Evaluation of the Increase of the Surface of Arid, Semi-arid Regions and the Decrease of Wet Lands in connection with Climate Change: Case study of West Africa during the last Century

David Monkam
Faculty of Science, Department of Physics, University of Douala Cameroon, P.O.Box: 24157 Douala, Cameroon
E-mail: monkam1@yahoo.fr

Abstract

By applying the cluster analysis (CA) method on the observation dataset produced by the climate Research Unit (CRU) for the base period 1901-1940, four regions spread in five areas are detected in West Africa. This CA method that has been applied to geophysical research during these two last decades is among the methods more frequently used for the rainfall classification. Clusters have been defined as relative constellations of contiguous points in space. For the four regions identified in West Africa, the first one, R1, an arid land, covers essentially the north of 16.75°N from west to east of the study zone. The second region, R2, a semi-arid land with a sahelian climate, less warm than the dry climate of R1, is centered on the Chad, with almost regular extension to the west towards Mauritania, and to the east, including the north of the Central African Republic. The region three, R3, a wet land, is centered on the Ivory Coast and covers totally the Liberia, the south part of Ghana, Togo, Benin and the south-west of Nigeria. The fourth region, R4 corresponding to the wet equatorial forest, covers a part of Senegal and a part of the Central Africa towards the equator. When this zonation is superposed with the regionalization for the African atlas (2000) that divides the African continent into six climate types distributed symmetrically around the equator as equatorial, humid tropical, dry tropical, sahelian, desert and Mediterranean climate types, it appears that except the Mediterranean, our study area contains five of these six climate types. One of our zones contains the two tropical climate types. In these regions, trends have a magnitude of up to 2 K per century, with a decreasing of the precipitation since the year 1970. To observe and evaluate the spatiotemporal variations of the climatic regions, a segment of 15 years is used, going from the base period P0, to obtain P1, P2, P3 and P4 periods corresponding respectively to 1916–1955; 1931–1970; 1946–1985 and 1961–2000. The 15-year segment mean filters out inter-annual variability, which is pronounced in the original time series. The application of a segment of 15 years with overlap going from 1901 to 1940 (P0), and 1961 to 1998 (P4) throughout the periods P1, P2 and P3, shows important spatiotemporal modifications of the climatic regions. From P0 to P4, the surface of arid and semiarid lands doubles while wetlands are reduced to half. The progression of arid and semi-arid land implied an impoverishment soil and the decrease of surface of lands under cultivation

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Keys words

Cluster analysis, Climatic zonation, Surface of climatic zone, Segment, Climatic change.

1. Introduction

Climatic changes at the local/regional scale are probably among the most important issues within the global change debate. These changes generally occur on rainfall and temperature as the recent severe prolonged drought south of the Sahara, in the Sahel , with the maximum in 1972 – 1973 and 1982 – 1984 (Nicholson et al ., 2000). As a consequence of the drought, understanding the interannual variability of rainfall in the Sahel has been a subject of a large number of studies during the last 20 years (i.e. Fontaine and Janicot, 1992; Janicot, 1992; Ward et al ., 1999; Nicholson et al., 2008). In some of these papers, rainfall data were used to determine the climatic zones. Janicot (1992) performed regionalization of annual and monthly rainfall fields for the period 1948 – 1978 and identified four coherent regions in West Africa. Ward et al . (1999) and Nicholson et al . (2000) have analyzed climatic zonation of West Africa using different approaches. Giorgi and Francisco (2000) investigated the climatic zonation of the globe. They have divided all land areas in the world (except for the Antarctica) into 21 regions. Three of these regions entirely cover West Africa.

However, all these works did not show the spatial variation of the climatic zones identified. Therefore, we propose to revisit the climatic zonation over West and Central Africa and try to make our contribution on how the spatial variation of the climatic zones could contribute to a better illustration and understanding of climatic changes and how to evaluate the evolution the surface of the climatic zones identified in this part of the African continent.

The main objective of this work is to detect climatic zones and to study their spatial variability during the 20th century. Thus, in the next section, we describe the data and the methods used. In the third section, we present the results of zonation, trends and spatial variability of the zones.

2. Data and methods

2.1 Data

We use the observation dataset produced by the Climatic Research Unit (CRU) of the University of East Anglia, and described by New et al. (1999, 2000) in some details. The CRU dataset includes a number of variables: surface air temperature and diurnal temperature range, precipitation, surface vapour pressure, cloud cover, wet-day frequency and ground frost frequency. For this study we use monthly surface air temperature and precipitation gridded on a regular latitude- longitude 0.5° global grid for the period of 1901 to 2000. Only land areas are included in the dataset. New et al. (1999, 2000) provided estimates of the uncertainty associated with this climatology using both an internal cross-validation procedure and a comparison with other available observed climatologies. They concluded that uncertainties in observed climatic averages for multi-decadal periods are of the order of 0.5 to 1.3 K for temperature and up to 10-25% for precipitation, and are largest over regions characterized by poor station coverage and high spatial variability, which was the case for the African continent.

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Moreover the uncertainty and variability for earlier periods of the century may be amplified by the even lower number of available stations. However, broad regional averaging tends to generally reduce the uncertainties associated with individual stations or periods. Therefore to reduce the uncertainties, we passed from a 0.5° x 0.5° grid of CRU to a 2.5° x 2.5° grid of ECMWF or NCEP/NCAR by averaging the values on the CRU grid (fig1). We adopted the ECMWF or the NCEP/NCAR grid. So a value in the ECMWF or NCEP/NCAR grid is a mean of 25 values of the CRU data.

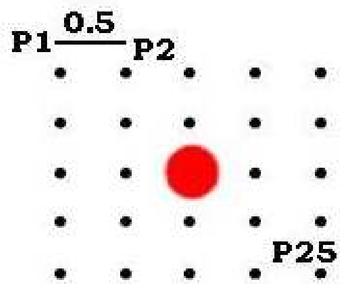

Figure 1: The passage from a 0.5° x 0.5° grid of CRU (in black) to a 2.5° x 2.5° grid of ECMWF or NCEP/NCAR (in red) by averaging the values on the CRU grid. The value of the grid point of ECMWF or NCEP/CAR system in the centre (in red) is a mean of 25 values of the grid points of CRU around (in black).

2.2 Methods

The Cluster Analysis (CA) is used to determine the climatic zones in West Africa. CA has been applied to geophysical research during these two last decades (Gong and Richman, 1995). It is among the methods more frequently used for the rainfall classification (Champeaux and Tamburini, 1994). Clusters have been defined as relative constellations of contiguous points in space (Punj and Stewart, 1983). Hierarchical algorithm performs the classification in five basic steps: (1) the chosen distance measured between entities is calculated; (2) the two closet entities are merged or split to form new clusters based on a defined criterion; (3) the distance between all entities is recalculated; (4) steps 2 and 3 are repeated until all entities are merged into one cluster (agglomerative); (5) a threshold is applied to the dendrogram, the deduction of different clusters.

Ward’s method is one of the most used clustering methodologies. An earlier work done by Blashfield (1976) compared complete link-age, average linkage and Ward’s method. He found that the last method groupings differ widely since it was designed to generate in such a way that mergers at each stage were chosen so as to minimize the within-group sum of squares. In the present work, the CA is used to determine rainfall regions on the base period 1901 – 1940 (P0).

To observe the spatiotemporal variations of the climatic regions, a segment of 15 years is used, going from this base period P0, to obtain P1, P2, P3 and P4 periods corresponding respectively to 1916 – 1955; 1931 – 1970; 1946 – 1985 and 1961 – 2000. The 15-year segment mean filters out interannual variability, which is pronounced in the original time series (Von Storch and Zwiers, 1999).

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The standard least square method, as described by Edwards (1984), is used to calculate linear trends for each variable and region for the whole 100-year period. Finally, statistical significance throughout the work is assessed using a two-tailed t -test at the 99% confidence level.

3. Results

3.1 Climatic zones

Figure 2 displays four regions on five areas obtained by applying the CA method on the July, August and September (JAS) rainfall anomalies of the base period. As the rainfall data are very erratic, the JAS months were chosen because they correspond to the rainy season in the studied area and the rainfall data are more regular.

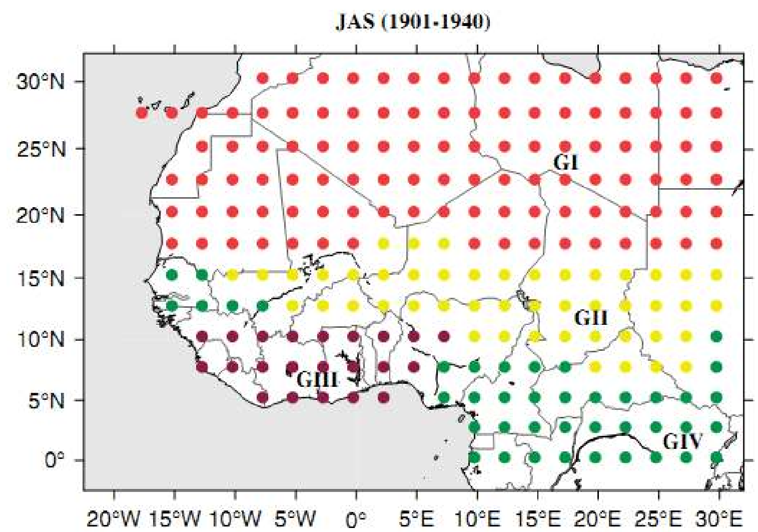

Figure 2: Climatic zones for the base period 1901 – 1940.

The first region (GI) occupies mainly the Sahara, north of 15 ◦N. The second region (GII) is centered on the Chad, with almost regular extension to the west towards Mauritania, and to the east, including the north of the Central African Republic. The third region (GIII) is centered on the Ivory Coast and covers one part of Nigeria. The fourth region (GIV) contains two areas geographically different: the first one is centered on the Senegal; the second area entirely covers Central Africa.

For the fourth region (GIV) containing two areas geographically different with the first one centered on the Senegal and the second covering entirely the Central Africa, we can note that similar results, where the analysis put two areas in the same cluster, were also obtained by Penlap et al (2004) when they analyzed possible changes in precipitation in Cameroon.

This can be due to the topography of the region that could create a local circulation generating a particular climate type in a limited area. Janicot (1992) considered the period 1948 – 1978 and using another method also found four regions. Three of the four zones are very similar to GII, GIII and GIV described above (Figure 1). This author did not extend his study area north of 20◦N, over the Sahara corresponding to GI here.

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The comparison of our results with the works of Giorgi (2002) also shows good similarities. Meanwhile, it would be better to superpose our zonation and the regionalization for the African atlas (2000). In this atlas, the African continent is divided into six climate types distributed symmetrically around the equator as equatorial, humid tropical, dry tropical, sahelian, desert and mediterranean climate types. Except the mediterranean, our study area contains five of these six climate types. One of our zones contains the two tropical climate types.

It is, thus, very interesting to obtain the same result for the zonation compared to previous works mentioned above, and to have very good correspondences between our climatic zones and the climate types in West Africa. However, the main objective of this work is not necessarily the improvement of climatic zonation in West Africa, but to examine the spatial variation of the climatic zones through the relevant time, as a result of climatic changes. Thus, in the following sections, we will analyze the trends in each region and we will also apply the CA method on the four periods, 1916 – 1955 (P1), 1931 – 1970 (P2), 1946 – 1985 (P3) and 1961 – 2000 (P4) obtained from the base period P0 (1901 – 1940) by the application of a segment of 15 years, to study the spatiotemporal variability of these regions during the last century. For example P1 is obtained from P0 as follow: P0[1901 – 1940] == > P1[1901+15 – 1940+15] = [1916 – 1955].

3.2 Trend analyses

For trend analyses, we computed the N-year running averages. N-year running averages are calculated from the individual anomalies. In particular, results for N = 5, 9 and 29 years are presented as representative of multi-year to multi-decadal periods ($\overline{X_N}$). The running average $\overline{X_N}$ at the year i is defined as:

$$\overline{X_N}(i) = \frac{1}{N} \sum_{j=i-\frac{(N-1)}{2}}^{j=i+\frac{(N-1)}{2}} x_j$$

The N-year running averages filter out low scales variability from the data series. For example, 5-year running mean filters out interannual variability, which is pronounced in the original time series (Giorgi and Francisco, 2000). The anomalies are calculated with respect to the 100-year average rather than the trend line in order to show trends throughout the century.

Figure 3 presents the time series of 5-year-running average observations of temperature and rainfall anomalies over the four regions during the last century. The period 1901–2000 can be divided into four subperiods: 1901–1938, 1938–1945, 1945–1976 and 1976–2000, corresponding to positive, negative, constant and positive anomalies, respectively.

The rainfall graph shows that the region GI (Sahara) does not vary enough, whereas the other regions, and particularly the equatorial (GIV) present fluctuations during the last century where the precipitations have decreased and the temperatures increased since the 1970s.

The linear trend values for the yearly average regional temperature and precipitation were computed for the four regions. The results exhibit warming trends in the range of 0.5 – 2K per

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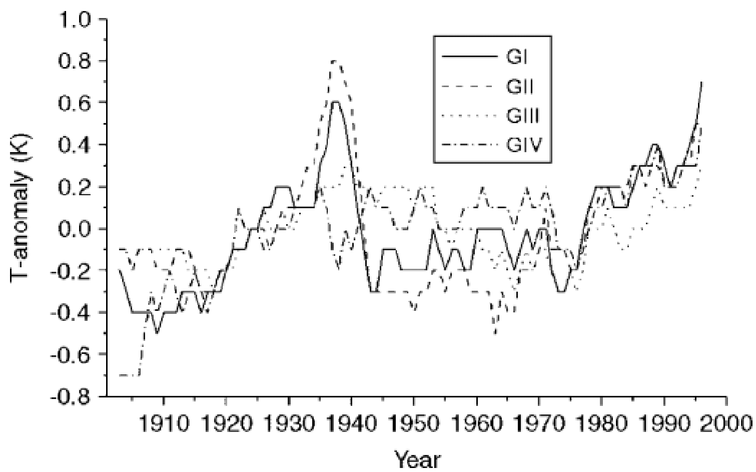
century. We also found periods of warming in the first 3 – 4 decades and the last 2 – 3 decades, separated by cooling in the inter-mediate decades. Hence, the temperature trends are characterized by pronounced interdecadal variability with the first 3 – 4 and the last 2 – 3 decades of the century being the primary contributors to the average warming trends in many cases where the trend is significant. This result is generally consistent with the observed trend in global temperature (Jones et al., 1999; Giorgi, 2002). All these annual trends are statistically significant at the 99% confidence level. The largest temperature trends are observed over the wet-land (GIV). This could be linked to the deforestation. The precipitation trends are less significant than the temperature, with only 25% of the trends being statistically significant at the 99% confidence level. Statistically significant positive trends are found in the zone GI. In the other zones, the precipitation trends can be associated with African monsoon circulation.



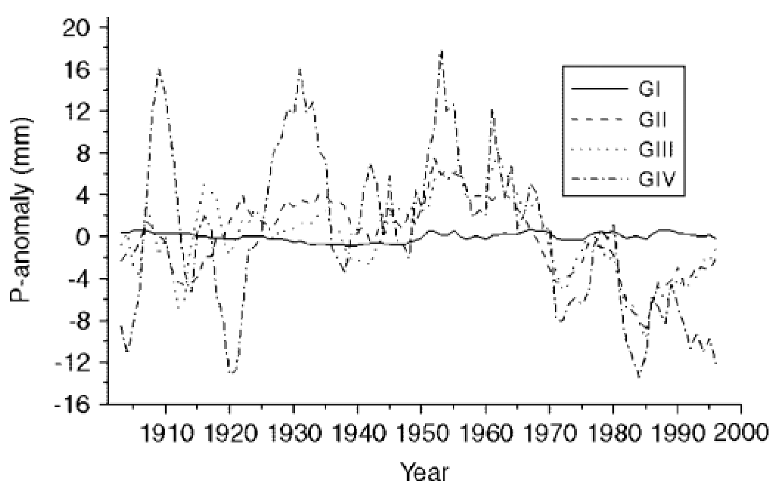


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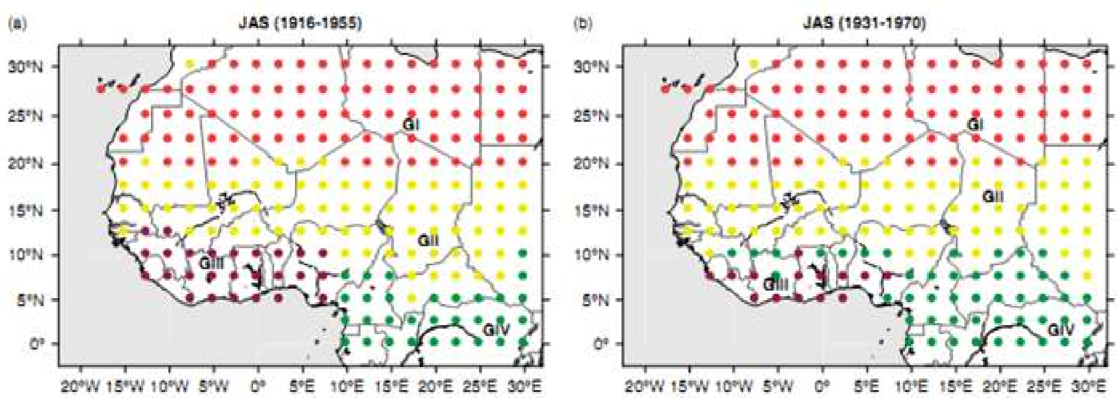
Figure 3: Time series of 5-year-running average of the yearly average temperature (T, at the Top) and precipitation (P, at the bottom) anomalies

3.3 Spatial variability of t he climatic zones during the last century

The spatiotemporal evolution of the regions is clearly visible in Figure 4, presenting the zones for the periods P1, P2, P3 and P4. On a time scale of 15 years, the modifications of rainfall regions between the base period and P1 (1916 – 1955) appear in Figure 4(a). There are 4 regions distributed in 5 areas: region GI which overlaps North Africa up to 17.5 ◦N has been shifted 2.5◦ to the north. Region GII grows at the detriment of GI and GIV. GIII has a few extensions through Senegal. GIV disappears from Senegal in favour of GII and GIII.

Between P1 and P2 (1931 – 1970), GI is unchanged and GII continues to grow. It extends to the Ethiopian coast, whereas GIII is shrinking continuously in favour of GII and GIV. This last region occupies two areas with the first one between the east of Guinea Bissau and west of Nigeria. The second space covers the Central African Republic and the south of Sudan.

During P3 (1946 – 1975), GI keeps the same configuration as the base period, with 2.5◦ growing towards the south, thus occupying the north of Sudan, all of Libya and one wide part of Chad, Niger and Mali. This growing of GI leads to a shrinking of GII. GIII grows towards Central Africa by covering the northwest of Congo and a wide part of Nigeria and southern Cameroon. GIV has still changed its configuration and covers the south part of 10◦N, between 5◦E and 30◦E. P4 (1961 – 2000) is characterized by predominance of GI and GII. GI moves south of 15 ◦N and GII occupies the major part south of this latitude. GIII is restricted around the Ivory Coast and GIV is confined to the Gulf of Guinea.



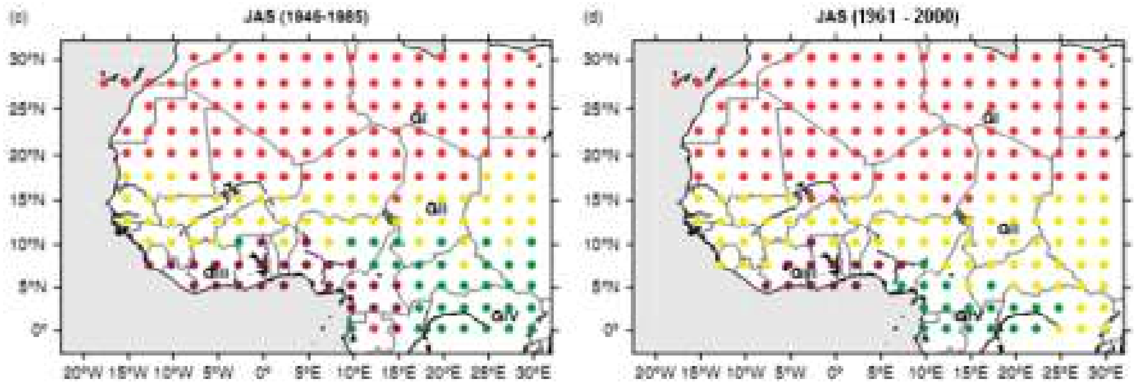


Figure 4 : Climatic zones variation of JAS season during 1901 – 2000. The basic state P0 is identical as the figure 2 and one can note the extension of GII during the last century, from P0.

The Sehelian zone which is a semi-arid region (GII) grows continuously from P1 to P4 where it is maximum. The wetlands GIII and GIV are rather minimum in P4. Compared to the base period P0 (fig .2), finally, the last 40 years of the 20th century, West Africa is characterized by two mean climatic zones: the desert (GI) and the Sahelian (GII). To confirm these results, we computed the surfaces of the climatic zones for the four periods.

3.4 Computation of the Surfaces of the Climatic Zones from P0 to P4

For the computation of the surfaces, as we have considered the ECMWF and NCEP/NCAR systems, each gird point is a square of 2.5°. The results of the computation of the surfaces of the climatic regions are shown in Table I. On this table, there appears for each region and period the surface and the mean rainfall per unit area (MRUA).

To obtain the MRUA in a zone, the mean rainfall is computed at each grid point for a given period. Next, the sum is computed for all the grid points of the zone and the result is then divided by the surface of the zone.

In general, the surfaces of region GIII and GIV decrease during the century. On the contrary, the surfaces of GI and GII increase. In the base period, GI and GII occupy about 11.94 106 km2 (i.e. 8.32 + 3.62 in Table I). This corresponds to 71.11% of the total study area. GIII and GIV, about 4.85 106 km2 (1.69 + 3.16) occupy only 28.89%. At the end of the century, GI and GII occupy about 14.48 106 km2 (8.78 + 5.70), while GIII and GIV cover only 2.31 106 km2 (0.92 + 1.39). Hence, the percentage of GI and GII is now 86.24%, whereas that of GIII and GIV is 13.76%. The time variation of MRUA is very weak in GI and its fluctuations are also weak during the century in agreement with the trend of the precipitation (Figure 3(b)). In GII, this quantity slightly increases during the century and decreases in GIII and GIV.

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Table I. Evolution for 15-year segment of the region surface (Surf) in 10^6 km^2 and the mean rainfall per unit area (MRUA) in mm/km^2 over West Africa during the twentieth century

	1901–1940		1916–1955		1931–1970		1946–1985		1961–2000	
Regions	Surf	MRUA	Surf	MRUA	Surf	MRUA	Surf	MRUA	Surf	MRUA
GI	8.32	0.70	6.62	0.24	6.31	0.22	8.24	0.73	8.78	0.87
GII	3.62	15.59	5.78	13.62	5.70	12.09	4.08	17.57	5.70	15.72
GIII	1.69	30.17	2.00	18.02	1.08	27.38	1.93	27.41	0.92	20.09
GIV	3.16	15.11	2.39	12.65	3.70	17.93	2.54	13.44	1.39	24.11

4. Discussion

For the four regions, the downward trends began in the late 1960s. The region GII which corresponds to the semiarid land, is the main area of squall line occurrence during northern summer. It is located slightly north of 10 ◦N. The region GIII is located between 10◦N and the Guinea coast. It is the region of monsoon rainfall during northern summer. This latitude of 10◦N boundary between region GII and GIII was also noted by Nicholson et al . (2000) and Janicot (1992).

The last author analyzed the Sahelian rainfall for the period 1948 – 1978. He found that the intertropical convergence zone (ITCZ) mean position was southern (10◦N) than the normal in summer. Divergent meridional circulation (Hadley cells) extending into the mid-latitudes and divergent zonal circulation (Walker cells) within low latitudes form the main part of the tropical atmospheric circulation. The interannual variability of this divergent circulation is responsible of the West Africa rainfall variability, and was examined by Fontaine and Janicot (1992).

The progression of the region GII during the period, P4, can be explained by the southern position of the ITCZ that could be linked to a less vertical continuity of Hadley and Walker cells over Sahel during the dry period 1968 – 1975 as was mentioned by Janicot (1992). The application of a segment of 15 years with overlap going from the base period 1901 – 1940 (P0) to 1961 – 2000 (P4) throughout the periods 1916 – 1955 (P1), 1931 – 1970 (P2) and 1946 – 1985 (P3), shows that the spatiotemporal modifications of rainfall regions are more marked south of 15◦N. For the region GI, the surface during P4 is greater than in P0. In P4, the surface of region GII centered on the Chad, and including a large part of the semiarid land, is about double of P0, while that of GIII and GIV covering the West African coast and the wetland, respectively, are around half of P0. An analysis of observed temperature and precipitation variability and trends throughout the twentieth century over these four regions shows that the trends have a magnitude of up to 1.5K per century with a decrease in the precipitation since the 1970s.

5. Conclusion

Finally, the spatiotemporal evolution of the zones has been shown through the extension of severe climate zones (Sahara and Sahelian zones) and the reduction of wet climate zones (coastal and Equatorial zones). The precipitation decrease was associated with the temperature increase mainly after the 1970s. Particularly, the region GI which corresponds to the desert

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climate with weak precipitation has been subjected to a slight extension toward the south. This situation contributes to desert extension.

For region GII which corresponds to the Sahelian climate which is less warm than the desert, its extension was more marked during the last century. This extension to the west occurred to the total disappearing of the characteristics corresponding to region GIV in the Senegal and Gambia. In the Central Africa zone, its progression towards the south has overspread totally the north of Cameroon, the whole of Central African Republic, and the entire south of Sudan and almost all of the north of Democratic Republic of Congo.

Between the beginning (P0=1901 – 1940) and the end (P4=1961 – 2000) of the century, this progression has substantially reduced regions GIII and GIV by about 50%. Finally, the semiarid land has widely grown during the twentieth century.

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Biography

Professor Monkam holds a PhD in Atmospheric Physics and is in the Dept of Physics in the University of Douala, Cameroon. His research areas are Atmospheric waves, climatology and climate modeling. He is an associate at Abdus Salam International Centre for Theoretical Physics (ICTP) and a member of the International Association of Climatology and of AMMA Africa