Earth and Space Science

RESEARCH ARTICLE
10.1029/2019EA000619

Key Points:
- Detection of climate change signal over the major cities of Chad that scattered within different climatic zones is of utmost importance
- The rainfall was decreasing during wet period, which recovers gradually at a slower rate over most cities
- A consistent increasing trend in temperature is found over all the cities, but substantially, warming is found after 1980–1985

Supporting Information:
- Supporting Information S1

Correspondence to:
P. Maharana,
maharanapyarimohan@gmail.com

Citation:
Pattnayak, K. C., Abdel-Lathif, A. Y., Rathakrishnan, K. V., Singh, M., Dash, R., & Maharana, P. (2019). Changing climate over Chad: Is the rainfall over the major cities recovering? *Earth and Space Science*, *6*, 1149–1160. https://doi.org/10.1029/2019EA000619

Received 10 MAR 2019
Accepted 31 MAY 2019
Accepted article online 7 JUN 2019
Published online 10 JUL 2019

Changing Climate Over Chad: Is the Rainfall Over the Major Cities Recovering?

Kanhu Charan Pattnayak[1,2], Ahmat Younous Abdel-Lathif[3], K. V. Rathakrishnan[2], Muskan Singh[4], Renuka Dash[5], and Pyarimohan Maharana[6]

[1]School of Earth and Environment, University of Leeds, Leeds, UK, [2]School of Geography, University of Leeds, Leeds, UK, [3]Département d'énérgétique, Institut National Supérieur des Sciences et Techniques, Abéché, Chad, [4]Agriculture Advisory Services Division, India Meteorological Department, New Delhi, India, [5]Department of Physics, Kotpad College, Kotpad, India, [6]Delhi College of Arts and Commerce, University of Delhi, New Delhi, India

Abstract Chad is the largest country of the Sahel region with different climatic zones, varying from arid in the north to tropical in the south. These climatic zones respond differently to climate change signals. Therefore, their detection over major cities, which are scattered within different climatic zones, is of utmost importance. The changes in hydroclimatic fields such as rainfall and temperature were examined over the major cities in various regions for the period 1950 to 2014. Rainfall shows a significant decreasing trend especially over cities close to Lake Chad (Lere, Mondou, Mongo, and Sarh), whereas no significant trend is observed for cities farther from the Lake. However, a consistently increasing trend in temperature is found across all cities. The cities in the north (Faya, Abeche, and Ati) receive far less rainfall than those located in southern Chad. All cities (except Faya and Lere) received higher rainfall during 1950–1965 (wet period), entering a dry regime between 1966 and 1990 (dry period) and subsequently recovering rainfall totals, toward previous levels, between 1991 and 2014 (recovery phase). A substantial rise in air temperature is observed after 1980–1985, reflecting the gradual rise of temperature in recent times. In summary, rainfall is recovering from a dry regime and temperature is rising over all the major cities of Chad. More researches in this region is needed to develop local scale mitigation strategies and adaptation technology.

1. Introduction

Africa is the second populous continent with a diverse climate system, which is split into several climatic zones. The Koppen climate classification shows that the vastness of Africa gives rise to eight different climatic zones (Koppen, 2011). These major climatic zones include the arid Sahara desert in the north, savanna grassland in the center, and a tropical climate in the south. These climatic zones are mainly determined by rainfall distribution across the continent and each is differentially sensitive and vulnerable to the increasing global temperature and climatic change (Odada & Olago, 2005). Therefore, the climate change signal detection over major cities, which are scattered within different climatic zones, is of utmost importance.

With the increase of global CO_2 concentration due to anthropogenic activity, global temperature is rising; this is no exception for the cities in the African continent. The year 2013 was reported to be the warmest year across Africa with respect to the long-term average of 1960 to 1990 (Stocker et al., 2013). According to the World Meteorological Organization report, the rate of warming over Africa is lowest as compared to other continents during 2011 to 2015, while 2016 is the warmest year recorded with temperatures exceeding the preindustrial level by 1.1 °C. Global temperatures have been increasing since 1850, with an increase of 0.75 °C experienced between 1850–1899 and 2001–2005 (Trenberth et al., 2007). Similarly, the rainfall over the African continent has been reported to be increasing, while the precipitation variability seems to be very high (Intergovernmental Panel on Climate Change, 2007). In general, the Sahel and West African region have experienced a decreasing trend in rainfall, which has recently begun to increase (Maharana et al., 2018; Trenberth et al., 2007). Many researchers have tried to understand the temperature variability over Africa. Few studies involve the continuous rise of temperature (Collins, 2011; Hulme et al., 2001), while few others analyze the wintertime increase of minimum and maximum temperature (Caesar et al., 2006) over Africa. In addition, the magnitude of extreme hot day and night temperature and the decrease of cold climate extremes are also analyzed (Frich et al., 2002; New et al., 2006). Collins (2011) reported significant warming over the northern and southern parts of Africa in recent decades; however, the wintertime warming is more significant over northern Africa.

Few studies also focused on rainfall variability, its distribution and trend over Africa. Rainfall extremes have increased over Africa but without any trend (New et al., 2006) in an oscillatory nature (Ogallo, 1979). The Sahel region of the African continent experienced higher rainfall during 1950s–1960s (wet period), which gradually entered a dry regime with frequent drought between 1970s and 1990s (dry period). Afterward, rainfall began to recover at a very slow rate from the 1990s onward (recovery period; Caminade & Terray, 2009; Maharana et al., 2018). These characteristics have been reported from the analysis of long-term rain-gauge, observational and reanalysis data sets (Le Barbé et al., 2002; Maharana et al., 2018). Charney et al. (1977) found that the feedback between land surface conditions (soil humidity, vegetation, and albedo) and atmospheric radiation equilibrium affects the regional precipitation. Many studies show that the rainfall over Africa and along its subregions does not follow any particular trend (Bunting, 1975; Kruger, 2006; Rodhe & Virji, 1976). Intergovernmental Panel on Climate Change 2007 (Pachauri & Reisinger, 2007) reported a contrasting view point of change in the rainfall trend over Africa. In addition, the interdecadal variability of rainfall is analyzed for the period between 1960 and 1990 (Hulme et al., 2001). The decadal rainfall variability was attributed to the interaction of Hadley and Walker cells over Africa at decadal frequency through anomalous north-south displacement of the near-equatorial trough (Jury, 2009). This variability was attributed to global warming (Paeth & Hense, 2004) and vegetation feedback processes (Charney et al., 1977; Zeng, 1999). Recently, rainfall extremes are found to increase over western part of South Africa (Kruger, 2006). Few teleconnections also seem to influence the rainfall distribution over Africa, the rainfall over Namibia and South Africa is modulated by the warming and cooling over the western Indian Ocean (Landman & Mason, 1999) while the global SST pattern play a major role in defining the rainfall variability over northern and western Africa (Nicholson, 2000; Rowell et al., 1995).

Chad is mostly an agricultural country with 70% of the population depending on this sector for their livelihoods; thus rainfall is intrinsically important to the country (Le Barbé et al., 2002; Maharana et al., 2018; Washington et al., 2006). Several studies have been dedicated to understand the decreasing size of Lake Chad (Armitage et al., 2015; Coe & Foley, 2001; Ndehedehe et al., 2016; Niel et al., 2005; E. Nkiaka et al., 2017; Elias Nkiaka et al., 2018). The current rainfall in Chad Basin is 350 mm/year (Kutzbach, 1980). Okonkwo et al. (2014) found an increasing trend in annual rainfall over the lake basin using gridded gauge monthly time series for the period 1970–2010. On the contrary, Niel et al. (2005) reported a significant decrease in annual rainfall in the central part of the basin by analyzing a longer rainfall record from rain gauges covering the period 1950–2002. Coe and Foley (2001) suggested that climate variability controls the interannual fluctuations of the water inflow in the Lake Chad basin. Many studies have been carried out to understand the intra-seasonal variability of the West African monsoon (WAM; N'Datchoh et al., 2018; Poan et al., 2016; Roehrig et al., 2013) because of its huge socio-economic impact, particularly over Sahel region. The above discussed literatures mainly stressed on the climate analysis of Africa as a whole or different regions of the African continent. There are almost no studies which focuses on the climate change in the city level due to the nonavailability of long-term station data. The present study is an attempt to study the change in the climate pattern of the different cities of Chad, which represents different climatic zones within Chad.

Further investigation of climate across different cities in Chad will provide important detail on the regional changes in precipitation and temperature in response to a warming climate. This information will be very useful for the local water resource management, agriculture, hydroelectricity, disaster management, flood, and drought control and the overall sustainable development of the major cities of the country. Alongside this, information on the local scale will also help to develop local scale mitigation strategies and adaptation technologies in this region of the world. The following section deals with the study area, data sets used, and methodology. Section 3 describes the results and discussion while the summary and concluding remarks are provided in section 4.

2. Study Area, Data, and Methodology

Eight different major cities of Chad have been chosen for this study namely, Ndjamena, Sarh, Moundou, Lere, Mongo, Abeche, Ati and Faya (Figure 1a). Only one city, "Faya," from northern Chad has been selected for the study. Other cities are scattered over the southern part of Africa below 15°N, where most of the WAM activity occurs (Maharana et al., 2018). The capital city, Ndjamena, is located close to Lake

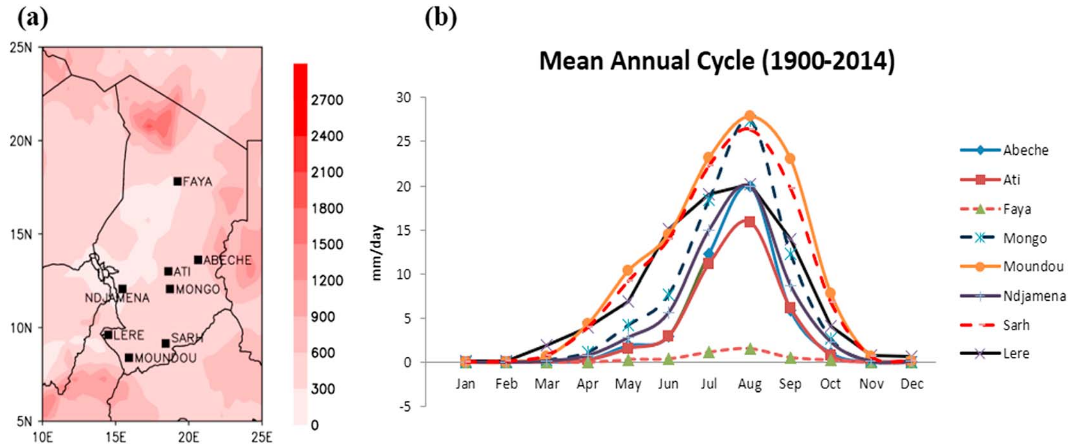

Figure 1. (a) Map of Chad with the major cities. The shade represents the surface topography (m) and (b) mean annual cycle of precipitation for the period 1950–2014 over the major cities of Chad (marked in a).

Chad in the western border of the country, while Abeche, Ati, and Mongo are at the center of Chad while Lere, Sarh, and Moundou are located in the south.

The monthly temperature and precipitation data sets at 0.5° × 0.5° horizontal resolution from University of Delaware (hereafter, UDEL; Willmott et al., 2001) and Climate Research Unit (hereafter, CRU; Harris et al., 2014) have been used for the analysis. The data series have been extracted from the nearest grid point close to the locations considered in the study. The coordinates of the major cities of Chad are provided (Table 1). This monthly data series is used to prepare the mean annual cycle or the temporal variation of rainfall over different cities. The monthly rainfall time series for each month are averaged for the entire period to prepare the mean annual cycle. The standardized anomaly time series of temperature and precipitation are prepared by subtracting the long-term mean from the monthly time series (anomaly) and then dividing this anomaly with the standard deviation of the same monthly time series. The standardized anomaly helps to identify the normal, excess, and deficit (rain and temperature) years. The standardized value greater (or smaller) than one corresponds to the excess (or deficit) rainfall years while the value in between +1 and −1 represents the normal rainfall year. The box plots are prepared to analyze the median and variability of rainfall and temperature at different stations. The probability distribution of average rainfall during monsoon (June, July, and August, JJA hereafter) is analyzed for the wet period (1950–1965), dry period (1966–1990), and recovery period (1991–2014) to study the behavior of rainfall along the different cities of Chad.

A nonparametric Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945) is applied to analyze the monthly, seasonal, and annual trend statistics of rainfall and temperature over these locations (Alexander et al., 2006; Maharana et al., 2018; Tan & Gan, 2015; Westra et al., 2013). The slope of the trend is computed using a nonparametric Theil-Sen's method (Sen, 1968). This method is robust to the effect of the outliers in the data and avoids a distribution for the residual. In addition, it is very useful for data sets without a seasonal cycle

Table 1
Coordinates of the Major Cities of Chad Considered for This Study Along With Their Mean and Standard Deviation of Rainfall and Temperature

			Rainfall (cm per month)		Temperature (°C)	
Locations	Latitude	Longitude	Mean	Standard deviation	Mean	Standard deviation
Abeche	13.84	20.83	3.59	1.0	29.07	1.03
Moundou	8.57	15.08	9.09	1.32	27.10	0.64
Ndjamena	12.12	15.07	4.47	1.87	28.38	0.5
Sarh	9.15	18.38	8.37	1.4	27.93	0.49
Faya	17.93	19.10	0.30	0.33	28.61	0.73
Mongo	12.18	18.68	6.16	1.26	30.0	0.62
Ati	13.22	18.33	3.26	0.92	29.3	0.65
Lere	9.77	14.15	6.96	1.02	28.23	0.62

10.1029/2019EA000619

and having a monotonic trend. This method also helps to identify the relative contribution of months and seasons toward the annual trend of temperature and rainfall. The *Z* value from the MK test determines the nature of the trend; that is, the positive (negative) value corresponds to increasing (decreasing) trend and the rate of the trend is determined by Sen's slope method.

3. Results and Discussions

This section includes the description of the mean annual cycle of rainfall, interannual variability of rainfall and temperature, their trend, and the rainfall distribution during different periods considered in the study.

3.1. Rainfall Seasonal Cycle

The rainfall seasonal cycle, represented over the eight major cities of Chad (Figure 1b and supporting information Figure S1), shows that peak rainfall occurs during the summer (June to August) through the WAM system (Diallo et al., 2014; Le Barbé et al., 2002; Maharana et al., 2018; Sylla et al., 2015). Rainfall increases with the advancement of WAM and peaks in August and decreases thereafter. The WAM process brings rain over Chad during summer (JJA), which is the major source of water over Chad, while the rest of the months are dry. Rainfall is highest over Moundou (9.09 cm per month), Sarh (8.37 cm per month), and Lere (6.96 cm per month), while least over Faya (0.30 cm per month; Table 1). These findings agree with earlier studies (Maharana et al., 2018). Therefore, cities in southern Chad receive more rainfall than those in north/northeast of the country. With the onset of WAM, the rainfall belt propagates up to 10–12°N during the height of summer (Thorncroft et al., 2011). Hence, northern Chad receives very less rainfall. It is interesting to observed that the monsoonal winds from Atlantic Ocean bends toward right in the northeast direction once it crosses the equator (Maharana et al., 2018). This northeastward moving wind carrying moisture enters Chad from south and hence the mean rainfall is more in the stations in the southern part. It is interesting to observe that although the moisture is coming from the western side of Chad (from Atlantic Ocean) but most of the moisture get transported to the eastern boarder through this northwesterly and hence the rainfall over the cities in the eastern border is higher than that of the cities in the western border at the same latitude (Table 1).

3.2. Rainfall and Temperature Interannual Variability

The interannual variability in the form of standardized anomaly of rainfall and temperature are analyzed over the major cities of Chad (Figure 2). The interannual rainfall variability shows a decrease in rainfall with time over Moundou. Most of the excess rainfall years (rainfall greater than 1 standard deviation) are observed during 1950–1980. Since then rainfall has decreased as is evident from the negative standardized rainfall anomalies. The peak rainfall is at Moundou (9.09 cm per month) with a standard deviation (1.32 mm/day, Table 1). Similarly, Lere and Sarh (both in southern Chad) experience higher precipitation rates of 6.96 and 8.37 cm per month, respectively, with corresponding standard deviations of 1.02 and 1.4 cm per month. Lere rainfall is continuously fluctuating between positive and negative anomalies between 1950 and 2003. After 2003, permanent negative anomalies imply the steady decline of rainfall in recent years. Sarh has five excess rainfall years (no deficient years) during 1950–1975. Afterward, the rainfall decreases subsequently with seven deficient years (two excess years) between 1976 and 2006. The major cities in central eastern Chad (Ati, Mongo, and Abeche) receive mean rainfall of 3.26, 3.59, and 6.16 cm per month, respectively. Though lower mean rainfall rates (Diallo et al., 2014; Maharana et al., 2018), the variability is comparable to the cities in southern Chad (Table 1). Abeche had frequent excess rainfall years during the wet period (1950–1965). The precipitation decreases strongly after 1965 with many deficit years until 2014. The rainfall variability of Ati and Moundou closely follows the behavior of Abeche. The capital city of Chad, Ndjamena, is situated close to the western border near the Lake Chad. Ndjamena receives the highest mean rainfall (4.47 cm per month) with the strongest rainfall variability among all locations (1.87 cm per month). The rainfall behavior is similar to Ati, Abeche, and Moundou, except that standardized rainfall anomalies are much higher in recent years. Faya, the most northern city in this study, is located next to the Sahara desert. The WAM generally cannot penetrate this far north resulting in low average rainfall (Diallo et al., 2014; Maharana et al., 2018). However, the standardized anomaly is higher than the rainfall, which may be attributed to the occasional showers in these regions. The overall analysis is that most cities experience excess rainfall during the initial phase of the study period (wet period). Thereafter, it decreases tending toward a lower rainfall rate. This stabilized during the recovery period with standardized

10.1029/2019EA000619

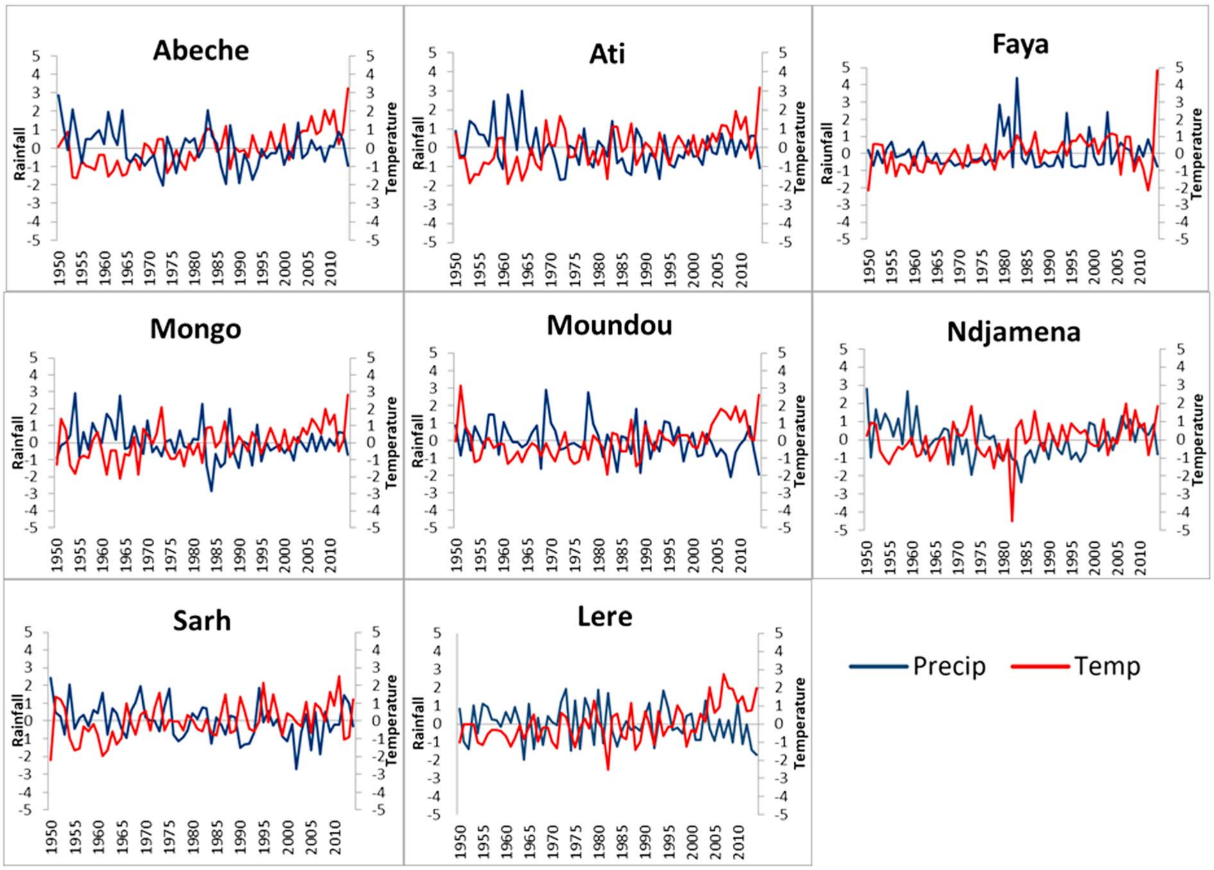

Figure 2. Standardized anomalies of annual precipitation (primary *Y* axis, blue) and temperature (secondary *Y* axis, red line) over major cities of Chad for the period 1950–2014.

anomalies between +1 and −1. This behavior of rainfall over these locations is in agreement with the overall monsoon behavior over Chad (Maharana et al., 2018).

The mean temperature over these cities ranges between 27.10 °C (Moundou) and 30 °C (Mongo). Similarly, the variability ranges between 0.5 °C (Ndjamena) and 1.03 °C (Abeche). Temperature anomalies between 1980 and 1985 were cooler (negative standardized values), but temperatures steadily increased afterward (i.e., standardized anomalies toward positive value; Figure 2). The temperature anomalies are greater than 1 standard deviation after the year 2000, which is an indicator of the recent temperature rise.

Further, the interannual variability of rainfall (Figure 3a) and temperature (Figure 3b) have been analyzed using box-whiskers over the eight locations. The middle line of the plots represents the median of the respective fields, while the top and bottom of the rectangle box represent the 25th (1st quartile) and 75th (2nd quartile) percentiles, respectively. The dashed lines extending above and below the boxes (the whiskers) show the range of time series (i.e., the minimum and maximum values between 1950 and 2014). Figure 3a highlights significant rainfall over all the locations. Faya receives the least rainfall (~3 cm/year) with least variation (~5 cm/year), while Moundou receives maximum rainfall (110 cm/year) with maximum interannual variation (~60 cm/year). The distinct rainfall pattern is found over the stations close to the Sahara desert such as Faya, Abeche, and Ati. These stations receive far less rainfall than the stations which lie in southern Chad, while Ndjamena is the transition region between the two zones. Temperature (Figure 3b), however, does not show much variability among the stations or within the stations. For all locations, the annual mean temperature lies between 27 and 30 °C while the variability ranges between 4 and 5 °C.

3.3. Climatic Trend

The long-term trend of annual, seasonal as well as the monthly trends rainfall and temperature are over the major cities have been analyzed to compute the annual, seasonal as well as the monthly trends using a well-

10.1029/2019EA000619

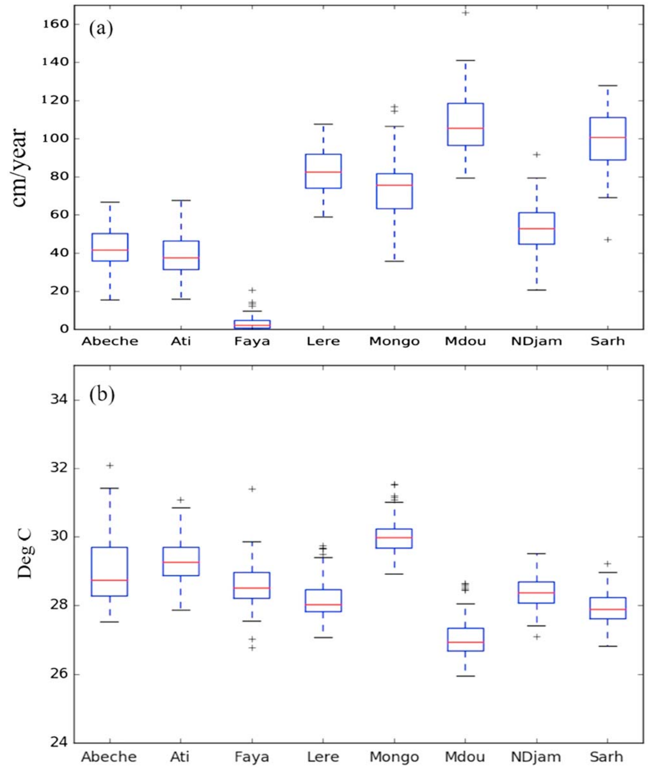

Figure 3. Box and whisker plots of annual (a) precipitation and (b) temperature over the major cities of Chad for the period 1951 to 2014. Red line indicates the median value. The lower caps indicate the first quantile (Q1, 25%), the upper caps indicate the third quantile (Q3, 75%), the upper whiskers are placed at Q3 + 1.5 * IQR, and the lower whiskers are placed at Q1 − 1.5 * IQR, where IQR is the interquartile range. The fliers which are outsides these limits are indicate by cross.

adopted nonparametric MK test (Alexander et al., 2006; Maharana et al., 2018; Tan & Gan, 2015; Westra et al., 2013).

3.3.1. Rainfall Trend

Annual rainfall trends are significantly decreasing at all locations except for Faya, which is evident from the analysis of *Z* value (Tables 1 and 2). Faya is located close to the Sahara desert and receives less rainfall in the form of occasional showers. This is the major reason why the rainfall over Faya does not show any statistically significant and the rainfall variability is very high. The rainfall trend over Lere, Mongo, Moundou and Sarh have significantly decreased by 0.15, 0.16, 0.21, and 0.16 cm per decade respectively. These locations are situated in the southern and eastern part of Chad, which experiences the maximum rainfall due to WAM (Maharana et al., 2018). Similar trend analysis of the seasonal rainfall trend (Table S1) shows that the JJA rainfall over all the locations is also decreasing. The decreasing trend is significant over Sarh (1.43 cm per decade) and Moundou (1.42 cm per decade). The declining trend during June to August (JJA) is confirmed by the lower negative *Z* value (Table S1). As JJA is the dominant rainfall contributing season over Chad (Maharana et al., 2018), the decreasing JJA rainfall trend leads to decline in the annual rainfall trend. The significant increase in rainfall during the September to November (SON) contributes toward the increase in the annual rainfall trend over Faya. Although the rainfall contribution during March to May (MAM) and SON toward the total annual rainfall is less, a declining rainfall trend during these seasons are observed over southern cities such as Sarh, Ndjamena, Moundou, Mongo, and Lere. The seasonal rainfall trend during the wet, dry and recovery periods helps to determine the behavior of the rainfall at the major cities of Chad. During the wet period, few locations such as Abeche, Moundou, and Ndjamena show a declining rainfall trend of 1.63, 1.73, and 10.6 mm per decade respectively but these are not statistically significant (Table S2). While the increasing rainfall trends are observed over Ati, Faya, Lere, Mongo, and Sarh ranging from 0.26 to 6 mm per decade (Table S2). In addition, most of the stations during the wet period show negative rainfall trend during MAM and SON. This support the statement above that positive JJA rainfall trends dominates it. During the dry period, the locations such as Sarh, Ndjamena, Moundou, Mongo, and Ati show decreasing rainfall rate of 4.55, 4.65, 2.84, 5.91, and 1.42 mm per decade respectively. The deceasing trend is in the southern cities of Chad, which gets maximum rainfall due to WAM. The central Chad cities (e.g., Abeche, Faya, and Lere) also experience increases in rainfall rates although to a lesser degree. Most locations during the recovery period show an increase in the rainfall rate although with less magnitude as compared to the wet period except Lere and Moundou, which reported

Table 2
Annual Rainfall and Temperature Trend Statistics (1950–2014) Over the Major Cities of Chad

	Rainfall			Temperature		
Locations	Level of significance	Rate (cm per decade)	*Z* value	Level of significance	Rate (°C per decade)	*Z* value
Abeche		−0.8	−1.50	0.001	0.42	6.26
Ati		−0.09	−1.48	0.001	0.23	5.41
Faya		0.03	1.40	0.001	0.19	5.13
Lere	0.1	−0.15	−1.95	0.001	0.19	5.13
Mongo	0.05	−0.16	−2.18	0.001	0.17	4.53
Moundou	0.05	−0.21	−2.27	0.001	0.19	4.42
Ndjamena		−0.04	−0.38	0.001	0.13	3.85
Sarh	0.1	−0.16	−1.94	0.001	0.16	4.73

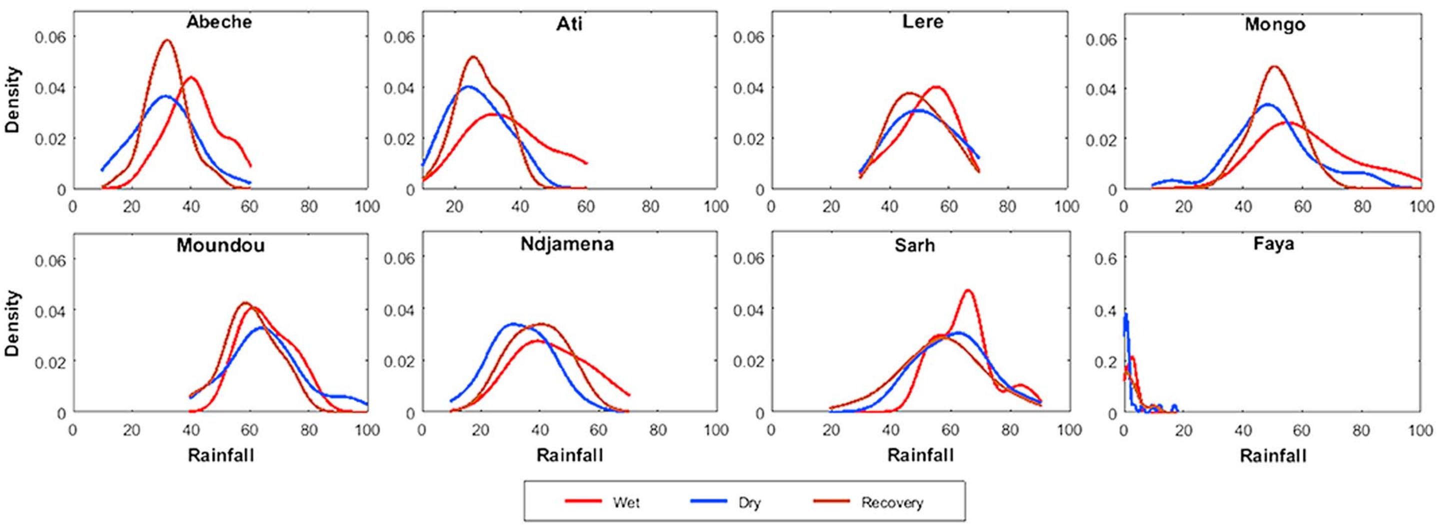

Figure 4. The probability distribution of summer (June, July, and August) rainfall over the cities chosen for this study. The lines in red, blue, and brown correspond to the period wet period (1951–1965), dry period (1966–1990), and recovery period (1991–2014), respectively.

further decline in the rate of rainfall. The increasing rate among the stations varies from 0.82 mm per decade in Mongo to 2.32 mm per decade in Abeche. The increasing rainfall rate is statistically significant over Abeche, Ati, and Ndjamena. However, the decrease of significant rainfall trend over Lere is of higher magnitude (5.39 mm per decade). The stronger decreasing rainfall trends over Lere and Moundou during the recovery period is the reason of suppressing the higher rainfall trend over Chad. The monthly trend analysis for the entire study period shows the major rainfall-contributing month toward the total annual rainfall trend (Table S3). It is important to note that the overall trend for all monsoon months (JJA) is mostly declining for the entire period of analysis. During June, Abeche, Lere, Mongo, and Moundou show statistically decreasing trends of magnitude 0.46, 0.47, 0.47, and 0.69 mm per decade. Decreasing trends of 0.66 mm per decade during July is observed over Moundou, while 0.05 and 0.96 mm per decade during August over Faya and Sarh, respectively.

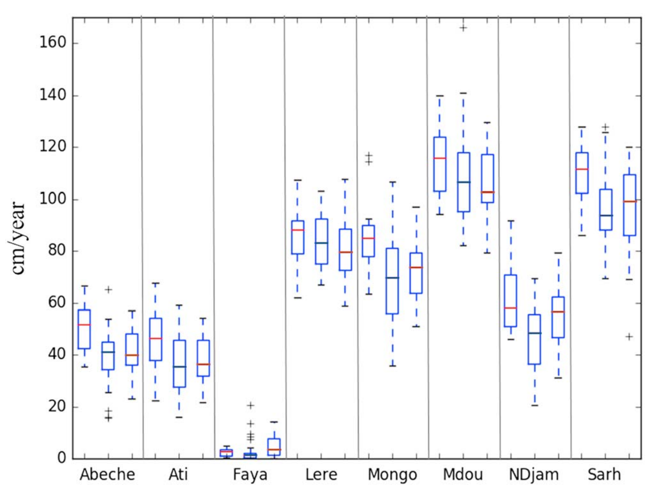

Figure 5. Box and whisker plots of annual precipitation over the cities for the wet period, dry period and recovery period. The lines in red, blue, and brown correspond to the period wet period (1951–1965), dry period (1966–1990), and recovery period (1991–2014), respectively. The lower caps indicate the first quantile (Q1, 25%), the upper caps indicate the third quantile (Q3, 75%), the upper whiskers are placed at Q3 + 1.5 * IQR, and the lower whiskers are placed at Q1 − 1.5 * IQR, where IQR is the interquartile range. The fliers which are outsides these limits are indicate by cross.

3.3.2. Temperature Trend

The annual temperature trend shows statistically significant (99.9% confidence level) increasing trend over all locations for the entire study period (Table 2 and Figure 4). The strongest trend (0.42 °C per decade) is at Abeche and coldest trend (0.13 °C per decade) at Ndjamena. The warming trend is large south of the Sahara desert, which is evident at Abeche and Ati. The increasing temperature trend is potentially attributable to the decline in the rainfall and the increase in the bare land over Chad (Maharana et al., 2018). Similar to the annual averaged temperature trends, the seasonal temperatures are also increasing over all the locations (Table S1). The highest (lowest) rising temperature trend is found during MAM (DJF) for all the locations, which are statistically significant at 0.001 level. The highest rising seasonal trend is found for Ati and Abeche, which agree with the annual temperature trend. A similar analysis of monthly temperature trend shows a statistically significant increase during recovery increase for all months (Table S4), which agree with the global temperature rise.

3.4. Rainfall Change/Variability Over the Three Periods

The behavior of the rainfall magnitude and its trend during has been analyzed using probability density function (PDF, Figure 4), box-whisker plot (Figure 5), and annual cycle (Figures S2 and S3) during the wet period, dry period, and recovery period. The mean JJA rainfall is used for the plotting of PDF. The bin size of the histogram used to prepare the PDF 10 units. Since the rainfall for Faya station is very less, hence the bin size selected for this location is 2. The red, blue, and brown colors are used for wet, dry, and recovery period, respectively. The PDF and the box plots illustrate the change in mean as well as the variability of rainfall during the three phases. Over Abeche, the mean rainfall (the peak of the distribution) during the wet (dry) period is highest (lowest) with at 42 cm/year (30 cm/year). Higher rainfall temporal variability occurs during the wet and dry periods, whereas the recovery period has less variability. The PDF of Ati shows that mean annual rainfall is lower than Abeche for all the three periods (Figure 4). The rainfall distribution at Ati is similar to Abeche and shows highest peak during the wet period, which further decreases during the recovery period and dry period. The largest variability is during the wet period followed by the dry and recovery periods (Figure 5). Mongo, in eastern Chad, also shows similar rainfall distributions to that of Abeche and Ati. Although all these locations are close, the position of Mongo is further south and receives higher rainfall relatively (i.e., 56 cm/year in wet period, 48 cm/year in dry period, and 53 cm/year during recovery period). The temporal variability is lowest for the recovery period and highest for the wet period. In addition, these locations also have lower temporal variability when compared to other locations.

Ndjamena experiences mean rainfall of 38 cm/year during the wet period with very high temporal variability. The mean rainfall decreases to 27 cm/year during the dry period, but then reaches 41 cm/year; which exceeds the mean rainfall of the wet period. This implies the recovery of rainfall over Ndjamena is highest in recent years as compared to other locations. This is important, as the Lake Chad is close to Ndjamena represents the major fresh water source. Sarh rainfall during the wet period is 67cm/year, which decreases to 62 cm/year during the dry period and then 54 cm/year during the recovery period. Lere has similar rainfall distribution to Sarh, where mean rainfall declines from the wet period (56 cm/year) to the recovery period (45 cm/year) followed by the dry period (48 cm/year). The declining rainfall is also associated with higher temporal variability during the dry and recovery period. Moundou rainfall during the wet period is around 61 cm/year with high temporal variability. Unexpectedly, the rainfall increases to 66 cm/year during the dry period, where the entire country experiencing decline in rainfall. Further, the rainfall during the recovery period has reduced to 56 cm/year. The temporal variability of rainfall during the dry and recovery periods is reasonably similar. It is very important to remember that the whole period of study is divided into wet, dry, and recovery periods based on the analysis of area-averaged rainfall over Chad, as discussed in earlier study (Maharana et al., 2018). However, the rainfall distribution within the cities are not following the same trend as the area averaged rainfall over Chad. This reflects the behavior of rainfall is different for different cities in these periods of study in terms of both mean rainfall and median value (Figure 5). It is discussed earlier that the rainfall band during monsoon abruptly jumps northward with the onset of WAM and causes rainfall over Chad (Maharana et al., 2018). This is the reason the maximum rainfall received in the cities of southern Chad. They also carefully analyzed the vertically integrated moisture flux, transport, associated rainfall pattern during the wet, dry, and recovery phases. The moisture transport toward southern chad showed a sharp decline from wet to recovery period through dry phase, however the convergence over eastern boarder recovers at a faster rate which is represented by the higher mean rainfall value over Ndjamena. The declining moisture in the southern Chad leads to decrease in the mean precipitation over cities like Sarh, Lere, and Moundou, which are significantly influenced by WAM circulation. On the contrary, Faya (closer to the Sahara desert) shows a decline in rainfall during the dry and recovery phase when compared to the wet period. Therefore, it is apparent that the differential behavior of the rainfall pattern over different cities within Chad (represented by different climatic regime) is behaving differentially to the changing climate. Although the largescale dynamics like the moisture transport, wind pattern can partially interpret these variabilities; however, various modeling approached will be very useful to understand these rainfall pattern at city level.

Furthermore, the change in the rainfall pattern is examined using the mean annual cycle during the three periods for all locations (Figures S2 and S3). Significant changes in rainfall is found during the monsoon months (JJA), while no change occurs in other months. During the wet period, the monsoon rainfall is 5–10 mm/day greater than the other periods over Abeche, Ati, Mongo, Ndjamena, and Sarh. In the recovery period, the monsoon rainfall strengthens by 2–3 mm/day as compared to the dry period over the same five cities. There is no noticeable monthly trend observed in the remaining cities.

10.1029/2019EA000619

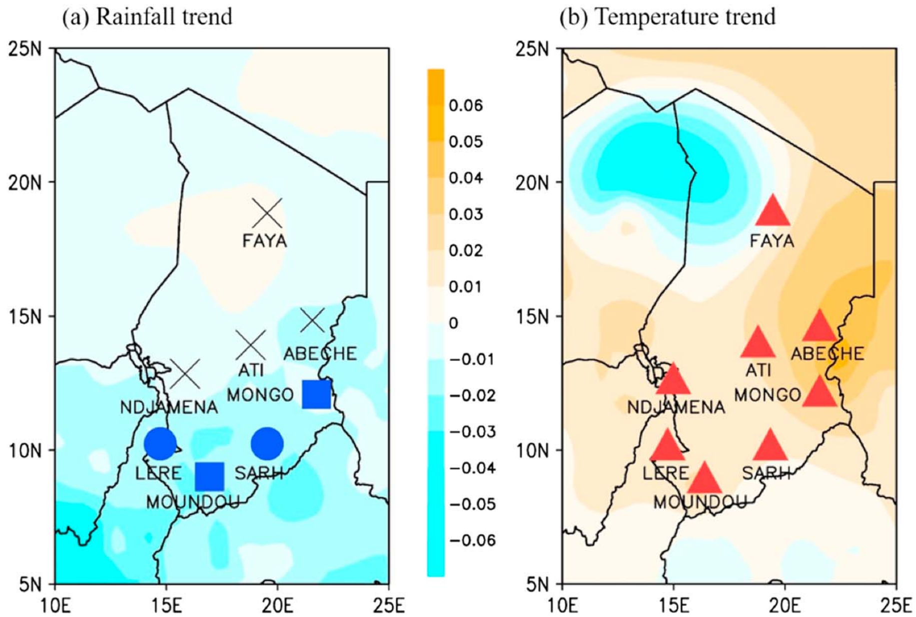

Figure 6. Trend of (a) annual rainfall (cm/year) and (b) temperature (°C/year) over of the Chad for period of study. The red color signifies the increasing trend, while blue represents decreasing trend and cross mark reflects no trend. The closed triangle represents the 99.9 significance level while the closed square and circle represent significance at 95% and 90% level, respectively.

4. Summary and Conclusions

The observed changes of hydroclimatic variables such as rainfall and temperature have been examined on a city scale over Chad for 1950–2014 period. The mean annual rainfall cycle shows that there is a strong increase in rainfall with the advancement of WAM, which peaks in August for all the major cities. Hence, WAM represents the source of rainfall/water over Chad. Cities in northern Chad (Faya, Abeche, and Ati) receive far less rainfall than the cities of southern Chad, while Ndjamena is the transition region between the two zones.

Few cities received higher rainfall during the wet period, then gradually enters a dry regime with frequent deficient rainfall years; afterward the rainfall starts to increase but at a very slow rate (recovery phase), which is consistent with the earlier studies (Caminade & Terray, 2009; Maharana et al., 2018). However, many cities show deviation from this behavior, which is attributed to the variability of rainfall distribution within Chad, which further, vary during different periods considered in the study. The large-scale variability in the moisture flux and transport and the associated rainfall in different periods is attributed to the city scale rainfall variability. The declining rainfall in most of the cities in the southern Chad is explained by them. The rainfall distribution in the three distinct subperiods shows a higher rainfall during the wet phase followed by a dry phase for all the location except Faya and Lere. In the recovery phase, five cities have slightly recovered from the dry phase but have not received as much as rainfall that occurred in the wet phase, hence making the overall rainfall trend as a decreasing trend for the entire period of study. The JJA is the major rainfall-contributing season toward the annual rainfall. Significant changes in rainfall have been noticed during the monsoon months (JJA) in the three periods, while no significant change has been observed in the other months. The rainfall is showing a statistically significant decreasing trend over the four cities in the south of Chad or near to the Lake Chad (Lere, Mondou, Mongo, and Sarh), whereas the cities to north Chad do not show any statistical trend (Figure 6a). These findings of the present study agree with the findings of the earlier works (Niel et al., 2005; E. Nkiaka et al., 2017). The recent increase in the rainfall over Ndjamena (which is close to Chad Lake) is interesting and encouraging for the people Chad, as this lake is the major supply of fresh water around the capital.

Similar analysis for temperature shows that the temporal variability of temperature is less (4–5 °C) among the stations or within the stations for different periods as compared to rainfall. It is interesting to note that the temperature overall the cities prior to 1985 were much colder. Afterward, the temperature started to rise and very warm temperature regime (positive value of standardized anomaly more than +1) is observed after 2000, reflecting the effect of global temperature rise over the cities of Chad. Hence, the temperature is showing a significantly increasing trend over all the cities (Figure 6b). The overall finding of the study is that the temperature is consistently increasing, and rainfall was initially decreasing but gradually recovering over most of the cities except for the cities in the southern Chad. The further declining of rainfall over Sarh and Lere during recovery period slows down the overall rainfall recovery over Chad.

The present study is still a preliminary climate analysis over different locations/cities of Chad. More such studies need to be carried out with different observed, reanalysis data sets and models for better understanding of the processes regulating this variability. The better understanding of large-scale as well as local atmospheric conditions will further enhance the knowledge of the rainfall variability within the cities. These better process-based understanding of this variability will help to develop the local scale mitigation strategies and adaptation technologies in this region. The authors have planned to work on the climate variability over Chad under 1.5–2 °C global temperature rise with respect to preindustrial period in the near future.

Data Availability Statement

All data used in this study are freely available and can be requested from the authors or obtained directly from the source: UDEL data (https://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html) and CRU data (http://www.cru.uea.ac.uk/data).

Competing Interest

The authors declare no competing interest.

Contributions

K. C. P. and P. M. conceptualized the idea of the work. A. Y. A.-L. and P. M. processed the data sets and prepared the figures and tables. K. C. P. and P. M. prepared the manuscript. A. Y. A.-L., K. V. R., M. S., and R. D. provided their inputs while interpreting the results and shaping the manuscript.

Acknowledgments
We acknowledge CRU and NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, for providing the precipitation and temperature data, from their website (https://www.esrl.noaa.gov/psd/). K. C. P. acknowledges the support from the NERC (UK Natural Environment Research Council) AMAZONICA and Amazon Hydrological Cycle grants (NE/F005806/1 and NE/K01353X/1). K. V. R. acknowledges the funding support from the Malaysian Ministry of Education and the University Utara Malaysia. We acknowledge Richard Pope, Ailish Graham, and Amy Peace for their help in correcting english language in the manuscript.

References

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., et al. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*, *111*, D05109. https://doi.org/10.1029/2005JD006290

Armitage, S. J., Bristow, C. S., & Drake, N. A. (2015). West African monsoon dynamics inferred from abrupt fluctuations of Lake Mega-Chad. *Proceedings of the National Academy of Sciences*, *112*(28), 8543–8548. https://doi.org/10.1073/pnas.1417655112

Bunting, A. H. (1975). Time, Phenology and the Yields of Crops*. *Weather*, *30*(10), 312–325. https://doi.org/10.1002/j.1477-8696.1975.tb05259.x

Caesar, J., Alexander, L., & Vose, R. (2006). Large-scale changes in observed daily maximum and minimum temperatures: Creation and analysis of a new gridded data set. *Journal of Geophysical Research*, *111*, D05101. https://doi.org/10.1029/2005JD006280

Caminade, C., & Terray, L. (2009). Twentieth century Sahel rainfall variability as simulated by the ARPEGE AGCM, and future changes. *Climate Dynamics*, *35*(1), 75–94. https://doi.org/10.1007/s00382-009-0545-4

Charney, J., Quirk, W. J., Chow, S. h., & Kornfield, J. (1977). A comparative study of the effects of albedo change on drought in semi–arid regions. *Journal of the Atmospheric Sciences*, *34*(9), 1366–1385. https://doi.org/10.1175/1520-0469(1977)034<1366:Acsote>2.0.Co;2

Coe, M. T., & Foley, J. A. (2001). Human and natural impacts on the water resources of the Lake Chad basin. *Journal of Geophysical Research*, *106*(D4), 3349–3356. https://doi.org/10.1029/2000jd900587

Collins, J. M. (2011). Temperature variability over Africa. *Journal of Climate*, *24*(14), 3649–3666. https://doi.org/10.1175/2011jcli3753.1

Diallo, I., Bain, C. L., Gaye, A. T., Moufouma-Okia, W., Niang, C., Dieng, M. D. B., & Graham, R. (2014). Simulation of the West African monsoon onset using the HadGEM3-RA regional climate model. *Climate Dynamics*, *43*(3-4), 575–594. https://doi.org/10.1007/s00382-014-2219-0

Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A. M. G., & Peterson, T. (2002). Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research*, *19*, 193–212. https://doi.org/10.3354/cr019193

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*, *34*(3), 623–642. https://doi.org/10.1002/joc.3711

Hulme, M., Doherty, R., Ngara, T., New, M., & Lister, D. (2001). African climate change: 1900-2100. *Climate Research*, *17*(2), 145–168. https://doi.org/10.3354/cr017145

Jury, M. R. (2009). Ethiopian decadal climate variability. *Theoretical and Applied Climatology*, *101*(1-2), 29–40. https://doi.org/10.1007/s00704-009-0200-3

Kendall, M. (1975). *Rank Correlation Methods*. London: Griffin & Co.

Koppen, W. (2011). The thermal zones of the Earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world. *Meteorologische Zeitschrift*, *20*(3), 351–360. https://doi.org/10.1127/0941-2948/2011/105

Kruger, A. C. (2006). Observed trends in daily precipitation indices in South Africa: 1910–2004. *International Journal of Climatology*, *26*(15), 2275–2285. https://doi.org/10.1002/joc.1368

Kutzbach, J. E. (1980). Estimates of Past Climate at Paleolake Chad, North Africa, Based on a Hydrological and Energy-Balance Model. *Quaternary Research*, *14*(02), 210–223. https://doi.org/10.1016/0033-5894(80)90049-6

Landman, W. A., & Mason, S. J. (1999). Change in the association between Indian Ocean sea-surface temperatures and summer rainfall over South Africa and Namibia. *International Journal of Climatology*, *19*(13), 1477–1492. https://doi.org/10.1002/(sici)1097-0088(19991115)19:13<1477::Aid-joc432>3.0.Co;2-w

Le Barbé, L., Lebel, T., & Tapsoba, D. (2002). Rainfall Variability in West Africa during the Years 1950–90. *Journal of Climate*, *15*(2), 187–202. https://doi.org/10.1175/1520-0442(2002)015<0187:Rviwad>2.0.Co;2

Maharana, P., Abdel-Lathif, A. Y., & Pattnayak, K. C. (2018). Observed climate variability over Chad using multiple observational and reanalysis datasets. *Global and Planetary Change*, *162*, 252–265. https://doi.org/10.1016/j.gloplacha.2018.01.013

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, *13*(3). https://doi.org/10.2307/1907187

N'Datchoh, E. T., Diallo, I., Konaré, A., Silué, S., Ogunjobi, K. O., Diedhiou, A., & Doumbia, M. (2018). Dust induced changes on the West African summer monsoon features. *International Journal of Climatology*, *38*(1), 452–466. https://doi.org/10.1002/joc.5187

Ndehedehe, C. E., Agutu, N. O., Okwuashi, O., & Ferreira, V. G. (2016). Spatio-temporal variability of droughts and terrestrial water storage over Lake Chad Basin using independent component analysis. *Journal of Hydrology*, *540*, 106–128. https://doi.org/10.1016/j.jhydrol.2016.05.068

New, M., Hewitson, B., Stephenson, D. B., Tsiga, A., Kruger, A., Manhique, A., et al. (2006). Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research*, *111*, D14102. https://doi.org/10.1029/2005JD006289

Nicholson, S. (2000). Land surface processes and Sahel climate. *Reviews of Geophysics*, *38*(1), 117–139. https://doi.org/10.1029/1999rg900014

Niel, H., Leduc, C., & Dieulin, C. (2005). Caractérisation de la Variabilité Spatiale et Temporelle des Précipitations Annuelles sur le Bassin du Lac Tchad au Cours du 20ème Siècle/Spatial and temporal variability of annual rainfall in the Lake Chad Basin during the 20th century. *Hydrological Sciences Journal*, *50*(2). https://doi.org/10.1623/hysj.50.2.223.61800

Nkiaka, E., Nawaz, N. R., & Lovett, J. C. (2017). Analysis of rainfall variability in the Logone catchment, Lake Chad basin. *International Journal of Climatology*, *37*(9), 3553–3564. https://doi.org/10.1002/joc.4936

Nkiaka, E., Nawaz, R., & Lovett, J. C. (2018). Assessing the reliability and uncertainties of projected changes in precipitation and temperature in Coupled Model Intercomparison Project phase 5 models over the Lake Chad basin. *International Journal of Climatology*, *38*(14), 5136–5152. https://doi.org/10.1002/joc.5717

Odada, E. O., & Olago, D. O. (2005). Holocene climatic, hydrological and environmental oscillations in the tropics with special reference to Africa. *Climate Change and Africa*, *20*.

Ogallo, L. (1979). Rainfall variability in Africa. *Monthly Weather Review*, *107*(9), 1133–1139. https://doi.org/10.1175/1520-0493(1979)107<1133:Rvia>2.0.Co;2

Okonkwo, C., Demoz, B., & Gebremariam, S. (2014). Characteristics of Lake Chad level variability and links to ENSO, precipitation, and river discharge. *ScientificWorld Journal*, *2014*. https://doi.org/10.1155/2014/145893

Pachauri, R. K., & Reisinger, A. (2007). Synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. Climate change 2007, 10.

Paeth, H., & Hense, A. (2004). SST versus Climate Change Signals in West African Rainfall: 20th-century variations and future projections. *Climatic Change*, *65*(1/2), 179–208. https://doi.org/10.1023/B:CLIM.0000037508.88115.8a

Poan, E. D., Gachon, P., Dueymes, G., Diaconescu, E., Laprise, R., & Seidou Sanda, I. (2016). West African monsoon intraseasonal activity and its daily precipitation indices in regional climate models: Diagnostics and challenges. *Climate Dynamics*, *47*(9-10), 3113–3140. https://doi.org/10.1007/s00382-016-3016-8

Rodhe, H., & Virji, H. (1976). Trends and periodicities in East African Rainfall Data. *Monthly Weather Review*, *104*(3), 307–315. https://doi.org/10.1175/1520-0493(1976)104<0307:Tapiea>2.0.Co;2

Roehrig, R., Bouniol, D., Guichard, F., Hourdin, F., & Redelsperger, J.-L. (2013). The present and future of the West African Monsoon: A process-oriented assessment of CMIP5 simulations along the AMMA transect. *Journal of Climate*, *26*(17), 6471–6505. https://doi.org/10.1175/jcli-d-12-00505.1

Rowell, D. P., Folland, C. K., Maskell, K., & Ward, M. N. (1995). Variability of summer rainfall over tropical north Africa (1906–92): Observations and modelling. *Quarterly Journal of the Royal Meteorological Society*, *121*(523), 669–704. https://doi.org/10.1002/qj.49712152311

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., et al. (2013). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *IPCC, 2013. Climate change 2013: The physical science basis*.

Sylla, M. B., Giorgi, F., Pal, J. S., Gibba, P., Kebe, I., & Nikiema, M. (2015). Projected changes in the annual cycle of high-intensity precipitation events over West Africa for the late twenty-first century. *Journal of Climate*, *28*(16), 6475–6488. https://doi.org/10.1175/jcli-d-14-00854.1

Tan, X., & Gan, T. Y. (2015). Contribution of human and climate change impacts to changes in streamflow of Canada. *Science Reports*, *5*(1). https://doi.org/10.1038/srep17767

Thorncroft, C. D., Nguyen, H., Zhang, C., & Peyrillé, P. (2011). Annual cycle of the West African monsoon: regional circulations and associated water vapour transport. *Quarterly Journal of the Royal Meteorological Society*, *137*(654), 129–147. https://doi.org/10.1002/qj.728

Trenberth, K. E., Jones, P. D., Ambenje, P. G., Bojariu, R., Easterling, D. R., Tank, A. M. G. K., et al. (2007). Observations: Surface and atmospheric climate change. Climate Change 2007. In S. Solomon, et al. (Eds.), *The Physical Science Basis* (pp. 235–336). Cambridge University Press.

Washington, R., Todd, M. C., Lizcano, G., Tegen, I., Flamant, C., Koren, I., et al. (2006). Links between topography, wind, deflation, lakes and dust: The case of the Bodélé Depression, Chad. *Geophysical Research Letters*, *33*, L09401. https://doi.org/10.1029/2006GL025827

Westra, S., Alexander, L. V., & Zwiers, F. W. (2013). Global increasing trends in annual maximum daily precipitation. *Journal of Climate*, *26*(11), 3904–3918. https://doi.org/10.1175/jcli-d-12-00502.1

10.1029/2019EA000619

Willmott, C. J., Matsuura, K., & Legates, D. (2001). Terrestrial air temperature and precipitation: Monthly and annual time series (1950–1999).

Zeng, N. (1999). Enhancement of interdecadal climate variability in the sahel by vegetation interaction. *Science*, *286*(5444), 1537–1540. https://doi.org/10.1126/science.286.5444.1537