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Variability changes of some climatology parameters of Nigeria using wavelet analysis

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ABSTRACT

Monthly total rainfall and monthly average temperature data of Nigeria were downloaded from World Bank Data Group site for year 1901 to 2015. Annual total rainfall and annual average temperature were calculated from the data. The decadal average and thirty-year-average of total rainfall and average temperature were also calculated. In order to describe the time-frequency of rainfall and temperature variability, wavelet analysis was employed on time series of the monthly total rainfall, monthly average temperature, annual total rainfall, and annual average temperature using MATLAB software. The constitution of the monthly rainfall and temperature frequency was studied by the global wavelet spectrum. In order to obtain more information, separate bands were modulated. Take for instance, on examining the 8-16-month band by mean of the scales within the range of 8 and 16 months, the periods with low or high variance of the mean monthly and annual temperature were discovered. Variability of the considered climatological parameters was more vivid on thirty-year-average basis than that of annual and decadal basis.

1. Introduction

The weather can be referred to as the daily chaotic, non-linear dynamic system of the atmosphere; while the climate is the average state of the weather. The climate is fairly stable and predictable. Climate change refers to the change in the state of climate that can be identified by changes in mean or variability of its properties and that persists for extended periods, typically decades or longer [1]. Although there is no particular time frame to define climate, scientists have however been taking an average of thirty years of weather conditions into consideration in order to determine the climate of a particular location. The thirty-year averages are called climatological normal, and they can be obtained for a variety of weather parameters, such as temperature or precipitation based on data from weather stations in the area of concern or interest. Climate fluctuates annually above or below a long-term mean value. This fluctuation is called climate variability. The climate system shows high natural variability on different time scales, and scientists have developed a large variety of techniques to reduce the dimensionality of the system and to find the most relevant patterns explaining the variation. Nigeria's climate is tropical with a rainy as well as dry season. Seasonal weather conditions are turning into the extreme and also getting prolonged. Dry seasons are becoming hotter, while more heavy rainfalls are being reported during the rainy seasons.

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Climate change is a very important and widely discussed subject. Climate change manifests in many respects apart from increase in rainfall, resulting into flood and the rising sea level. These include increased frequencies of extreme climatic events like strong storms, inundation of coastal lands by sea water and above average daily minimum and maximum temperature. The most common parameters of climate change are: increase in average global temperatures and precipitations. Thus increase in average global temperature and average global precipitation are indicators of climate change. A common method for the assessment of climatic changes is the analysis of historical climatic data, in which trend detection and analysis play important roles [2–3].Wave transform was used on Czech Republic climatic data and it was discovered that the temperature showed a positive trend from 1930 to 2001 with a dominant periodicity of 8 to 14 years [4]. A different study used the Morlet wavelet to breakdown air temperature time series and showed that some regions (e.g., Europe) seem to be under a 30 month-period oscillation, while other areas (e.g., northwestern USA) are under a 43 month-period, both of which are quite similar to largescale atmospheric–oceanic phenomena, such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) [5]. A lot of studies have been carried out on rainfall across the globe. While working on rainfall of 96 stations in Turkey for a period of 64 years (1929–1933), a general downward trend of rainfall with the exemption of few stations with increasing trend was discovered [6]. Whereas while working with hundred years of rainfall data across Sri Lanka, different trends were observed. Some parts recorded decreasing trend, some increasing trend while some locations showed no coherent trend. It was also shown that the trend characteristics vary with the duration of the data analyzed [7]. Working with rainfall data of Jordan over a period of eighty one years (1922–2003), different trends for different seasons across three close-by stations were discovered [8]. Latin America region in recent years is being affected by climate variability [9]. For instance, Venezuelan experienced extreme rainfall in 1999 and 2005. Intense rain and floods were recorded in Southern Brazil in 2008. Studies on climate change in South America show that over the course of the last 50 years the surface temperatures increased by 0.75 °C, whereas minimum temperatures have raised almost 1 °C [10–11]. The durations and intensities of rainfall have increased in Nigeria in the last three decades, producing large runoffs, floods and water logging in many places. Also temperature has continued to be above normal with relatively higher figures in 1973, 1987 and 1998. Most stations have had temperature increases of 0.2 to 0.3 °C per decade [12]. Evaluating the rainfall trend in six geopolitical zones within a thirty-year period (1978–2007) in Nigeria, it was revealed that an increase in trend was experienced in only one of the zones [13].

Most meteorology and climatology data in their raw form are time-domain. Signals plotted or measured are time dependent. Sufficient information is not usually extracted from signals represented in time-amplitude frame. Important information is usually embedded in the frequency content of the signal. The frequency spectrum of a signal, revealing what frequencies exist in the signal, provides more relevant information. Cases whereby both the frequency of a signal, as well as the times of occurrence of the frequency components are taken into consideration are referred to as non-stationary.

Climatic elements and phenomena such as temperature, precipitation, humidity, and hurricanes are the results of various complex and often periodic processes in the atmosphere [14–15]. Evaluating the trend and periodic components of climatic time series separately provides more valuable results than those that can be obtained from direct trend analysis on the raw data. In recent years, signal processing methods have become widely used in the environmental studies field, especially in atmospheric and hydrological sciences. Recently, wavelet analysis technique, which analyze data for local and global climate changes and reveal active frequencies in time series and their changes over time are being employed in climate research [16–21].

In meteorology and climatology, time series are nonstationary and it is necessary to apply an advanced transformation to decompose a series into the time-frequency domain. At present, the wavelet transform seems to be one of the most appropriate methods of such analyses.

The wavelet transform is a strong mathematical tool that provides a time-frequency representation of an analysed signal in the time domain [22]. Wavelet transform has advantages over classical spectral analysis, because it allows the analysis of different scales of temporal variability and it does not need a stationary series [23]. Thus, it is appropriate to analyse irregular distributed events and time series that contain non-stationary power at many different frequencies. Wavelet analysis maintains time and frequency localization in a signal analysis by decomposing or transforming a onedimensional (1-D) time series into a diffuse 2-D time-frequency image simultaneously. Then, it is possible to get information on both the amplitude of any periodic signals within the series, and how this amplitude varies with time.

For instance, in comparison with the Fourier transformation, it is possible to differentiate not only values of particular frequencies in non-stationary series, but also their location in time can be determined [24]. On the other hand, the possibility of time-frequency representation is connected with a problem of resolution. Another advantage of wavelet analysis is that this method, contrary to the other types of transformation providing time-frequency presentation, like the windowed Fourier transformation, solves the dilemma of resolution to a certain extent [25].

The main purpose of this research is to investigate how some climatological parameters (surface temperature and rainfall) vary trend-wise, periodically and temporally over Nigeria synoptically.

2. Methodology and data

The climate of Nigeria is basically tropical; exhibiting two climatic sessions (dry and wet) annually. Monthly average temperature as well as monthly total rainfall data of Nigeria, spanning 115 years; from 1901 to 2015 were collected from World Bank Data Group (http://sdwebx.worldbank.org/climateportal/index.cmf?page=downloadscaled_data_download&menu=historical). The annual temperature in Nigeria is defined as the mean of the temperature over all the months (January to December) of the year. While the annual total rainfall accounted for the sum of all the total monthly rainfall. Decadal and climatic trends of the temperature and rainfall were examined by calculating the mean over ten years and thirty years respectively. Wavelet analysis was preferred to Fourier analysis because it considered both the frequency and time domains of non stationary climatology signals. MATLAB software was used: (i) for the wavelet analysis of monthly average temperature, yearly average temperature, monthly total rainfall and yearly total rainfall; (ii) in drawing the temperature and rainfall contours for the periods under consideration; (iii) in determination of the temperature and rainfall anomalies of ten-yearly and thirty-yearly averages.

3. Theoretical background

3.1. Wavelet transform (WT)

Fourier transform is a useful instrument when it comes to the analysis of the components of a stationary signal. It is applicable for time series where the interest lies only in having the knowledge of the spectral components of the signals of the series. If one's interest is in knowing the spectral component as well as the time of occurrence, then Fourier transform would not be recommended. It cannot be used when it comes to analyzing the constituents of non-stationary signals. This is a major setback of Fourier transformation. Whenever one is interested in the time localization of the spectral components, the suitable transform that takes the time–frequency representation of the signal into cognisance is recommended; wavelet transform takes care of such. Thus the major advantage of wavelet transform over Fourier transform is that the time localization of the frequencies will not be lost. The major reason for considering wavelet transform for this work.

Wavelet transform is a new instrument for signal analysis. And it is considered as oscillation that decays fast with zero mean localized in frequency and time. The concept was introduced in 1982 by Jean Morlet. He saw wavelets are family of functions constructed from translations and dilations of a single function called the "mother wavelet" $\psi(t)$.

Wavelet can be characterized by how localized it is in time (Δt) and frequency ($\Delta\omega$ or the bandwidth).

By definition,

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\Psi\left(\frac{t-b}{a}\right),\ a, b \in R\ a\ \neq 0 \tag{1}$$

where a, is the scaling parameter that measures the degree of compression. b, the translation parameter which determines the time location of the wavelet. If $|a| \langle 1$, the wavelet in (1) is the compressed version (smaller support in time- domain) of the mother wavelet and corresponds mainly to higher frequencies. When $|a| \rangle 1$, then $\psi_{a,b}(t)$ has a larger time-width than $\psi\ (t)$ and corresponds to lower frequencies. The success of the Morlet wavelets in signal processing and time-frequency signal analysis depends on the adaptation of time-widths to their frequencies.

In other words, the product of a complex exponential wave and a Gaussian envelope gives the Morlet wavelet:

$$\Psi_0(\eta) = \pi^{-1/4}\ e^{i\omega_0\eta}\ e^{-\eta^2/2} \tag{2}$$

$\Psi_0(\eta)$ being the wavelet value at nondimensional time η, and ω_0 is the nondimensional frequency. In order to satisfy an admissibility condition, for this study, $\omega_0 = 6$. Implying that the function must have zero mean and be localized in both time and frequency space to be "admissible" as a wavelet. This is the basic wavelet function, but it will be now needed some way to change the overall size as well as slide the entire wavelet along in time. Thus, the "scaled wavelets" are defined as:

$$\Psi\left[\frac{(n'-n)\delta t}{s}\right] = \left(\frac{\delta t}{s}\right)^{1/2}\Psi_0\left[\frac{(n'-n)\delta t}{s}\right] \tag{3}$$

s in Eq. (3) is the "dilation" parameter used to change the scale. n is the translation parameter used to slide in time.

The factor $s^{-1/2}$ is a normalization to keep the total energy of the scaled wavelet constant. Given a time series X, with values of x_n, at time index n; each value is separated in time by a constant time interval dt. The wavelet transform $W_n(s)$ is just the inner product of the wavelet function with the original time series:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'}\Psi * \left[\frac{(n'-n)\delta t}{s}\right] \tag{4}$$

where the asterisk Ψ^* represents complex conjugate. N is the number of points in the time series.

3.2. Wave power spectrum

The local wavelet power spectrum is defined as $|W_n(s)|^2$ and represents the squared absolute value of the wavelet transform coefficients. Concerning the fact that the wavelet power spectrum gives more information in one picture, it is often practical to show the information as the averaged value of the result in the range of scale or time.

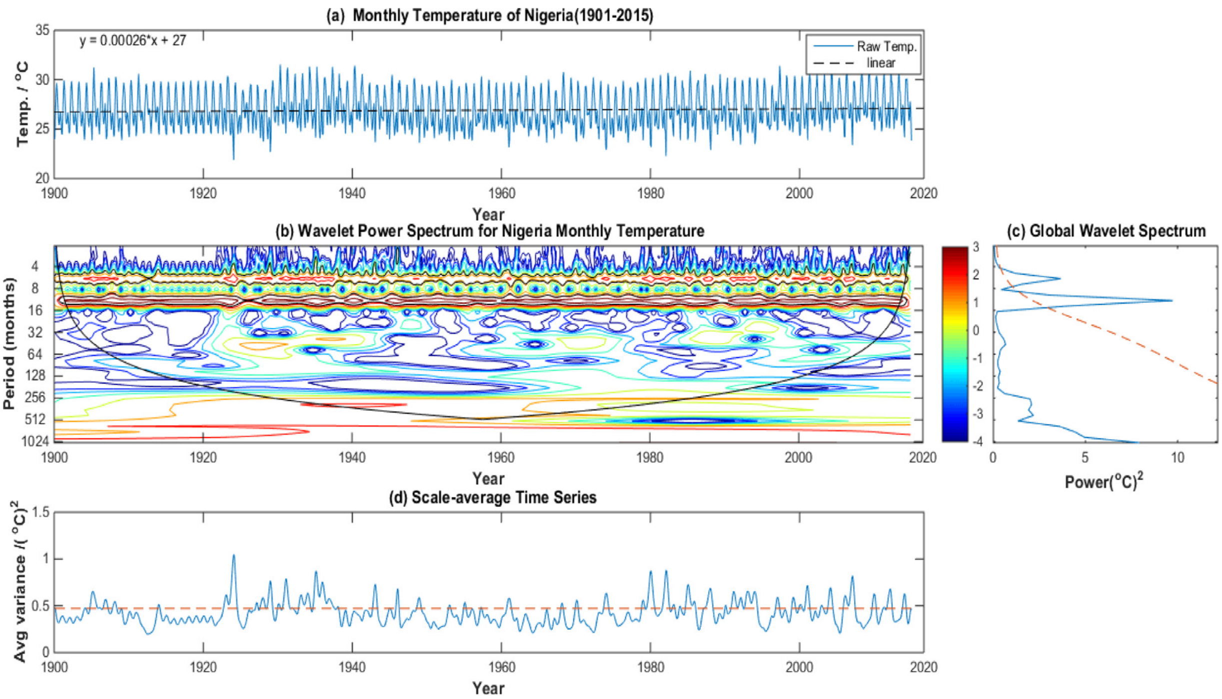

Fig. 1. (a) Monthly average temperature in Nigeria for 1901–2015 period. (b) The wavelet power spectrum. (c) The global wavelet power spectrum. (d) Scale-average wavelet power over the 8–16 months band.

The parameters used for the wavelet analysis of the monthly temperature and rainfall data in this study were: $\delta t = 1$month and $S_0 = 2\,\delta t$, $\delta j = 0.25$ to do 4 sub-octaves per octave, $j_1 = 7/\delta j$ to do 7 powers-of-two with δj sub-octaves each. Information on the relative power of a particular scale and a particular time is provided by power of the monthly temperature and rainfall data. It reveals the magnitudes of the scaled and shifted version of the mother wavelet in addition to their actual oscillations.

3.3. Global wavelet power spectrum (GWS)

Torrence and Compo showed the average variations of the whole time series on every scale, called the global wavelet spectrum (GWS) (time-averaged wavelet spectrum), which is defined as [26]

$$\bar{W}^2(s) = \frac{1}{N} \sum_{n=0}^{N} |W_n(s)|^2 \tag{5}$$

The scales are a series of fractional powers of 2 and are defined as:

$$s_j = s_0\ 2^{k\delta_j}\ k = 0,\ 1,\ \ldots, J, \tag{6}$$

where s_0 is the least resolvable scale and J determines the highest scale [16]. Moreover, the scale $\delta_j = 0.25$ is used, which will do 4 sub octaves per octave. The smaller values of δ_j give a finer resolution [16].

3.4. Cone of influence (COI)

Errors occur at the beginning and at the end of wave power spectrum when considering a time series of finite length. The edge effects are reduced when number of the elements of the time series is equal to a power of 2. Thus, there is need to pad the time series with zeroes to bring the length of the time series to the next higher power of 2 before calculating wavelet transform [16]. The padding reduced the amplitude at the edges, as more zeros were involved in the analysis. The region of the wavelet spectrum in which edge effects become important is referred to as the cone of influence (COI). And it is defined as the e-folding time for the autocorrelation of wavelet power at each scale [16].

3.5. Scale-average time series

The scale-average wavelet power (Figs. 1d and 3d) is a time series of the average variance in a certain band, in this case 8–16-month band, used to examine modulation of one time series by another, or modulation of one frequency by another within the same time series. This figure is made by the average of Figs. 1b and 3b over all scales between 8 and 16 months, which give a measure of the average year variance versus time.

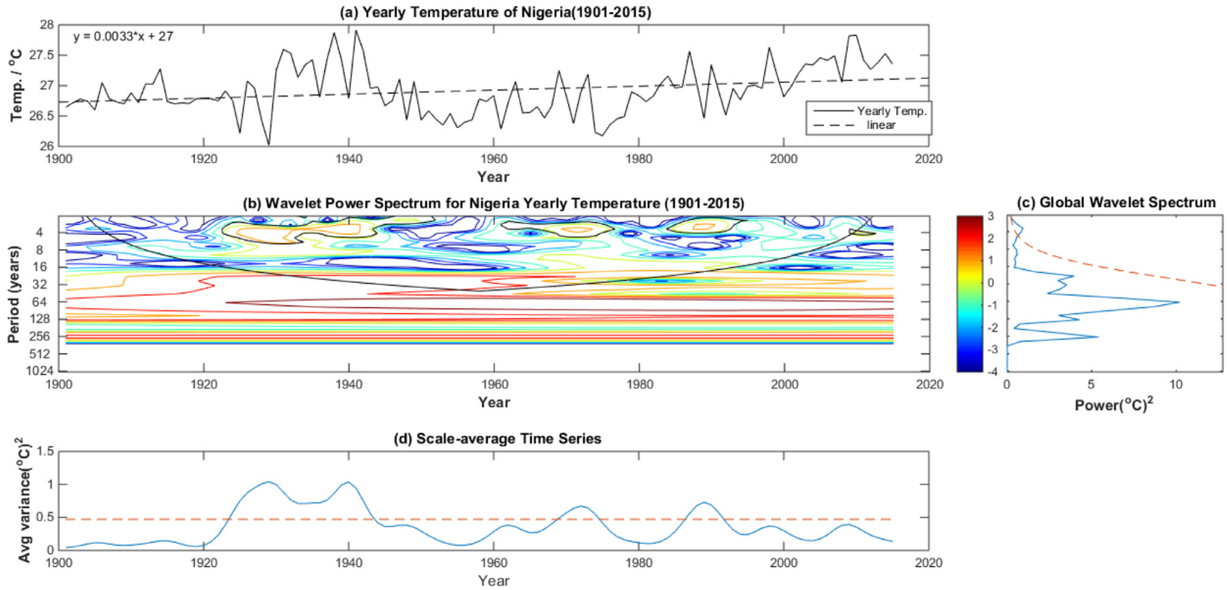

Fig. 2. (a) Yearly average temperature in Nigeria for 1901–2015 period. (b) The wavelet power spectrum. (c) The global wavelet power spectrum. (d) Scale-average wavelet power over the 8–16 months band.

4. Results and discussions

4.1. Monthly and annual trend

The monthly average temperature of Nigeria from the year 1901 to 2015 is shown in Fig. 1(a). The monthly average temperature over these 115 years period is 26.76 °C. Fig. 1(a) reveals that average monthly temperature time series show the periodicity in one year period. The wavelet transform power spectra of temperature in Fig. 1(b) is evaluated using 115 years data and over range of period from 2 to 1024 months (i.e., frequency from 1/512 = 0.0009766 to 1/2 = 0.5 c3ycles/month). The colour in the figure stands for the structure of temperature variety (the power ranges from weak (deep blue shades) to strong (dark brown shades). Thus, differences in time-series data were mapped into wavelet region and into various different scales. Throughout the 115 years, there was oscillation of periods 2 to 4 months with low power of −3 (blue colour). Other dominant oscillations of 4 to 8 months and 8 to 16 months with high power of 3 (dark brown colour), surrounded by an “envelope” of relatively lower power of 1 (light brown colour) were also observed.

Fig. 1(b) shows the power (absolute value squared) of the wavelet transform for the monthly temperature for 115 years in Nigeria which is shown in Fig. 1(a). The square of the absolute value gives information on the relative power at a certain scale and a certain time. This figure shows the actual oscillations of the individual wavelets, rather than just their magnitude. Fig. 1(b) reveals that there is more concentration of power between the 8 - 16-month band, which shows that these time series have a strong annual signal. Fig. 1(b) reveals the magnitudes of the scaled and shifted version of the mother wavelet in addition to actual oscillations.

The annual frequency (periodicity at 12 months) of these time series are confirmed by an integration of power over time, which show only one significant peak above the 95% confidence level for the global wavelet spectra, assuming red noise, represented by the dashed lines (Fig. 1(c)). Global wavelet spectrum provides an unbiased and consistent estimation of the true power spectrum of the time series, and thus it is a simple and robust way to characterize the time series variability. Global wavelet spectra should be used to describe temperature variability in non-stationary thermal representation of graph. Fig. 1(c) revealed that two major peaks occurred at 6-month and 12-month periods with power 4 and 12 respectively on the global wavelet power spectrum.

Discontinuities or abrupt changes in the time series give a high variance in the wavelet spectrum over a wide range of scales [27]. Calculation of the scale-averaged spectrum can give more information about possible abrupt changes in the time series. The more abrupt such changes are, the higher the averaged variance would be. Fig. 1(d) gives the 8–16 month period-averaged spectrum of the temperature series with a 95% significance level.

The first significant peak giving rise to the highest averaged variance in the scale-averaged spectrum occurred in 1925, the second and third occurred in 1980 and around 1983 respectively. Other peaks that could still be considered as significant occurred between years 2000 and 2015.

The yearly average temperature of Nigeria from the year 1901 to 2015 is shown in (a) of Fig. 2. The yearly average temperature over these 115 years period is 26.92 °C. The “dash-line” in Fig. 2(a) reveals that yearly temperature time series follows a trend of increase in temperature of 0.0033 °C per year.

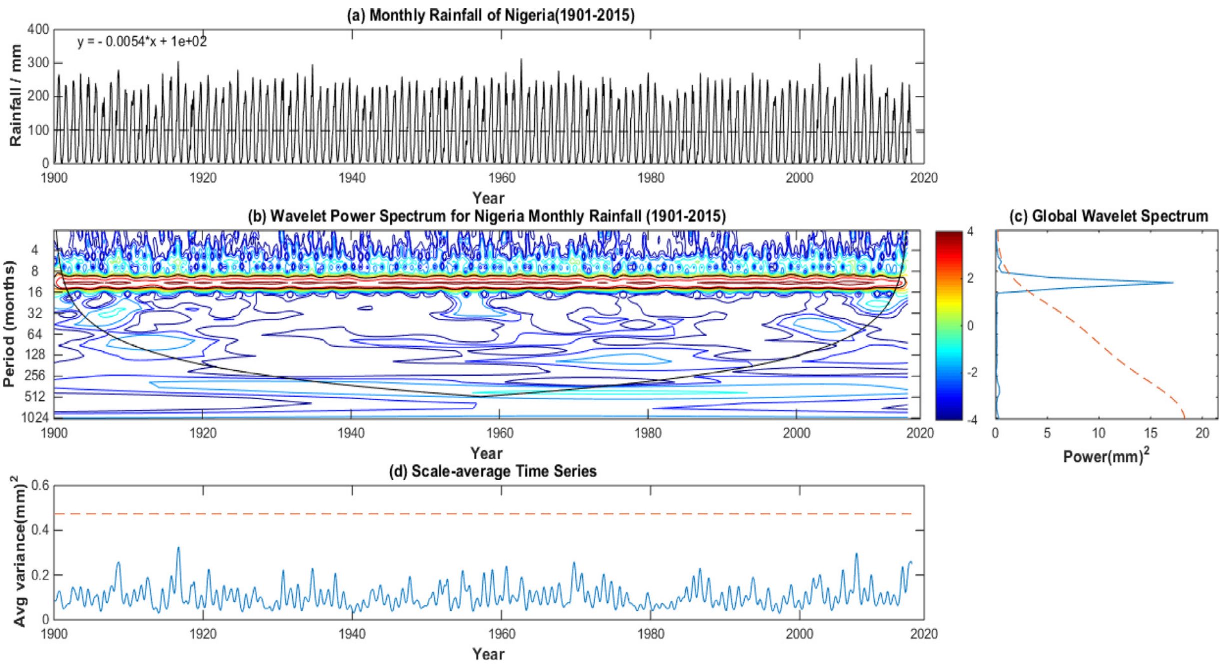

Fig. 3. (a) Monthly total rainfall in Nigeria for 1901–2015 period. (b) The wavelet power spectrum. (c) The global wavelet power spectrum. (d) Scale-average wavelet power over the 8–16 months band.

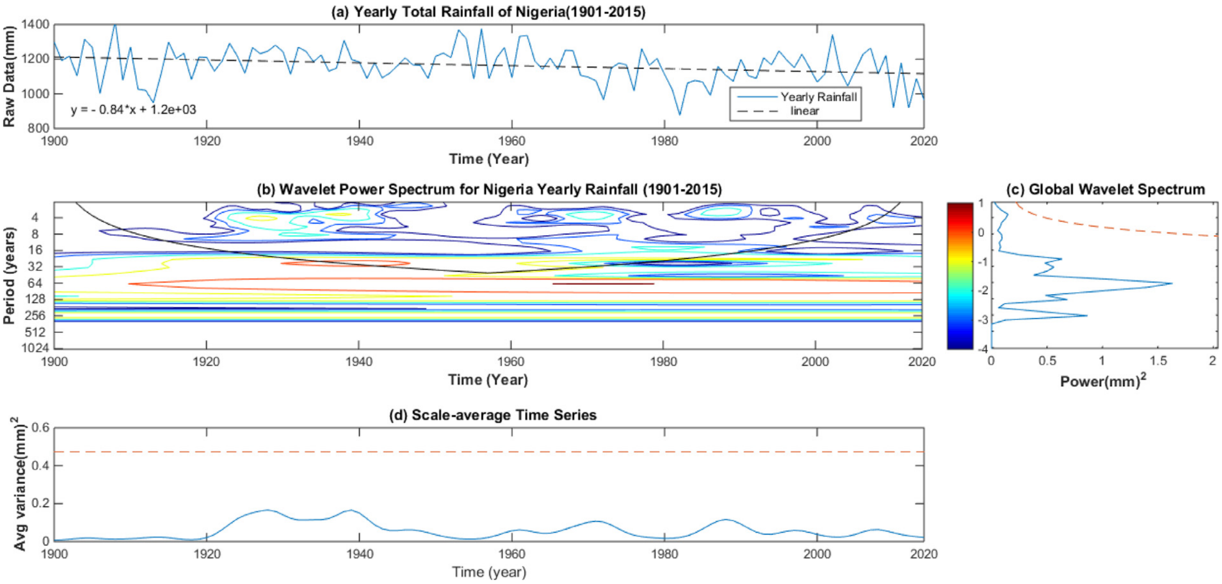

Fig. 4. (a) Yearly total rainfall in Nigeria for 1901–2015 period. (b) The wavelet power spectrum. (c) The global wavelet power spectrum. (d) Scale-average wavelet power over the 8–16 months band.

Fig. 2(b) showed that generally throughout the 115-year period, there was oscillation of periods 2 to 16 years with low power of −3 (blue colour); interjected with average power of 1(light brown colour) between 1922 to 1942, 1972 to 1974 and 1988 to 1990. Other dominant oscillations of 128 to 256 years with power of 1(light brown colour) sandwiching a relatively lower power of −1(light green colour) were recorded throughout the 115 years of observation. Fig. 2(c) revealed multi-level power peaks on the global wavelet spectrum, with the maximum of 10 occurring around the 64-year- period. However, the power peak of about 2 occurring around the 4-year- period is the most significant at the 5% significance level. Fig. 2(d) showed that significant peaks can be found around 1928, 1940, 1970 and 1990. Peaks of averaged variance in the scale-averaged spectrum recorded in around 1928 and 1940 were almost at the same level; but higher than that of 1970 and 1990, ironically also almost at same level.

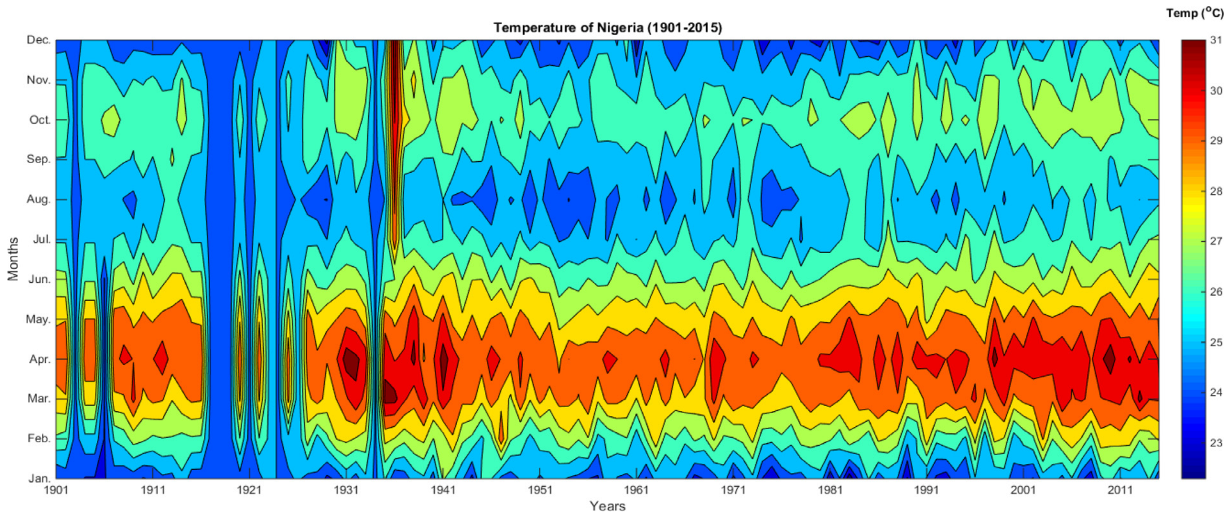

Fig. 5. Temperature contour of Nigeria 1901–2015.

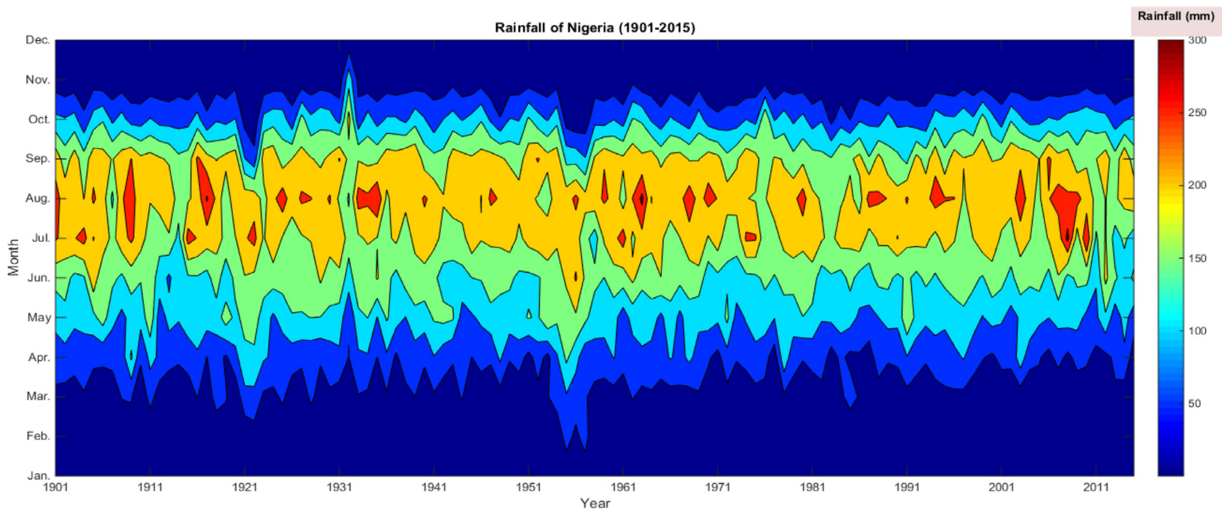

Fig. 6. Rainfall contour of Nigeria 1901–2015.

The average monthly total rainfall of Nigeria from the year 1901 to 2015 is shown in (a) of Fig. 3. The total monthly rainfall over these 115 years period is 97.07 mm. Fig. 3(a) reveals that average total monthly rainfall time series show the periodicity in one year period.

Fig. 3(b) reveals that there is more concentration of power between the 8 −16-month band, which shows that these time series have a strong annual signal. Fig. 3(c) revealed a 12-month period with peak power of 18mm^2 on the global wavelet power spectrum.

The average yearly total rainfall of Nigeria from the year 1901 to 2015 is shown in (a) of Fig. 4. The average yearly total rainfall over these 115 years period is 1164.95 mm. The "dash-line" in Fig. 4(a) reveals that total yearly rainfall time series follows a trend of decrease in rainfall of 0.0 84 mm per year. The periodicity of the time series cannot easily be determined from Fig. 4(b). Though Fig. 4(c) revealed 3 power peaks on the global wavelet spectrum, none could be significant at the 5% significance level.

A significant and peculiar observation from Fig. 5 is that the temperature recorded throughout the months of the years around 1903, 1917–1919, 1921, 1923–1924, 1926 and 1934 fall within same colour region of blue i.e. between the range of 23 °C and 25 °C. Fig. 5 reveals that generally on annual basis, the temperature increases gradually from around 23 °C to 24 °C in January to a maximum and turning point of around 29 °C to 31 °C (brown colour) in April (the hottest month). Thereafter the temperature begins to decrease until a minima turning point of around 23 °C and 24 °C is attained in August. Another maxima turning point is experienced around October with temperature of 27 °C and 28 °C (light-olive green colour). And temperature finally decreases to around 23 °C in December. Notably, intense temperature of around 31 °C (dark brown

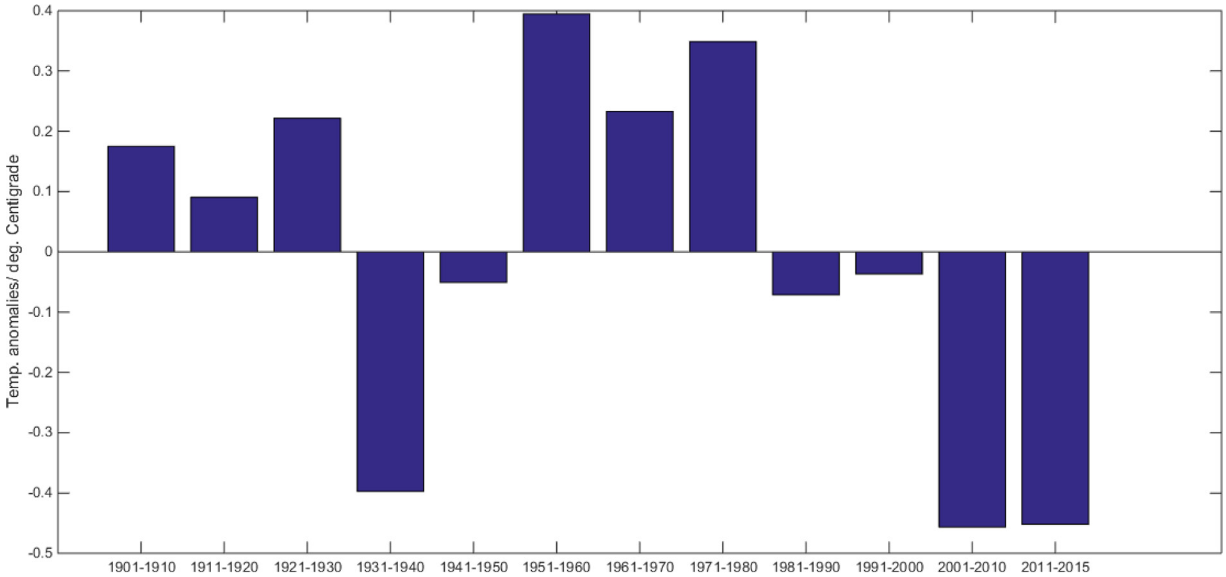

Fig. 7. Decade-to decade variability of temperature in Nigeria.

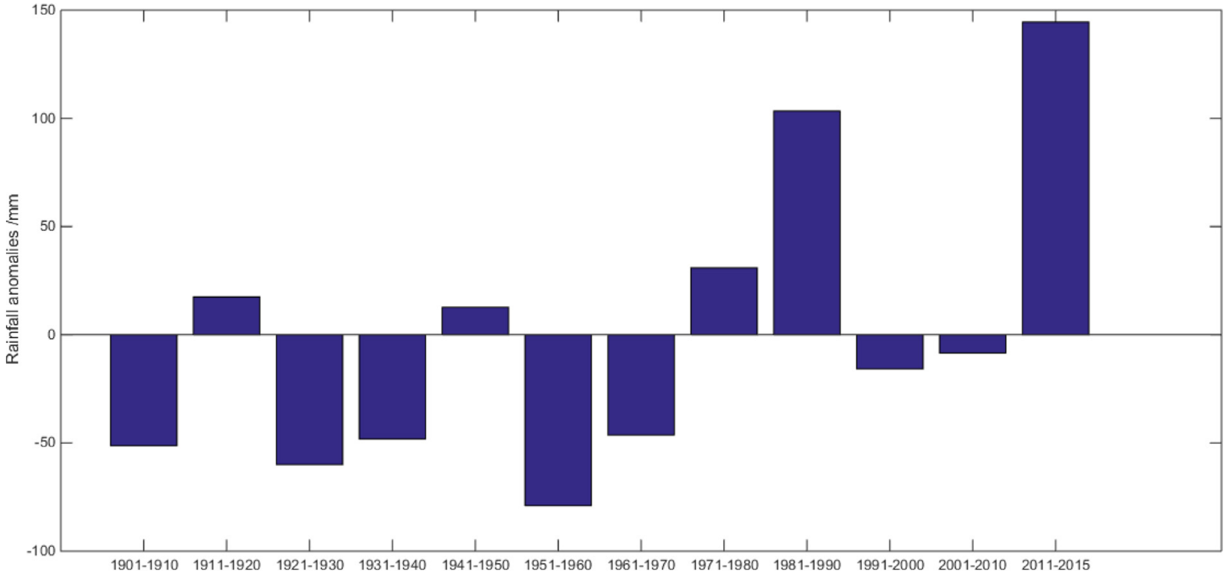

Fig. 8. Decade-to decade variability of rainfall in Nigeria.

colour) were recorded in April of years 1931,1932 and 1933; March of years 1935,1936 and 1937; March and April of 1941 and April of 2010.

Fig. 6 reveals that annually, two major climatic seasons exist in Nigeria. Namely, rainy season, with the rainfall being generally within the range of 50 mm to 300 mm per month; and the dry season, with rainfall being below 50 mm per month. The rainy season commences around April, lasting until October. The rainfall picks up its momentum gradually, becoming more intense from June and reaching its maximum around August; and thereafter begins to decrease. This is attributed to meeting of the North-East and South-West trade winds at the inter tropical convergent zone. Also according to Fig. 6 the rainfall was generally low in the following years: 1914, 1915, 1975, 1976, 1982, 1983,1984,1986,2005, 2011 and 2013 when the maximum rainfall recorded was in the neighbourhood of 180 mm and 150 mm (olive-green colour). This is attributed to the effect of el Nino or la Nina during these periods, in that 1976–1977 experienced weak el Nino, 1982–83 (very Strong el Nino), 1983–1984(weak la Nina); 1984–1985(weak la Nina) 2004–2005(weak el Nino) and 2010–2011 (strong la Nina)

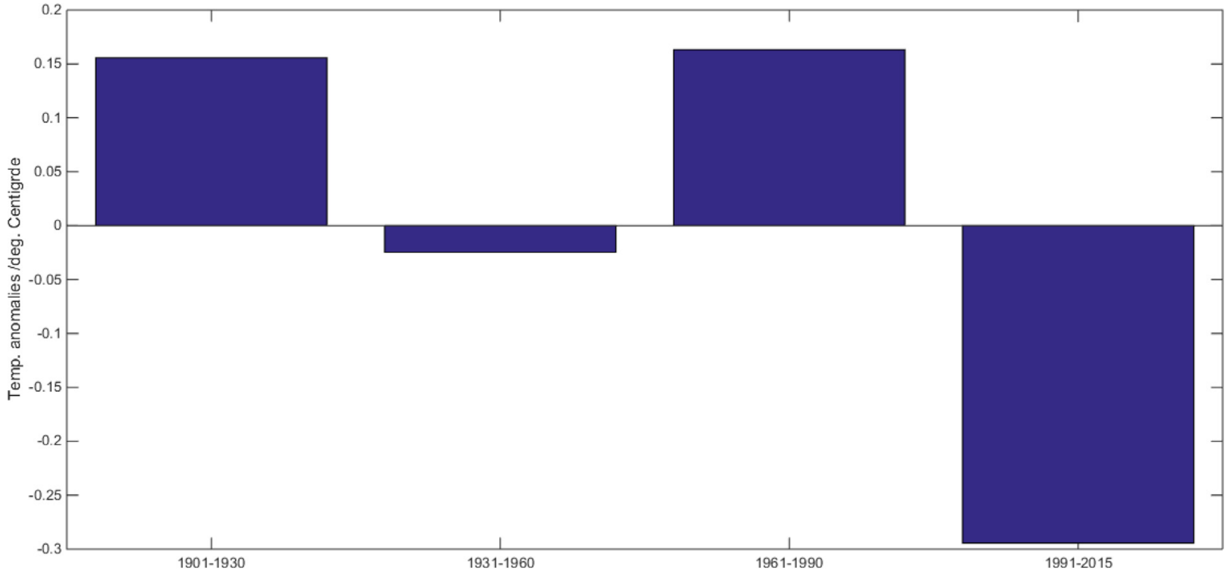

Fig. 9. A-thirty-year-average variability of temperature in Nigeria.

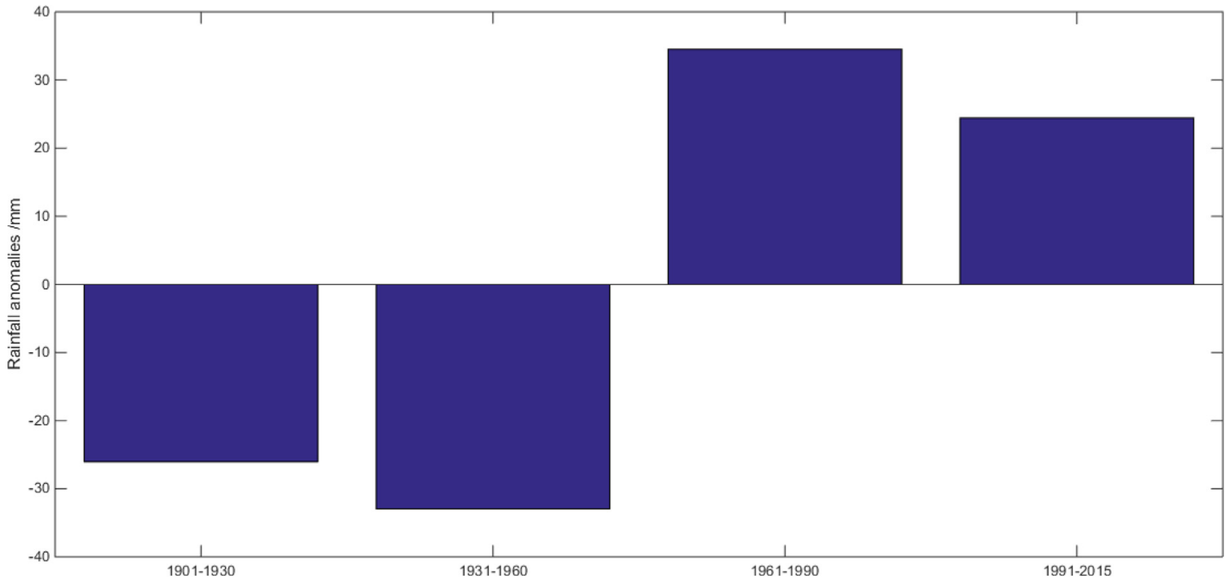

Fig. 10. A-thirty-year-average variability of rainfall in Nigeria.

4.2. Decadal trend

Decadal mean temperature of 26.94 °C during 1901 to 2015, was taken as "normal" temperature; while decadal mean total rainfall of 1158.66 mm was taken as "normal" total rainfall.

From Fig. 7, temperature was below normal in the 1931–1940, 1941–1950, 1981–1990, 1991–2000, 2001–2010 and 2011–2015, with negative anomalies; and above normal in 1901–1910, 1911–1920, 1921–1930, 1951–1960, 1961–1970 and 1971–1980, with positive anomalies. The highest negative anomaly of −0.4565 °C was recorded in 2001–2010; while the highest positive anomaly of 0.395 °C was in 1951–1960.

From Fig. 8, rainfall was below normal in the 1901–1910, 1921–1930, 1931–1940, 1951–1960, 1961–1970, 1991–2000 and 2001–2010, with negative anomalies, and above normal in 1911–1920, 1941–1950, 1971–1980, 1981–1990 and 2011–2015, with positive anomalies. The highest negative anomaly of −79.01 mm was recorded in 1951–1960; while the highest positive anomaly of 144.49 mm was in 2011–2015.

4.3. Climatological trend

The “climatological normal” was taken as the respective mean of the 115 years (1901–2015) for temperature and rainfall; being 26.93 °C and 1163.88 mm.

Fig. 9 revealed an alternative trend of change in temperature anomalies every 30 years, i.e. from positive to negative, then back to positive. In other words, a pattern of change of average temperature over every thirty years from above mean to below mean was observed. From Fig. 10, the positive anomalies for years 1961–1990 and 1991–2015 looked like an “inverted mirror image of negative anomalies of years 1931–1960 and 1901–1930″ about year 1960. It was observed that after two consecutive thirty-year-period, average rainfall changes from below mean to above mean.

5. Conclusions

In this study, we applied wavelet transformation to analyze the 115-year time series of temperature and rainfall of Nigeria. With spectral wavelet analysis, the time-frequency power characteristics of the analyzed data were estimated, thus providing an insight into the dynamic behavior of the observed average temperature and total rainfall over time. For both the monthly average temperature and total monthly rainfall of the analyzed time series, several local maximums were identified in the GWS graphs, where the largest is that in a 12-month period, showing that these time series have strong annual signals. There is more concentration of power between the 8-16-month band. The trend of increase in the monthly average temperature observed in Nigeria is not that obvious, in comparison with the yearly trend. Also the trend of decrease in the total monthly rainfall observed is not that obvious, in comparison with the annual. Change in climate is attributed to natural variability and anthropological activities. A pattern of change in the variability of climatological parameters for temperature and rainfall, over a-thirty-year and two periods of thirty-year respectively; is an indication that the climate of Nigeria changed with variability of climate parameter.

6. Conflict of interest

No conflict of interest

Acknowledgements

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2018.e00017.

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