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Climatic trends in Sahel during 1950 - 2014: A case study of Ouaddaï region in Chad

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Abstract: This work focused on the study of climatic trends (rainfall and temperature) in the region of Ouaddaï in eastern Chad. Evolution trends and breaks are detected during the most comprehensive measurement period available from 1950 to 2014, using statistical methods. Dry, normal, wet years and temperature anomalies are diagnosed by the application of the standardized index. The 9-year moving average method is used to search for possible internal trends in precipitation and temperature and to identify dry, normal and wet periods. Complete data from only two climatological stations (Abéché and El Geneïna) in the study area are processed. Rainfall shows that the rupture was established in 1964 and for the temperature in 1960. The reduction in rainfall is 21% for the Abéché substation and 20% for the El Geneïna substation. The temperature increase is 18%. Since 1992, the temperature continues to increase until today. By application of the standardized rainfall index, a wet phase was observed from 1950 to 1964, a dry phase from 1965 to 2000 and a phase with a mixture of normal and wet years from 2001 to 2014. These results would be useful to understand the impact of the combined effect of drought and the continuing rise in temperatures on the agricultural, pastoral and forest ecosystems of the study area.

Keywords: Sahel, Chad, Ouaddaï, rainfall, temperature, drought.

Introduction

The climate of a period, as used in this study, refers to the averages and irregularity of variables such as temperature, rainfall, wind, and so on. The relative importance given to each of these variables depends on the region of the globe considered. In the Sahel, rainfall and temperature are by far the most important climatic variables for the life of ecosystems and populations [1]. Since the beginning of the 20th century, the Sahel has experienced three major droughts, the last of which has lasted more than 20 years and caused a veritable ecological catastrophe [2]. Climate change and its induced in socio-economic and environmental consequences, in recent decades have increasingly received interest at local and international levels [3]. Since the late 1960s, a tendency for rainfall decreases and temperature increases, which have continued at the beginning of the 21st century [4-7].

Sahel is particularly affected by recurrent and prolonged droughts [8], and has been the subject of constant and sustained interest from research community [9-23].

Previous works on rainfall and temperatures in the Sahel has produced many results. Nevertheless, studies of climate trends at the local level are very rare. Using results obtained at the Sahel level to conduct agricultural, pastoral or forest management at the local scale may be inaccurate [24]. Extrapolation of large-scale precipitation characteristics in the Sahel at the local level has always been marred by a major error due to the dominant convective precipitation and the network of measurements, usually too loose (of the order from one to five posts per 10,000 km2) [25]. The case of the Ouaddaï area in eastern Chad illustrates this problem.

The forest and pre-forestry formations of this zone are located mainly in the shallows along the borders of the temporary watercourse beds and in some locations in the south where the precipitation is relatively greater [26]. These vegetation formations are therefore very vulnerable to water availability which decrease during the dry years and may explain, partly, the degradation of forest plant resources in the Ouaddaï area. However, no analysis of climatic variations at the local level has been undertaken.

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In this study, we analyze and determine the climatic characteristics of the Ouaddaï region in eastern Chad from complete data of two weather (rainfall) stations located in the town of Abéché, the capital of the Ouaddaï region and Genena on the Sudanese border. The specific objectives of this study are to: (i) determine trends in rainfall and temperature between 1950 and 2014; (Ii) detect rainfall shortages and temperature ruptures during 1950 - 2014 measurement period, using statistical tests; (Iii) Diagnose dry, normal, wet years and temperature anomalies between 1950 and 2014 by applying the standardized index.

Materials and Methods

Presentation of the Study Area

The study area is located between the 12°Nth – 15°N and the 20°E – 23°E and covers 29,980 km2 in eastern Chad over the entire region of Ouaddaï. It is bounded on the north by the Wadi-Fira region, on the south by the Sahelo-Sudanian area (Sila region), on the west by the Batha region and on the east by the Sudan (Figure 1). The population is estimated at 721,166 inhabitants [27] and is mainly composed of farmers and/or cattle breeders. This area has an estimated domestic livestock population of 2,119,020 heads of cattle; 5,361,870 heads of goats /ovines, 100,067 head, of camels, 131,247 head of equine and 413,589 heads of asins [28]. The zone belongs to the northern Sahelian phytogeographic domain characterized by a strong differentiation of plant formations ranging from the steppe to the savanna [29]. The perennial component is linked to the nuances of soil moisture regimes [30, 31]. *The Acacia ehrembergiana, Acacia Seyal, Balanites aegyptiaca* [29], *Acacia raddiana, Faidherbia albida* [32], *Ziziphus mauritiana, Grewia bicolor, Commiphora africana, Grewia villosa, Grewia tenax, Acacia senegal, Anogeisus leocarpus, Calotropis procera* [26].

The climate is generally characterized by a dry season from October to June and a rainy season from July to September. The annual rainfall is highly variable and varies between 220 mm and 400 mm from north to south and average monthly temperatures range from 24 °C to 33 °C [33].

Figure 1. Location of the study area and locations of rainfall stations in the Ouaddaï region (source: SIDRAT, NOAA).

Climatic data

The climatic data used for this study come from two meteorological stations (rainfall), namely that of the city of Abéché and that of the city of Geneïna located at the Sudanese border (Figure 1). These data were downloaded from the Daily Observations Data (NOAA) database (https://gis.ncdc.noaa.gov) and consist of rainfall data and daily temperatures from 1950 to 2014 for the station.

Analysis of the evolution of rainfall and temperature

The data was analyzed using the XLSTAT software (available for download at https://www.xlstat.com/en/download), which is an add-on for statistics and data analysis for Microsoft Excel. The quality control of the data was done in Microsoft Excel to detect erroneous data (negative precipitation, a maximum temperature lower or equal to the minimum temperature). Missing data were automatically completed by the XLSTAT software using the average replacement technique of the previous and next values [34].
Overall precipitation and temperature trends over the period 1950-2014 were visualized using graphical plots of annual mean time series (precipitation, maximum, mean and minimum temperatures) over time (years).

Detection of ruptures in rainfall series and temperatures

A "break" can be defined by a change in the probability distribution of the random variables whose successive realizations define the time series studied [35]. They make it possible to detect a variation of the average of the variable treated in the series [36]. The Pettitt [37] and Buishand [38] approaches were used to detect the break, and Fisher's two-way F, Levene, and Bartlett were applied to the variances to see if they were statistically identical.

The approaches of Pettitt, Buishand and the bilateral F tests of Fisher, Levene, and Bartlett are grouped in the XLSTAT software based on Microsoft Excel. The details of these posts are as follows:

- Pettitt's approach is nonparametric and derives from the Mann Whitney test. The absence of rupture in the series (Xi) of size N constitutes the null hypothesis. The implementation of the test assumes that for any instant t between 1 and N, the time series (Xi) i = 1 to t and t + 1 to N belong to the same population. The variable to be tested is the maximum in the absolute value of the variable Ut, N defined by:

$$U_{t,N} = \sum_{i=1}^{t} \sum_{j=i+1}^{N} D_{ij}$$

Where Dij = sgn (Xi-Xj) with sign (X) = 1 if (X)> 0; 0 if X = 0 and - 1 if X <0.
If the null hypothesis is rejected, an estimate of the break-up date is given by the time t defining the maximum in the absolute value of the variable U_ (t N).

-The Buishand procedure refers to the same model and assumptions as the Lee and Heghinian approach. Assuming a uniform a priori distribution for the position of the breakpoint t, the Buishand statistic is defined by:

$$U = \frac{\sum_{K-1}^{N-1} \left(\frac{S_k}{D_X} \right)^2}{N(N+1)} \quad \text{where} \quad S_k = \sum_{i=1}^{k} (X_i - \acute{X})$$

For $K = 1 \ldots \ldots.., N \; et \; D_X$ denotes the standard deviation of the series. In the event of rejection of the null hypothesis, no estimate of the break-up date is proposed by this test. In addition to this process, the construction of a control ellipse also allows to analyze the homogeneity of the series of (X_i). The variable S_K, defined above, follows a normal distribution of mean zero and variance $[K(N-K)\delta^2]/N, \quad K = 0 \ldots \ldots.., N$ under the null hypothesis of homogeneity of the Series of (Xi). It is therefore possible to define a confidence region called control ellipse associated with a confidence threshold containing the series of S_K.

Detection of dry, normal, wet and temperature anomalies

Measurement of the climatic evolution was made by the calculation of the Standardized Precipitation Index (SPI) [39]. This index is used to quantify precipitation deficits at different time scales. Its formula is as follows:

$$SPI = \frac{X_i - X_m}{S_i} \quad \text{where}$$

Xi is the cumulative rainfall for a year I;
Xm and S_i are respectively the averages and the standard deviation of the annual rainfall observed for given series.

For clarity, it is assumed that it is acceptable to consider [40] that:
One dry year: IPS <- 0.5;
A wet year: IPS> + 0.5.
A normal year: - 0.5 ≤ ISP ≤ + 0.5

Results

Evolution of annual rainfall and temperature (1950 - 2014).

The precipitation recorded by the Abéché and Geneïna stations from 1950 to 2014 shows a general downward trend. However, rainfall increases have been observed since 2000. The most severe decline was observed from 1964 to 2000, particularly in 1972-73 and 1983-1985 (Figure 2).

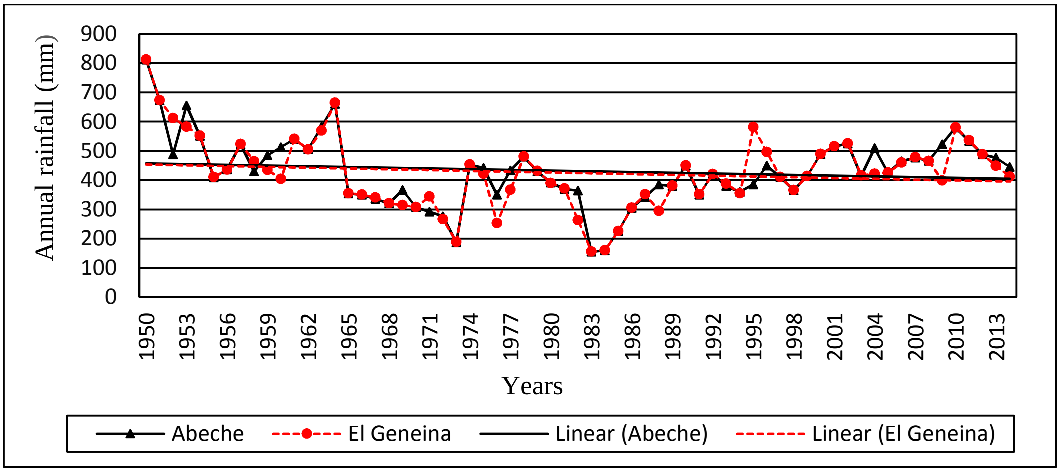

Figure 2. Variability of annual rainfall (mm) and trend lines from 1950 to 2014 at the Abéché station and that of El Geneïna (Ouaddaï region, Eastern Chad).

For temperature, the two stations studied show an upward trend in mean annual temperatures (maximal, minimal and average) (Figure 3 and 4).

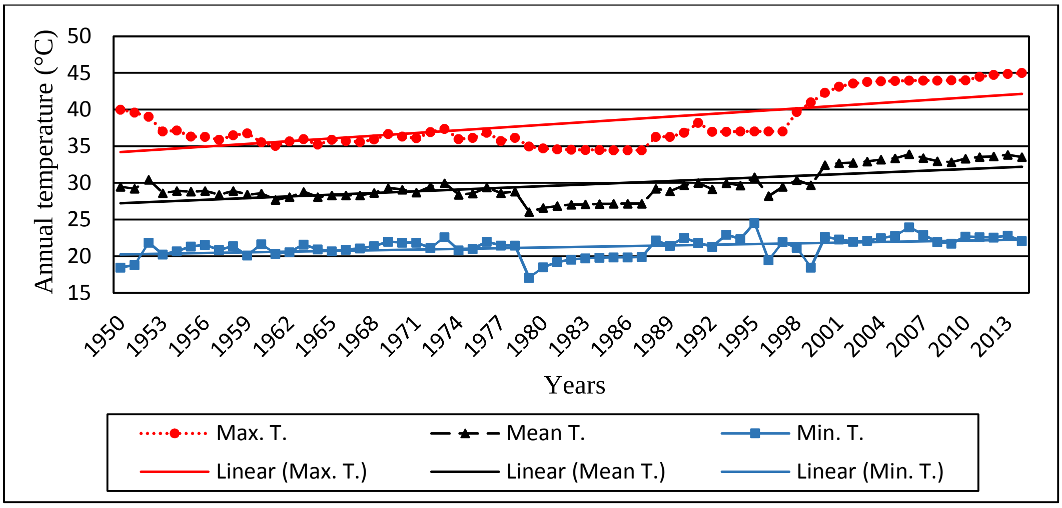

Figure 3. Annual (maximal, minimal and average) temperatures in (°C) between 1950 and 2014 at Abéché station (Ouaddaï region, Eastern Chad)

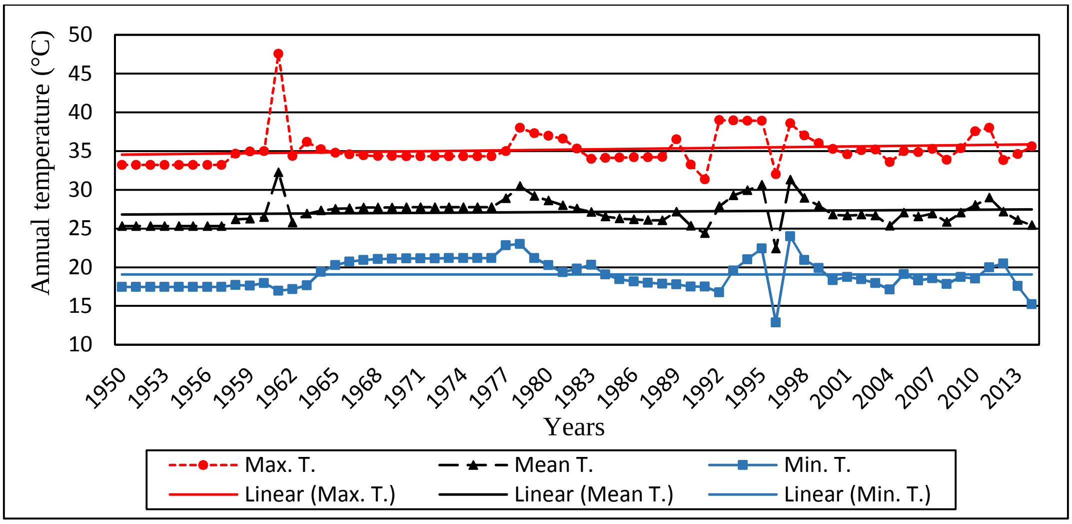

Figure 4. Annual (maximal, minimal and average) temperatures in (°C) between 1950 and 2014 at the El Geneïna station (Ouaddaï region, eastern Chad).

Ruptures of rainfall and mean annual temperatures

• Rupture of rainfall

According to randomness and normality tests, as well as the results obtained on the selected stations, it appears that the two selected stations recorded a downward trend and the breakdown, which was established in 1964 (Table 1, Figure 5 and 6).

Table 1. Levene, Fisher, and Bartlett tests (comparison of the variances between the data before and after the year of rupture).

Station	Pettitt test (year of break)	Buishand test (year of break)	Levene test Alpha = 0,05	Fisher F test Alpha = 0,05	Bartlett Alpha = 0,05	Reduction Rate %
Abéché	1964	1964	P= 0,72	P = 0,0001	P= 0,62	21
Geneïna	1964	1964	P= 0,76	P = 0,0001	P= 0,65	20

Thus, a significant decline in precipitation is observed between the years before and after the breaking year (1964). This statistically significant decline is -113 mm which corresponds to -21% rainfall for the Abéché station (Figure 5) and -106 mm corresponding to -20% rainfall for the Geneïna station (Figure 6).

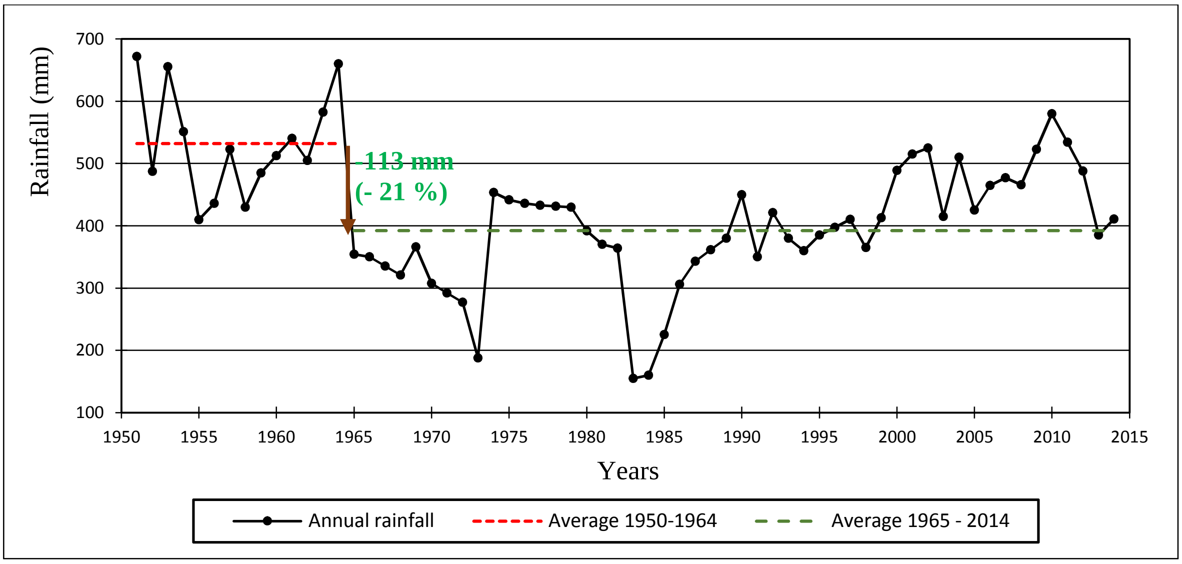

Figure 5. Rupture of annual rainfall (mm) between 1950 and 2014 at the Abéché station (Ouaddaï region, eastern Chad)

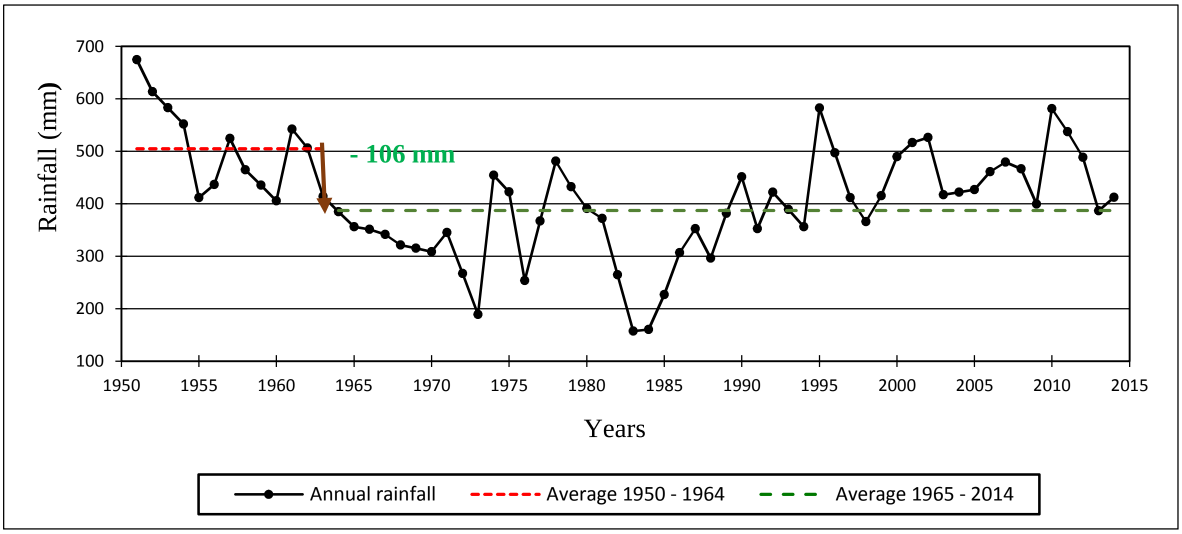

Figure 6. Rupture of annual rainfall (mm) between 1950 and 2014 at the El Geneïna station (Ouaddaï region, eastern Chad)

Average monthly precipitation

Precipitation Rainfall begins tentatively in May and June and sometimes extends to September, but a large amount of rainfall is concentrated in the two months (July and August) of each year from 1950 to 2014 (Figure 7). The temporal distribution of rainfall over the years remained the same before and after the year of rupture (Figure 7).

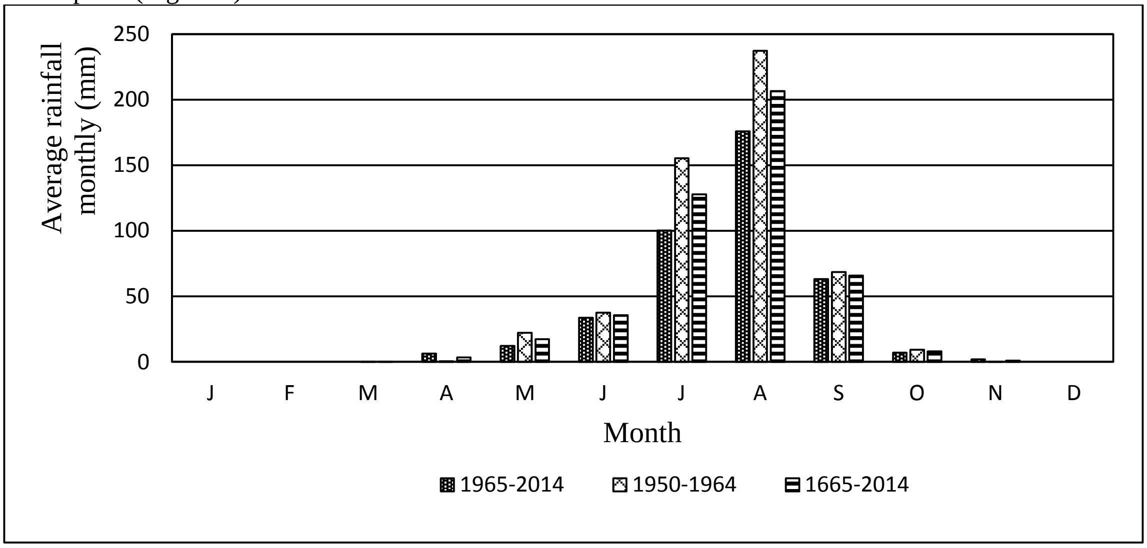

Figure 7. Distribution of mean monthly rainfall (mm) during the study period (1950-1964, 1965-2014 and 1950-2014 in the Ouaddaï Region, Eastern Chad.

- **Rupture of temperature**

During the study period, a break in average temperatures was observed in 1960 with an increase of 18% (Figure 8).

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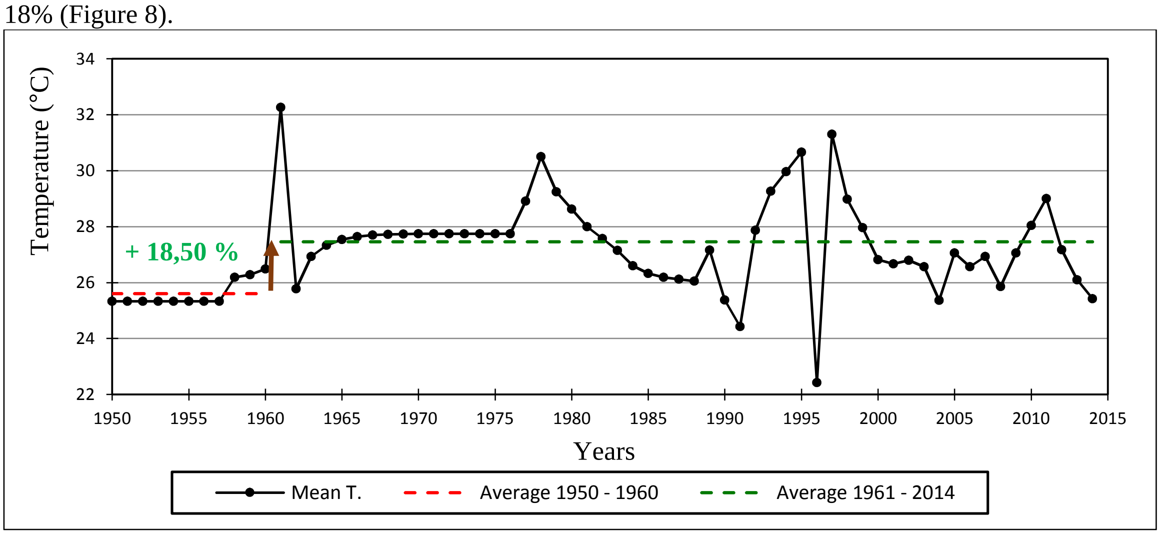

Figure 8. Annual average temperature (°C) breaks in 1960 during the period 1950 - 2014 in the Ouaddaï region (Abéché and El Geneïna, Eastern Chad).

- **Average Monthly Temperatures**

Two distinct warm periods come from this area in the year. The first warm period covers three months (September, October, and November). It is attenuated by the cold of the winter period from December to February. The second period, warmer than the first, covers three months (March, April, May) and ends only with the onset of the rainy season (Figure 8). The average monthly temperature varies from 15 to 40 °C.

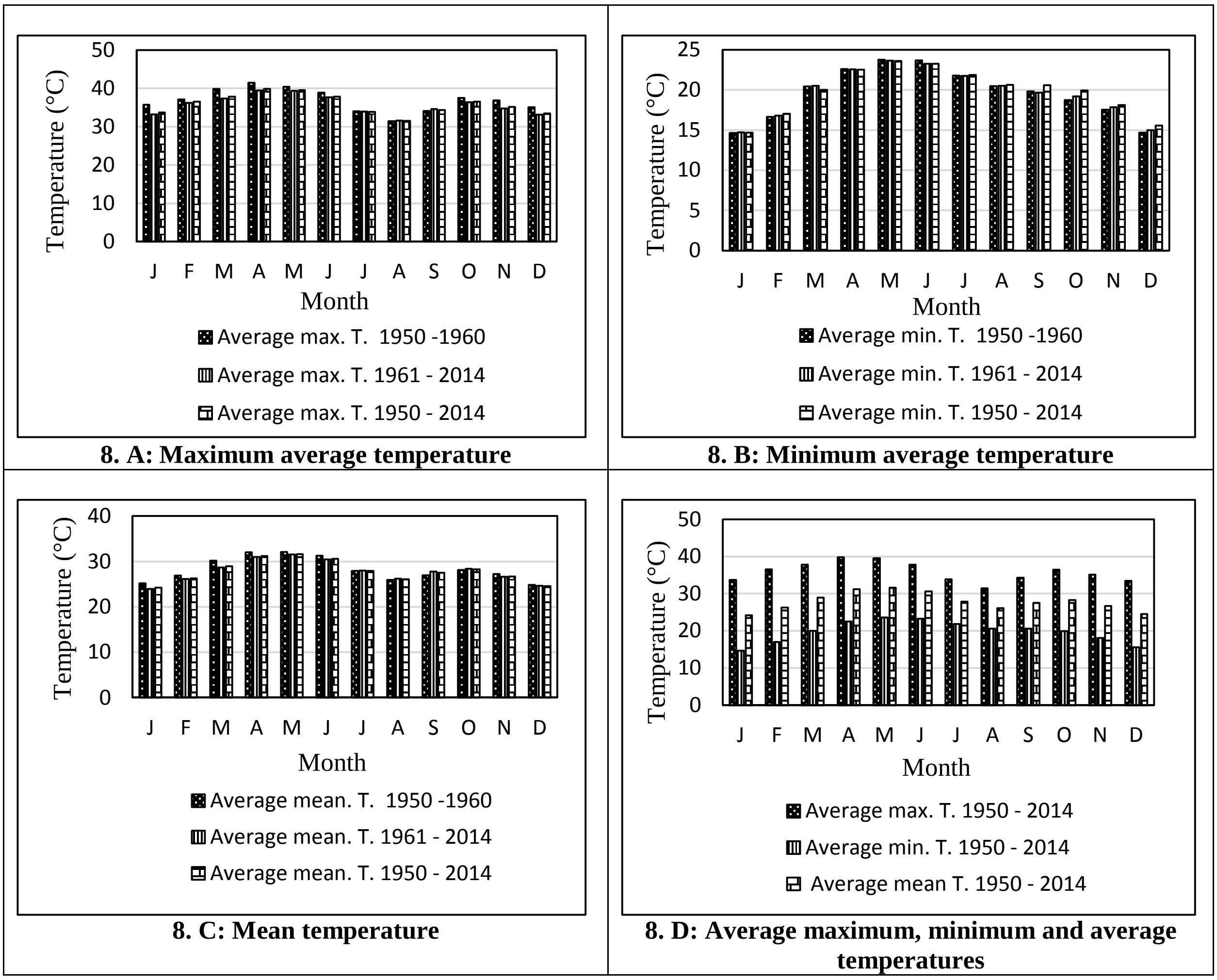

Figure 9. Mean monthly temperatures (°C) in the Ouaddaï region of eastern Chad.

Determination of wet, normal, dry years and temperature anomalies

• Dry, normal and wet years

There is generally an upward trend in annual rainfall over the period from 1950 to 1964 (Figure 7), a downward trend from 1965 to 1994, followed by a rainfall increasing from 1995 to 2014 (Figure 10).

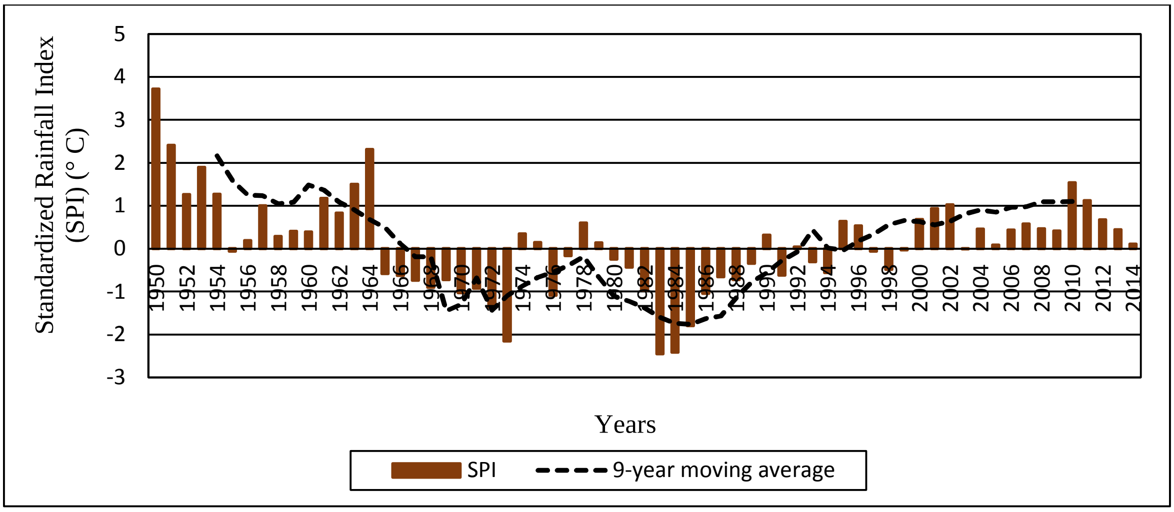

Figure 10. Standardized Rainfall Index (SPI) in the Ouaddaï region (eastern Chad) over the period 1950-2014

The figure (10) shows three phases of rainfall:

- a wet phase beginning in the 1950s (IPS> + 0.5) and ending in 1964;
- a dry phase which follows the wet period from 1965 to 2000 (IPS <- 0,5); and

- a mixing phase of normal and wet years from 2000 and continues to this day.

Comparing the number of dry, wet and normal years before and after rupture (1964), a very significant increase (+ 40%) is observed in the number of dry years after the break, (-51%), and a slight increase in the number of normal years (+ 12%) (Figure 11).

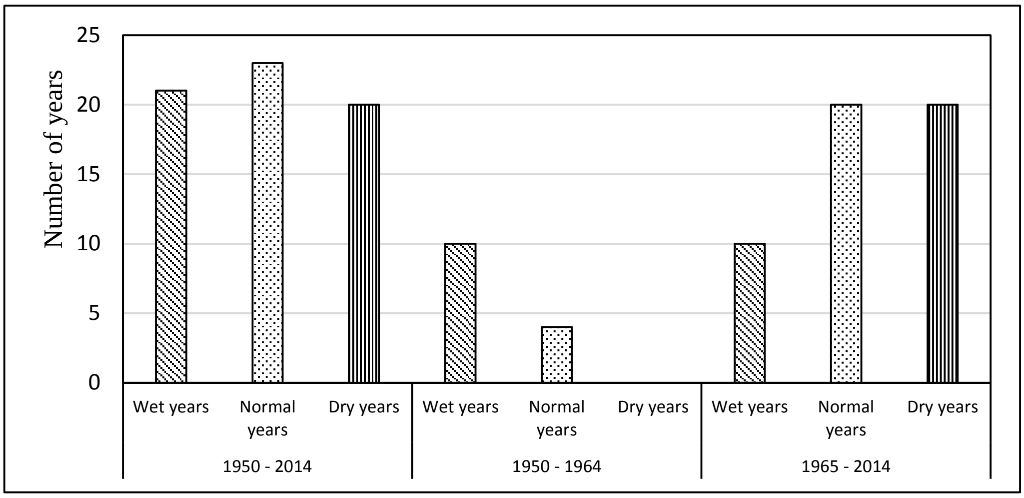

Figure 11. Number of dry, wet and normal years in the Ouaddaï region before and after the 1975 break.

• **Anomalies of average annual temperatures**

The results show that from 1950 to 1992, the temperatures remained normal and the increase has been observed since 1992. Since 1992, the temperature has continued to increase until today (Figure 12). Thus, the past 25 years are considered as hottest years. The moving averages centered on 9 years shows a significant increase in temperature since 1992.

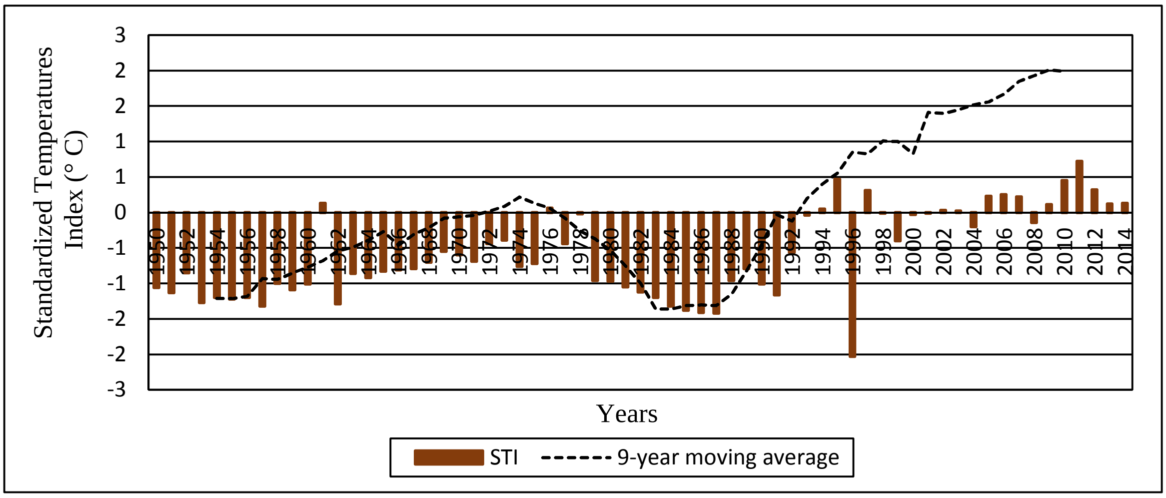

Figure 12. Interannual Evolution of Average Annual Temperature Anomalies in the Ouaddaï Region (Chad), 1950-2014.

The results show that from 1950 to 1992, temperatures remained around average and the increase has been observed since 1992. Since 1992, the temperature has continued to increase until today (Figure 12). Thus, the last 25 years are considered the hottest years. The 9-year moving averages show a significant increase in temperature since 1992.

Discussions

Precipitation and temperature trends from 1950 to 2014 for the Ouaddai region (Chad) revealed a decrease in precipitation associated with rising temperatures as a general overview. However, the upward trend in rainfall has been observed since 2000 after a significant fall in 1964 of about 20%. The same decline in precipitation rates was observed in a study in Niger with the difference that the break was in 1967 [41]. The same study shows an increase of + 18% in rainfall since 2004. [42] Since 1950, West Africa is the region of the world with the largest rainfall deficit. Several authors have tried to explain this decline in recent decades. [16] The decline in precipitation is due to the low monsoon circulation. For Nicholson [20], these precipitation fluctuations can be explained by many other monsoon and ITCZ paradigms that have emerged. These include the characteristics of the upper atmosphere, as well as the Saharan heat. Being at the door of the Sahara, the drop-in precipitation in our study area could also be explained by this parameter. According to the same author, the role of the effects of the earth's surface on convection is also increasingly demonstrated. N'Datchoh et al., [23] have shown that hatching of mineral dust particles in the African atmosphere can interact with the main West African Monsoon (WAM) circulation, which turn could induce changes in key features.

The calculation of the standardized rainfall index made possible to distinguish a wet phase before 1964, a dry phase from 1965 to 2000 and another phase with alternating normal and wet years from 2000 to the present. These dry and wet phases are observed by several authors in the study of precipitation in the Sahel and in non-Sahelian western and central Africa [40, 41, 43]. Beyond the Sahel, in the Maghreb, studies of recent rainfall regimes in Morocco between 1935 and 2004 highlighted these phases [44] and also in Algeria [45]. On the other hand, a study conducted in West Africa between 1950 and 1990 showed a longer wet phase from 1951 to 1970 and a dry phase from 1971 to 1990 [17]. This rainfall deficit during the dry years can be explained by a general decrease in the rate of rainfall occurrence [46].

At the temperature level, the rupture occurred since 1960 and the warmest years are observed from 1992 and which persists until today. These observations are in line with the IPCC's view of global warming in recent decades [5].

It is clear from this study that there has been a prolonged decreasing tendency phase in rainfall from 1965 to 2000. During this rainfall decreasing phase, severe droughts from 1972 to 1973 and from 1983 to 1984 were observed [12, 47]. Throughout the study period (1950-2014), a variation in precipitation and temperature were noticed. However, the total yearly rainfall less in the Ouaddaï region. Rainfall usually begins in June and ends in September. Corresponding to the rainy season in the northern Sahel [24]. The average monthly temperature varies from 15 to 40 °C, which is well above the national average of 20 to 33% [33].

It is clear from this study that a period of decreasing rainfall was observed between 1965 and 2000. The drought episodes from 1972 to 1973 and from 1983 to 1984 [12, 47] known the Sahel belong to this interval. Throughout the study period (1950-2014), a variation in precipitation and temperature was observed. However, total annual precipitation is lower in the Ouaddai region. Precipitation usually starts in June and ends in September which corresponds well to the rainy season in the northern Sahel [24]. There is no change between the years before and after the break from the temporal distribution of rainfall. Nevertheless, Nicholson [20] reports that the contrast between conditions in the east and west of the Sahel is becoming stronger. The peak month seems to have moved from August to July in the western Sahel. The non-observation of the displacement of the peak month in our study can be explained by the fact our study area is almost in the middle. As a result, it is neither in the East nor in the West of the Sahel. The average monthly temperature ranges from 15 to 40 °C, which is well above the national average of 20 to 33% [33].

After the rains fell in 1964, the number of dry years increased by 40%, associated with 40% of rainy years and 20% of normal years. This recrudescence of dry years and the significant decrease in wet years confirms that wet years have not yet returned to the Sahel Ozer and Ozer [41]. Which means that the rains of the 1950s are not yet reached.

Conclusion

While the entire Sahel experienced two severe droughts between 1972-1973 and 1983-1984, the study of climatic patterns in the Ouaddai region of eastern Chad revealed a prolonged period of dry years between 1964 and 2000 associated with a continuous rise in temperatures. After 1964 precipitation decreased by an average of 100 mm and the temperature increased by 2 °C on average after 1960. Being the two most important climatic parameters in the Sahel, the results obtained could be used to understand the impact of the climate on agricultural, pastoral and forest ecosystems.

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