount of rainfall over all West African countries. The results of this study can be used as a tool to help raise awareness among populations for sustainable management of water resources in response to climate change and its adverse effects.

Keywords

Rainfall, Variability, Segmentation Method, Empirical Mode Decomposition Method, West Africa

1. Introduction

The West African region is densely populated. In 2019, the number of inhabitants, which was estimated at 391 million, could reach 796 million by 2050 and

1.5 billion by the end of this century [1]. This region is full of countless precious ecosystems and fertile lands, suitable for agricultural development that contributes to the well-being of the populations. In the past, the relative abundance of crops and the availability of water have helped meet the needs of this growing population. But today, the reduction in annual rainfall observed since the middle of the previous century due to climate change and human activities such as deforestation, soil and water pollution and bushfires [2] are exposing these populations to famine and increasing ecosystem degradation. Moreover, with the exception of Nigeria, the economy of West African countries is mainly based on the agricultural sector, which represents about 35% of the gross domestic product and mobilizes more than 50% of the active population [3] [4]. This sector is also impacted by the negative effects of rainfall variability.

In order to guarantee food security and to sustainably manage the resources available in this region, it seems important to deepen our knowledge on the spatio-temporal evolution of rainfall. Some authors [3]-[10] have analyzed the variability of rainfall in West African countries on different time scales, but their results seem to be the subject of debate because the trend obtained varies from one author to another. The differences observed could be related to the fact that these authors used data from different sources and different methods to analyze the evolution of the rainfall regime in these countries. In addition, some changes in rainfall patterns could be rapid while others could occur very slowly from one country to another.

The aim of this study is to analyze the variability of rainfall at different time scales in selected West African countries using a common dataset and analysis method. This study reinforces the knowledge on the past and recent evolution of rainfall and its impacts on population and agriculture in West Africa.

The first section is devoted to the description of the study area, the data and the method used. The results and discussion are described in the second and third sections respectively. A summary of the main results is presented in the last section.

2. Study Area

The study area is composed of countries belonging to West Africa such as Benin (6˚10'N - 12˚30'N; 0˚40'E - 3˚50'E), Burkina Faso (9˚20'N - 15˚3'N; 5˚3'W - 2˚20'E), Côte d'Ivoire (4˚N - 11˚N; 2˚25'W - 7˚30'W), Ghana (4˚N - 11˚N; 2˚25'W - 1˚E), Guinea (4˚N - 10˚N; 0˚W - 10˚W), Liberia (4˚N - 9˚N; 7˚W - 12˚W), Nigeria (4˚10'N - 14˚N; 2˚30'E - 14˚50'E), Niger (11˚37'N - 23˚33'N; 0˚10'W - 16˚W), Mali (10˚N - 25˚N; 4˚W - 12˚W), Mauritania (15˚N - 27˚N; 5˚W - 17˚W), Senegal (12˚13'N - 16˚N; 12˚W - 17˚W), and Togo (4˚N - 11˚N; 1˚E - 1˚50'E) (**Figure 1**).

The rainfall regime of the region is governed by the latitudinal shift of the inter-tropical front. Some West African countries such as Côte d'Ivoire, Ghana, Liberia and Guinea have a bimodal regime with a maximum annual rainfall not

Figure 1. Map of study area. Scale: 1/2,500,000.

exceeding 600 mm/year. The climate of these countries is equatorial. It is composed of two rainy seasons and two dry seasons that alternate. The long and short rainy seasons extend from mid-April to mid-July and from October to November respectively [5] [11]. In this coastal zone, economic activities are dominated by agriculture (coffee, cocoa, cotton, etc.), fishing, mining and oil extraction and trade, which are favored by the presence of numerous ports.

A uni-modal regime characterizes the rainfall of the other countries. The climate is semi-arid towards the south and arid towards the north [3] [7]. This type of climate is characterized by a short rainy season that lasts about 4 months and a relatively long dry season that lasts the rest of the year. The rainy season, which occurs between May and October, is relatively longer in the south than in the north of these countries. The main crops that depend heavily on the abundance and duration of rainfall are millet, sorghum, maize and groundnuts [8].

3. Data

The Full Data Product (V7) of the Global Precipitation Climatology Centre (GPCC) datasets, covering the period from 1901 to 2013, based on quality-controlled data collected from 67,200 stations around the world with a record duration of more than 10 years, was used in this study. This data, which can be retrieved at https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html, con-

tains monthly precipitation totals on a regular grid with a spatial resolution of 1.0˚ × 1.0˚ in latitude and longitude [12]. These data have been extensively validated through comparisons with field data [13] [14] and have been used in studies of rainfall variability in some West African countries [11] [15]. These data were spatially averaged according to the longitude and latitude of each country in the study area to produce time series. The resulting time series were analyzed using the methods described below.

4. Trend Analysis Method

The temporal evolution of annual rainfall amounts can sometimes include breakpoints that express changes in the regime of this parameter. These changes clearly show an increase or decrease in rainfall intensity from one period to another. To highlight these probable changes in the yearly accumulation of precipitation heights, Hubert's statistical test or segmentation [16] was applied to the time series of each country. This technique breaks down the initial series into two or more temporal subseries and highlights the presence or absence of one or more breakpoints characteristic of probable changes in the regime of the parameter studied.

The analyzed precipitation accumulation time series can also present trends. To characterize these trends, the method based on the empirical modal decomposition [17] [18] was applied to the time series of each country. This method decomposes the original signal into a finite number of intrinsic mode functions (IMF) with different time scales, and the trend function with at most one extremum corresponds to the last intrinsic function. This intrinsic trend here corresponds to the instantaneous rate of change of precipitation in millimeters per year. The EMD method provides a better estimate of the trend than the conventional linear regression technique [17].

5. Results

5.1. Spatial Variability of Rainfall in West Africa

Figure 2 shows the monthly rainfall climatology calculated for each country in the study area between 1901 and 2013 and then analyzed to quantify the seasonal signal. From the analysis of this figure, with the exception of countries such as Senegal and Nigeria, a bimodal structure is observed in the seasonal cycle of the rainfall regime of coastal countries including Liberia, Côte d'Ivoire, Ghana, Togo, Benin and Guinea. In Liberia, Côte d'Ivoire and Ghana, the main rainy season extends from mid-May to mid-July with a maximum centered on the month of June. The short rainy season occurs between September and November of each year with the maximum rainfall recorded in September (**Figure 2**).

In Burkina Faso, Mali, Senegal, Niger, Nigeria and Mauritania, the rainfall regime has a uni-modal structure in the seasonal cycle and is centered in August. The main rainy season occurs between June and September, and the rest of the year is characterized by the dry season.

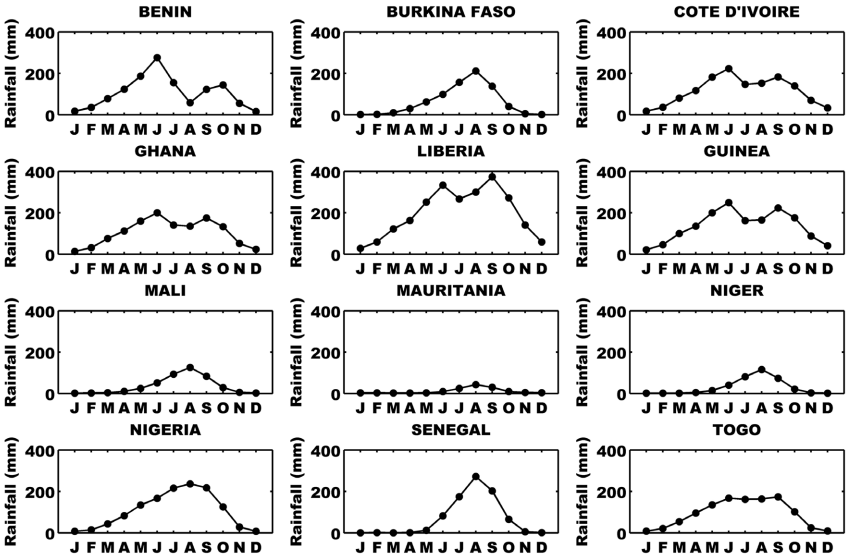

Figure 2. Monthly seasonal cycle of precipitation calculated from data ranging from 1901 to 2013 for each country in the study area.

5.2. Temporal Variability of Rainfall in West Africa

The temporal analysis of annual rainfall totals shows several regime changes in the interannual evolution of rainfall in some countries during the study period. These changes, which are characterized by a number of breakpoints obtained by Hubert's statistical segmentation test [16], have unequal durations and the associated cumulative rainfall intensities are also not the same (**Table 1**).

The main break point appears in 1967 in Niger and Senegal, and in 1969 in Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Liberia, Mali, Mauritania and Nigeria. Only one breakpoint is observed in the rainfall time series of Burkina Faso, Ghana, Guinea, Liberia, Mali and Senegal. These breakpoints appear in 1969 in Burkina Faso, Guinea, Liberia and Mali, in 1968 in Ghana, and in 1967 in Senegal. Negative (decreasing rainfall amounts) and positive (increasing rainfall amounts) trends are observed before and after these breakpoints in Burkina Faso and Mali respectively. Negative trends reflecting a decrease in rainfall intensity were observed in Liberia and Guinea, and a positive trend but associated with a decrease in rainfall intensity was also observed in Senegal before and after the regime change point (**Table 1**). Based on the study period (1901-2013), the changes in rainfall regime all occurred after 67 years.

The temporal trends in the cumulative rainfall time series of Côte d'Ivoire and Nigeria are characterized by three (3) break points which were recorded in 1906, 1913, 1969 and 1903, 1981, 1987 respectively. In Côte d'Ivoire, negative and positive trends, corresponding to dry and wet periods, were observed during the periods 1901-1906, 1970-2013 and 1907-1969 respectively. A positive trend, corresponding to an abundance of precipitation is observed between 1901 and 1903, and between 1982 and 2013. A negative trend (decreasing rainfall) was recorded between 1904 and 1981 in Nigeria. Changes in rainfall patterns occur after 5, 50 and 2, 5, 25 and 70 years respectively in Côte d'Ivoire and Nigeria.

Table 1. Breakpoints years and associated trends of rainfall time series of West African countries.

Country	Period	Trend (mm/yr)
Benin	No trend	-
Burkina Faso	1901-1969	−0.57
	1970-2013	1.94
Côte d'Ivoire	1901-1906	−27.04
	1907-1913	22.64
	1914-1969	0.84
	1970-2013	−0.31
Ghana	1901-1968	1.84
	1969-2013	−1.42
Guinea	1901-1969	−2.38
	1970-2013	−0.29
Liberia	1901-1969	−5.04
	1970-2013	−1.03
Mali	1901-1969	−0.12
	1970-2013	0.74
Mauritania	1901-1906	23.83
	1907-1969	−0.12
	1970-2013	0.56
Nigeria	1901-1903	11.88
	1904-1981	−0.27
	1982-1987	1.18
	1988-2013	0.08
Niger	1901-1903	−1.33
	1904-1909	6.67
	1910-1915	−7.81
	1916-1967	0.59
	1968-2013	0.97
Senegal	1901-1967	1.62
	1968-2013	1.13
Togo	No trend	No trend

Four breakpoints appear in the Niger rainfall time series. These points marking a change in the rainfall regime appear in 1903, 1909, 1915 and 1967. From 1901 to 1915, the temporal evolution of cumulative rainfall in this country is

characterized by alternating dry and wet periods of unequal duration. An increase in cumulative precipitation has been observed since 1916. No break points were observed in the rainfall time series in Togo and Benin (Table 1).

Figure 3 illustrates the long-term variability of cumulative rainfall over different West African countries between 1901 and 2013. This long-term trend shows a linear decrease with negative slopes during the period 1901-2013. These slopes are respectively worth: −62.03 mm/yr (Benin), −103.61 mm/yr (Burkina Faso), −326.79 mm/yr (Côte d'Ivoire), −143.63 mm/yr (Ghana), −286.47 mm/yr (Guinea), −707.45 mm/year (Liberia), −89.02 mm/year (Mali), −68.05 mm/year (Mauritania), −62.63 mm/year (Nigeria), −49.92 mm/year (Niger), −127.65 mm/year (Senegal), and −5.01 mm/year (Togo). From the observation of these results, it can be seen that there was a decrease in rainfall over all West African countries from one year to the next. The highest and lowest decreases were observed respectively in Liberia (−707.45 mm/year) and Togo (−5.01 mm/year).

6. Discussion

The bimodal structure observed in the seasonal cycle of the rainfall regime in the coastal zone countries including Liberia, Ghana, Côte d'Ivoire, Guinea, Togo and Benin is in agreement with the results of previous authors [4] [6] [19] [20] who worked in the study area. The short rainy season is centered on the month of September. However, in previous studies [5] [19], this season is centered in October. This difference may be related to the fact that this season is governed by Sahelian processes [21] that produce a single rainy season with maxima located between August and September per year.

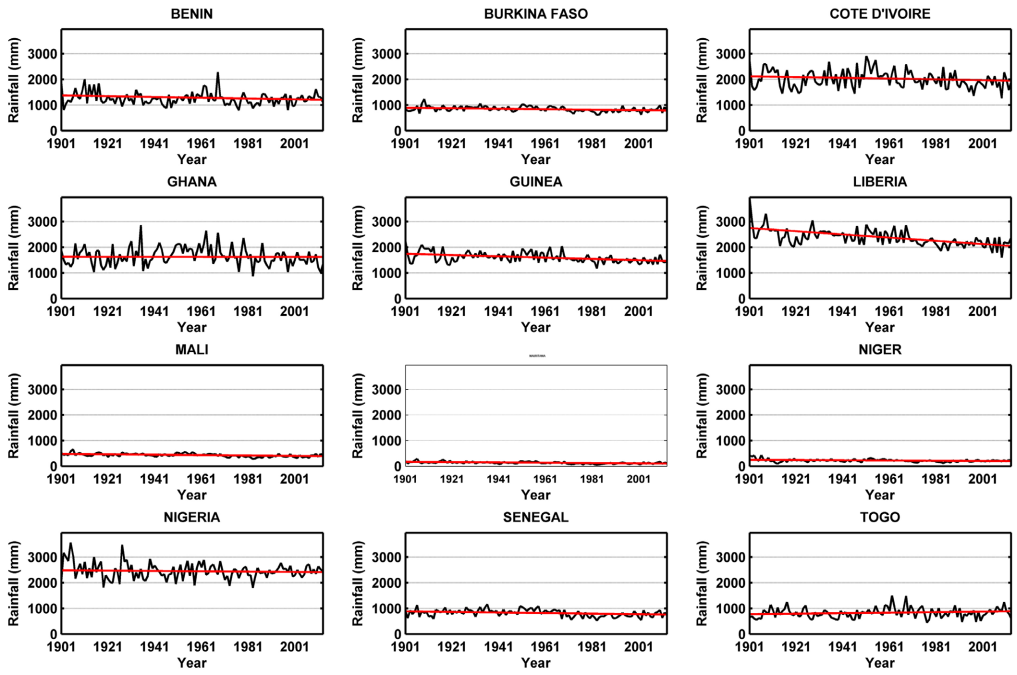

Figure 3. Variability and trend of annual cumulative rainfall (mm) in West Africa during 1901-2013 period. Linear trend (in red) was added on each figure.

The uni-modal structure observed in the seasonal cycle of the rainfall regime of countries such as Nigeria, Niger, Senegal, Burkina Faso, and Mauritania is in agreement with previous studies conducted in these countries by [22] [23] [24] [25] [26]. The non-linear distribution of rainfall over these different countries could be attributed to the latitudinal shift of the ITCZ, convection intensity, land use and land cover.

The analysis of cumulative rainfall time series of some West African countries such as Benin, Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Liberia, Nigeria, Niger, Senegal and Togo shows a temporal variability of rainfall at different time scales. These time scales range from 2 to 70 years. The largest change after 1960 [9] could have been influenced by the drought in 1968-1973 and 1982-1983 [27] [28] and deforestation revealed by several studies like those of [29] in West Africa, [30] in the Brazilian Amazon. Moreover, the reduction of the land-sea thermal gradient which leads to a weakened monsoon circulation and a northward shift of monsoon rainfall, induces changes in rainfall in West Africa.

The negative slope of the linear trend in cumulative rainfall in the study area indicates a decrease in rainfall in all West African countries. This decrease observed in this work is in perfect agreement with previous work done in this region [6] [9] [11] [31] despite the fact that the slopes are not the same. The difference observed in the rapid decrease in rainfall could be attributed to the data and/or the method used in these different studies.

This decrease could have negative impacts on agriculture, water availability and ecosystem balance. The lack of food and subsistence products due to reduced rainfall could cause famine and create crises in West African countries.

The downward trend in rainfall in the different regions of West Africa can be reversed by the reforestation of desert areas as shown by [32] [33] [34] in this regions and, [35] in Europe, through model simulations.

7. Conclusions

The variability and trend of rainfall in some West African countries were analyzed in this paper in order to deepen our knowledge on the spatio-temporal behavior of this climate parameter.

The analysis of monthly rainfall climatology in each country of the study area confirmed the bimodal structure of the seasonal cycle of rainfall regime in coastal countries such as Liberia, Côte d'Ivoire, Ghana, Togo, Benin and Guinea. The main rainy season extends from mid-May to mid-July with a maximum centered on June in Liberia, Côte d'Ivoire and Ghana. The short rainy season is established between September and November of each year and the maximum rainfall recorded is located in September. The seasonal cycle of rainfall regime in other coastal countries (Senegal and Nigeria) and countries such as Burkina Faso, Mali, Niger and Mauritania, is characterized by a uni-modal structure and centered on August. The main rainy season is between June and September, and the rest of the year is characterized by the dry season.

Apart from the rainfall time series in Benin and Togo, which do not show any break points, the temporal evolution of rainfall in the other countries in the study area shows a number of break points ranging from one to four. Only one breakpoint is observed in the rainfall time series in 1967 Senegal, 1968 in Ghana, and 1969 in Burkina Faso, Guinea, Liberia and Mali. Three breakpoints were observed in Côte d'Ivoire (1906, 1913, 1969) and Nigeria (1903, 1981, 1987). The analysis of rainfall time series in Niger showed four break points. These changes in rainfall patterns marked by these breakpoints have varying durations and the associated rainfall has varying intensities. The main breakpoints appear after 1960. The trends observed before this year (1960) are generally positive (abundant precipitation) and those observed after 1960 are generally negative (decreasing precipitation).

The long-term variability of rainfall in all West African countries is characterized by a negative slope ranging from −707.45 mm/yr (Liberia) to −5.01 mm/yr (Togo). This means that rainfall is decreasing over the period 1901-2013. This decrease could have negative impacts on agriculture, water availability and ecosystem balance. The lack of food and subsistence products due to reduced rainfall could cause famine and create crises in West African countries.

The results of this study could contribute to raising awareness on sustainable resource management in response to climate change and its negative impacts on populations.

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Data Availability

There are no other data used in this study apart from the one included in the manuscript.

Author Contributions

This study has been conducted by a team, so all members have the same contribution.

Conflicts of Interest

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

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