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# Identification of Rainfall and Temperature Trends in the Context of Climate Change for the Towns of Bol, Fianga, Moundou and N'Djamena in Chad

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***Abstract***

*Climate change, characterised by extreme weather events, is one of the most serious threats to sustainable development, with expected adverse effects on human health and food security. Chad, which is half arid, is more than threatened by these increasingly frequent extreme hydrometeorological events, which will weaken its economy and have a negative impact on public health. The aim of this study is to identify rainfall and temperature trends in the context of climate change in the study area, which is made up of four (4) towns (N'Djaména, Bol, Fianga and Moundou) that are representative of Chad. They are divided according to bioclimatic zones, i.e. two in urban areas and two in rural areas. The selection criteria were based on previous malaria and cholera epidemiological situations. Of the 4 towns selected, two are considered to be endemic and at risk, and the other two are those that rarely experience epidemics. In situ observation data from observation stations in the study area will be used to identify obvious signals of climate change. To this end, an analysis of changes in annual precipitation and temperature over the last four (4) decades (1980-2023) was carried out before and after the detected break using statistical tests, as well as a trend and variability analysis of precipitation and extreme temperature indices.The results show that over the last few decades, there has been a change in the precipitation regime in terms of frequency and intensity at all sites.This general downward trend over the 1981-2020 series is linked to the extremely severe droughts of the 1980-1990 and 1990-2000 decades, marked by the El Niño phenomenon of 1983/1984 and a statistically significant increase in temperatures.The study thus contributes to modelling efforts to better predict the resurgence of climate-sensitive diseases.*

***Keywords****: Chad, Extreme Hydrometeorological Events, Rainfall, Temperature, Trend.*

## Introduction

Climate change is considered as one of the greatest threats to sustainable development and livelihoods of the people in developing countries, with adverse effects expected on human health, food security, economic activity, natural resources, and infrastructure [1]. The sixth report of the Intergovernmental Panel on Climate Change (IPCC) [2] predicts an accelerated warming of more than 1.5˚C over the next few decades, which will be beyond the global limit of 1.5˚C warming.

Sub-Saharan Africa is the most vulnerable region in the world to climate change. Rising temperatures, sea-level rise, and rainfall anomalies increase the frequency and intensity of natural disasters such as devastating cyclones, locust invasion in East Africa, and the desertification in the Sahel [3].

Landlocked Sub-Saharan country, Chad covers an area of 1,284,000 km2 with more

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than half being arid. It is more threatened than ever by the negative effects of climate variability and change, characterized by an increase in intensity and frequency of extreme weather events, including floods, droughts and heatwaves, as evidenced by the severe floods in recent years that have caused material damage and loss of human life [4, 5].

Highlighting these changes can only be achieved through analysis of climatic data at the local scale or high resolution, whereas IPCC studies are often conducted at large scale of 2.5° by 2.5, equivalent to approximately 250 km by 250 km [6]. Such a resolution does not allow for appreciation of the evolution of climatic parameters at a local scale, even if in recent years, other studies have been conducted at finer scales, with a grid of 0,5° by 0,5° (or 50 km by 50 km), but again, this grid is too large for our studies. Several studies have relied on these large-scale data for localised vulnerability analyses, leading to biased results, hence the need to use observed data for optimal results. Moreover, the variability and trends of precipitation and temperature at the local scale are of great importance for assessing their impacts on the evolution of climate-sensitive diseases and population vulnerability [7,8] . This situation therefore justifies the need to highlight the evolution of temperatures and precipitation, the main meteorological parameters characteristic of climate change.

The objective of this article is to carry out a localised detection of climate change at the stations of Bol, Fianga, Moundou, and N'djamena using appropriate indicators. The work will extend the analysis of [9;10] on extreme climate indices in Chad. To accomplish this, four key indicators have been chosen for examination: anomalies (both deviation and percentage), normalized indices, extreme climate indices, and trends in precipitation, as well as maximum and minimum temperatures.

## Context, Data and Methods

### Presentation of the Study Area

The study area consists of four (4) cities distributed across the bioclimatic zones of Chad, including two rural areas. These cities are Bol, Fianga, Moundou, and N'djamena. The selection criterion is based on previous epidemiological situations of malaria and cholera. Among the four target cities, two are considered endemic and high-risk areas, while the other two rarely experience epidemics [11]. Cholera and malaria emerge during the period from July to September considered to be the heart of the rainy season (see Figure 5). Moundou and Fianga are two cities located in the Sudanian zone. Moundou is recognised as an area where malaria is endemic, while Fianga is recognised as a cholera hotspot. For the Sahelian zone, the choice is focused on N'djamena, a city recognised as a hub for malaria epidemics, while Bol is recognised as a hub for cholera epidemics. The choice also considers the differences in socio-economic conditions between urban and rural areas. Another reason that justifies the choice of the study area is the availability of climate data.

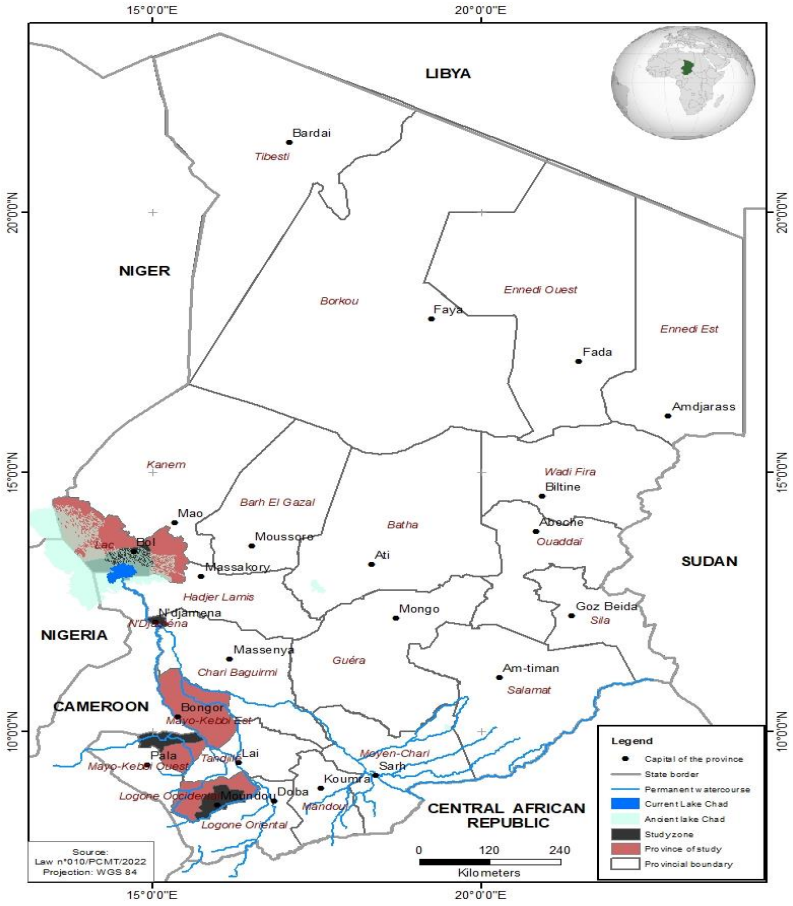


**Figure 1**. Map of Chad Including the 4 Towns in the Study Area

## Geographical Characteristics of the City of Bol

The city of Bol is located on the shores of Lake Chad, 153 km north of the capital city, in the Sahelian zone of Chad, between 13° 27' 31'' North latitude and 14°42' 53'' East longitude (see Figure 1). Its desert climate is dry and hot. The city of Bol is the capital of the Lake Province and the Mamdi Department. It has around 15,000 inhabitants.

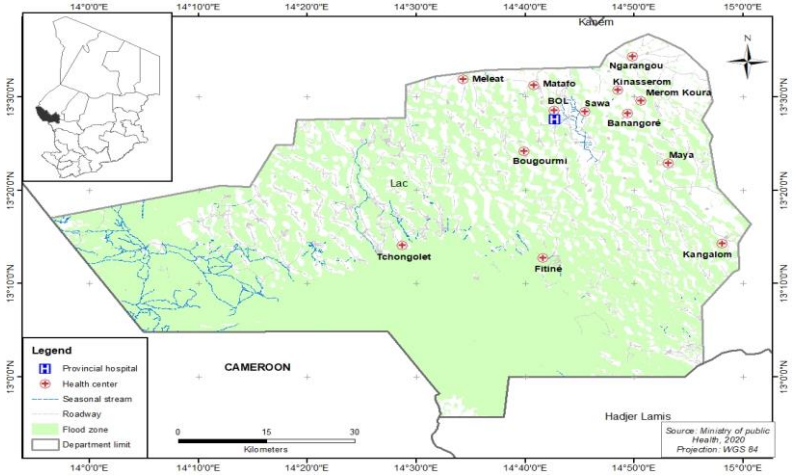


**Figure 2**. Geographic Location Map of the City of Bol

## Geographical Characteristics of the City of Fianga

The city of Fianga is located approximately 8 km from Lake Fianga, at a latitude of 9° 54′ 55″ North, a longitude of 15° 8′ 15″ East (see Figure 2 below), and an altitude of 339 meters. Fianga has a hot and slightly humid climate. Over the year, the average temperature in Fianga is 30,6°C and the average rainfall is 890.6mm (Table 1). As the capital of Mont Illi Department in the Mayo-Kebbi East province, Fianga has a population of approximately 17,000 inhabitants as of 2020.

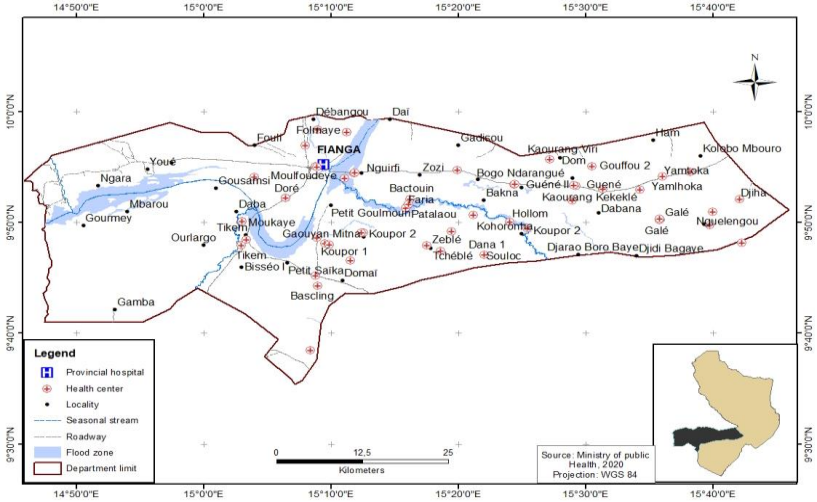


**Figure 3**. Geographic Location of the Town of Fianga and the Number of Inhabitants

## Geographical Characteristics of the City of Moundou

Located at the latitude of 8°34′00″ N, a longitude of 16°04′59″ E (see Figure 3), and an altitude of 401 meters, Moundou is the second city and economic capital of Chad. The city is belt on the left bank of the Logone River, near Lake Wey, which poses a flooding threat to the city. As the capital of Logone region and the Lake Wey department, Moundou has a population of approximately 200,000 as of 2020.

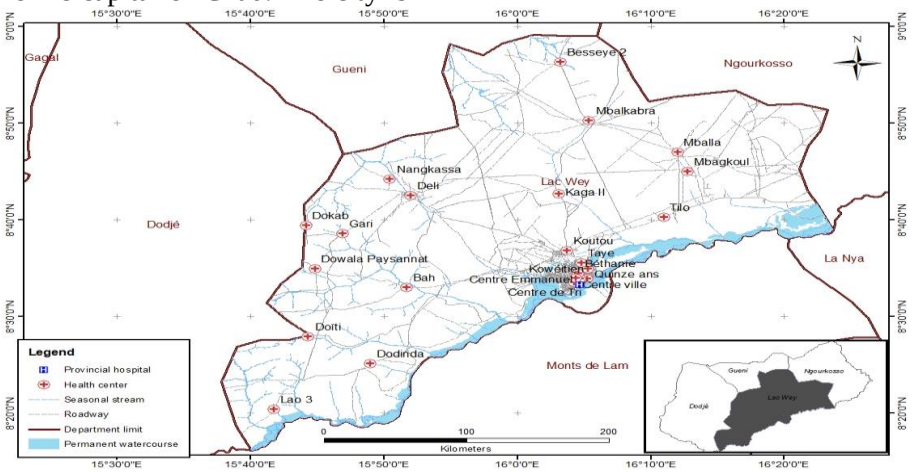


**Figure 4**. Geographic Location Map of the City of Moundou.

## Geographical Characteristics of the City of N'Djamena

Located at a latitude of 12° 07' N; a longitude 15° 03' E (Figure 4), and an altitude of 295 meters in the Sahelian zone, the city of N'djamena is the capital city of Chad, at the confluence of the Chari and Logone rivers. N'djamena is the only major city in a poorly urbanized country. It experiences an arid climate with a 9-month dry season, while the humid season lasts for 3 months (from July to September). The cumulative annual rainfall is less than 500 mm (Table 1) per year

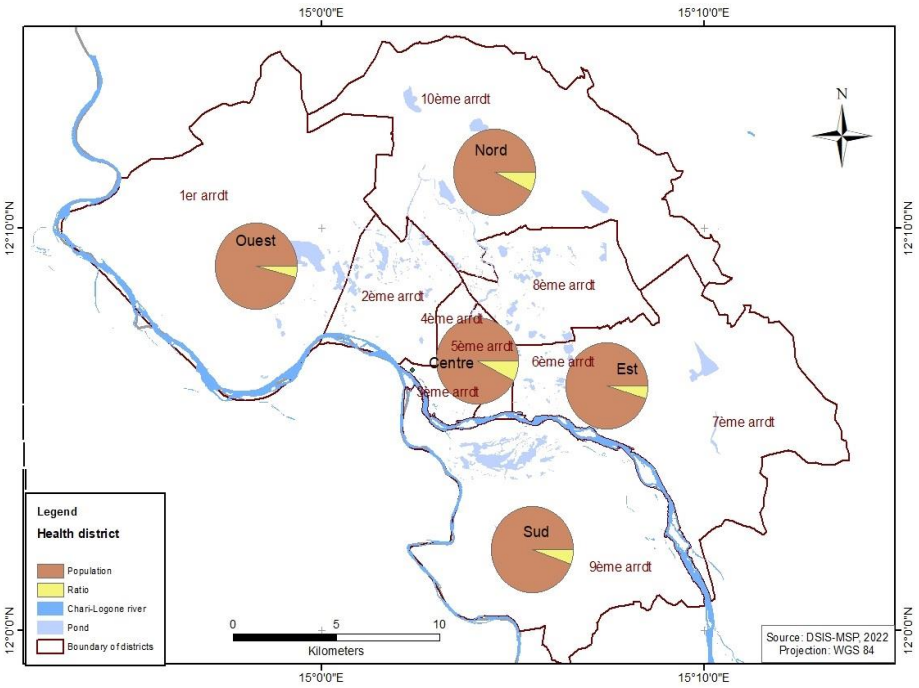


**Figure 5**. Geographic Location Map of the City of N'djamena

**Table 1**. Presentation of the Weather Condition of the Study Area (Bol, Fianga, Moundou, and N'djamena): Values of Averages and Standard Deviations of Minimum, Maximum and Average Temperatures, Rainfall and Relative Humidity

| Station | Maximal temperature (°C) | | Minimal temperature (°C) | | Mean temperature (°C) | | Annual rainfall average (mm) | | Relative humidity (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Average | SD | Average | SD | Average | SD | Average | SD | Average | SD |
| **Bol** | 42 | 2.3 | 22.4 | 1.8 | 29.5 | 2 | 231 | 1.9 | 31 | 7 |
| **Fianga** | 36.5 | 4.3 | 13.1 | 3.2 | 30.6 | 5.6 | 890.6 | 92 | 49.5 | 28.3 |
| **Moundou** | 36 | 4.3 | 12.6 | 3 | 27.5 | 1.1 | 1040 | 104 | 58 | 23 |
| **NDjamena** | 44 | 3.6 | 22 | 4 | 29 | 3.8 | 548 | 6 | 39 | 25 |

**NB :** SD : standard deviation

## Data

The data of this study come from the climatological database of the National Meteorological Agency of Chad. These are daily and monthly precipitation and temperature data from the stations under discussion from 1981 to 2020 (40 years). However, resource to reanalysis data was necessary to compensate for the missing data. The reanalyses provided datasets combining

satellite and station observation data, particularly useful for climate studies [12].

The reanalysis data used are those of the ARC2 model with a 10 km (0,1°x 0,1°) spatial resolution produced by the Climate Prediction Centre (CPC) of the National Oceanic and Atmospheric Administration (NOAA) [13] The use of these data was validated by comparing them with observed data to retain datasets close to real data. The quality of the data was then evaluated by filling in missing data with median values and eliminating aberrant data easily detected by the Rclimdex software.

## Analysis methods

To determine the extent to which human activities have disrupted the climate system, climatologists have developed processes for detecting and attributing climate change. Detection involves showing that the climate has changed in a statistically significant sense, without giving the reason for the change [14]. It is therefore a matter of statistically justifying the existence of a real change, as opposed to a "normal" climate fluctuation. Moreover, we have on one hand studied the evolution (variability and trend) of annual precipitation and temperatures before and after the break detected by statistical tests and on the other hand, we have analysed the trends and variability of extreme precipitation and temperature indices.

For the analysis of interannual rainfall variability, we used Nicholson's method [15], which made it possible to identify the periods of dry and humid years at each station. It is defined as a centered and reduced variable expressed by the equation [16]

$$I = \frac{Xi - \overline{X}}{\sigma}$$

With $Xi$: variable for year i, $\overline{X}$: average of variable over the studied period, and $\sigma$: standard deviation of the variable over the period under study. The centered and reduced 5-year moving average was applied because it reduces small internal fluctuations and highlights the major trends of rainfall indices.

The approach adopted in this study to analyse extreme rainfall and temperature events is that of climate indices [9, 17, 18]. It was proposed by the team of expert on climate change detection and indices (ETCCDI) using the ClimPACT 2 master program generated with RCLIMDEX software.

In this study, 7 indices were retained, including 5 characterising extreme rainfall are presented in Table 2. These include the amount of total annual rainfall (PRCPTOT), daily rainfall intensity (SDII), the number of days of heavy rain (R20), the total amount of annual on very humid days (R95p) and the percentage of total annual rainfall on very humid days (R95pTOT).

For temperature extremes, 2 indices namely TX90p and TN90p were retained, representing the percentage of climatologically hot days and nights, respectively. The choice of these indices is justified by the fact that they are the most relevant to highlight the extent of climate variability and change and the evolution of floods in terms of frequency and intensity of floods as factors of proliferation of malaria and cholera vector agents.

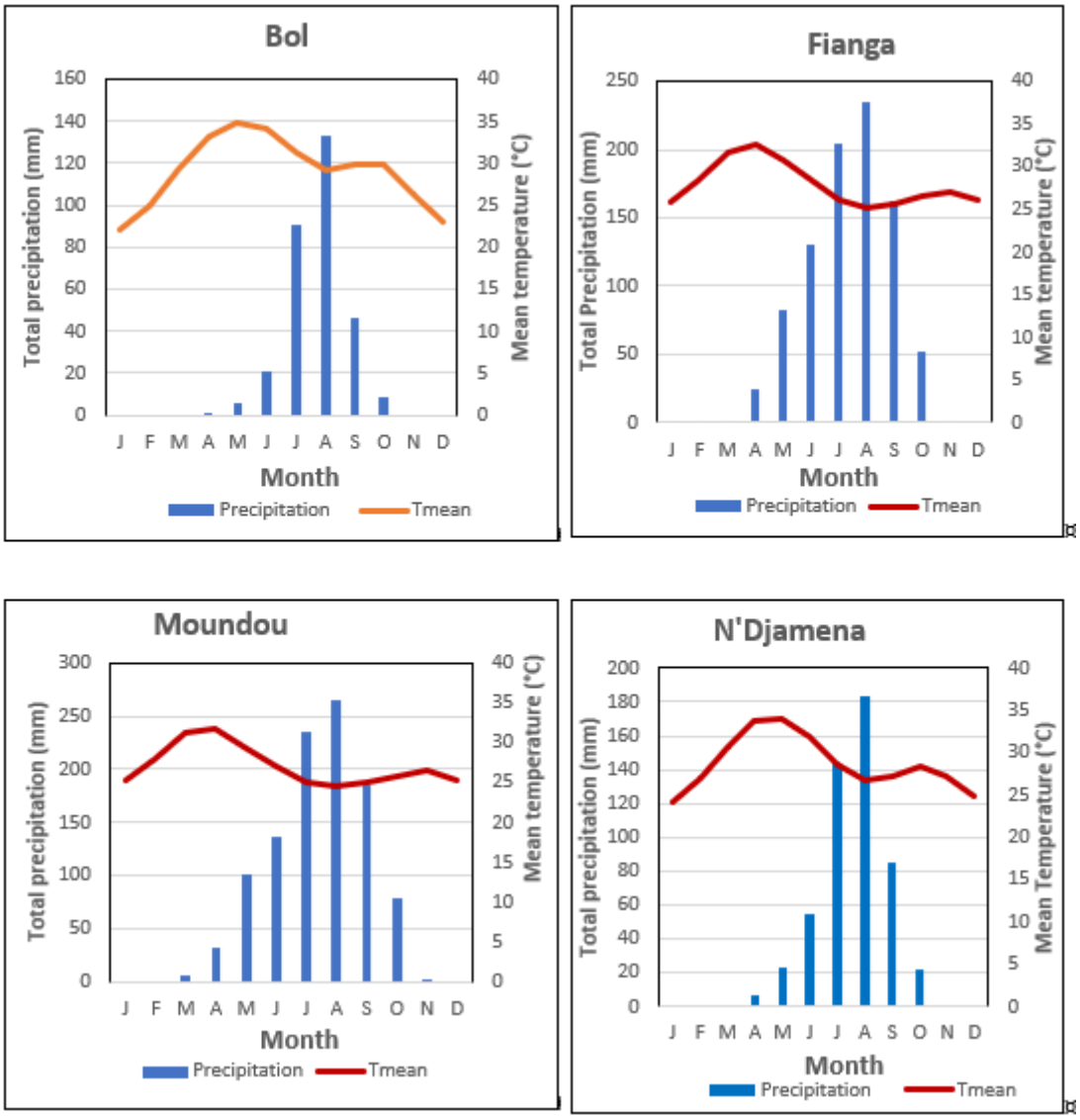


**Figure 6**. Annual Cycle of Precipitation Regimes and Average Temperatures (1981-2020) of the Cities of Bol, Fianga, Moundou and N'Djamena

**Table 2**. Description of Extreme Rainfall and Temperature Indices

| Indices | Description | Definition | Unity |
|---|---|---|---|
| **PRCPTOT** | Total annual precipitations on rainy days | PRCP annual total on wet days (RR>=1mm) PRCPTOT is expressed as percentage changes relative to the pre-industrial reference period 1861–1880.j | Mm |
| **SDII** | Simple index of precipitation intensity | Let RRwj be the daily volume of precipitation recorded on rainy days, w (RR ≥ 1mm) of period j. If W represents the number of rainy days of j | Day |

| | | | |
|---|---|---|---|
| **R20mm** | Annual number of days where precipitation ≥ 20mm | Let RRij be the daily volume of precipitation recorded on a day i of period j.Count the number of days where: RRij ≥ 20mm | Day |
| **R95p** | Annual PRCP total when RR > 95th percentile | RRwj the daily volume of precipitation recorded on arainy day, 'w', (RR ≥ 1.0mm) of period i, and RRwn95 the 95th percentile for precipitation recorded on rainy days during the reference period 1981-2010. | Day |
| **R95PTOT** | Percentage of total annual rainfall amounts on very humid days | Let RRwj be the daily volume of precipitation recorded on a rainy day, 'w', (RR ≥ 1.0mm) for the period (1981-2010), and RRwn95 the 95th percentile. R95pTOT=100 x R95p/PRCPTOT | % |
| **TN90P** | Percentage of days where TN> 90th percentile | Percentage of climatologically warm nights (Minimum temperatures above the last decile (daily decile calculated over 5 consecutive days). | % |
| **TX90P** | Percentage of days where TX > 90th percentile | Percentage of climatologically hot days (days where the maximum temperature is above the last decile (daily decile calculated over 5 consecutive days). | % |

To highlight the chronological variability of precipitation, maximum and minimum temperatures at each station, we proceeded to detect breaks within the series then analysed their evolution, general trend and their significance. Breaks in the data series were detected using statistical tests of Pettitt and the segmentation method of Hubert [19, 20, 21], which made it possible to detect potential changes in precipitation patterns and temperatures. These tests are grouped together in the Khronostat software developed by the Research Institute for Development (RID) and the University of Montpellier [22]. The annual trend was identified using the linear regression method [23]. The evolution of statistical significance was performed using the Mann-Kendall criterion [24] . This non-parametric test looks for the presence of a long-term trend in the data. In order to validate this trend, the probability, p-value, was then evaluated, which expresses the strength of the evidence for or against this hypothesis (the trend is accepted with a p-value < 0,05 considering a 95% confidence level).

## Results

### Analysis of the Evolution of Precipitation Indices

Figure 6 shows the interannual variability of rainfall through standardized values (anomalies) over the 1981-2020 data series of rainfall from the N'djamena, Moundou, Fianga, and Bol stations. The application of the segmentation method of Hubert and Paturel [25] on the 1981-2020 rainfall series detects

break points for the four locations in the following years: Bol in 1995, Fianga in 1984, Moundou in 2010 and N'Djamena in 1996. Except for Fianga, which had a highly variable rainfall pattern with a downward trend, all other locations experienced a trend of increasing precipitation conditions during the decade 2010-2020, particularly during the last 4-5 years (2015-2020). Overall, there was an alternation of dry and wet years after the 1980s, marked by an extremely severe drought episode of about 5 consecutive years.

The Bol location experienced three periods from 1981-1995 marked by high variability, followed by a persistent drought period from 1996 to 2010 (Figure 6d) with a 17% decrease (see Table 3) in precipitation compared to the average. During the period from 2011 to 2020, a return to excess precipitation conditions was observed. The locations in N'djamena (figure 6a), Moundou (figure 7b) and Fianga (figure 6c) experienced strong variability with a general upward trend, even if they are not statistically significant except in the N'djamena station where the trend is significant at the 5% threshold after a Mann-Kendall test. The localities of N'Djamena, Moundou et Fianga recorded rainfall surpluses of approximately 31,5%, 8% et 23,8% (Table 3) during the 2010-2020 period, with episodes of heavy rainfall during the last 5 years (2015-2020) in N'Djamena and Moundou. This situation could explain the severe flooding of 2020, which affected 87% of the national territory.

This study is a step towards integrating the climate change dimension into the national public health policy on malaria and cholera epidemics. The aim is to help set up a climate-health model for monitoring these epidemics, based on meteorological parameters. At the end of the study, opportunities for climate-health research into meningitis will also be explored.

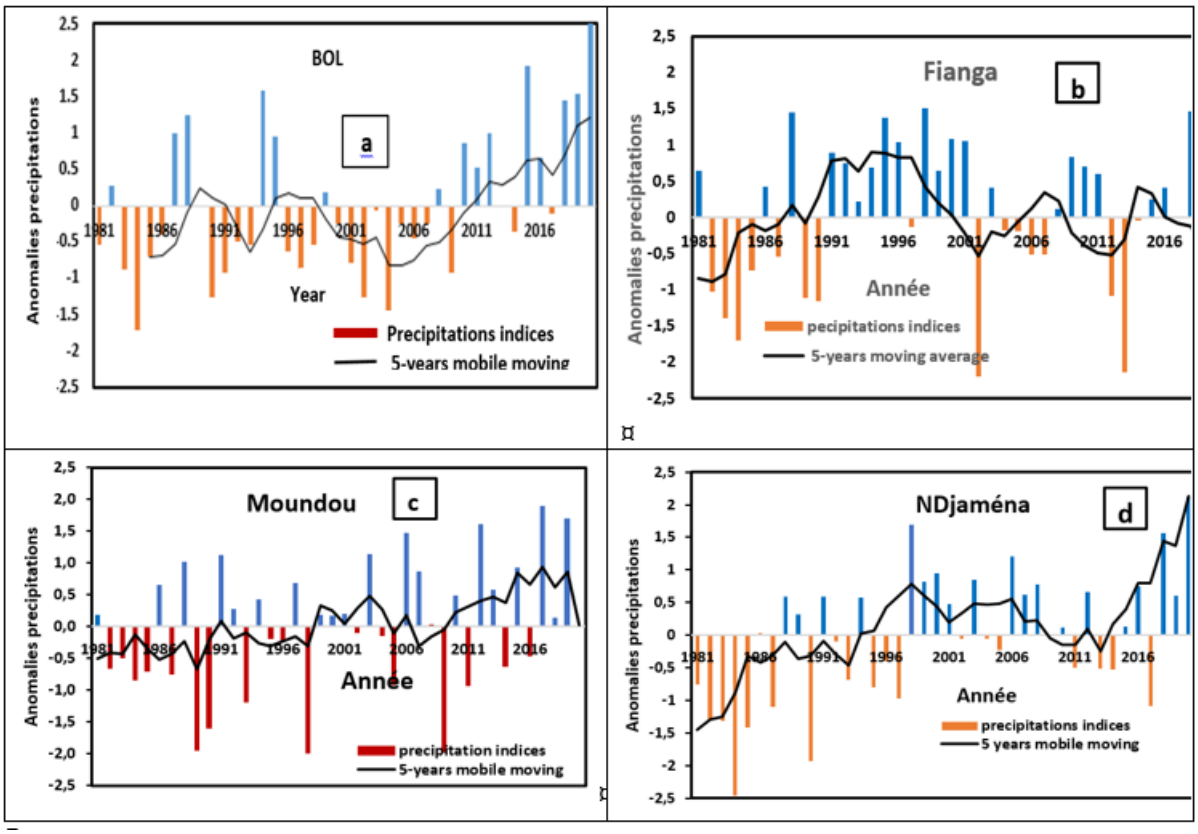


**Figure 7**. Interannual evolution of the standardized rainfall index (blue and red color) and moving average (curve in black color in the localities of Bol(a), Fianga(b), Moundou (c) and N'Djamena (d)

**Table 3.** Evolution of Rainfall before and after the Break Years Obtained by the Pettitt Test and Rate of Variation of Localities (Bol, Fianga, Moundou and Minimum Temperatures N'djamena)

| Locality | Period before rupture | Period after rupture | Average before rupture | Average After rupture | Rate of change |
|---|---|---|---|---|---|
| **Bol** | 1981-1995 | 1996-2020 | 211.7 | 174.9 | -17.4% |
| **Fianga** | 1981-1984 | 1985-2020 | 683.6 | 846.1 | 23.8% |
| **Moundou** | 1981-2010 | 2011-2020 | 1014.2 | 1100.9 | 8.0% |
| **N'Djamena** | 1981-1996 | 1997-2020 | 464.9 | 611.4 | 31.5% |

## Analysis of Extreme Temperature Evolution

The annual averages of maximum and minimum temperatures for the study area were calculated using the 1981-2020 data series. These averages are represented in the graphs of figures 7 and 8. Both variables, minimum temperatures (Tmin) and maximum temperatures (Tmax), have increased during the period under review. West and Central Africa are particularly threatened by climate change. This increase is significant at 5% level using the Mann-Kendall test (see Figures 7 and 8). In general, it can be seen that minimum temperatures have increased more than the maximum temperatures in all the studied locations and in a linear manner, while the maximum temperatures experienced variability from one decade to another (see the temperature maps of N'Djamena and Moundou). A particular increase in both minimum and maximum temperatures is noted during 1997-2007 period.

## Analysis of Minimum and Maximum Temperatures at Bol and N'Djamena Stations (Sahelian zone of Chad)

From the Pettitt test carried out on the minimum and maximum temperature data series at Bol and N'djamena stations from 1982 to 2020, two years of rupture (1995 and 1996) were identified for minimum and maximum temperatures respectively, at the Bol station, with two sub-periods (sub-series) for minimum temperatures from 1982 to 1989 and 1990 to 2020, and for maximum temperatures from 1981 to 1996 and 1997 to 2020. The minimum temperature values varied from 18,2 to 19°C (an increase of 1.2 °C), and the maximum temperature values varied from 39.9 to 40.7°C (an increase of 0.8°C). These trends were confirmed by the Mann-Kendall test result, which highlighted the significance of the trend at 5% level. The minimum temperatures at N'djamena varied from 21.4 to 22.2°C (an increase of 0.7°C) during the periods 1982-1996 and 1997-2020. Meanwhile, the maximum temperatures experienced an increase of 1.7°C between 1981 and 2007, followed by a decrease of 1°C during the period 2008-2020. However, the trend of maximum temperatures over the entire series from 1981 to 2020 is upward, with an increase of 0.7°C, and is significant at 5% level using the Mann-Kendall test (Figure 7).

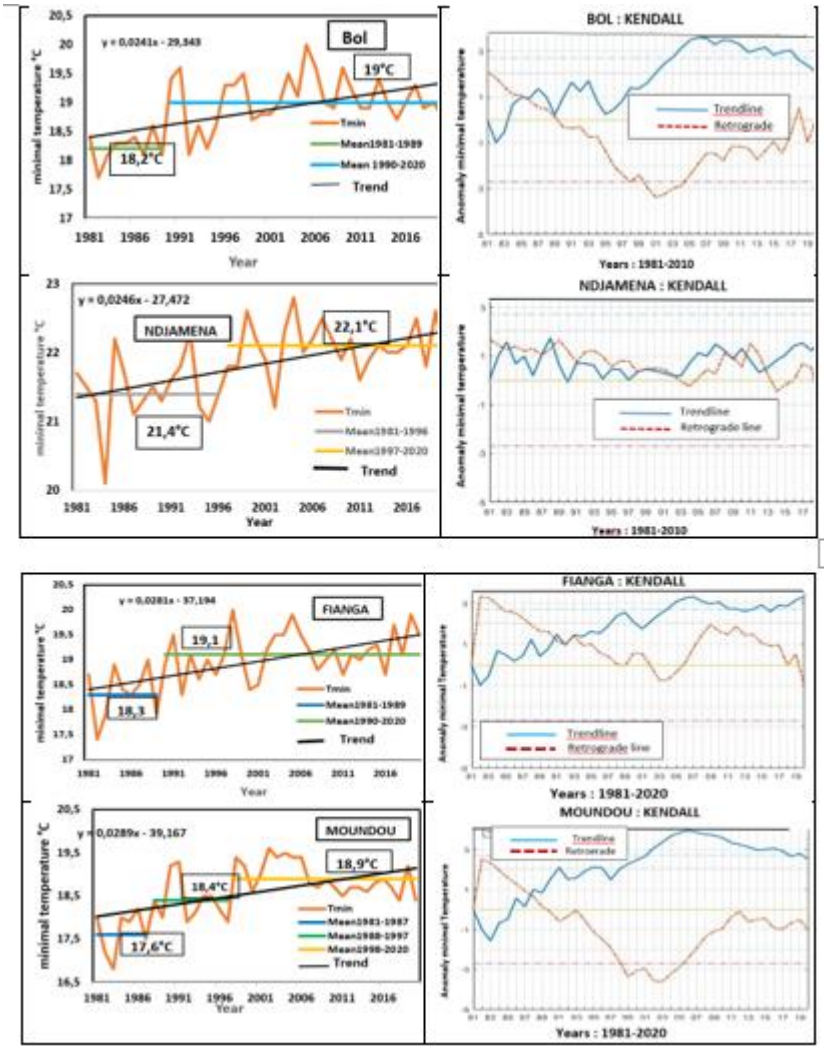


**Figure 8.** Evolution of the Average Minimum and Maximum Temperatures from 1981 to 2020 and the Periods Identified by the Hubert Segmentation Test. Averages by Period and Trends at the N'djamena and Bol Stations from 1981 to 2020 (Sahelian zone)

## Analysis of Minimum and Maximum Temperatures at Fianga and Moundou Stations (Sudanian Zone of Chad)

The Moundou and Fianga stations, located in the Sudanian zone, experienced a significant increase in both minimum and maximum temperatures as confirmed by the Mann-Kendall test at 5% level (Figure 8). The temperature data series recorded breaks with multiple sub-series. The Pettitt's tests identified 1997 as the break year for both Moundou and Fianga.

The minimum temperatures in Moundou increased from 20.7 to 21.5°C, a rise of 0.8°C, during the sub-periods 1981-1997 and 1998-2020, with a normal (1981-2010) minimum temperature of 21.1°C. Meanwhile, the maximum temperatures, despite an overall upward trend, experienced an alternation of low and high values, with an average maximum temperature of 32.9°C between 1981-1997, 34,9°C between 1998-2007, a variation of 2°C which then dropped to 33.5°C between 2008-2020. However, there was an overall increase of 0.6°C from 1981 to 2020. The normal (1981-2010) maximum temperature is 33.5°C. At the Fianga station, the maximum temperatures varied from 34.2°C to 35.5°C, respectively during the periods 1981-1997 and 1998-2007, an increase of 1.3°C. They then experienced a decrease of 0.6°C between 2008 and 2020. The general trend over the entire 40-year series is an

increase of 0.8°C, during the periods 1981-1989 and 1990-2020.

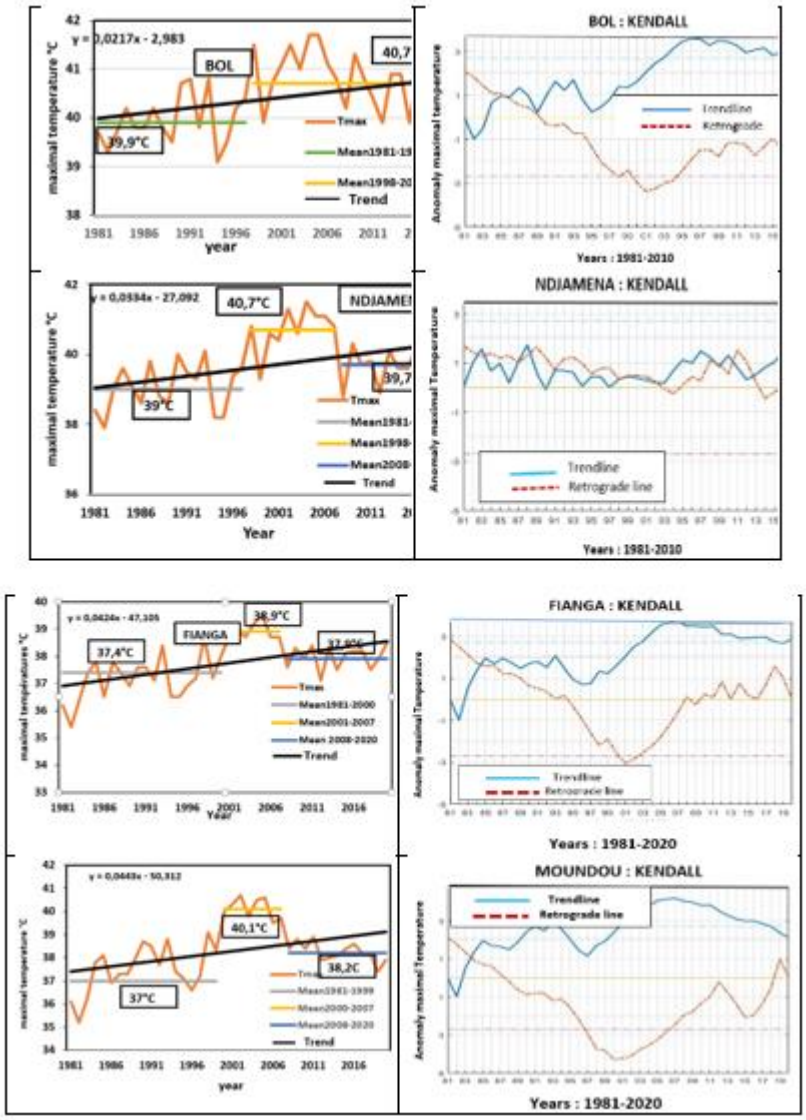


**Figure 9.** Averages by Periods and Trends at Fianga and Moundou Stations from 1981 to 2020 (Sudanese Zone)

## Analysis of Climate Extreme Indices

## Trend using the Mann-Kendall Test

The results obtained by applying the Mann-Kendall test at a risk level of $\alpha = 5\%$ (P-value = 0,05), on the climate indices (PRCPTOT, R95p, R95pTOT, SDII, R20, TN95p, and TX95p) retained for the 4 studied stations are recorded in table 4. For the applied test, a significance threshold of 5% was used, indicating whether or not there are monotonic trends. P-values less than 0.05 are considered as indicators of a trend. If the slope value is positive, the trend is upwards, and if it is negative, the trend is downwards (Table 4).

**Table 4.** Results Of Mann-Kendall Tests at 5% Threshold Expressed by P-Values Less than 0.05

| Indices | BOL | | FIANGA | | MOUNDOU | | N'Djamena | |
|---|---|---|---|---|---|---|---|---|
| | P-Value | Slope | P-Value | Slope | P-Value | Slope | P-Value | Slope |
| **TX90p** | 0.138 | 0.153 | 0.055 | 0.221 | 0.293 | 0.160 | 0.123 | 0.153 |
| **TX90p** | 0.683 | 0.040 | 0.000 | 0.295 | 0.016 | 0.226 | 0.149 | 0.040 |
| **SDII** | 0.039 | 0.037 | 0.525 | 0.009 | 0.039 | 0.027 | 0.278 | 0.037 |
| **R20 mm** | 0.023 | 0.059 | 0.324 | 0.045 | 0.046 | 0.107 | 0.124 | 0.059 |
| **R95p** | 0.029 | 2.255 | 0.479 | 1.206 | 0.009 | 4.093 | 0.546 | 2.255 |
| **R99p** | 0.294 | 0.878 | 0.174 | 1.443 | 0.004 | 2.881 | 0.780 | 0.878 |
| **PRCPTOT** | 0.054 | 2809 | 0.177 | -2.682 | 0.488 | -1.902 | 0.382 | -1.700 |

## Annual Cumulative Rainfall

From 1982 to 1990, the annual cumulative rainfall values oscillated between1514.4 mm in Moundou in 1982 and 725 mm in Fianga in 1984, two localities in the Sudanian zone of Chad (see Figure 10). In contrast, Bol and N'djamena in the Sahelian zone recorded a cumulative rainfall ranging from 756.3 mm in 1982 in N'djamena and 157.4 mm in 1984 in Bol during the same period. During the periods 1990-1999 and 2000-2011, all locations in both the Sudanese and Sahelian zones recorded low cumulative rainfall, with 833 mm in Moundou, a drop of 500 mm compared to the highest cumulative rainfall in 1982. The lowest cumulative rainfall was recorded in Bol, with 147 mm in 2004.

This condition gradually improved during the period 2011-2020, reaching high values of 1347.5 mm. The general trend is decreasing, but not statistically significant at 5% level, except at Bol station where the upward trend is significant (Table 4).

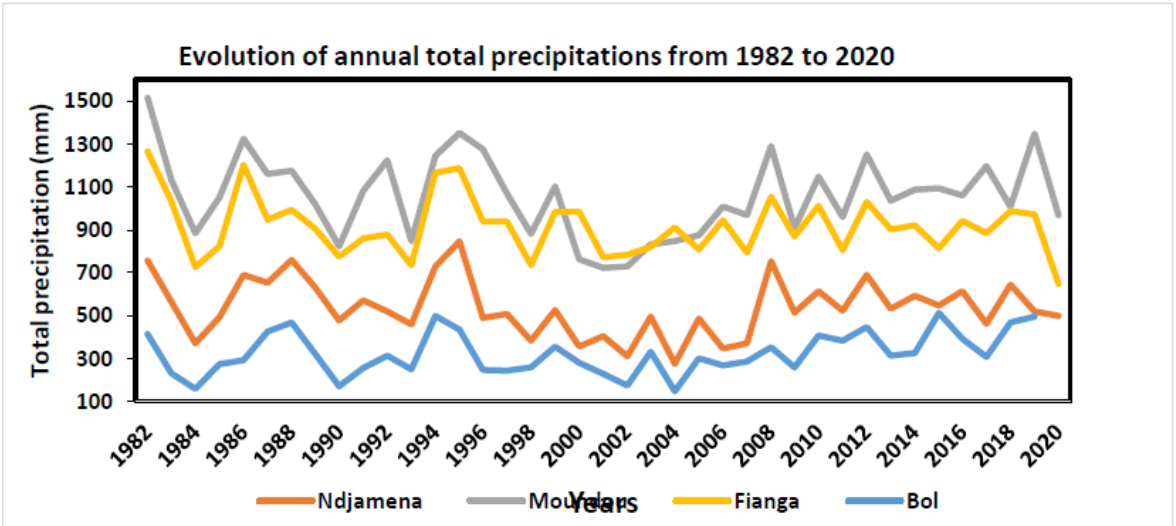


**Figure 10**. Evolution of Annual Cumulative Rainfall Amounts (Prctot) from 1981 To 2020 at the Stations of Bol, Fianga, Moundou et N'Djamena.

## Annual Evolution of Extreme Rainfall Heights and Frequency

The annual evolution of heights (R95p) and frequency of extreme rainfall (R95pTOT) was characterised by a strong variability of decrease and increase in extreme rainfall accumulations in most stations except for Moundou, which experienced a clear upward trend from 21 to

573 mm with a frequency evolution of 15 to 27%. The period from 1981 to 1990 was marked by significant disruptions in the distribution in time and space.

In general, the decades 2000-2010 and 2010-2020 were marked by good rainfall, both in height and frequency with quantities reaching up to 573 mm in Moundou, while Bol experienced the highest frequency (42%) the period 2011-2020. These extreme rainfall events are responsible for the severe flooding in recent years in N'Djamena and Moundou causing significant damage [26].

**Table 5.** Ten-Year Change in Percentage of Total Annual Rainfall on Very Humid Days (R95p) and Frequency (R95ptot) of Extreme Rainfall

| Decade | BOL | | FIANGA | | MOUNDOU | | N'DJAMENA | |
|---|---|---|---|---|---|---|---|---|
| | R95p | R95pTOT | R95p | R95pTOT | R95p | R95pTOT | R95p | R95pTOT |
| **1981-1990** | 0-232 | 20,2% | 0-329 | 21,1% | 21-329 | 15,3% | 0-383 | 28,3% |
| **1991-2000** | 0-118 | 13,5% | 19-371 | 18,2% | 0-320 | 18% | 19-295 | 17% |
| **2001-2010** | 15-68 | 13% | 67-323 | 20,1% | 141-287 | 18,7% | 23-105 | 13,1% |
| **2011-2020** | 32-218 | 42,3% | 41-308 | 24% | 134-573 | 27% | 63-331 | 31,4% |

## Analysis of the Evolution of Frequency and Intensity of the Days of Heavy Rainfall

The frequency and intensity of extreme weather events are two relevant indicators characteristic of climate change. Figure 10 shows a strong variability in frequency and intensity during the period 1981 to 2013, with a decreasing trend in the number of days with rainfall above 20 mm (R20), thus confirming the results of the study by Panthou [26] which revealed that the Sahelian rainfall regime over the last 10 years was characterised by a significant deficit in the number of rainy days. From 2014, an increase in frequency and intensity of rainfall events at all stations, except for Moundou which experienced a decrease in intensity (SDII). The locality of Fianga recorded a persistent increase in frequency and intensity during the two periods, 1999-2004 and 2014-2020. It is worth noting that the stations in N'djamena and Bol in the Sahelian zone experienced episodes of high frequency and intensity rainfall over the last five years.

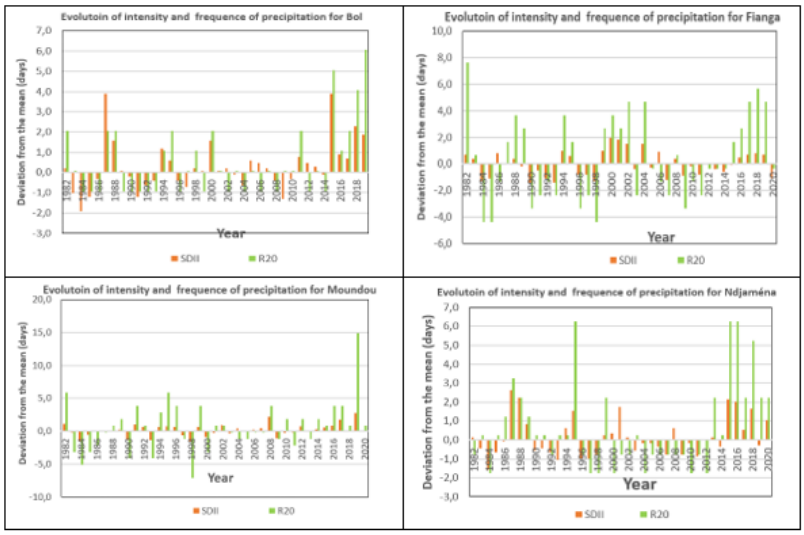


**Figure 11.** Interannual Evolution from 1981 to 2020 of Intensity (Sdii): Histogram in Red and Frequency (R20); Histogram in Green of Precipitation from the Stations of Bol, Fianga, Moundou and N'djamena

## Analysis of Climatologically Hot Nights

The percentage of climatologically hot nights (TN90p) is a relevant indicator for identifying signs of change. Statistical tests using the Pettitt test at the 10%, 5% and 1% levels made it possible to detect break years and sub-series by segmenting the data using the Hubert method. The trends in the indices are presented in Table 6. Between 1997 and 2006, hot nights increased at all locations except for Bol station where they remained stable at 8% over the entire series. However, a decrease in hot nights was observed between 2007 and 2020 (see Figure 7) at all four locations, despite an overall increasing trend over the 40-year period. Nevertheless, the highest values were observed at the Moundou and Fianga stations in the humid Sudanese climate zone.

**Table 6.** Analysis of the Percentage of Climatologically Hot Nights in Relation to the Break Date Detected by the Pettitt test and the Periods Released by Hubert' S Segmentation.

| Station | Pettitt test | Hubert segmentation | Average before rupture (%) | Average after rupture (%) | Rate of variation (%) |
|---|---|---|---|---|---|
| **Bol** | 1988 | 1982-1988 | 9.9. | | 9.9 |
| **Fianga** | 1996*** | 1982-2004 | 6.6 | | |
| | | 2005-2006 | | 23.5 | 16.9 |
| | | 2007-2020 | | 11.5 | 4.9 |
| **Moundou** | 1997*** | 1982-2000 | 5.1 | | |
| | | 2001-2006 | | 21 | 15.9 |
| | | 2007-2020 | | 8.8 | 3.7 |
| **N'Djamena** | 1996** | 1982-1996 | 6.2 | | |
| | | 1997-2006 | | 15.8 | 9.9 |
| | | 2007-2020 | | 9 | 2.8 |

N.B: *; ** and *** significant respectively at the 10% threshold; 5% and 1% according to the result of the Pettitt test (1979).

## Analysis of Climatologically Hot Days

The frequency of hot days (TX90p) increased after the break years (1995, 1996, and 2007) detected by the Pettitt test at the 10%, 5% and 1% levels at the four stations during the periods from 1997 to 2006. The rates of change ranged from 3% to 26.4% in N'djamena, 1% to 14.8% in Bol, 6.3% to 30.1% in Moundou and 3.7% to 19.7% in Fianga. As shown in Table 7, there was a decrease in hot days during the period from 2007 to 2020 at all the four stations.

**Table 7.** Analysis of the Percentage of the Number of Climatologically Hot Days in Relation to the Break Date Detected by the Pettitt Test and the Periods Released by Hubert's Segmentation

| Station | Pettitt test Year of rupture | Hubert segmentation | Average before rupture (%) | Average after rupture (%) | Rate of variation (%) |
|---|---|---|---|---|---|
| **Bol** | 1995*** | 1982-2000 | 7.1 | | 9.9 |
| | | 2001-2005 | | 21.9 | 14.8 |
| | | 2006-2018 | | 8.8 | 1.1 |
| **Fianga** | 1997*** | 1982-2000 | 4.9 | | |
| | | 2001- 2006 | | 24.6 | 19.7 |
| | | 2007- 2020 | | 8.6 | 3.7 |

| | | | | | |
|---|---|---|---|---|---|
| **Moundou** | 1996*** | 1981-1996 | 3.5 | | |
| | | 2001- 2006 | | 33.6 | 30.1 |
| | | 2007- 2020 | | 9.8 | 6.3 |
| **N'Djamena** | 1996*** | 1982-1996 | 6.4 | | |
| | | 1997- 2003 | | 15.3 | 8.9 |
| | | 2004-2006 | | 29.9 | 26.4 |
| | | 2007-2020 | | 9.4 | 3 |

The signs * and ** *** mean that the break is respectively significant at 90 and 95% and 99% according to the result of the Pettitt test (1979)

## Discussion and Conclusion

The purpose of this study is to detect signals of climate change in the localities of Bol, Fianga, Moundou and N'Djamena. The results obtained show that over the past few decades, there has been a modification of the rainfall regime in terms of frequency and intensity across all locations. However, a slight decrease in annual rainfall accumulation was observed from 1981 to 2020. This overall decreasing trend over the 1981-2020 series is linked to episodes of extremely severe drought that lasted for about 5 consecutive years during the 1980-1990 and 1990-2000 decades, marked by the strong El niño phenomenon of 1983/1984 and 1997 [27] and the historic drought of 1983-1984 that affected Central Africa and the Sahel [28]. These results were also observed in the works of New et al., and Aguilar et al. [29, 9]. In fact, in their studies on the evolution of extreme daily climate conditions covering southern and western Africa,[9] showed that regions are experiencing an overall decrease in total annual rainfall and the number of rainy days. Aguilar et al. also reached the same conclusions in their analysis of precipitation in Central Africa between 1955 and 2006 [9] . While the general trend of rainfall is decreasing from 1981 to 2020, there is however an increasing variability observed from 2011-2020 decade in all locations, with N'Djamena, Moundou and Fianga recording rainfall surpluses of approximately 31,5%, 8% and 23,8% respectively, during the 2010-2020 period with episodes of heavy rainfall over the last 5 years (2015-2020) in N'djamena with annual cumulative deviations of over 100 mm compared to the norm (1981-2010). These variabilities were considered by some of the authors as a return to normal rainfall conditions, particularly [30] who noted for the Sudanian and Sahelian regions of the Sahel an upward trend in total annual rainfall accompanied by an increase in frequency of short episodes of extreme drought and heavy rainfall events (flooding), making the rain season more uncertain and unpredictable.

The results of the study also show a general increase in extreme rainfall events in terms of frequency of heavy rains (R20), intensity (SDII), rainfall heights (R95), and frequencies of very humid days (R95pTOT) across all locations over the last five years (2015-2020). However, a more notable increase in frequencies of very humid days (R95pTOT) was observed in the Sahelian zone than in the Sudanian zone, with 42% in Bol and 31% in N'Djamena. These analyses confirm the results of the recent studies [31, 32, 33]. This trend has already been observed by IPCC studies [34], predicted an intensification of extreme climate phenomena over the next few decades in the Sahel. This was confirmed by several studies [35, 36, 31]. The increase in rainfall accumulation, frequency, and intensity led to serious flooding in 2020, which affected 87% of the national territory [5]. If this trend continues, we will see an increase in disasters with associated damages and costs [37,38,39,40] and a resurgence of epidemics of climate sensitive diseases such as malaria and cholera [41].

Extreme temperatures, both minimum and maximum, have risen throughout the 1981-2020 period, corroborating the IPCC's publication [31] findings that forecast temperature shifts and heightened precipitation extremes across West and Central Africa. This aligns with a projected global average temperature rise of 1.5°C to 2°C above pre-industrial levels [42,43]. We generally notice that the minimum temperatures increased more than the maximum temperatures in all the localities studied, and in a linear fashion, while the maximum temperatures experienced variability from one decade to another (see the temperature maps of N'Djamena and Moundou). The localities of Bol and N'Djamena in the Sahelian zone recorded an increase in minimum temperatures of 0.7°C and 1.2°C respectively; and maximum temperatures of 0.7°C and 0.8°C, while the localities of Moundou and Fianga in the Sudanese zone recorded a rise in minimum temperatures of 0.8°C for both localities and maximum temperatures of 0.6°C and 0.7°C thus showing an increase in both minimum and maximum temperatures, slightly higher compared to the values of localities in the Sudanese zone. We note a particular increase in both minimum and maximum temperatures during the period 1997-2007.

The frequency of hot days (TX90p) and hot nights (TN90p) showed an increasing trend during the period between 1996/1997 and 2007, which corroborates the results of Mbaiguedem [44] which reveal that from 2006, there is a persistence of hot nights of more than 20 days, and also the results of Bedoum [45] whose indices indicate an increase in hot nights in both Chad and Central Africa. On the other hand, we note a significant drop in both TN90p and TX90p between 2007 and 2020. This could be explained by the improvement in precipitation conditions.

Annual rainfall in Chad has experienced alternating periods of humidity and drought, with a general trend of decline between 1981 and 2020. A change of rainfall regime since the late 1990s, detected by statistical tests as a break year in the chronological series has been observed. The study allowed us to show and highlight a succession of dry and humid periods. It appears that the decades of 1980-1990 and 1990-2000, and part of the 2000s, were characterised by episodes of severe rainfall deficits. Except for the locality of Bol, where the precipitation trend decreased by around 17%, all other localities experienced high variability and a tendency to excessive rainfall conditions during the 2010-2020 decade. This recovery seems more pronounced in the Sahelian zone than in the Sudanese zone. The return of rains in the studied localities was marked by a sharp increase in frequency and intensity of extreme rainfall, which could explain the severe flooding of recent years that affected 87% of the national territory between 2019 and 2022. On the other hand, maximum and minimum temperatures increased by 0.6 to 1.2°C respectively, with a more accelerated increase in minimum temperatures and an increasing trend in climatologically hot nights (TN90p), which is one of the major characteristics of climate change.

It can be concluded that the localities of the study area are characterised by unstable rainfall patterns associated with rising temperatures. Such a climatic context is not without consequences for the development of key sectors. These conditions are conducive to and favor the proliferation of mosquitoes, which are vectors for the Plasmodium parasite [46]. The study by Huston [47] reveals that long-term shifts in temperatures and precipitation patterns, along with increased climate variability and more frequent extreme weather events, will distinctly affect the risk of various infectious diseases.

In conclusion, real signals of climate variability and change characterised by a general trend of decreasing rainfall have been identified across all localities, although increased variability with intensified rainfall

has been noted over the past few decades, explaining the serious flooding in recent years (between 2010 and 2020). The results obtained in this study are consistent with those obtained in other regions of the globe. The disruptions in the spatio-temporal distribution of rainfall and the increasing temperature trend revealed are statistically significant, indicating a warming pattern with steps and jumps, allowing us to appreciate the magnitude of recent climate change (1981-2020). It is essential to extend such a study to other stations across the national territory to better understand the evolution of climate change and adjust public policies in key development sectors.

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## Conflict of Interest Statement

The authors of this article declare that there is no conflict of interest that could be perceived as influencing the results or interpretation of the data presented.

This research was conducted with complete independence, without any external influence that could compromise the scientific integrity of the work performed.

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