Atmospheric Research xxx (xxxx) xxx-xxx

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com

Changing characteristics of meteorological droughts in Nigeria during 1901 2010

Mohammed Sanusi Shiru [a, b], , Shamsuddin Shahid [a], Eun-Sung Chung [c], Noraliani Alias [a]

[a] Department of Water and Environmental Engineering, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Malaysia
[b] Department of Environmental Sciences, Faculty of Science, Federal University Dutse, P.M.B 7156 Dutse, Nigeria
[c] Department of Civil Engineering, Seoul National University of Science and Technology, Republic of Korea

ARTICLE INFO

Keywords:
Seasonal droughts
Standardized precipitation evapotranspiration index
Modified Mann-Kendall trend
Climate change
Nigeria

ABSTRACT

The objective of this study was to assess the changes in the severity and return periods of meteorological droughts during major cropping seasons of Nigeria for the period 1901 2010 in order to understand the impacts of climate variation on seasonal droughts. Gauge-based gridded global precipitation climatology center (GPCC) rainfall and climate research unit (CRU) potential evapotranspiration (PET) data having a spatial resolution of 0.5° were used for the reconstruction of droughts using standardized precipitation evapotranspiration index (SPEI). SPEI values were fitted with the best distribution function to estimate seasonal droughts return periods and the modified Mann-Kendall test was used to assess the secular changes in climate variables and drought index. The temporal variations in droughts and their interrelations with rainfall and temperature trends were assessed using a 50-year moving window with a 10-year time step. The results showed that meteorological drought severity has increased for all the cropping seasons of Nigeria. Temperature was found to be the dominating factor for defining droughts in semi-arid regions in the north while rainfall in the monsoon and tropical savanna climatic zones dominates in the south. Rises in temperature in the range of 0.14 0.42 °C/decade and almost no change in rainfall have caused decreases in SPEI up to 0.25/decade in some regions. The number of grid points with decreasing SPEI was found to vary between 50 out of 323 for millet and 152 for yam growing season. The moderate droughts were found to become more frequent compared to other classes of droughts. Amongst the cropping seasons, the highest increases in drought frequency were observed during corn growing season. The highest decrease in the median value of the return period of moderate, severe and extreme droughts during the two corn growing seasons were observed to be 6.25, 12.86 to 13.20, 23.15 to 24.31 years in 1901 1950 to 6.25, 12.92 to 12.94, 23.51 to 23.64 in 1961 2010. Compared to other drought severities, the return periods of the moderate droughts were found to decrease more. A general decrease in the return periods of droughts indicates more frequent droughts during all cropping seasons of Nigeria. Therefore, it can be concluded that the rising temperature due to global warming would increase drought severity and frequency in all the cropping seasons of Nigeria.

1. Introduction

The changing characteristics of the global climate have resulted in the variations of rainfall and temperature patterns around the world (Almazroui et al., 2016; Sung et al., 2017; Nashwan et al., 2018a, 2018b; Vinnarasi and Dhanya, 2016; Salman et al., 2017; Sa'adi et al., 2017; Pour et al., 2018; Tao et al., 2018). These changes in climate have significantly affected the hydrological system (Zahabiyoun et al., 2013) which eventually increased the frequency and intensity of hydro-meteorological disasters like floods (Khazaei et al., 2012; Sharafati, 2014; Nashwan et al., 2018a, 2018b; Shiru et al., 2015) and droughts (Zhang et al., 2012; Sung and Chung, 2014; Liu and Hwang, 2015; Ahmed et al., 2015; Zhang et al., 2017; Mohsenipour et al., 2018; Ahmed et al., 2018). Drought is a shortfall of water resources due to the deficit of rainfall over a prolonged period that occurs in a recurring manner (Tsakiris and Vangelis, 2005). Therefore, the changes in drought due to climate change will affect water stress, food security and national economy in the context of global warming (Nam et al., 2015; Touma et al., 2015). It has been reported that a 1% increase in drought affected area can reduce growth rate of gross domestic product

Corresponding author at: Department of Water and Environmental Engineering, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Malaysia.
Email address: shiru.sanusi@gmail.com (M.S. Shiru)

https://doi.org/10.1016/j.atmosres.2019.03.010
Received 18 December 2018; Received in revised form 3 March 2019; Accepted 4 March 2019
Available online xxx
0169-8095/

(GDP) of a country by 2.7% per year (Brown et al., 2013). The implementation of necessary adaptation and mitigation measures is crucial to improve water security and ensure economic growth in the context of increasing severity and frequency of droughts due to climate change. Understanding the influence of climate variability on droughts in different climatic regions is very important for sustainable development.

Droughts are more devastating when they occur in developing countries, particularly agriculture-based developing countries. Most of the world's populations are concentrated in developing countries and more than half of these population is at the risk of the various impacts of climate change. Therefore, increasing frequency of droughts would certainly have severe implications for the developing nations (Abiodun et al., 2013; Collins et al., 2013). Nigeria, located in high drought risk region of the world may be severely affected by global climate change induced increase frequency and severity of droughts due to high density of population and reliance on agriculture (Dilley et al., 2005). Agriculture provides 70% Nigerians with their sources of livelihoods and contributes about 20% to the country's GDP (World Bank Group, 2018). The agricultural practices are mainly rain fed and only 1% of cropped land is irrigated (Food and Agricultural Organization, 2018). Therefore, the spatial and temporal changes in droughts have a very significant impact on food production, people livelihoods, and agricultural sustainability of the country.

The meteorological drought is a form of drought that occurs as a result of deficiency in precipitation over an area for some particular period of time (Vu et al., 2015). It is the trigger of all other types of droughts and thus most important for assessment of water stress in the context of climate change. A large number of studies have assessed various aspects of meteorological droughts in Nigeria using different indices (Prothero, 1974; Sonuga, 1977; Watts, 1983; Adefolalu, 1986; Acheampong, 1990; Tarhule and Woo, 1997; Keylock, 1999; Adeaga, 2002; Medugu et al., 2011; Usman and Abdulkadir, 2014; Okorie et al., 2015; Adeniyi and Uzoma, 2016; Oloruntade et al., 2017; Shiru et al., 2018) including standardized precipitation index (SPI) (McKee et al., 1993) and standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010). However, none of the aforementioned studies attempted to assess the impact of climate changes on droughts in Nigeria, though it is supposed to have significant impact on droughts affected regions of Africa.

The climate of Nigeria is changing like many other regions of the globe. Recent study revealed that temperature of the country is rising in the range of 0.014 0.04°C/year, while a decreasing trend in precipitation is observed in some parts in the range of 0.2 to 0.90 mm/year (Shiru et al., 2018). It is anticipated that the changes in climate have changed the characteristics of droughts in Nigeria. However, the impacts of climate change on droughts would vary in different parts of the country due to diversity in climate and seasons. Furthermore, the influence of climate on droughts can also vary with time depending on the dominance of climatic variables. Besides, climate change impacts on meteorological droughts are important to be assessed during cropping seasons as the droughts are found to be more destructive when they occur during these seasons.

Thus, the major objective of this study is to analyze the changing characteristics of meteorological droughts during major crop growing seasons of Nigeria for the period 1901 2010 in order to assess the changing characteristics of seasonal droughts over the diverse climate of the country. The SPEI which combines the effect of precipitation and temperature to quantify the condition of droughts was used for this study. Gauge-based gridded precipitation and potential evapotranspiration (PET) data provided by the Global Precipitation Climatology Centre (GPCC) of the Deutscher Wetterdienst (Becker et al., 2013) and the Climatic Research Unit (CRU) of the East Anglia University (Harris et al., 2014) respectively were used for the assessment of the changes in droughts characteristics over the period 1901 2010 using a 50-year moving window with a 10-year time step. A modified version of Mann-Kendall trend (MMK) test which can distinguish natural variability of climate from anthropogenic climate change was used to analyze the secular trends in climate and drought index. Although Nigeria produces various crops including rice, corn (maize), yam, sorghum (guinea corn), millet, beans, cassava, soya beans, and melon, five widely consumed crops in the country namely, yam, rice, corn, sorghum, and millet are considered in this study.

The novelty of this study is to assess the impacts of climate variability and changes on meteorological droughts in different climatic zones and different crop growing seasons. It is expected that the assessment of the spatio-temporal changes in the characteristics of seasonal droughts over a diverse climate of Nigeria would help to understand how future climate variations will affect droughts of different climatic zones during different cropping seasons of the country.

2. Study area and data

2.1. Study area

Nigeria (Latitude: 4015 13055 N; Longitude: 2040 14045 E), located in West Africa covers an area of 923,000 km2 (Fig. 1). The topography of the country is mostly flat in the south and some elevated areas and mountains exist in the north. The lowest elevation is 0 m near the Atlantic Ocean in the south while the highest elevation is 2419 m at Chappal Waddi in the north eastern part of the country. The climate of the country can be divided into two main seasons: (a) dry winter from November to March, and (b) rainy summer from April to October.

The climate varies from the north to the south; therefore, the onset of the seasons varies for the two regions. The rainy season in the semi-arid and arid north is between June and September while rainfall starts in April and occurs till October in the central and southern parts of the country. The annual average rainfall in the country varies from >2000 mm in the south to <500 mm in the north (Fig. 2). The daily maximum temperature in the south ranges from 30 °C to 37 °C. In the north, it can reach up to 45 °C during summer. The minimum temperatures during the dry cold season in the north are as low as 12 °C, while it ranges from 17 °C to 24 °C in the south. Average temperature varies from <22 °C in high elevation areas to >28 °C across the country (Fig. 2). In terms of climate, Nigeria is divided into four zones from the south to the north: tropical savanna climate, monsoon climate, warm semi-arid climate, and warm desert climate (Fig. 1). In addition, there is significant variation in the ecology of Nigeria with Sahel Savanna, Sudan Savanna, Guinea Savanna, Rainforest, and Mangrove Swamp ecological types occurring from the north to the south in respective order. Nigeria is geopolitically divided into six zones namely: north-west, north-east, north-central, south-west, south-east, and south-south. This study doesn't consider these zones for the description of the occurrences of droughts, but instead the geographical locations of areas based on the size of the country.

The cropping seasons of the five major crops considered in this study are shown in Fig. 3. There is variation in the cropping seasons of rice and corn between the north and the south of the country. Therefore, the cropping seasons for these two crops are separately considered in this study.

2.2. Data and sources

One of the major problems in hydro-climatological investigations in Nigeria is the lack of long term records of reliable climate observations. Gridded climate data can be used in the region where long-term reliable climatic observation is not available. Amongst the gridded climate data, the in-situ based data are most often used because of their spatial

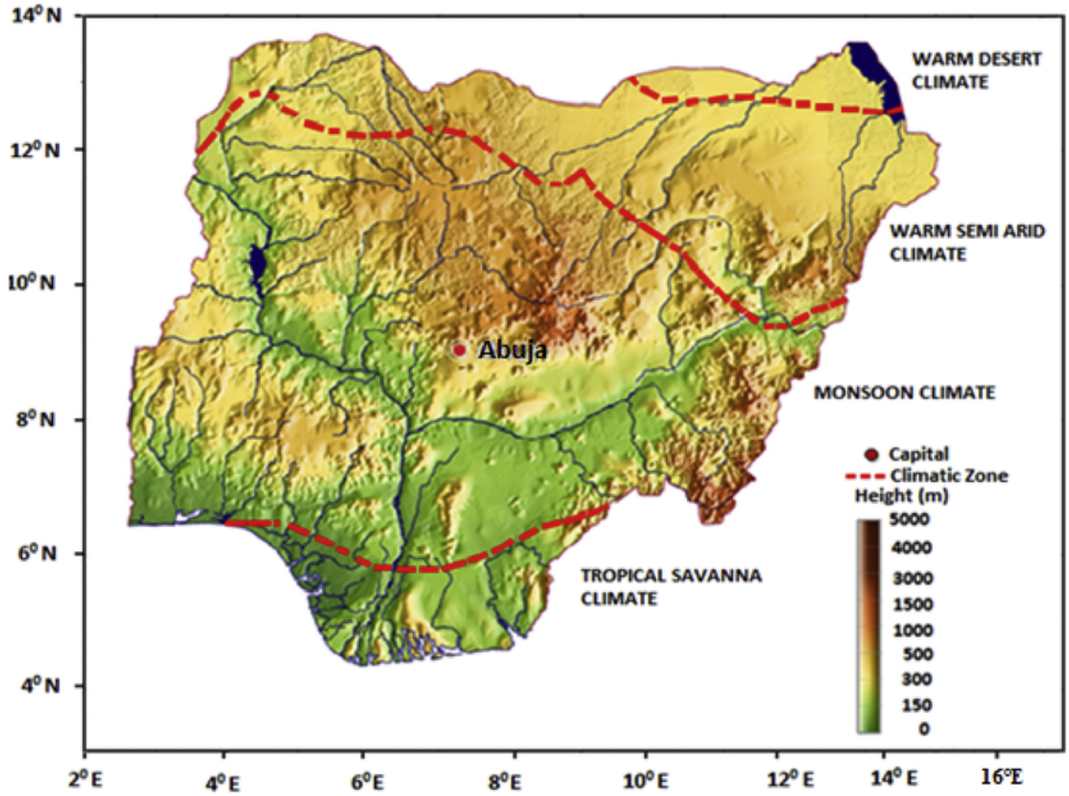

Fig. 1. The topography and climatic zones of Nigeria.

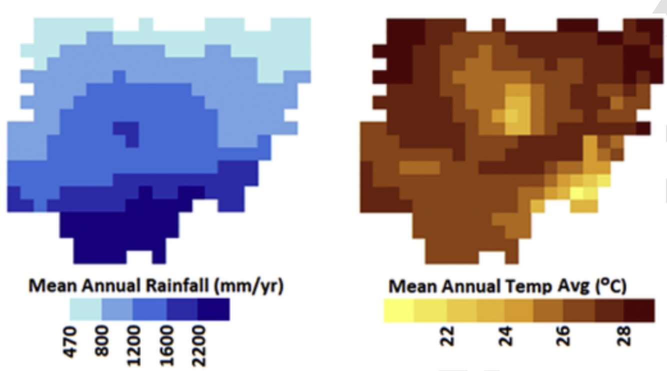

Fig. 2. The spatial variation of mean annual rainfall (mm/yr) and daily average temperature (°C) over Nigeria.

and temporal continuity and availability over longer periods (Ahmed et al., 2017). In the present study, the monthly full reanalysis precipitation data of GPCC (Becker et al., 2013) and the monthly average of daily gridded PET data CRU TS v. 3.23 of CRU (Harris et al., 2014) of the East Anglia University at 0.5° spatial resolution (323 grid points covering Nigeria) for the period 1901 2010 were used. Besides monthly average of daily gridded mean temperature data of CRU TS v. 3.23 of CRU have a same resolution (0.5°) was used for the same temporal extent (1901 2010) to assess the influence of temperature changes on droughts. A moving window of 50 years with a time step of 10 years was used for the assessment of the changes in droughts during different periods. Therefore, period of data analysis was chosen as a multiple of 10, which allow a maximum period of data use until 2010.

The monthly precipitation data of GPCC was developed from rainfall records obtained from various sources (Schneider et al., 2014). The data includes available near real time such as synoptic weather reports (SYNOP) and monthly climate reports (CLIMAT) distributed by national meteorological and hydrological services (NMHSs) through the World Meteorological Organization (WMO) and global telecommunication system (GTS), and non-real time rainfall data obtained from over 85,000 rain-gauges located in about 190 countries (Schneider et al., 2011). For gridding, the GPCC employs a smart interpolation technique which has the ability of considering the systematic relationship between elevation and station observations, and consequently, the ability

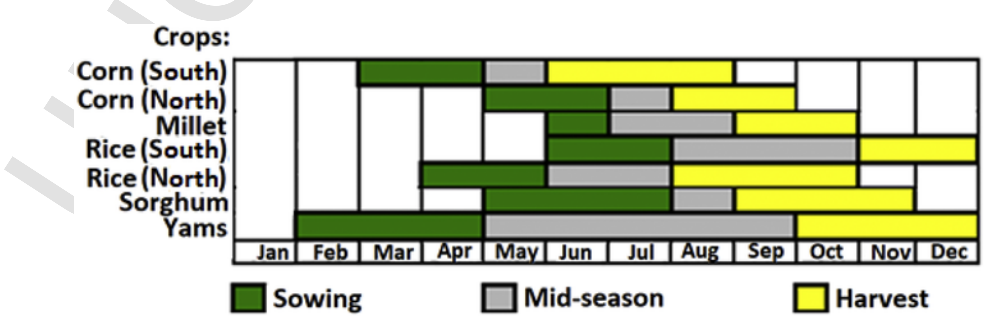

Fig. 3. Cropping season calendar of selected crops of Nigeria.

to enhance estimation accuracies (Funk et al., 2007). Other advantages of using GPCC data include: (1) the data set quality is good enough for hydro-climatic analysis; (2) it is a climate model derived dataset which uses the highest number of observed rainfall records; and (3) time span of data is long enough for conducting hydro-climatic studies (Spinoni et al., 2014). The GPCC has been used in a number of studies for hydro-climatic analysis in Africa (Dinku et al., 2008; Yang et al., 2014; Tierney et al., 2013; McNally et al., 2017).

The CRU database is developed from gauge measurements obtained from about 4000 weather stations located around the world. All the collected data are passed through two-stage extensive manual and semi-automatic quality control measures to develop the gridded monthly temperature anomalies (Harris et al., 2014). An interpolation method known as angular distance-weighted was used to develop CRU gridded data from gauge measurements. A number of studies found that CRU was suitable in reconstructing historical PET and temperature of Africa (Hao et al., 2013; Omondi et al., 2014; Wolski et al., 2012; Tirivarombo et al., 2018; Oguntunde et al., 2017).

Uncertainties as a result of complex terrains, sparse network of observations, interrupted/limited data records, instrument errors, data assimilation and interpolation techniques, etc. can exist between gauged data and gridded data (Vu et al., 2017a), which can affect climate trends, hydro-climatic characteristics and return periods of hydrological phenomena estimated using gridded climate data. The number of gauge data used for the development of GPCC and CRU data was different. The number of gauge per grid used for the development of GPCC and CRU data are presented in Fig. 4(a) and (b) respectively. The number of gauges was found to vary over time for both cases. Fig. 4 shows the number of stations used for the preparation of gridded data for the year 1990. It was found that more gauges were used for the preparation of GPCC rainfall compared to CRU temperature. The gauges were also found sparsely distributed, which indicates presence of uncertainty in gridded data. Therefore, the capability of GPCC and CRU data to replicate observed data was required to assess.

The performance of gridded data according to their ability to replicate the observed data is required to confirm before their use for drought analysis. In this study, the performance of GPCC and the CRU data were validated using observed data obtained from the global historical climatology network. Rainfall data is available for 37 stations and the temperature data for 8 stations. As there were missing data for some periods for both the observed rainfall and the temperature data, common years for which both the observed and the gridded data are available were used for the validation. The validations were conducted using standard statistical indices namely, percentage of bias (Pbias), normalized root mean square error (NRMSE%), Nash-Sutcliff efficiency (NSE), modified index of agreement (md), volumetric efficiency (VE) and coefficient of agreement (d). The mean and the range of the performance metrics obtained for GPCC and CRU at different gauged locations are presented in Table 1. It indicates less errors and good association between observed and selected gridded data for Nigeria.

Besides, time series plots of observed and gridded data and residuals were prepared. Comparison was also made using probability distribution function (PDF) and cumulative distribution function (CDF) plots of observed and gridded data (not presented here). It was found that the gridded data were able to replicate the properties of observed data efficiently. Number of previous studies also reported better performance of GPCC and CRU data in replicating observed rainfall and temperature of Nigeria and nearby regions as mentioned earlier.

3. Methodology

The procedure used to understand the influence of climatic factors on the severity and return period of droughts during major crop growing seasons of Nigeria is presented using a flow chart given in Fig. 5.

The procedure used in this study for assessing the changing characteristics of meteorological droughts in Nigeria is as follows.

1. The SPEI was calculated at each GPCC/CRU grid point over Nigeria (total 323 grid points) for the period 1901 2010 using a 50-year moving window with a 10-year time step.
2. The trends in rainfall, temperature and SPEI during different crop growing seasons for different 50-year time periods were estimated using modified version of Mann-Kendall trend test (Hamed, 2008).
3. The return periods of moderate, severe, and extreme droughts during major crop growing seasons for different 50-year time periods

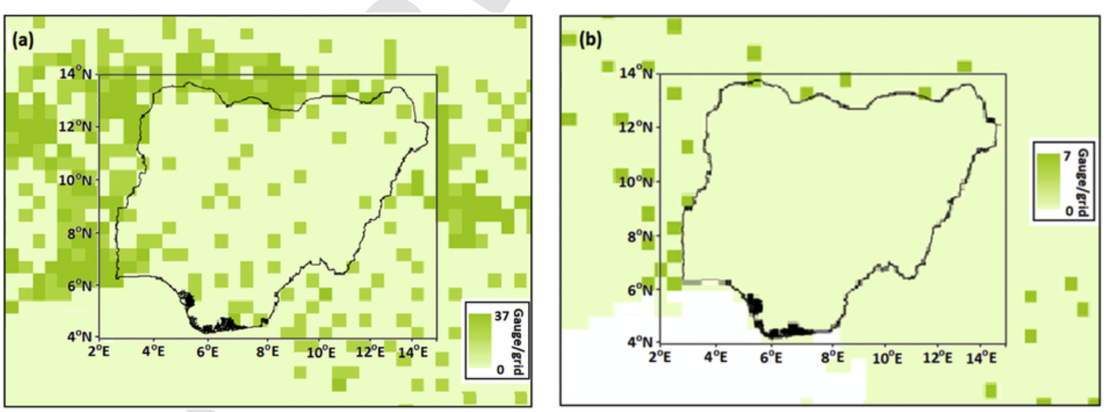

Fig. 4. Number of gauge per grid in and around Nigeria was used for the preparation of (a) GPCC and (b) CRU data.

Table 1
The performance of GPCC rainfall and CRU temperature when compared with observed data. Numbers represent mean (maximum minimum) values of the metrics estimated for all stations over Nigeria.

Variable	Pbias	NRMSE	NSE	Md	Ve	d
Rainfall	4.4 (27.6 35.1)	30.9 (2.9 75.9)	0.87 (0.42 1.0)	0.88 (0.65 0.99)	0.82 (0.23 0.98)	0.96 (0.81 1.0)
Max Temp	1.76 (3.6 4.9)	75.6 (52.8 116.4)	0.39 (0.36 0.72)	0.67 (0.51 0.77)	0.96 (0.92 0.97)	0.89 (0.78 0.95)
Min Temp	0.83 (10.5 9.5)	99.2 (37.8 166.1)	(1.76 0.86)	0.58 (0.35 0.84)	0.94 (0.89 0.96)	0.80 (0.51 0.96)

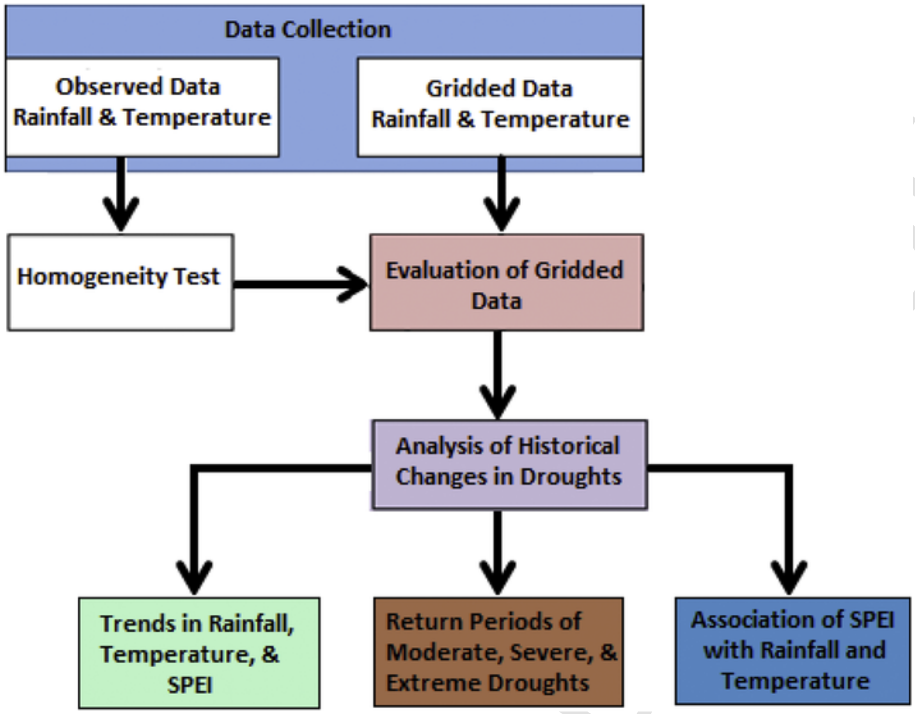

Fig. 5. Flow chart showing the procedure used in the study for assessing the changing characteristics of meteorological droughts in Nigeria.

were estimated by fitting best probability distribution function (PDF) of seasonal SPEI values.

4. The associations of SPEI with rainfall and temperature for different 50-year time periods were estimated using non-parametric Kendall-tau correlation coefficient.
5. The results were analyzed to assess the influence of rainfall and temperature during different periods and crop growing seasons.

The details of the methods used in the study are described in the following sections.

3.1. Standard precipitation evapotranspiration index for estimation of seasonal droughts

In SPEI, the water deficit or surplus aggregated at different time scales (D) is estimated as the difference between precipitation (P) and potential evapotranspiration (PET). The obtained values of *D* are then fitted with the best PDF to estimate the return periods for SPEI values. The SPEI values of 1.0 to 1.5, 1.5 to 2.0 and below 2.0 means moderate, severe and extreme droughts, respectively.

In calculating PET, different methods such as radiation, temperature, and mass transfer-based methods can be employed (Tuklimat et al., 2012). Stagge et al. (2014) reported the sensitivity of the SPEI to the radiation methods but not to the temperature-proxy methods. Also, the differences in the SPEI series from the different PET methods and their significances in regions such as semi-arid areas were reported by Beguería et al. (2014). The Penman Monteith was therefore proposed as the first choice while the Hargreaves and the Thornthwaite methods follow respectively. Therefore, gridded PET data of CRU estimated using Penman-Monteith method was used in the present study.

The SPEI value at the last month of a season estimated for the time span of the season is used in determining the drought for that season. Because sowing and mid-season periods require more water than the harvesting period, the assessment of droughts for each of the crops were conducted based on their sowing and vegetative periods. For example, Rice (N) needs total 5 months for its sowing and vegetative period, therefore a 5-month SPEI value computed in October (end of the mid-season) was used for the analysis of droughts for this crop. The periods used for the calculation of the SPEI and droughts estimation for all the crops are given in Table 2.

The season's values of SPEI were used to estimate the return periods (RP) of seasonal droughts. In the present study, SPEI value less than 1.0 was considered as drought and thus, the years without droughts were assigned a value of zero. The drought frequency analysis was carried out only on the non-zero values and a correction was conducted using non-exceedance probability (F') in order to account for the zero values,

$$F' = q + (1 - q)F \quad (1)$$

where *F* is the non-exceedance probability value obtained using frequency analysis on the non-zero values, and *q* is the probability of zero values, which can be calculated as the ratio of the number of time intervals without drought occurrences to the total number of time intervals for the recording period (Santos et al., 2011; Ahmed et al., 2015; Alamgir et al., 2015; Mohsenipour et al., 2018).

3.2. Sen's slope estimator

The Sen's slope estimator (Sen, 1968) was used to assess the rate of change in SPEI, rainfall and temperature. In Sen's slope method, the

Table 2
The periods used for the calculation of the standardized precipitation evapotranspiration index (SPEI) values in order to estimate droughts during different crop growing seasons.

Crop	Season	Period (Month)
Corn (S)	March–May	3
Corn (N)	May–July	3
Millet	June–August	3
Rice (N)	June–October	5
Rice (S)	April–July	4
Sorghum	May–August	4
Yam	February–September	8

change in a time series (Q_{med}) is computed as the median of N slopes estimated from consecutive two points of the series as follows.

$$Q_{med} = \begin{cases} Q_{\left[\frac{N+1}{2}\right]} \; if\, N\, is\, odd \\ \frac{Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]}}{2} \; if\, N\, is\, even \end{cases} \tag{2}$$

3.3. Modified Mann-Kendall test

The MMK test was used to assess the significance of trend in SPEI, rainfall and temperature. The classical Mann-Kendall test statistic (S) for a time series, x with n number of data points is calculated as follows (Mann, 1945).

$$S = \sum_{k=1}^{n-1} \cdot \sum_{i=k+1}^{n} \text{sign}\ \left(x_i - x_k\right) \tag{3}$$

where

$$sign\ \left(x_i - x_k\right) = \begin{cases} +1 \text{ when } \left(x_i - x_k\right) > 0 \\ 0 \text{ when } \left(x_i - x_k\right) = 0 \\ -1 \text{ when } \left(x_i - x_k\right) < 0 \end{cases} \tag{4}$$

The significance of the trend is calculated using Z statistics as follows.

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var\ (S)}}\ when\ \text{S}>0 \\ 0\ when\ \text{S} = 0 \\ \frac{S-1}{\sqrt{Var\ (S)}}\ \text{when S}<0 \end{cases} \tag{5}$$

where, ***Var*** (***S***) is the variance of *S*.

In MMK test (Hamed, 2008), the significant trend estimated using MK test is first removed from the time series. The equivalent normal variants of rank (R_i) of the de-trended series is then estimated as,

$$Z_i = \text{ffi}^{-1}\left(\frac{R_i}{n+1}\right) \tag{6}$$

where, ^{1} is the inverse standard normal distribution function. The correlation matrix of self-similarity of the time series or the Hurst coefficient (H) is derived using the following equation (Koutsoyiannis, 2003):

$$C_n\ (H) = \left[\rho_{|j-i|}\right], for\ i = 1 : n; j = 1 : n \tag{7}$$

$$\rho_l = \frac{1}{2}\ \left(|l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H}\right) \tag{8}$$

where, $_l$ is the autocorrelation function of lag l for a given H. The value of H is obtained using maximum log likelihood function. The significance level of H is determined by using mean and standard deviation for $H = 0.5$. If H is found significant, the biased estimate of the variance of S is calculated for given H as,

$$V(S)^{H\prime} = \sum_{i<j} \cdot \sum_{k<l} \frac{2}{\pi} \sin^{-1}\left(\frac{\rho\,|j-i| - \rho\,|i-l| - \rho\,|j-k| + \rho\,|i-k|}{\sqrt{(2-2\rho\,|i-j|)\,(2-2\rho\,|k-l|)}}\right) \tag{9}$$

The bias in estimation of $V(S)^H$ is removed using a bias correction factor, B as below:

$$V(S)^H = V(S)^{H\prime} \times B \tag{10}$$

where B is a function of H. The significance of MMK test is computed using Eq. (5) by replacing $V(S)$ with $V(S)^H$.

3.4. Mapping spatial patterns of trends

Drought is a complex phenomenon that varies over time and space (Patterson et al., 2013). Therefore, complete understanding of drought requires studying their spatial extents. In the present study, the magnitude of change in SPEI, precipitation and temperature estimated using Sen's slope estimator at all the GPCC/CRU grid points over Nigeria are presented using color ramps. The change at each grid point is presented in original resolution of GPCC/CRU data (0.5° × 0.5°). Symbols + or - are used to show the significant increases or decrease in trends at 95% confidence level estimated by MMK test at each grid point.

4. Results

4.1. Droughts in yam growing season

The spatial pattern of the trends in rainfall, temperature and SPEI during yam growing season in recent years (1961 2010) are presented in Fig. 6a, b and c respectively. The rainfall decrease only at few grid points in the southeast of the country. Whereas, temperature was found to increase in almost the entire country. It was found to increase at higher rates in the northeast and northwest parts. The SPEI was found to decrease in the semi-arid northwest and northeast parts as well as in the monsoon dominated southeast, southwest and central regions of Nigeria. The results revealed that almost no change in rainfall but the increase in temperature have caused the decrease of SPEI in monsoon dominated central region of Nigeria. Similarly, the SPEI in the northern arid region was found to decrease due to a sharp increase in temperature.

The number of grid points showing significant change in rainfall, temperature and SPEI for a 50-year moving window with a 10-year time step over the period 1901 2010 are shown in Fig. 6d, e and f, respectively. These figures show sensitivity of SPEI to rainfall and temperataure during yam growing season. The SPEI was found to increase (decrease in drought severity) in the period when rainfall was increasing and temperature was decreasing and vice-versa. For example, the increase in rainfall and the decrease in temperature at few grid points caused an increase in SPEI during 1931 1981. On the other hand, a decrease in rainfall at 50 to 55 grid points (about 14 to 15% of area) and an increase in temperature at a large number of grid points (96%) during 1951 2000 caused a sharp rise in the number of grid points with decreasing SPEI. In recent years (1961 2010), spatial patterns showed decrease in rainfall only at a few grids in the southeast part while a significant increase in temperature over almost the entire country. This has caused decrease in SPEI in about 46% area (152 grid points). The figures clearly indicate that the recent increase in drought severity during yam growing season is due to the sharp rise in temperature. The result can be verified with the correlation of SPEI with rainfall and temperature (Fig. 6g). It was found that the correlation between rainfall and SPEI has decreased while the correlation between temperature and SPEI has increased in recent years. The relationship between temperature and SPEI in recent years was also found significant. Though correlation does not mean causation, decrease in SPEI with the increase of temperature as evident from Fig. 6h and i and the significant association of temperature with SPEI in recent years (Fig. 6g) indiates that recent increase in drought severity is due to the rise of temperature.

The increases in drought severity has also caused a gradual decrease in drought return periods. The return period of different severities of yam droughts estimated at different grid points are presented using box plots in Fig. 6h, i and j. The box plot displays the full range of variation of drought return periods estimated at different grid points. The box represents the interquartile range of return period, where the

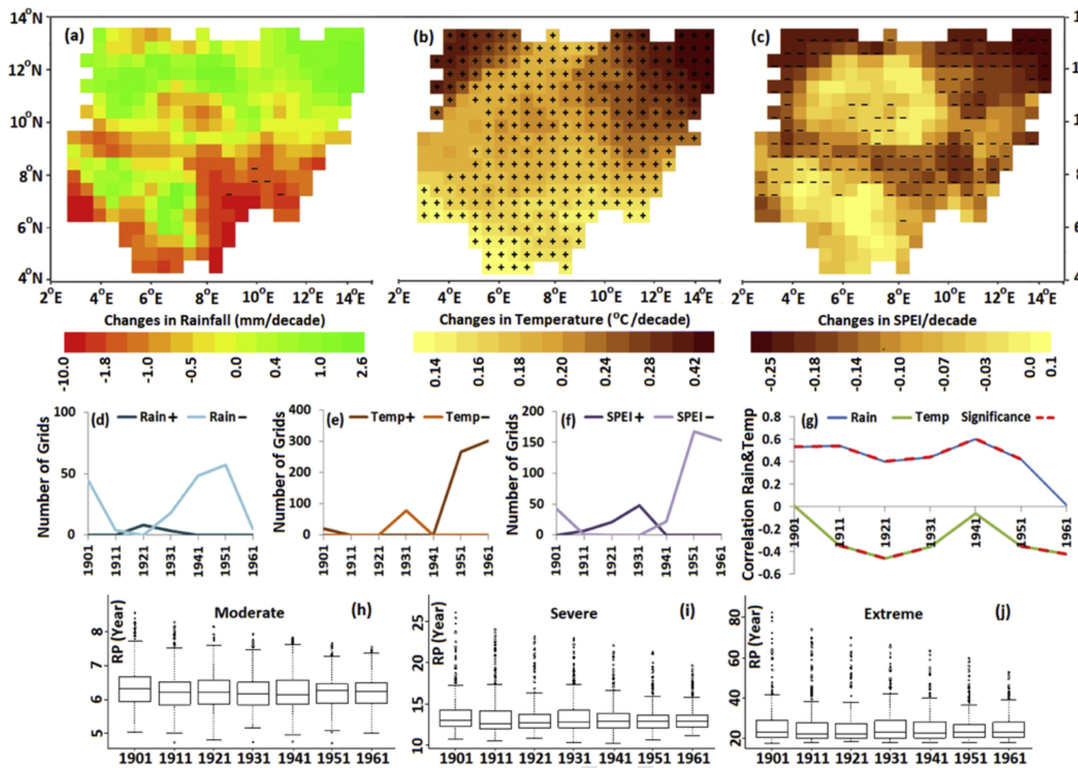

Fig. 6. Trends in (a) rainfall; (b) daily mean temperature; (c) SPEI during yam growing period for the period 1961 2010; the number of grid points showing significant changes in (d) rainfall; (e) daily mean temperature; (f) SPEI for different 50-year periods with a 10-year time step between 1901 and 2010 for yam growing period; (g) correlation of SPEI with rainfall and temperature; the return periods of (h) moderate; (i) severe; and (j) extreme droughts during yam growing period for a 50-year moving window with a 10-year time step for the period 1901 2010.

lower and the upper bound of the box represent 25-th and 75-th percentile values and the horizontal line inside the box represents median (50-th percentile) value of return period for the entire study area. The whiskers represent 1.5 time of interquartile range above or below the 75-th or 25-th percentile values. A longer size of box or a large extent of whisker indicates a wide range of drought return periods while a shorter box or extent of wisher indicates drought return periods at all the grid points are very close to median value.

The return periods for moderate, severe and extreme yam droughts were found in the ranges of 5.8 6.7, 13 14.5 and 20 30 years, respectively. The median values of the return period of different categories of droughts for different cropping seasons and different periods are presented in Table 3. The median values of the return period of moderate, severe and extreme droughts during yam growing period were found in the range of 6.14 6.31, 12.59 12.99 and 22.05 23.87 respectively. For moderate droughts, there was a decrease in the return period between 1901 and 1911 which followed an increase. Intermittent increase and decrease were observed till the end of the century. For severe droughts, the whiskers showed decrease in return period from 1901 to 1921 after which there was an increase in return period in 1931 which followed a

Table 3
Median value of return periods for the moderate, severe, and extreme droughts for different cropping seasons.

Crop	Severity	Period						
		1901 50	1911 60	1921 70	1931 80	1941 90	1951 00	1961 2010
Yam	Moderate	6.31	6.22	6.20	6.16	6.14	6.26	6.22
	Severe	12.99	12.59	12.65	12.78	12.83	12.86	12.87
	Extreme	23.22	22.05	22.19	23.08	22.82	23.87	23.75
Rice (N)	Moderate	6.21	6.20	6.26	6.21	6.22	6.31	6.27
	Severe	12.88	12.75	13.00	12.89	12.88	12.75	13.02
	Extreme	23.81	23.59	23.70	23.79	23.65	22.77	23.35
Rice (S)	Moderate	6.38	6.21	6.17	6.14	6.15	6.23	6.29
	Severe	12.97	12.76	12.76	12.90	12.71	12.57	13.06
	Extreme	23.21	22.75	22.75	23.07	23.10	22.15	24.48
Corn (N)	Moderate	6.25	6.22	6.20	6.21	6.17	6.18	6.25
	Severe	13.20	12.93	12.69	12.71	12.53	12.90	12.92
	Extreme	24.31	23.53	22.32	23.00	21.79	23.71	23.51
Corn (S)	Moderate	6.25	6.12	6.09	6.16	6.13	6.23	6.25
	Severe	12.86	12.47	12.66	12.70	12.62	12.73	12.94
	Extreme	23.15	21.95	22.70	22.39	22.12	23.15	23.64
Millet	Moderate	6.30	6.19	6.19	6.18	6.17	6.15	6.27
	Severe	12.73	12.84	12.79	12.58	12.42	12.64	12.88
	Extreme	22.95	22.47	22.84	22.23	21.59	22.78	22.18

continuous decrease till the end of the century. The extreme droughts return periods also showed a decrease from 1901 to 1921 after which there was an increase till 1931 which followed a decrease until 1951. Overall a decreasing trend was observed from the median values and whiskers of the return periods of moderate and severe droughts, though there were fluctuations for different periods. The box plots were found to narrow down gradually with time for all categories of yam droughts. This is mainly due to shortening of upper whisker of the box plot. The decreases of upper whisker of box plots for all categories of droughts indicate decreases in drought return period or increases of drought frequency in the areas where droughts were previously less frequent.

4.2. Droughts in rice (N) growing season

The spatial patterns of the trends in rainfall, temperature and SPEI during rice (N) growing season for the recent years 1961 2010 are presented in Fig. 7a, b and c, respectively. The figures show decrease of rainfall in the central part while increases of temperature occured in the entire country except in the central east and central west of the country. Higher increase in temperature was observed in the northern arid region at a rate of 0.42 °C/decade. The SPEI was found to decrease mostly in the central part where rainfall was found to decrease. Besides, it was found to decrease at few grid points in the northern arid region where temperature is increasing fast. The results indicate that rainfall is a dominant factor of decreasing SPEI or increasing severity of droughts during rice (N) growing period. However, the decrease in SPEI at few locations in northern arid region revealed that inspite of no change in rainfall, a fast increase in temperature has increased the severity of droughts. The results revealed rainfall as the major factor in monsoon dominated central region and temperature as the major factor in northern arid region in defining droughts for the rice (N) growing season.

The number of grid points showing significant change in rainfall, temperature and SPEI for 50-year time periods at a 10 year time step are shown in Fig. 7d, e and f respectively. The figures show higher sensitivity of SPEI to rainfall compared to temperature. An increase in the number of grid points with increasing rainfall during 1911 1990 caused an increase in the number of grid points with positive SPEI trend for the period. In recent years (1961 2010), temperataure increased at more number of grid points compared to 1951 2000, but the number of grids showing decreasing rainfall decreased from 54 in 1951 2000 to 21 in 1961 2010. The grid points showing decrease in SPEI were found to decrease sharply from 148 to 46 between these two periods. This indicates that drought during rice (N) growing period is more sensitive to rainfall compared to temperature. This can also be seen from the correlations shown in Fig. 7(g). The figure shows higher correlation of SPEI with rainfall compared to temperature.

The return periods for different categories of droughts during rice (N) growing period are shown in Fig. 7h, i and j. They show a gradual decrease of return period and an increase in drought frequency. The return periods of moderate, severe and extreme droughts during the rice (N) growing period were found in the ranges of 5.8 6.8, 13 15 and 18 32 years respectively. The median values of the return period of moderate, severe and extreme droughts were found in the range of 6.20 6.31, 12.75 13.02 and 22.77 23.81 respectively (Table 3). The ranges of box plots narrowed down gradually with time for all categories of droughts indicating decreases of return periods in the areas where droughts were previously less frequent.

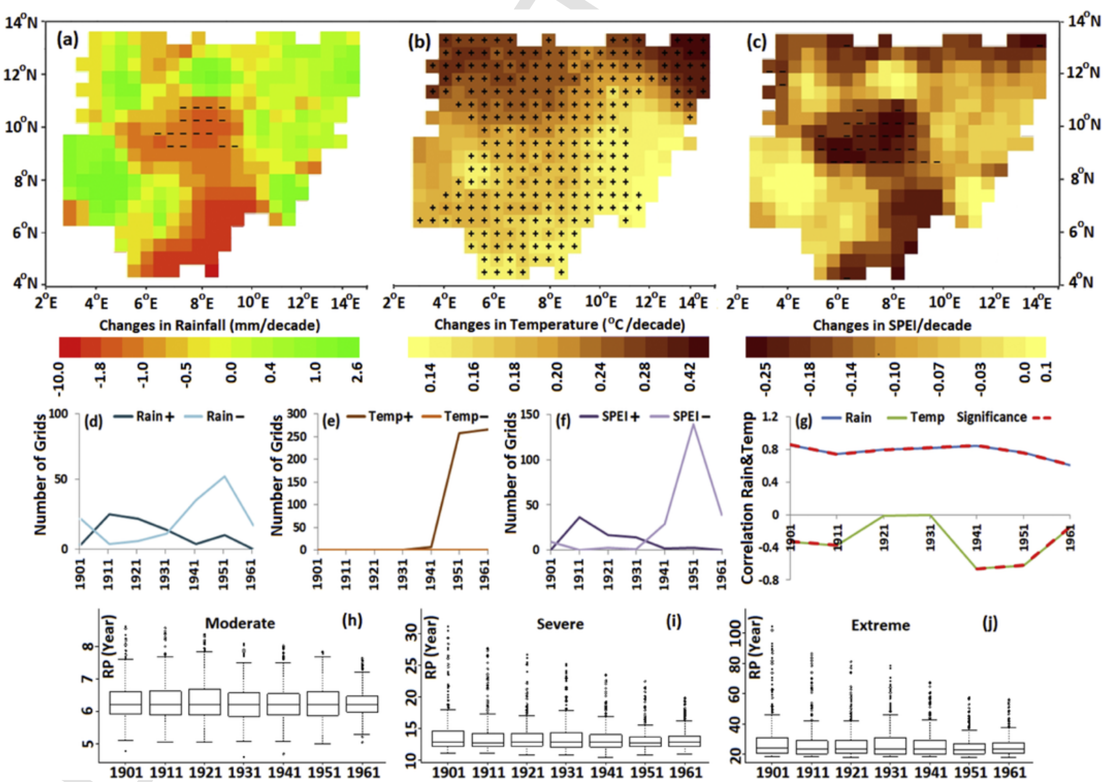

Fig. 7. Trends in (a) rainfall; (b) daily mean temperature; (c) SPEI during rice (N) growing period for the period 1961 2010; the number of grid points showing significant changes in (d) rainfall; (e) daily mean temperature; (f) SPEI for different 50-year periods with a 10-year time step between 1901 and 2010 for rice (N) growing period; (g) correlation of SPEI with rainfall and temperature; the return periods of (h) moderate; (i) severe; and (j) extreme droughts during rice (N) growing period for a 50-year moving window with a 10-year time step for the period 1901 2010.

4.3. Droughts in rice (S) growing season

Rice (S) is the growing season in southern tropical savanna climatic zone and in the lower part of monsoon climatic zone. The spatial pattern of the trends in rainfall, temperature and SPEI during rice (S) growing season in recent years (1961 2010) are presented in Fig. 8a, b and c, respectively. Figures show significant decrease in rainfall only at six grid points located in the south eastern region. On the other hand, temperature was found to increase in the entire country except in central western region. SPEI values were found to decrease in the southeast region due to the decrease in rainfall and the increase in temperature. However, compared to rainfall, SPEI remains unchanged at more grid points especially in the south west due to the increase in rainfall. The results indicate that drought severity during rice (S) growing period has increased in the south eastern part of the country. Both rainfall and temperature have significant impacts on the increasing severity of droughts. As the rice (S) is not grown in the north, the results are discussed for the south only.

The number of grid points showing significant change in rainfall, temperature and SPEI for 50-year time periods are shown in Fig. 8d, e and f respectively. The figures show sensitivity of SPEI to both rainfall and temperataure during the rice (S) growing season. A sharp decrease in the number of grid points showing decreasing rainfall from 1951 to 2000 to 1961 2010 has not caused a sharp decrease in the number of grid points showing decreasing SPEIs. The influnece of both rainfall and temperature during rice (S) growing period is visible from the correlation of SPEI with rainfall and temperature in Fig. 7(j).

The return period of different categories of rice (S) droughts estimated at different grid points are presented using box plots in Fig. 8h, i and j. The return periods for moderate, severe and extreme droughts were found in the ranges of 5.7 6.8, 12 15 and 20 33 years respectively. The median values of the return period of moderate, severe and extreme droughts were found in the range of 6.14 6.38, 12.57 13.06 and 22.15 24.48 years respectively. A gradual decrease in return period with time of all categories of droughts indicates more frequent droughts during rice (S) growing period.

4.4. Droughts in corn (N) growing season

Corn (N) is grown in the northern arid region and in the upper part of monsoon climatic zone. The spatial patterns of the trends in rainfall, temperature and SPEI during corn (N) growing season are presented in Fig. 9a, b and c, respectively. The figures show no change in rainfall while increase in temperaure almost over the entire country. The temperature was found to rise at a rate of 0.42 °C/decade in the northeastern region. The sharp increase in temperature has caused a decrease in SPEI in the northeast. The changes in the number of grid points showing significant changes in rainfall, temperature and SPEI are given in Fig. 9d, e, and f respectively. It can be seen that temperature is the most influencing factor for determining droughts in this season. It is also clear from the correlation of SPEI with rainfall and temperature shown in Fig. 8g. The rising temperature has caused decrease in the SPEI and an increase in drought severity and therefore, decreases in the return periods of moderate, severe, and extreme droughts during Corn (N) growing season as shown in Fig. 9h, i and j, respectively. The whiskers for the three dought classes continously decreased indicating the increase in the frequency of droughts in some grids in recent times.

4.5. Droughts during corn (S) growing season

The spatial patterns of the trends in rainfall, temperature and SPEI during corn (S) growing season in recent years (1961 2010) are presented in Fig. 10a, b and c, respectively. There were very few signifi-

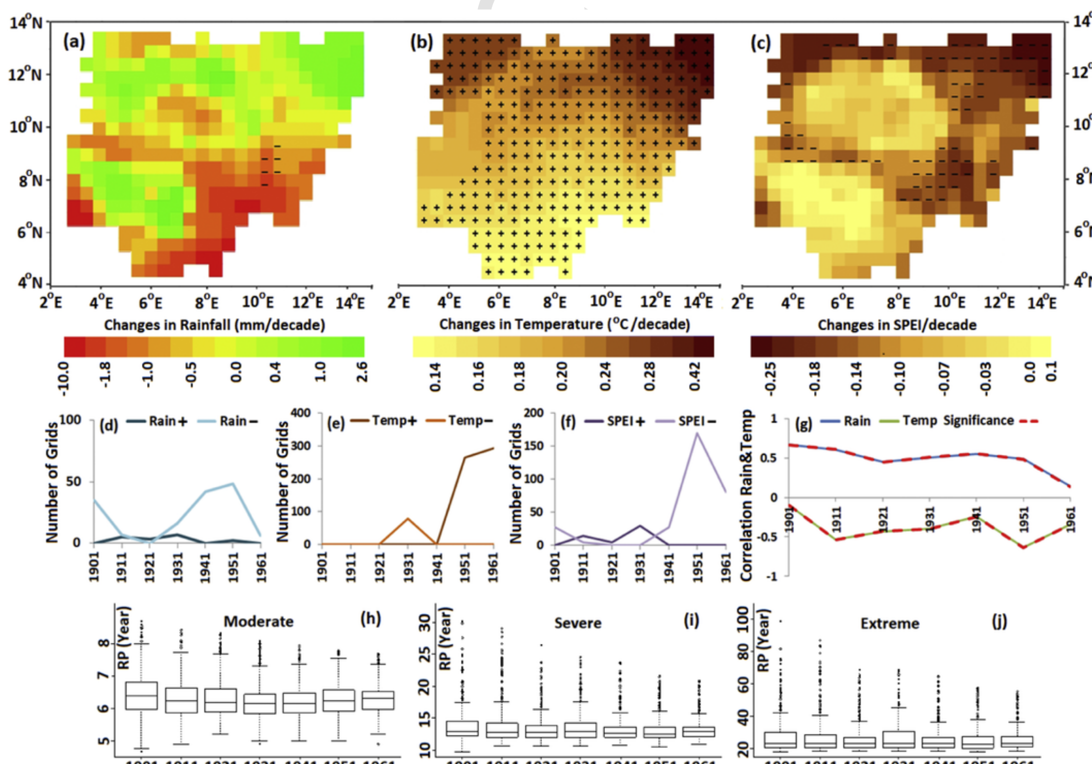

Fig. 8. Trends in (a) rainfall; (b) daily mean temperature; (c) SPEI during rice (S) growing period for the period 1961 2010; the number of grid points showing significant changes in (d) rainfall; (e) daily mean temperature; (f) SPEI for different 50-year periods with a 10-year time step between 1901 and 2010 for rice (S) growing period; (g) correlation of SPEI with rainfall and temperature; the return periods of (h) moderate; (i) severe; and (j) extreme droughts during rice (S) growing period for a 50-year moving window with a 10-year time step for the period 1901 2010.

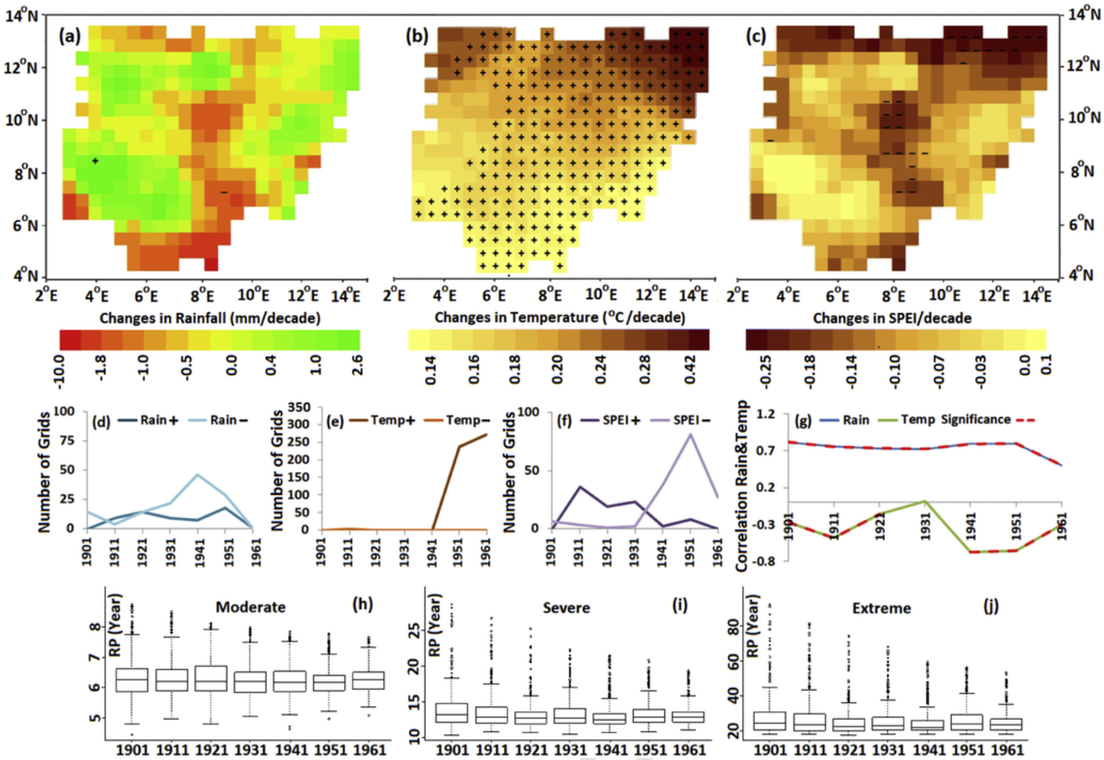

Fig. 9. Trends in (a) rainfall; (b) daily mean temperature; (c) SPEI during corn (N) growing period for the period 1961 2010; the number of grid points showing significant changes in (d) rainfall; (e) daily mean temperature; (f) SPEI for different 50-year periods with a 10-year time step between 1901 and 2010 for corn (N)growing period; (g) correlation of SPEI with rainfall and temperature; the return periods of (h) moderate; (i) severe; and (j) extreme droughts during corn (N) growing period for a 50-year moving window with a 10-year time step for the period 1901 2010.

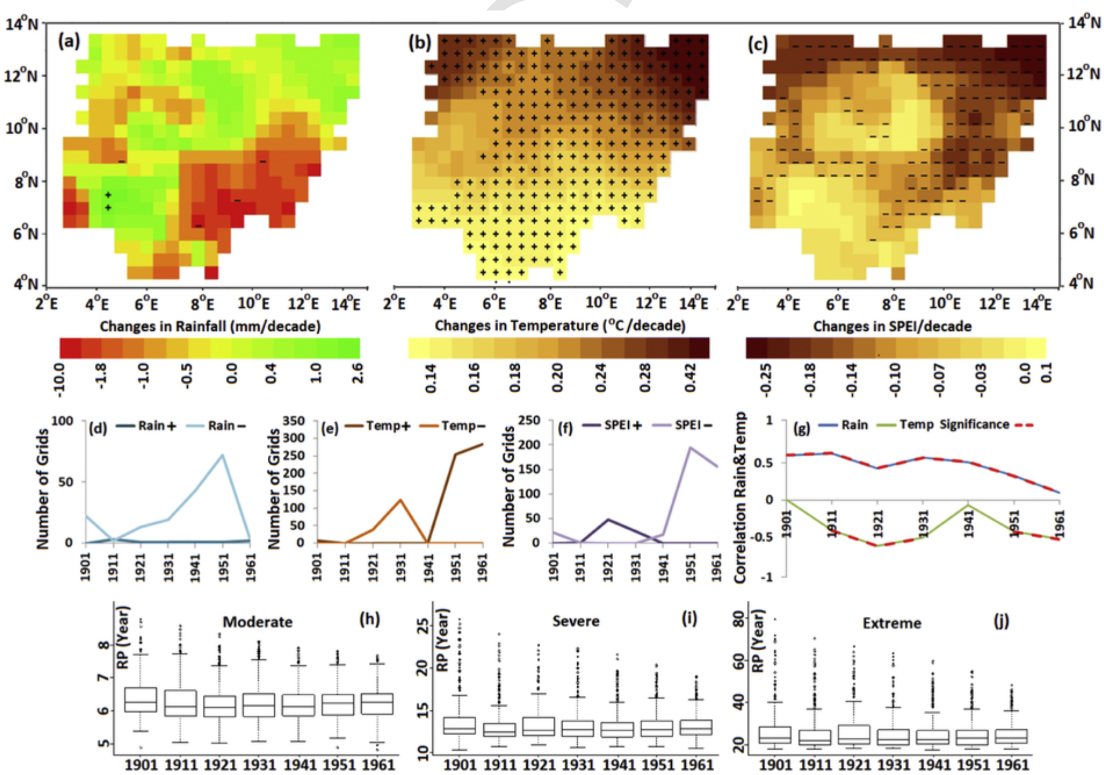

Fig. 10. Trends in (a) rainfall; (b) daily mean temperature; (c) SPEI during corn (S) growing period for the period 1961 2010; the number of grid points showing significant changes in (d) rainfall; (e) daily mean temperature; (f) SPEI for different 50-year periods with a 10-year time step between 1901 and 2010 for corn (S)growing period; (g) correlation of SPEI with rainfall and temperature; the return periods of (h) moderate; (i) severe; and (j) extreme droughts during corn (S) growing period for a 50-year moving window with a 10-year time step for the period 1901 2010.

cant changes in rainfall in the southern Corn (S) growing region. It was found to increase at 2 points in the southwest and decrease at 2 points in the southeast. On the other hand, temperature has increased in most of the southern parts of Nigeria except in a small area in the west. The SPEI was found to decrease in the entire southeast and few grids in the southwest. The changes in grid points showing significant changes in rainfall, temperature and SPEI in Fig. 10d, e, and f respectively show that temperature is the most influencing factor determining droughts in this season. The rises in temperature in recent years have caused decreases in SPEI at large number of grid points in the southern region during Corn (S) growing period. It can also be justified from the correlation of SPEI with rainfall and temperature shown in Fig. 10g. The rising temperature has caused decrease in the return periods of moderate, severe and extreme droughts during Corn (S) season as shown in Fig. 10h, i and j, respectively. The increase in the extent of drought affected area during this season is also visible from the narrowing down of the upper whiskers of the box plots.

4.6. Droughts during Millet growing season

The spatial patterns of the trends in rainfall, temperature and SPEI during Millet growing season for the period 1961 2010 are presented in Fig. 11a, b and c, respectively. They show significant decrease of rainfall at a small area in the central part of Nigeria and increases of temperataure in almost the entire country. The SPEI was found to decrease in the region where temperature was increasing. However, SPEI was found to decrease at more grid points in the central area compared to the grid points where rainfall was decreasing. This is due to the increase in temperature. The results indicate the influence of both rainfall and temperature on Millet droughts. The number of grid points showing significant changes in rainfall, temperature and SPEI during Millet growing season are shown in Fig. 11d, e, and f, respectively while the correlation of SPEI with rainfall and temperature are shown in Fig. 11g. The figures also show the influence of both rainfall and temperature on SPEI. A sharp decrease in number of grid points showing significant decrease in rainfall between 1951 and 2000 and 1961 2010 did not cause a similar decrease in number of grid points with decreasing SPEI. This was due to the increase in the number of grid points with increasing rainfall. The decreases in return periods of moderate, severe and extreme droughts during Millet season were also observed with time, as shown in Fig. 11h, i and j, respectively. The increase in the extent of drought affected area during this season was also visible from the narrowing down of most of the upper whiskers of the box plots.

5. Discussion

The increasing frequency and intensity of droughts as a result of the changing climate and its ravaging impacts are being reported from different parts of the world. This has led to crop destructions, environmental damages, and economic losses of several billions of dollars across the globe. Understanding of droughts characteristics is pivotal to the planning of adaption measures to mitigate the impacts of droughts (Vu et al., 2017b). Over several decades, various methods have been developed for this purpose, amongst which the SPEI incorporates evapotranspiration, an important variable for the assessment of water stress particularly in semi-arid and arid environments. Therefore, SPEI has been widely used in different parts of the world for droughts assessment.

However, the SPEI has not been widely used in Nigeria for the purpose of meteorological droughts assessment compared to other drought indices. Amongst studies that have used the SPEI in the country, Oloruntade et al. (2017) showed that at the Niger south basin of Nigeria, the period, 1970 1981 was dominated by wet conditions, and the

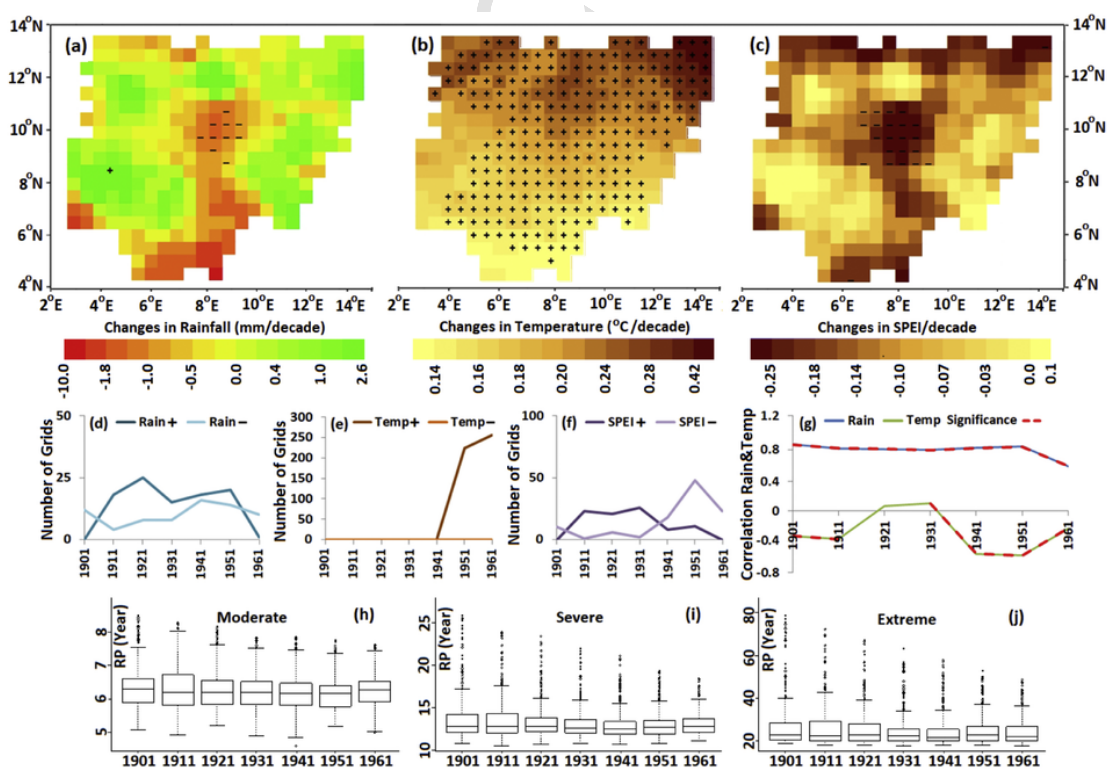

Fig. 11. Trends in (a) rainfall; (b) daily mean temperature; (c) SPEI during Millet growing period for the period 1961 2010; the number of grid points showing significant changes in (d) rainfall; (e) daily mean temperature; (f) SPEI for different 50-year periods with a 10-year time step between 1901 and 2010 for Millet growing period; (g) correlation of SPEI with rainfall and temperature; the return periods of (h) moderate; (i) severe; and (j) extreme droughts during Millet growing period for a 50-year moving window with a 10-year time step for the period 1901 2010.

period 1982 1998 was affected by a moderate to extreme droughts with intermittent moderate wet conditions, while the period 1999 2008 showed a round of severe droughts with occasional moderate wet conditions. The SPEI showed drying tendencies over Nigeria in a study conducted by Oguntunde et al. (2016). It reported that about 40 50% of the land of Nigeria is showing shifts towards aridity. The results of both of these studies are supported by the study of Shiru et al. (2018). This increasing frequency of droughts also collaborates with the finding of this study. The study clearly showed that the areas that experienced less frequent droughts in the past are facing more frequent droughts in recent years. No study has been conducted in Nigeria so far to assess the impacts of climate variability on droughts according to the crop growing seasons.

A number of studies have been conducted in the African region to assess the impacts of climate change on droughts. The studies suggested an increasing trend in the intensity and frequency of droughts in different parts of Africa (Dai, 2013; Masih et al., 2014; Spinoni et al., 2014; Sheffield et al., 2012). Masih et al. (2014) reported that changes in climate have increased the frequency and severity of droughts in different African countries. Spinoni et al. (2014) reported the significant increase in drought frequency, duration, and severity in Africa. More recently, Awange et al. (2016) assessed droughts over the greater horn of Africa for the period 1979 2014 using remote sensing and reanalysis products and concluded that six to seven major droughts events occurred amongst the studied areas using SPI and total storage deficit indices (TSDI) (Lake Victoria Basin, Ethiopia-Sudanese border, South Sudan, and Tanzania). Byakatonda et al. (2018) used both SPI and SPEI to access droughts over semi-arid Botswana for the period 1960 2016 and found significant drying trends in recent times compared to the past. This study also suggests that the frequency of droughts in Nigeria is increasing in the line of African droughts.

The intensity and frequency of droughts have been found to increase in many other parts of the world (Vu et al., 2017b; Meza, 2013; Mohsenipour et al., 2018; Ahmed et al., 2018) with the increase in temperature and changes in precipitation patterns (Salman et al., 2018; D'Oria et al., 2017; Gorguner et al., 2019). For the development and planning of reliable adaptation and mitigation measures, understanding of the characteristics of droughts is critical. For better guidance in this respect, characterization of droughts and assessment of the impacts of climate variables on drought characteristics are invaluable, especially for Africa which may face more extensive and critical droughts in the future (Masih et al., 2014).

The results of the present study revealed that though the rainfalls were not changing significantly, the temperatures were increasing significantly in most parts of the country for all the crop growing seasons which caused a decrease in SPEI in some regions. The trends in SPEI during yam growing season showed a decrease in the northeast and northwest of the country where temperature rises were highest. The SPEI was also decreasing in the regions where a decreasing tendency in rainfall was observed. SPEI showed a significant decrease in the central part of the north of the country during rice (N) growing season where rainfall was decreasing and temperature was increasing. The SPEI was found to decrease in the southeast during rice (S) growing season where rainfall showed a decreasing tendency and in the northeast during corn (N) growing season where temperature was increasing at the highest rate. The corn (S) growing season showed similar trend in SPEI like the rice (S) growing season. During millet growing season, the SPEI was found to decrease in the central part of the country where rainfall was decreasing significantly. Compared to any other cropping seasons, the decrease in SPEI was found over the largest area during yam growing season.

The present study suggests that the impact of climate change varies for different seasons and climatic zones. Therefore, adaptation to droughts should be planned based on season and climate of the area. Furthermore, droughts should be assessed for crop growing period as it is more destructive when it occurs during these seasons. Besides, both rainfall and temperature should be considered for the assessment of droughts as the influence of different climate variables is different for different climatic zones. It is expected that the knowledge acquired from this study will be helpful to analyze the characteristics of droughts due to the changes in climate and take necessary adaptation actions to the changing pattern of droughts.

6. Conclusions

Gauge-based gridded data were used for the reconstruction of meteorological droughts in Nigeria using SPEI for the period 1901 2010. The SPEI values were fitted with the best distribution function for the estimation of the return periods of seasonal droughts and a modified version of Mann-Kendal trend test was used to assess the secular changes in climate and drought index. The temporal variations in droughts and their interrelations with rainfall and temperature trends were assessed using a 50-year moving window with a 10-year time step to understand the influence of climatic variables on droughts. Overall, temperature was found to have more influence on drought severity in the northern arid region where it was found to increase up to 0.42 °C/decade and rainfall in the central monsoon dominated and southern tropical savanna climate zones where it was found to decrease up to 10 mm/decade. However, the sharp increase in temperature in recent years was found to cause a decrease in SPEI up to 0.25 and an increase in the severity of droughts in all the climate zones. The increased severity of droughts has caused a decrease in return periods of droughts in all seasons. The return periods of moderate droughts decreased more compared to other severities of droughts. The drought affected areas also increased with time for all the seasons.

Rainfall was found to change only at some locations in Nigeria while temperature was found to increase in almost the entire country. Thus, a large increase of temperature in recent years is the main cause of increasing severity and frequency of droughts for the different crop growing seasons of Nigeria. Because it is generally forecasted that the temperature of Nigeria will continue to increase due to global warming, it can be anticipated that droughts will be more severe and frequent in Nigeria. However, it is not possible to make a concrete conclusion based on the findings of the present study as the increases in rainfall due to climate change may decrease droughts in some seasons, particularly in the central regions where rainfall is the dominating factor that defines droughts.

Acknowledgments

The authors are grateful to the Universiti Teknologi Malaysia for providing financial support for this research through grant No. 19H44. This study was also supported by funding from the National Research Foundation of Korea (NRF 2016R1D1A1B04931844).

References

Abiodun, B.J., Lawal, K.A., Salami, A.T., Abatan, A.A., 2013. Potential influences of global warming on future climate and extreme events in Nigeria. Reg. Environ. Chang. 13, 477 491.

Acheampong, P.K., 1990. Climatological drought in Nigeria. Geojournal 20 (26), 209 219.

Adeaga, O., 2002. Management of drought risk in the Sudano-Sahelian region of Nigeria. 2002. In: Flow Regimes from International Experimental and Network Data [FRIEND], 2002 Regional Hydrology. Bridging the Gap between Research and Practice, Proceedings of the Fourth International FRIEND Conference, Cape Town, South Africa. International Association of Hydrological Sciences IAHS Publ, Oxfordshire, UK, pp. 18 22, March 2002.

Adefolalu, D.O., 1986. Further aspects of Sahelian drought as evident from rainfall regime of Nigeria. Arch. Meteorol. Geophys. Bioclimatol. 36, 277 295.

Adeniyi, M.O., Uzoma, E.K., 2016. Assessment of severity of drought in some northern Nigeria states using Drought Severity Index (DSI5). Ghana J. Sci. Technol. Dev. 4, 1 10.

Ahmed, K., Shahid, S., Harun, S., Wang, X., 2015. Characterization of seasonal droughts in Balochistan Province, Pakistan. Stoch. Env. Res. Risk A. 30, 747 762. https://doi.org/10.1007/s00477 015 1117-2.

Ahmed, K., Shahid, S., Othman, R., Harun, S., Wang, X., 2017. Evaluation of the performance of gridded precipitation products over Balochistan Province, Pakistan. Desalin. Water Treat. 79, 73 86.

Ahmed, K., Shahid, S., Nawaz, N., 2018. Impacts of climate variability and change on seasonal drought characteristics of Pakistan. Atmos. Res. 214, 364 374. https://doi.org/10.1016/j.atmosres.2018.08.020.

Alamgir, M., Shahid, S., Hazarika, M.K., Shamsudin, S., 2015. Analysis of meteorological drought pattern during different climatic and cropping seasons in Bangladesh. J. Am. Water Resour. Assoc. 51, 794 806.

Almazroui, M., Saeed, F., Nazrul Islam, M., Alkhalaf, A.K., 2016. Assessing the robustness and uncertainties of projected changes in temperature and precipitation in AR4 global climate models over the Arabian Peninsula. Atmos. Res. 182, 163 175.

Awange, J.L., Khandu, Schumacher, Forootan, M.E., Heck, B., 2016. Exploring hydro-meteorological drought patterns over the Greater Horn of Africa (1979 2014) using remote sensing and reanalysis products. Adv. Water Resour. 94, 45 59.

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U., Ziese, M., 2013. A description of the global land-surface precipitation data products of the global precipitation climatology Centre with sample applications including centennial (trend) analysis from 1901-present. Earth Syst. Sci. Data 5, 71 99. https://doi.org/10.5194/essd-5-71-2013.

Beguería, S., Vicente-Serrano, S.M., Reig, F., Latorre, B., 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int. J. Climatol. 34, 3001 3023.

Brown, C., Meeks, R., Ghile, Y., Hunu, K., 2013. Is water security necessary? an empirical analysis of the effects of climate hazards on national-level economic growth. Phil. Trans. R. Soc. A 371, 20120416https://doi.org/10.1098/rsta.2012.0416.

Byakatonda, J., Parida, B.P., Moalafhi, D.B., Kenabatho, P.K., 2018. Analysis of long term drought severity characteristics and trends across semiarid Botswana using two drought indices. Atmos. Res. 213, 492 508. https://doi.org/10.1016/j.atmosres.2018.07.002.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., Wehner, M., 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Chang. 3 (1), 52 58. https://doi.org/10.1038/nclimate1633.

Dilley, M., Chen, R., Deichmann, U., Lerner-Lam, A., Arnold, M., 2005. Natural disaster Hotspots: a global Risk Analysis; disaster Risk Management Series. vol. 2005, World Bank, Washington, DC, USA, https://doi.org/10.1007/s00477-014-0930-3.

Dinku, T., Connor, S.J., Ceccato, P., Ropelewski, C.F., 2008. Comparison of global gridded precipitation products over a mountainous region of Africa. Int. J. Climatol. 28, 1627 1638.

D'Oria, M., Ferraresi, M., Tanda, M.G., 2017. Historical trends and high resolution future climate projections in northern Tuscany (Italy). J. Hydrol. 555, 708 723. https://doi.org/10.1016/j.jhydrol.2017.10.054.

Food and Agricultural Organization, 2018. Nigeria at a Glance. In: http://www.fao.org/nigeria/fao-in-nigeria/nigeria-at-a-glance/en/, Accessed 20 May 2018.

Funk, C., Husak, G., Michaelsen, J., Love, T., Pedreros, D., 2007. Third generation rainfall climatologies: satellite rainfall and topography provide a basis for smart interpolation. In: In Proceedings of the JRC FAO Workshop, Nairobi, Kenya, Available online https://pdfs.semanticscholar.org/b1a4/c37eb061880ed6e2ce0dc1a80458590d0c1c.pdf?_ga=2.20973368.224620038.1537329342-1720817195.1537329342Accessed 18 September 2018.

Gorguner, M., Kavvas, M.L., Ishida, K., 2019. Assessing the impacts of future climate change on the hydroclimatology of the Gediz Basin in Turkey by using dynamically downscaled CMIP5 projections. Sci. Total Environ. 648, 481 499. https://doi.org/10.1016/j.scitotenv.2018.08.167.

Hamed, K.H., 2008. Trend detection in hydrologic data: the Mann Kendall trend test under the scaling hypothesis. J. Hydrol. 349 (3), 350 363. https://doi.org/10.1016/j.jhydrol.2007.11.009.

Hao, Z., AghaKouchak, A., Phillips, J.T., 2013. Changes in concurrent monthly precipitation and temperature extremes. Environ. Res. Lett. 8, https://doi.org/10.1088/1748-9326/8/3/034014, 034014 (7pp).

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. Int. J. Climatol. 34 (3), 623 642.

Keylock, C., 1999. Towards an interpretation of historical droughts in Northern Nigeria: a comment on a paper by Aondover Tarhule and Ming-Ko Woo. Clim. Chang. 41, 259 260.

Khazaei, M.R., Zahabiyoun, B., Saghafian, B., 2012. Assessment of climate change impact on floods using weather generator and continuous rainfall-runoff model. Int. J. Climatol. 32, 1997 2006.

Koutsoyiannis, D., 2003. Climate change, the Hurst phenomenon, and hydrological statistics. Hydrol. Sci. J. 48 (1), 3 24. https://doi.org/10.1623/hysj.48.1.3.43481.

Liu, Y., Hwang, Y., 2015. Improving drought predictability in Arkansas using the ensemble PDSI forecast technique. Stoch. Env. Res. Risk A. 29, 79 91.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica https://doi.org/10.2307/1907187.

Masih, I., Maskey, S., Mussá, F.E.F., Trambauer, P., 2014. A review of droughts on the African continent: a geospatial and long-term perspective. Hydrol. Earth Syst. Sci. 18, 3635 3649. https://doi.org/10.5194/hess-18-3635-2014.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration of time scales. In: Proceedings of the Eighth Conference on Applied Climatology. vol. 17 23, American Meteorological Society, Anaheim, CA, USA, pp. 179 186.

McNally, A., Arsenault, K., Kumar, S., Shukla, S., Peterson, P., Wang, S., Funk, C., Peters-Lidard, C.D., Verdin, J.P., 2017. Scientific data. 4 (170012), 19. https://doi.org/10.1038/sdata.2017.12.

Medugu, N.I., Majid, M.R., Johar, F., 2011. Drought and desertification management in arid and semi-arid zones of Northern Nigeria. Manag. Environ. Qual. Int. J. 22, 595 611.

Meza, F.J., 2013. Recent trends and ENSO influence on droughts in Northern Chile: an application of the standardized precipitation evapotranspiration index. Weather Clim. Extrem. 1, 51 58. https://doi.org/10.1016/j.wace.2013.07.002.

Mohsenipour, M., Shahid, S., Chung, E.-S., Wang, X.-J., 2018. Changing pattern of droughts during cropping seasons of Bangladesh. Water Resour. Manag. 32, 1555 1568. https://doi.org/10.1007/s11269-017-1890-4.

Nam, W.H., Hayes, M.J., Svoboda, M.D., Tadesse, T., Wilhite, D.A., 2015. Drought hazard assessment in the context of climate change for South Korea. Agric. Water Manag. 160, 106 117. https://doi.org/10.1016/j.agwat.2015.06.029.

Nashwan, M.S., Ismail, T., Ahmed, K., 2018. Flood susceptibility assessment in Kelantan river basin using copula. Int. J. Eng. Technol. 7 (2), 584 590.

Nashwan, M.S., Shahid, S., Abd-Rahim, N., 2018. Unidirectional trends in annual and seasonal climate and extremes in egypt. Theor. Appl. Climatol.18. https://doi.org/10.1007/s00704-018-2498-1.

Oguntunde, P.G., Lischeid, G., Abiodun, B.J., Dietrich, O., 2016. Analysis of long-term dry and wet conditions over Nigeria. Int. J. Climatol. 37 (9), 3577 3586. https://doi.org/10.1002/joc.4938.

Oguntunde, P.G., Abiodun, B.J., Lischeid, G., 2017. Impacts of climate change on hydro-meteorological drought over the Volta Basin, West Africa. Glob. Planet. Chang. 155, 121 132.

Okorie, F.C., Ezedike, E.C., Nnaji, A.O., 2015. Analysis of drought episode in Borno State of North Eastern Nigeria. In: Andreu, J., Solera, A., Paredes-Arquiola, J., Haro-Monteagudo, D., van Lanen, H. (Eds.), Drought: Research and Science-Policy Interfacing. Taylor and Francis Group, London, UK.

Oloruntade, A.J., Mohammad, T.A., Ghazali, A.H., Wayayok, A., 2017. Analysis of meteorological and hydrological droughts in the Niger-South Basin, Nigeria. Glob. Planet. Chang. 155, 225 233. https://doi.org/10.1016/j.gloplacha.2017.05.002.

Omondi, P.A., Awange, J.L., Forootan, E., Ogallo, L.A., Barakiza, R., Girmaw, G.B., Fesseha, I., Kululetera, V., Kilembe, C., Mbati, M.M., Kilavi, M., King'uyu, S.M., Omeny, P.A., Njogu, A., Badr, E.M., Musa, T.A., Muchiri, P., Bamanya, D., Komutunga, E., 2014. Changes in temperature and precipitation extremes over the Greater Horn of Africa region from 1961 to 2010. Int. J. Climatol. 34, 1262 1277. https://doi.org/10.1002/joc.3763.

Patterson, L.A., Lutz, B.D., Doyle, M.W., 2013. Characterization of drought in the South Atlantic, United States. J. Am. Water Resour. Assoc. 49 (6), 1385 1397. https://doi.org/10.1111/jawr.12090.

Pour, S.H., Shahid, S., Chung, E.-S., Wang, X.J., 2018. Model output statistics downscaling using support vector machine for the projection of spatial and temporal changes in rainfall of Bangladesh. Atmos. Res. 213, 149 162.

Prothero, R.M., 1974. Some perspectives on drought in north-West Nigeria. Afr. Aff. 73, 162 169.

Sa'adi, Z., Shahid, S., Chung, E.S., Ismail, T., 2017. Projection of spatial and temporal changes of rainfall in Sarawak of Borneo Island using statistical downscaling of CMIP5 models. Atmos. Res. 197, 446 460.

Salman, S.A., Shahid, S., Ismail, T., Chung, E.-S., Al-Abadi, A.M., 2017. Long-term trends in daily temperature extremes in Iraq. Atmos. Res. 198, 97 107. https://doi.org/10.1016/j.atmosres.2017.08.011.

Salman, S.A., Shahid, S., Ismail, T., Ahmed, K., Wang, X.-J., 2018. Selection of climate models for projection of spatiotemporal changes in temperature of Iraq with uncertainties. Atmos. Res. 213, 509 522. https://doi.org/10.1016/j.atmosres.2018.07.008.

Santos, J., Portela, M., Pulido-Calvo, I., 2011. Regional frequency analysis of droughts in Portugal. Water Resour. Manag. 25 (14), 3537 3558. https://doi.org/10.1007/s11269-011-9869-z.

Schneider, U., Becker, A., Meyer-Christoffer, A., Ziese, M., Rudolf, B., 2011. Global Precipitation Analysis Products of the GPCC. Global Precipitation Climatology Centre (GPCC) Deutscher Wetterdienst, 13 pp. Available online ftp://ftp.dwd.de/pub/data/gpcc/PDF/GPCC_intro_products_v2011.pdf.

Schneider, U., Becker, A., Meyer-Christoffer, A., Ziese, M., Finger, P., 2014. GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. Theor. Appl. Climatol. 115, 15 40.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63 (324), 1379 1389. https://doi.org/10.1080/01621459.1968.10480934.

Sharafati, A., 2014. And Zahabiyoun, B. (2014) rainfall threshold curves extraction by considering rainfall-runoff Model uncertainty. Arab. J. Sci. Eng. 39, 6835 6849. https://doi.org/10.1007/s13369-014-1246-9.

Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. Nature 491 (7424), 435 438. https://doi.org/10.1038/nature11575.
Shiru, M.S., Johnson, L.M., Ujih, O.U., Abdulazeez, O.T., 2015. Managing FLOOD in Ilorin, Nigeria: strucutral and nonstructural measures. Asian J. Appl. Sci. 03 (05), 507 513.
Shiru, M.S., Shahid, S., Alias, N., Chung, E.-S., 2018. Trend analysis of droughts during crop growing seasons of Nigeria. Sustainability 10, 871, 13pp https://doi.org/10.3390/su10030871.
Sonuga, J.O., 1977. Hydrological aspects of the drought event in Nigeria-1972/1973. Hydrol. Sci. J. 22, 487 502.
Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., Vogt, J., 2014. World drought frequency, duration, and severity for 1951 2010. Int. J. Climatol. 34 (8), 2792 2804. https://doi.org/10.1002/joc.3875.
Stagge, J.H., Tallaksen, L.M., Xu, C.-Y., Van Lanen, H.A.J., 2014. Standardized precipitation-evapotranspiration index (SPEI): sensitivity to potential evapotranspiration model and parameters. In: Hydrology in a Changing World: environmental and Human Dimensions, Proceedings of the Flow Regimes from International Experimental and Network Data [FRIEND]-Water 2014, Montpellier, France. vol. 2014, International Association of Hydrological Sciences [IAHS] Publ, Oxfordshire, UK, pp. 7 10, October 2014.
Sung, J.H., Chung, E.S., 2014. Development of streamflow drought severity duration frequency curves using the threshold level method. Hydrol. Earth Syst. Sci. 18, 3341 3351.
Sung, J.H., Chung, E.S., Lee, B., Kim, Y., 2017. Meteorological hazard risk assessment based on the detection of trends and abrupt changes in the precipitation characteristics of the Korean Peninsula. Theor. Appl. Climatol. 127 (1), 305 326.
Tao, H., Diop, L., Bodian, A., Djaman, K., Ndiaye, P.M., Yaseen, Z.M., 2018. Reference evapotranspiration prediction using hybridized fuzzy model with firefly algorithm: regional case study in Burkina Faso. Agric. Water Manag. 208, 140 151.
Tarhule, A., Woo, M.-K., 1997. Towards an interpretation of historical droughts in Northern Nigeria. Clim. Chang. 37, 601 616.
Tierney, J.E., Smerdon, J.E., Anchukaitis, K.J., Seager, R., 2013. Multidecadal variability in East African hydroclimate controlled by the Indian Ocean. Nature 493 (17), 389 392.
Tirivarombo, S., Osupile, D., Eliasson, P., 2018. Drought monitoring and analysis: Standardised Precipitation Evapotranspiration Index (SPEI) and Standardised Precipitation Index (SPI). Phys. Chem. Earth 106, 1 10. https://doi.org/10.1016/j.pce.2018.07.001.
Touma, D., Ashfaq, M., Nayak, M.A., Kao, S.-C., Diffenbaugh, N.S., 2015. A multi-model and multi-index evaluation of drought characteristics in the 21st century. J. Hydrol. 526, 196 207. https://doi.org/10.1016/j.jhydrol.2014.12.011.
Tsakiris, G., Vangelis, H., 2005. Establishing a Drought Index Incorporating Evapotranspiration. European Water 9/10 3 11.
Tuklimat, N.N.A., Harun, S., Shahid, S., 2012. Comparison of different methods in estimating potential évapotranspiration at Muda Irrigation Scheme of Malaysia. J. Agric. Rural. Dev. Trop. Subtrop. 113, 77 85.
Usman, M.T., Abdulkadir, A., 2014. Review: an experiment in intra-seasonal agricultural drought monitoring and early warning in the Sudano-Sahelian Belt of Nigeria. Int. J. Climatol. 34, 2129 2135.
Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Clim. 23, 1696 1718.
Vinnarasi, R., Dhanya, C.T., 2016. Changing characteristics of extreme wet and dry spells of Indian monsoon rainfall. J. Geophys. Res. Atmos. 121, 2146 2160. https://doi.org/10.1002/2015JD024310.
Vu, M., Raghavan, V., Liong, S.-Y., 2015. Ensemble climate projection for hydro-meteorological drought over a river basin in Central Highland, Vietnam. KSCE J. Civ. Eng. 19 (2), 427 433.
Vu, T.M., Raghavan, S.V., Liong, S.Y., Mishra, A.K., 2017. Uncertainties of gridded precipitation observations in characterizing spatio-temporal drought and wetness over Vietnam. Int. J. Climatol.https://doi.org/10.1002/joc.5317, (Pgs. 15).
Vu, M.T., Vo, N.D., Gourbesville, P., Raghavan, S.V., Liang, S.-Y., 2017. Hydro-meteorological drought assessment under climate change impact over the Vu Gia Thu Bon river basin, Vietnam. Hydrol. Sci. J. 62 (10), https://doi.org/10.1080/02626667.2017.1346374.
Watts, M., 1983. Hazards and crises: a political economy of drought and famine in northern Nigeria. Antipode. 15, 24 34.
Wolski, P., Todd, M.C., Murray-Hudson, M.A., Tadross, M., 2012. Multi-decadal oscillations in the hydro-climate of the Okavango River system during the past and under a changing climate. J. Hydrol. 475, 294 305. https://doi.org/10.1016/j.jhydrol.2012.10.018.
World Bank Group, 2018. Agriculture, Value Added (% of GDP). Available online http://data.worldbank.org/indicator/NV.AGR.TOTL.ZS, Accessed 18 March 2018.
Yang, W., Seager, R., Cane, M.A., Lyon, B., 2014. The East African long rains in observations and models. J. Clim. 27, 7185 7202. https://doi.org/10.1175/JCLI-D-13-00447.1.
Zahabiyoun, B., Goodarzi, M.R., Bavani, A.R.M., Azamathulla, H.M., 2013. Assessment of climate change impact on the Gharesou River Basin using SWAT hydrological model. Clean Soil Air Water 41 (6), 601 609.
Zhang, L., Xiao, J., Li, J., Wang, K., Lei, L., Guo, H., 2012. The 2010 spring drought reduced primary productivity in southwestern China. Environ. Res. Lett. 7, 045706, (10pp) https://doi.org/10.1088/1748-9326/7/4/045706.
Zhang, L., Jiao, W., Zhang, H., Huang, C., Tong, Q., 2017. Studying drought phenomena in the Continental United States in 2011and 2012 using various drought indices. Remote Sens. Environ. 190, 96 106.