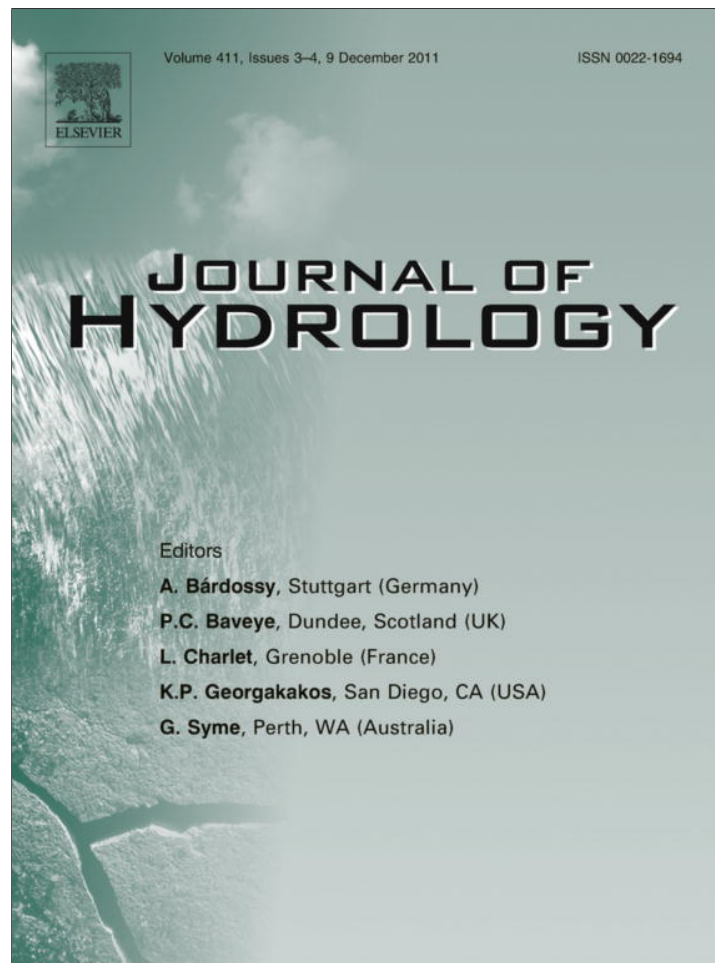


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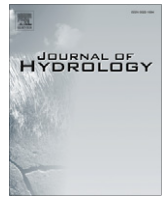
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Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Rainfall trends in Nigeria, 1901–2000

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ARTICLE INFO

Article history:

Received 24 April 2011

Received in revised form 29 August 2011

Accepted 25 September 2011

Available online 8 October 2011

This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Ercan Kahya, Associate Editor

Keywords:

Rainfall

Monotonic trend

Periodicity

Variability index

Nigeria

SUMMARY

There is the need to evaluate changes in the spatial and temporal patterns of rainfall in order to improve water management strategies of a given region. In this study, standard tests are used to examine the existence of trend in annual and monthly rainfall of Nigeria over the last century. Rainfall variability index was estimated as standardized rainfall departure while autocorrelation spectral analysis is used to obtain the periodicities inherent therein. Rainfall spatial distribution was highly latitudinal dependent ($r^2 > 0.90$) and had no clearly linear relations with the longitude. Rainfall variability index showed that 1950s was the wettest decade (+0.84) while 1980s was the driest (−1.19), with the two decades between 1970 and 1990 being drier than any other comparable period in the last century. Observed rainfall changes varied between −3.46 and +0.76 mm yr^{−2}. About 90% of the entire landscape exhibited negative trends but only 22% showed significant changes at 5% level. There was a sharp difference between changes in rainfalls in 1931–1960 and 1961–1990 periods. Annual precipitation reduced by 7% between the two periods. While more than 90% of the landscape showed no significant rainfall change in the first period, about 57% of Nigeria showed a significant ($P < 0.05$) decrease in the second. The dominant peaks can be classified into four distinct rainfall cycles with periods 2–3, 5–7, 10–15 and 30 yr. These cycles may be associated with the stratospheric Quasi-Biennial Oscillation (QBO), the El-Nino Southern Oscillation (ENSO); the sunspot cycles and the Atlantic Multi-Decadal Oscillation (AMO) sea surface temperature, respectively.

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1. Introduction

Knowledge of trends and variations of current and historical hydro-climatological variables is pertinent to the future development and sustainable management of water resources of a given region especially within the context of global warming, water and energy cycles and the increasing demand for water due to population and economic growth (Oguntunde et al., 2006; Cannarozzo et al., 2006). One of the very important necessities of research into climate change (Houghton et al., 1996) is to analyse and detect historical changes in the climatic system. Rainfall is a principal element of the hydrological cycle, so that understanding its behaviour may be of profound social and economic significance. The detection of trends and oscillations in precipitation time series yields important information for the understanding of climate. However, rainfall changes are particularly hard to gauge, because rainfall is not uniform and varies considerably from place to place and time to time, even on small scales.

Several studies have been carried out at different temporal scales and in different parts of the globe. Existing analyses of daily

series show for some areas a positive trend in the daily precipitation intensity and a tendency toward higher frequencies of heavy and extreme rainfall in the last few decades (Houghton et al., 1996). Many authors analyzed the precipitation patterns in several parts of Europe. For example, Brazdil (1992) described fluctuations of precipitation in Europe using a series of annual areal precipitation sums. Some of the results suggest that spatial and temporal non-uniformity in trend exists, which make generalization over large areas difficult if not impossible. Significant positive trends have been observed in the USA (Karl et al., 1995; Trenberth, 1998; Kunkel et al., 1999), east and northeast Australia (Suppiah and Hennessey, 1998; Plummer et al., 1999), South Africa (Mason et al., 1999), the United Kingdom (Osborn et al., 2000) and Italy (Brunnetti et al., 2001). Besides the increase in precipitation intensity, there are some indications that the overall percentage of the Earth's surface affected by either drought and/or excessive wetness has increased (Dai and Trenberth, 1998). Gemmer et al. (2004) analyzed the annual rainfall series of 160 stations in China. They observed a spatial clustering of the trends in certain months, including district trend belts in east and northeast China. Over India sub-continent, rainfall analysis between 1871 and 1994 indicated decreasing trends during 1880–1905 and 1945–1965 with increasing trends at other periods (Naidu et al., 1999). Similar studies over India reveal that there are significant differences in rainfall

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trends at the regional level (Guhathakurta and Rajeevan, 2007; Krishnakumar et al., 2009). Trends in long-term rainfall in Turkey showed significant trends in January, February, and September and in the annual means (Partal and Kahya, 2006). Tabari and Hosseinzadeh Talaee (2011) found negative trends in about 60% of the stations studied over Iran, with the significant trends occurring in the northwest part of the country.

There are ongoing debates regarding the recent trends in Sahelian rainfall. Some studies reported the continuation of the Sahelian drought till the end of the 20th century (L'Hôte et al., 2002), while others argue it may have ended in the 1990s (Ozer et al., 2003). Ojo (1987) examined rainfall variations between 1901 and 1985 in West Africa and found no observable regular pattern in its trend and periodicity. Hulme (1992) reported a 10% increase in rainfall in the southern coastal region of West Africa between 1931–1960 and 1961–1990 periods. Barrios et al. (2010) used a new cross-country panel climatic data set in an empirical economic growth framework to examine the role of rainfall trends in poor growth performance of sub-Saharan African nations relative to other developing countries. Their results showed that rainfall has been a significant determinant factor of poor economic growth for African nations but not for other countries.

Rainfall analysis in Nigeria have been more quantitative during the 20th century (e.g. Adefolalu, 1986; Hess et al., 1995; Olaniran, 1990, 1991, 2002; Olaniran and Summer, 1990; Bello, 1998; Ati et al., 2009; Alli, 2010; Oguntunde et al., 2011). Adefolalu (1986) analyzed rainfall data between 1911 and 1980 from 28 meteorological stations to examine trends in precipitation patterns, a general decrease of dry season rainfall was observed. There have been a number of reports on rainfall analyses in the Sahel and there exist pockets of studies for few observation stations in the north and south of Nigeria covering different periods. However, a comprehensive analysis of historical 20th century rainfall over Nigeria as currently presented here is still lacking. For example, previous rainfall studies have been reported for different periods and locations within Nigeria. Olaniran (1991, 2002) examined rainfall for periods 1921–1985 and 1921–2000, Hess et al. (1995) presented results for four stations in northern Nigeria during 1961–1990, Bello (1998) compared the seasonality of rainfall distribution in Nigeria during 1930–1961 and 1962–1993 periods and Alli (2010) studied rainfall trends and cycles for 20 stations scattered over Nigeria between 1960 and 2005. In Nigeria, with over 70% of the populace engaged in rain-fed agriculture, rainfall is the most important climatic variable. Therefore, the need for continuous rainfall studies cannot be over-emphasized for the purpose of long-term water resources planning and management. The main objective of these analyses was to examine trends, variability and oscillations in rainfall series of Nigeria over the 20th century.

2. The study area

Nigeria, located in West Africa between latitudes 4–14°N and longitudes 2–15°E, has a total area of about 925,796 km². The climate, highly varied across its length, is dominated by the influence of three main wind currents. These are the tropical maritime (MT) air mass, the tropical continental (CT) air mass and the equatorial easterlies (Ojo, 1977). MT originates from the southern high-pressure belt located off the Namibian coast, and along its way picks up moisture from over the Atlantic Ocean and is thus wet. The CT has the high-pressure belt north of the Tropic of Cancer as its origin. This air mass is always dry as a result of little moisture it picks along its way. MT and CT meet along a starting surface called the Inter-Tropical Discontinuity (ITD). The third air mass (equatorial easterlies) is a somehow erratic cool air mass, which comes from the east and flow in the upper atmosphere along ITD. This air mass

penetrates occasionally to actively undercut the MT or CT and give rise to squall lines or dust devils (Iloje, 2001). Nigeria is a country of marked ecological diversity and climatic contrasts. The lowest point is the Atlantic Ocean at sea level while the highest point is the Chappal Waddi at 2419 m (www.fao.org). The ecological zones of the country are broadly grouped into six (Fig. 1), which are Mangrove (MG), Fresh Water Swamp (FWS), Rain Forest (RF), Tall Grass Savanna (TGS), Short Grass Savanna (SGS) and Marginal Savanna (MS). The climate is varied from semi-arid, through sub-humid to humid from the north to the south. Rainfall commences at the beginning of the raining season around March/April from the coast (in the south), spreads through the middle belt, reaching its peak between July and September, to eventually get to the northern part very much later. According to Cleaver and Shreiber (1994), 57% of the surface area of Nigeria is believed to be either under crops or pastures while the remaining 43% is divided amongst forest, water bodies and other uses.

3. Datasets and methods

3.1. Dataset

Rainfall data were taken from the Global Gridded Climatology (CRU TS 2.1) presented at a new high resolution and made available by the Climate Impacts LINK project, Climate Research Unit, University of East Anglia, Norwich, UK (Mitchell et al., 2001; Mitchell and Jones, 2005). The Climatic Research Unit (CRU) data set is composed of monthly 0.5° latitude/longitude gridded series of climatic parameters over the periods 1901–2002. Amongst these parameters monthly accumulations of precipitation are generated from available gauge data sets. Although the time series extends back to 1901, it should be noted that the number of available gauges varies with time, for example, in 1901 a total of 4957 gauges contributed to the dataset, which by 1981 has increased to 14,579 gauges. Africa generally has poor coverage of rainfall stations, hence detailed information on CRU data quality control and interpretation can be found in relevant publications (New et al., 2000; Mitchell and Jones, 2005; Conway et al., 2009).

3.2. Data analysis

3.2.1. Rainfall variability index

Rainfall index is usually computed as the standardized precipitation departure and helps to separate the available rainfall time series into different climatic regimes such as very dry climatic year, normal climatic year and wet or very wet climatic years. Rainfall variability index (δ) was calculated as:

$$\delta_i = (P_i - \mu) / \sigma \quad (1)$$

where δ_i is rainfall variability index for year i , P_i is annual rainfall for year i , μ and σ are the mean annual rainfall and standard deviation for the period between 1901 and 2000.

3.2.2. Non-parametric trend test

The Mann–Kendall test, which is often used to test for trends in hydro-climatological time series (Tosic and Unkasevic, 2005; Oguntunde et al., 2006; Dinpashoh et al., 2011), was used to test for the presence of trends in this study. This is applicable in cases when the data values x of a time series can be assumed to obey the model:

$$\chi = f(t) + \sum t \quad (2)$$

where $f(t)$ is a continuous monotonic increasing or decreasing function of time and the Residual $\sum t$ can be assumed to be from the same distribution with zero mean. The Mann–Kendall test statistic S is given as:

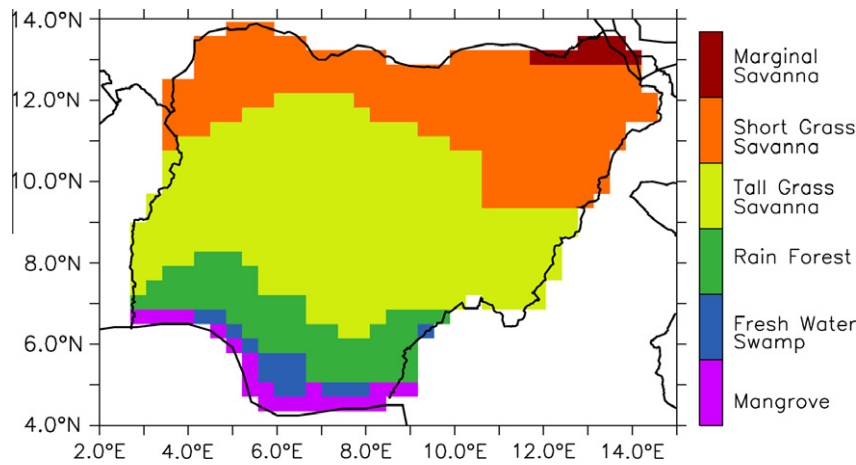


Fig. 1. Map of Nigeria showing for different agro-ecological zones of Nigeria (adapted and modified from www.fao.org).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (3)$$

where n is the length of the time series x_1, \dots, x_n , and $\text{sgn}(\cdot)$ is a sign function, x_j and x_k are values in years j and k , respectively. The expected value of S equals zero ($E[S] = 0$) for series without trend and the variance is computed as:

$$\sigma^2(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad (4)$$

Here q is the number of tied groups and t_p is the number of data values in p^{th} group. The test statistic Z is then given as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\sigma^2(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\sigma^2(S)}} & \text{if } S < 0 \end{cases} \quad (5)$$

As a non-parametric test, no assumptions as to the underlying distribution of the data are necessary. The Z -statistic is then used to test the null hypothesis, H_0 that the data is randomly ordered in time, against the alternative hypothesis, H_1 , where there is an increasing or decreasing monotonic trend. To estimate the true slope of an existing trend, the Sen's non-parametric method, widely acclaimed for its robustness (Salmi et al., 2002; Kahya and Kalayci, 2004; Jhajharia et al., 2011; Dinpashoh et al., 2011), was used.

3.2.3. Trend free pre-whitening

The M–K test requires time series to be without serial correlation. Significant positive serial correlation is expected to influence the power of M–K thereby leading to major source of uncertainty. To eliminate or minimize this effect, pre-whitening of the original dataset before applying the M–K test is recommended (Abdul Aziz and Burn, 2006; Jhajharia et al., 2011; Dinpashoh et al., 2011). Following Kumar et al. (2009), rainfall data for different zones of Nigeria were corrected for lag-1 serial correlation (r_1) by estimating the monotonic trend (Δ) for the series, removing this trend prior to pre-whitening and finally adding the trend to the pre-whitened data series. The M–K test was then used to detect trend in the final (or pre-whitened) series. This procedure can easily be represented as:

$$z_i = x_i - (\Delta \times i) \quad (6)$$

where Δ is Sen's estimator and have been described in different reports (Kahya and Kalayci, 2004; Jhajharia et al., 2011; Dinpashoh

et al., 2011). The value of r_1 of the new time series is first computed and later used to determine the residual series as

$$v_i = z_i - r_1 \times z_{i-1} \quad (7)$$

Then the value of $\Delta \times i$ is added again to the residual data set of Eq. (7) as

$$y_i = v_i + (\Delta \times i) \quad (8)$$

The y_i series is the final (or pre-whitened) series.

3.2.4. Autocorrelation spectral analysis

Autocorrelation spectral analysis is used to identify periodic signal in the rainfall datasets. Autocorrelation analysis correlates a time series dataset with itself at different time lags (Phillips et al., 2008). It is useful in checking randomness, finding repeating patterns, or identifying presence of a periodic signal in a time series dataset. Here, the autocorrelation coefficients at varying time lags were computed as:

$$R_h = \frac{C_h}{C_0} \quad (9)$$

where C_h is the autocovariance function:

$$C_h = \frac{1}{N} \sum_{t=1}^{N-h} (Y_t - \bar{Y})(Y_{t+h} - \bar{Y}) \quad (10)$$

and C_0 is the variance function

$$C_0 = \frac{1}{N} \sum_{t=1}^N (Y_t - \bar{Y})^2 \quad (11)$$

where N is the sample size, h is the time lag. The values of autocorrelation coefficient R_h (which are between -1.0 and $+1.0$) for a dataset are used to classify the dataset. If the values are near zero the dataset is random, otherwise, if the autocorrelations are significantly non-zero the dataset is non-random. If the values exhibit a sequence of alternating positive and negative signs, and do not decay to zero, the dataset has an underlying sinusoidal (periodic) signal. Filtering of dataset before the autocorrelation analysis usually enhances the results from the analysis. In this study a 10-yr moving average was used to filter the dataset before the autocorrelation analysis. Spectral analysis is used to decompose time series datasets into spectrum of cycles of different lengths. This was done to uncover reoccurring cycles of different length in a time series, which at first looks like a random noise. Here, we use the unfiltered datasets for the spectral analysis to retain the contribution of high frequency signals.

4. Results

4.1. Temporal and spatial distribution of rainfall

4.1.1. Summary of descriptive statistics

A summary statistic of the long-term (temporal) series for the respective ecological zones is given in Table 1. Rainfall varied mostly in the north (Marginal Savanna) with coefficient of variation (CV) of 28%, its value ranged from about 117 to 640 mm yr⁻¹ (mean = 347 ± 98 mm yr⁻¹). Rainfall values for Fresh Water Swamp ranged from about 1590 to 2710 mm yr⁻¹ with CV of 9.6%. For the country as a whole, precipitation varied between about 830–1450 mm yr⁻¹ (mean = 1170 ± 109 mm yr⁻¹).

Spatial distribution of annual rainfall and the corresponding coefficient of variation are shown in Fig. 2. Rainfall decreased with increasing latitude. Its value ranged from about 400 mm yr⁻¹ around the Lake Chad in the northeast corner to over 2500 mm yr⁻¹ in the south around the Niger Delta area of Nigeria. Spatial pattern of the CV (%) showed a reverse latitudinal trend as rains become more varied northwards. The coefficient of variation generally increased from less than 10% in the southernmost part to about 30% in the northeast. Temporal distribution and spatial averages of 1901–2000 rainfall estimates plotted as cumulative distribution function (cdf) for rainfall are shown in Fig. 3. The temporal pattern showed a general decline in rainfall over Nigeria in the last century. The cdf is very helpful to set threshold values below or above which certain rainfall events occurs. Fig. 3b shows that less than 10% of the entire Nigeria landscape experience about 500 mm yr⁻¹ of rainfall, 60% experience about 1300 mm yr⁻¹ while only about 10% of the southern part of the landscape experience very heavy storm above 2000 mm yr⁻¹.

4.1.2. Rainfall variability

Annual and decadal rainfall variability indices for Nigeria are presented in Fig. 4a and b. Similar to the findings of other researchers, e.g. Nicholson et al. (2000) and L'Hôte et al. (2002), three series of characteristic periods may be distinguished for Nigeria as: (1) from 1901 to 1915 (15 yr) an apparently random succession of seven dry years, four “normal” years and 4 wet years; (2) from 1916 to 1969 (54 yr), a series of 26 wet years, 4 dry years and 24 “normal” years; (3) from 1970 to 2000 (31 yr) of 15 dry years, 12 “normal” years and four wet years. The driest decade was the 1980s while the wettest decade was the 1950s. However, there are slight differences in the distribution of the decadal δ especially prior to the beginning of drought in 1970 as shown in Fig. 5. The ecological zones (MG, FWS and RF) in the south showed the wettest decade as 1901–1910 as against zones from the middle-belt upwards.

4.2. Annual and monthly trends

Summary of monotonic trend and slopes estimate for the rainfall series of different zones are given in Table 2. Fig. 6 shows the spatial distribution of the test Z-statistics and trends. Significant changes

have occurred in MG, TGS, SGS and MS, respectively at different periods. Slope values varied between -3.46 and +0.76 mm yr⁻². About 90% of the entire landscape exhibited negative trends while less than 10% showed positive trends. Z-statistic varied spatially from -3.33 to +0.91. The spatial pattern of the changes at 10%, 5% and 1% levels are vividly displayed towards the southern part of Nigeria in the Niger Delta area and in the north central. The actual changes in rainfall in the last century were plotted in Fig. 7a and changes at a fixed significance level of 5% are shown in Fig. 7b. About 4.4% of the total area experienced overall rainfall change in the order of between -350 and -200 mm yr⁻¹; 26.9% showed changes varying from -200 to -100 mm yr⁻¹ while about 8.8% of the total area showed changes with values above zero (i.e. between 0 to +80 mm yr⁻¹).

Comparison of trend results from Mann–Kendall (original and pre-whitened data) and least square regression including the change point year for annual rainfall over different zones of Nigeria are given in Table 3. The values of lag-1 correlation coefficients are generally low and statistically not significant in 4 of the 6 zones and the global (all zones) series for Nigeria. Apart from the two zones with significant r_1 , test Z and slope magnitude generally decreased but the all zones series showed a 6% increase in slope magnitude. The two zones with significant r_1 show no significant trends in rainfall. Similar results (Table 3), with slightly lower slope magnitude, were obtained using a parametric approach (least square regression analysis) after all the series passed the Shapiro–Wilk test for normality. The change point in the rainfall series of different zones of Nigeria was examined using the cumulative sum technique as presented by Kiely (1999). The result indicates that the change point year of significant downward shift in Nigeria as a whole was in 1969 but ranges between 1969 and 1971 for the six zones.

Analysis of each calendar month allows the identification of time characteristics peculiar to each month, which may be masked in annual analysis. Monthly values of rainfall between 1901 and 2000 are subjected to Mann–Kendal trend test and Sen's slope estimates. Monthly rainfall generally showed negative trends for most of the months (10 out of 12 for Nigeria) and zones. Most of the changes are occurring in the months of April, June, August and September. However, the highest significant ($P < 0.001$) decrease in rainfall was observed in the month of June at the rate of 0.54 mm yr⁻¹ in the Mangrove zone.

4.3. Trends during the WMO 'standard' periods

Temporal and spatial rainfall trends are estimated for 1931–1960 and 1961–1990 periods, that represent the reference periods indicated by the WMO (World Meteorological Organization) for climatologic studies (Hulme, 1992; Box, 2002; Cannarozzo et al., 2006). In general for both periods very sharp differences are observed. Summary of trends estimated are reported in Table 4 for the two periods and different zones. The results showed a relatively slight increase in rainfall (except in TGS) between 1931 and 1960 contrary to a 100% decrease in all the ecological zones for

Table 1
Annual rainfall summary for different agro-ecological zones of Nigeria.

Agro-ecological zone	Minimum (mm yr ⁻¹)	Maximum (mm yr ⁻¹)	Mean (mm yr ⁻¹)	SD (mm yr ⁻¹)	CV (%)
Mangrove	1575.0	2533.0	2024.5	188.8	9.3
Fresh Water Swamp	1586.0	2710.0	2221.2	213.6	9.6
Rain Forest	1304.0	2366.0	1831.1	183.3	10.0
Tall Grass Savanna	896.9	1535.0	1231.4	120.4	9.8
Short Grass Savanna	433.6	969.4	705.6	116.0	16.4
Marginal Savanna	116.9	639.7	347.1	98.0	28.2
All zones	834.2	1450.0	1170.0	109.5	9.4

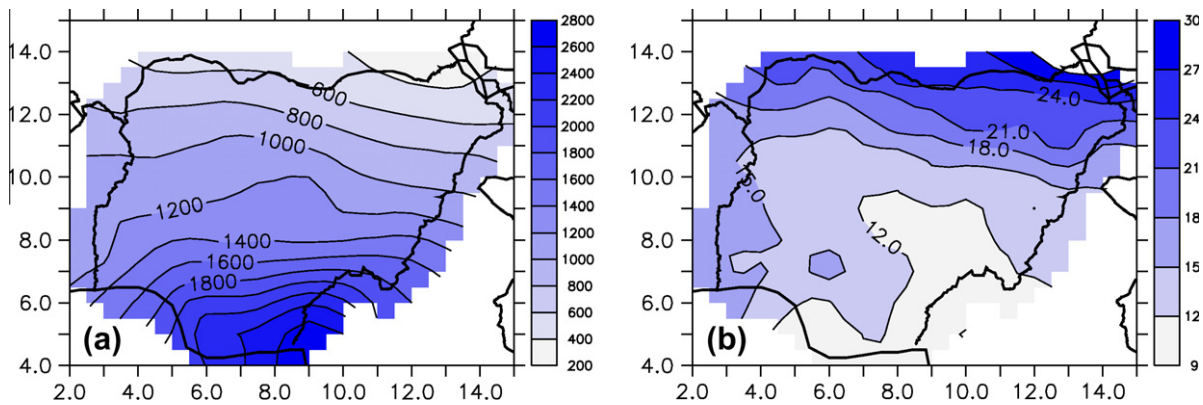


Fig. 2. Spatial distribution of annual rainfall (mm yr^{-1}) and the corresponding coefficient of variation (%).

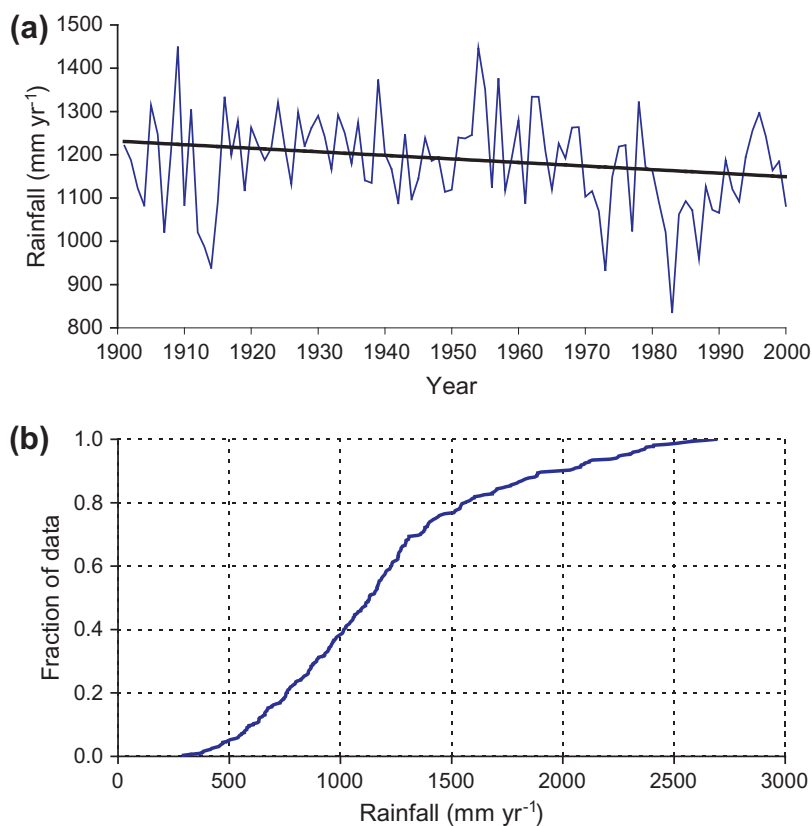


Fig. 3. Distribution of (a) spatial and (b) temporal averages plotted as cumulative distribution function (c, d, and f) of 1901–2000 annual rainfall for Nigeria.

the 1961–1990 period. Whereas mean annual precipitation significantly reduced by 7%, variability (CV) increased from 7.4% to 10.4%. During the first period, an increase of 0.6 mm yr^{-2} was observed while rainfall reduced at the rate of 7.1 mm yr^{-2} during the second period examined. Monthly changes between the two periods (not shown) showed that April, June, August and September are generally responsible for the observed changes in annual rainfall in the 1961–1990 periods.

Spatial averages of 1931–1960 and 1961–1990 rainfall values plotted as cumulative distribution function (cdf) are shown in Fig. 8. A forward shift in 1961–1990 cdf indicating general reduction in rainfall amount was noted throughout the landscape. A Kolmogrov-Smirnov test showed that the two cdfs are significantly different. The spatial Z-statistics and rate of change are plotted in Fig. 9 while the cumulative change in rainfall and change at 5% significant level are shown in Fig. 10. For the 1931–1960 period,

72.5% of landscape (only 1% has significant trends at 5%) showed increase in rainfall. However, for the 1961–1990 period, 99% of landscape (57% have significant trends at 5% level) showed reduction in rainfall.

4.4. Rainfall cycles and periodicity

Fig. 11 presents results of the autocorrelation spectral analysis for each of the zones. The figure reveals the characteristic of dominant rainfall cycles (peaks, significant at 95% confidence level) over the zones: MG (2.7, 3, 5.3, 12.5 and 33.3 yr); FWS (3, 5, 5.3, 12.5 and 33.3 yr); RF (3, 5.3, 7.7, and 33.3 yr); TGS (3, 14.3, and 33.3 yr); SGS (10, 13, and 33.3 yr) and MS (33.3, and 14 yr). Rainfall peaks with periodicity of 50 yr and above are neglected because they may not be well resolved in the dataset. The dominant peaks

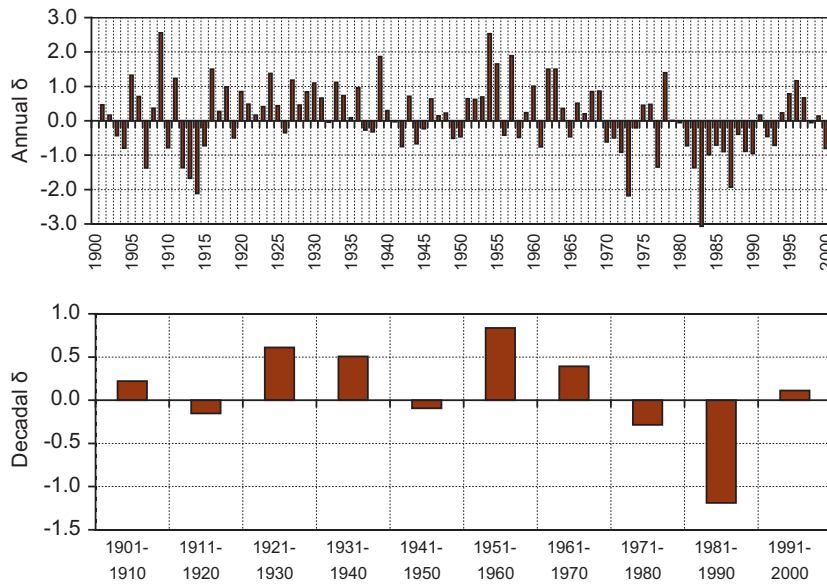


Fig. 4. Annual and decadal rainfall variability indices for Nigeria.

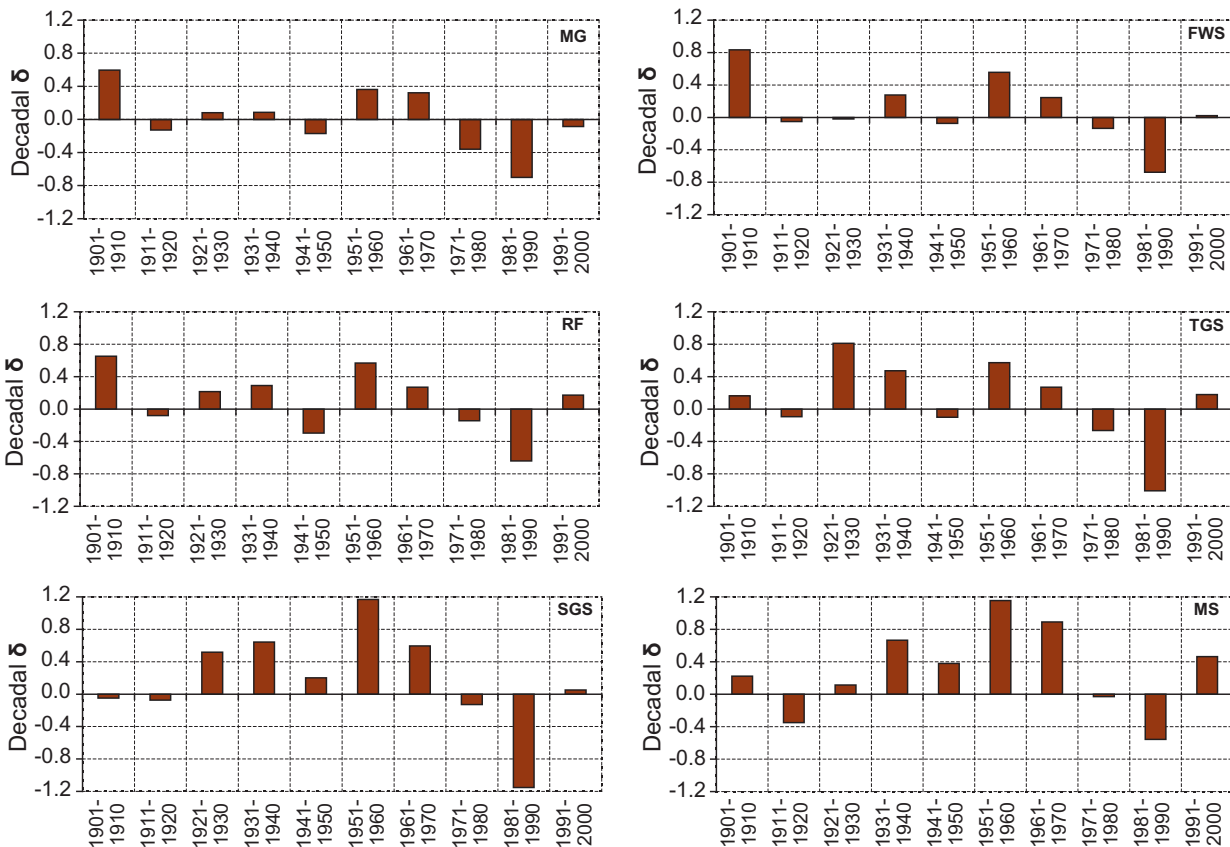


Fig. 5. Decadal rainfall variability index for different zones of Nigeria. Mangrove (MG), Fresh Water Swamp (FWS), Rain Forest (RF), Tall Grass Savanna (TGS), Short Grass Savanna (SGS) and Marginal Savanna (MS).

can generally be classified into four distinct rainfall cycles with periods 2–3, 5–7, 10–15 and 30 yr.

5. Discussions and conclusion

In the present study, a complete picture of historical 20th century spatio-temporal rainfall analysis over Nigeria is presented.

Compared to the findings of Liu et al. (2008) in the Yellow river Basin of China, the relationship between rainfall amount and latitude yielded a negative linear correlation suggesting that the precipitation possesses the latitudinal zonality, which implies that rainfall decreases with increasing latitude away from the Atlantic ocean and in line with reducing vegetal cover. Average *P* was found to decrease significantly when sub-series before 1970 was compared to

Table 2
Mann–Kendall and Sen's tests statistics for annual rainfall over different zones of Nigeria.

Agro-ecological zone	First year	Last year	No of years	Test Z	Slope (mm yr ⁻²)	Sig.
Mangrove	1901	1969	69	-0.17	-0.20	
	1970	2000	31	0.61	2.35	
	1901	2000	100	-2.11	-1.43	*
Fresh Water Swamp	1901	1969	69	-0.20	-0.25	
	1970	2000	31	0.02	0.05	
	1901	2000	100	-1.89	-1.56	+
Rain Forest	1901	1969	69	0.03	0.09	
	1970	2000	31	0.65	2.24	
	1901	2000	100	-1.55	-0.96	
Tall Grass Savanna	1901	1969	69	0.56	0.41	
	1970	2000	31	1.58	2.90	
	1901	2000	100	-2.04	-0.91	*
Short Grass Savanna	1901	1969	69	2.52	1.59	*
	1970	2000	31	0.71	1.65	
	1901	2000	100	-1.39	-0.63	
Marginal Savanna	1901	1969	69	2.92	1.57	**
	1970	2000	31	1.29	2.46	
	1901	2000	100	0.14	0.04	
All zones	1901	1969	69	1.09	0.69	
	1970	2000	31	1.34	2.57	
	1901	2000	100	-2.15	-0.82	*

* Trend is significant at $\alpha = 0.05$.
 ** Trend is significant at $\alpha = 0.01$.
 + Trend is significant at $\alpha = 0.1$.

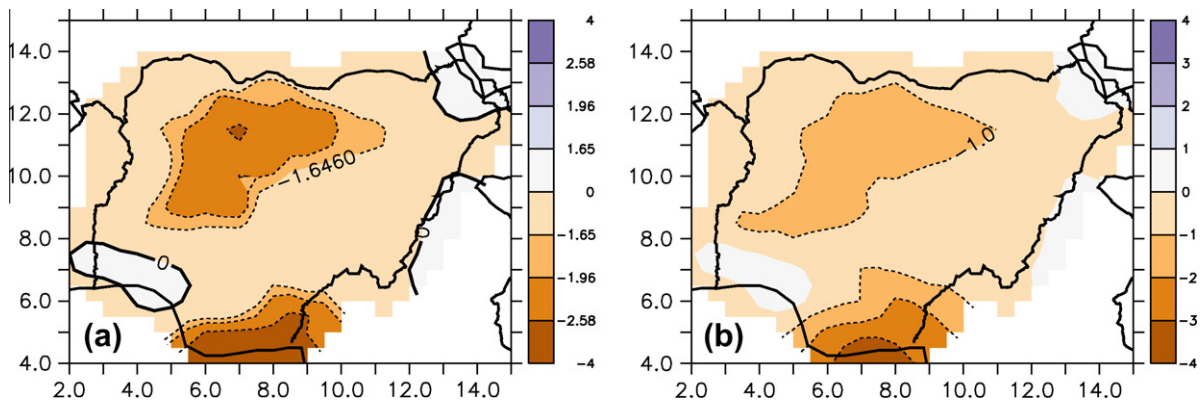


Fig. 6. Spatial distribution of (a) Z-statistics and (b) trends (mm yr⁻²) over Nigeria.

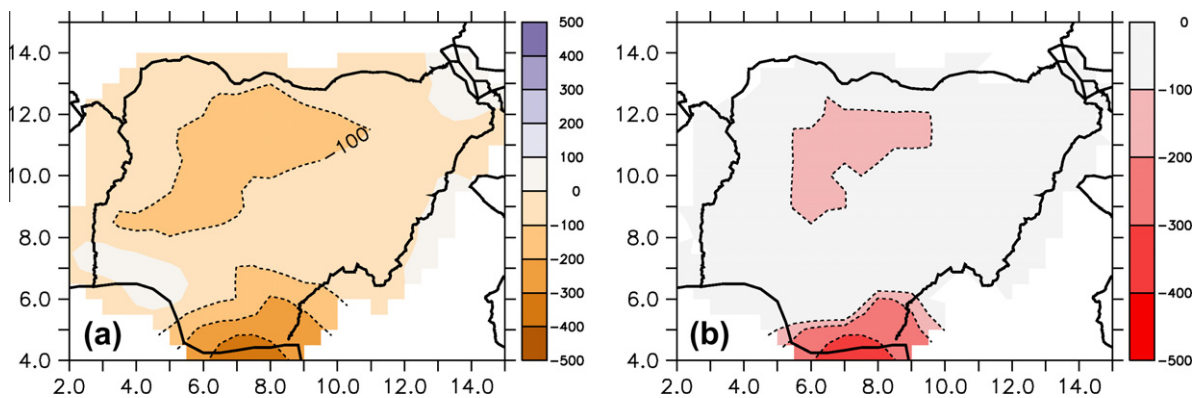


Fig. 7. Total change (mm yr⁻¹) in rainfall (a) and changes at 5% level of significance (b) in the last century (1901–2000).

the ones since 1970 (not shown). This is similar to estimated reduction of P in the Volta basin over a comparable period (Oguntunde et al., 2006). Expectedly spatial variability of P in Nigeria was

higher than the temporal variations. However, the observed annual δ was not significantly different from the pattern for the Sahelian belt of West Africa (Ojo, 1987; L'Hôte et al., 2002). Decadal average

Table 3
A comparison of trend results from Mann–Kendall (original and pre-whitened data) and least square regression for annual rainfall over different zones of Nigeria.

Agro-ecological zone	M–K		M–K (pre-whitened data)			LSR		Change point year
	Test Z	Slope (mm yr ⁻²)	r ₁	Test Z	Slope (mm yr ⁻²)	Test T	Slope (mm yr ⁻²)	
Mangrove	-2.11	-1.43*	0.001	-1.86	-1.21*	-1.94	-1.25*	1969
Fresh Water Swamp	-1.89	-1.56*	0.028	-1.72	-1.48*	-2.00	-1.46*	1971
Rain Forest	-1.55	-0.96	0.059	-1.37	-0.88	-1.50	-0.95	1971
Tall Grass Savanna	-2.04	-0.91*	0.068	-1.98	-0.88*	-1.96	-0.81*	1969
Short Grass Savanna	-1.39	-0.63	0.153*	-1.55	-0.67	-1.43	-0.57	1970
Marginal Savanna	0.14	0.04	0.142*	-0.22	-0.07	0.34	0.12	1970
All zones	-2.15	-0.82*	0.100	-2.19	-0.87*	-2.02	-0.75*	1969

M–K is Mann–Kendall, r₁ is lag-1 correlation coefficient, and LSR is least square regression.

* Trend is significant at α = 0.05.

† Trend is significant at α = 0.1.

Table 4
Observed annual rainfall trend statistics for the WMO 'standard' periods with the estimated relative change.

Agro-ecological zone	Annual rainfall over Nigeria (1931–1960)				Annual rainfall over Nigeria (1961–1990)				Relative change (%)
	Mean (mm yr ⁻¹)	CV (%)	Test Z	Slope (mm yr ⁻²)	Mean (mm yr ⁻¹)	CV (%)	Test Z	Slope (mm yr ⁻²)	
Mangrove	2041.9	9.0	0.4	2.3	1978.1	8.0	-1.9	-6.9*	-3.1
Fresh Water Swamp	2275.0	9.4	0.5	3.0	2180.7	8.6	-1.9	-7.1*	-4.1*
Rain Forest	1865.3	10.3	0.7	2.6	1799.5	9.4	-1.6	-6.1	-3.5
Tall Grass Savanna	1269.2	8.1	-0.1	-0.4	1191.1	10.8	-2.4	-7.0*	-6.2*
Short Grass Savanna	783.5	13.5	0.8	2.2	679.1	17.9	-3.8	-8.5***	-13.3**
Marginal Savanna	419.0	21.1	1.0	2.1	357.1	31.7	-2.9	-6.4**	-14.8*
All zones	1215.6	7.4	0.3	0.6	1130.5	10.4	-3.0	-7.1**	-7.0**

*** Trend is significant at α = 0.001.

** Trend is significant at α = 0.01.

* Trend is significant at α = 0.05.

† Trend is significant at α = 0.1.

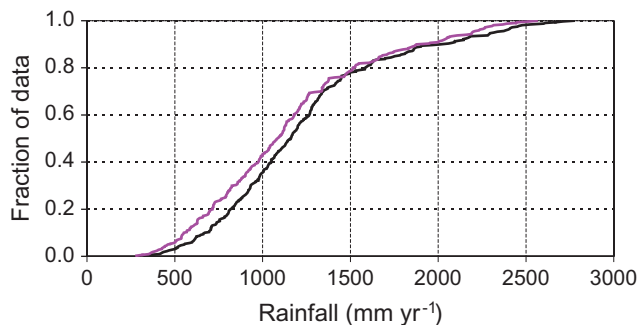


Fig. 8. Cumulative probability distribution curve for spatial rainfall averaged over Nigeria for 1931–1960 (bold face) and 1961–1990.

δ (Fig. 4b) showed the driest decade was the 1980s while the wettest decade was the 1950s but there are slight differences in the distribution of decadal δ especially at zonal levels regarding the wettest and driest decades.

During the period 1921–2000, a countrywide occurrence of droughts from 1930s to 1950 and from 1970 to the mid 1990s have been reported with drought event persisted more in northern Nigeria than the south in the last three decades of the century (Olaniran, 2002). The differential pattern of occurrence of dry and wet episodes between southern and northern Nigeria was further consolidated by rainfall variability in the country on the decadal analysis. Over northern Nigeria, rainfall was observed to decrease in an irregular pattern which intensified over time from 1921 to 2000 (Olaniran, 2002). The 1961–1970 and 1951–1960 decades were thereafter ranked as the wettest in southern and northern Nigeria during the 20th century, respectively. Our result agrees with the timing of wettest decade in the north while we observed 1901–1910 for the south of Nigeria. Unfortunately period

of analysis presented by Olaniran (2002) exclude the 1901–1920 making comparison impossible.

Negative trends were found, in about 22% of the land area, located in the Sahelian region and below 6°N in the Niger Delta region (are significant at 5%). Spatial rate of change in the northern portion is about 2 mm yr⁻² whereas it may be up to 4 mm yr⁻² in the Niger Delta. Positive insignificant values were observed in small pockets in southwest and Lake Chad. Rainfall temporal series was increasing at the rate of 0.6 mm yr⁻² from 1931 to 1960, but rapidly decreasing at 3.0 mm yr⁻² for the 1961–1990 period. Average P of 1200 mm yr⁻¹ was observed in the first period compared to 1100 mm yr⁻¹ in the second, leading to a decrease of 7% between the two periods (Table 4). A general shift in 1961–1990 cdf indicating reduction in rainfall amount is noted throughout the landscape. For the 1931–1960 period, only 0.9% of the land area showed increase in rainfall at 5% level. However, for the 1961–1990 period, 99.7% of landscape with 57.2% showed significant reduction in rainfall trends at 5% level. Hess et al. (1995), analysed four station between 11.42°N and 13.13°N in Nigeria and Niger republic, found average relative change in rainfall of -18.7% as compared to about -14.8% in this study for the same area but with larger extent.

Similar to our findings, others have reported shifts in rainfall belts in Nigeria. Comparing rainfall distribution over the country for the period 1941–1970 with that of 1971–2000, Olaniran (2002) reported a significant change in rainfall pattern during the recent three decades. This is similar to our observation when comparing 1931–1960 with 1961–1990. Rainfall distribution including trends was more latitudinal during the 1961–1990 (r² = 0.92) than the earlier period. The spatial distribution of annual rainfall ranged from 330 to 2770 mm yr⁻¹ during 1931–1960 and from 280 to 2560 mm yr⁻¹ during the later period translating to a reduction of 50 mm yr⁻¹ in the north (Marginal Savanna) and 200 mm yr⁻¹ in the south. The shift in rainfall belts and the corresponding

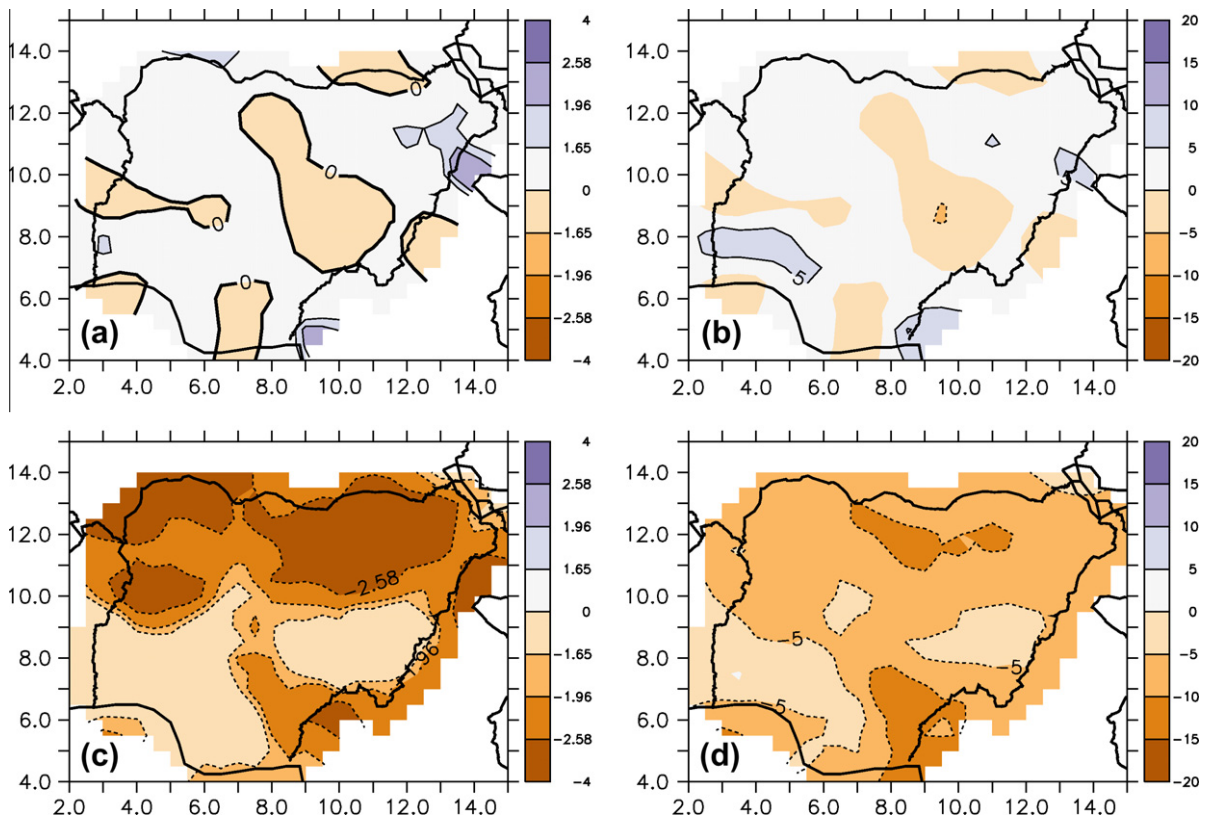


Fig. 9. Annual rainfall Z-statistics and trends (mm yr⁻²) for the periods 1931–1960 (a and b) and 1961–1990 (c and d), respectively.

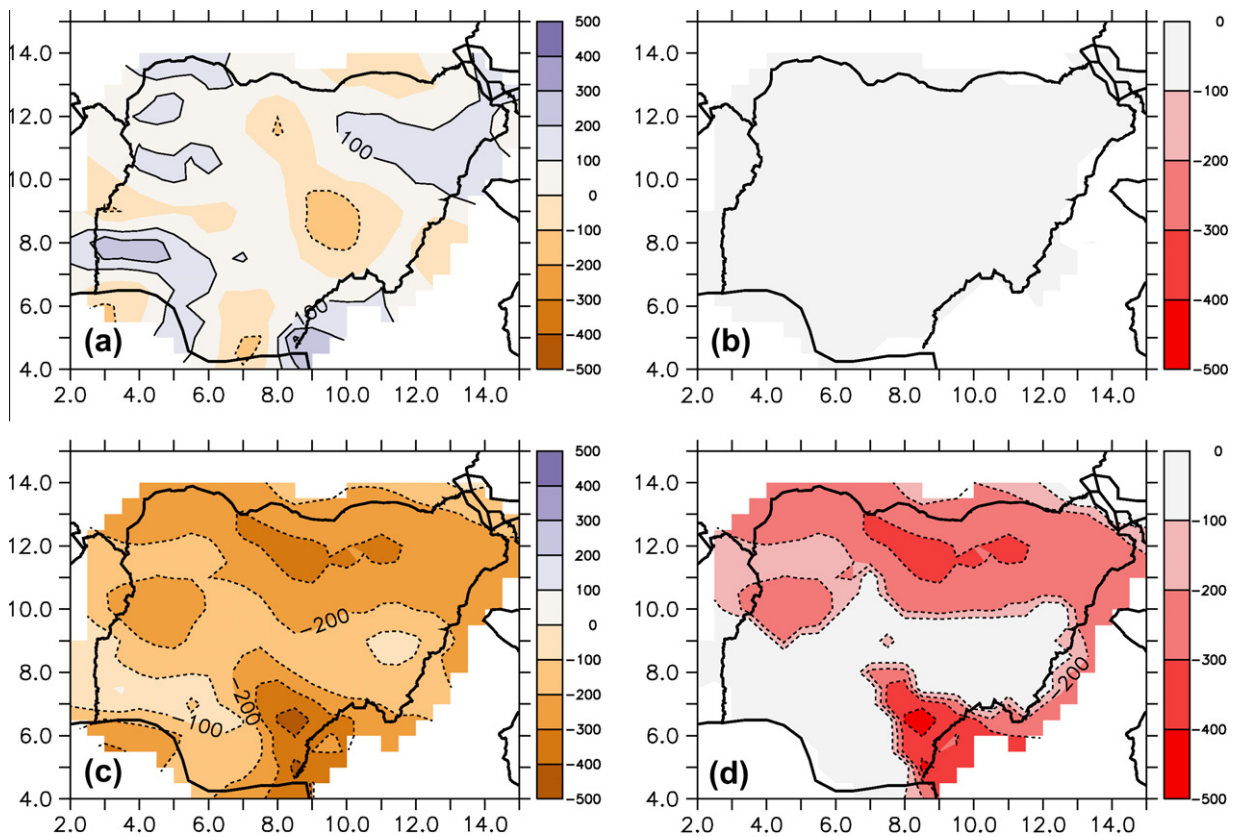


Fig. 10. Change in rainfall (mm yr⁻¹) and significant change at 5% levels for the periods 1931–1960 (a and b) and 1961–1990 (c and d), respectively.

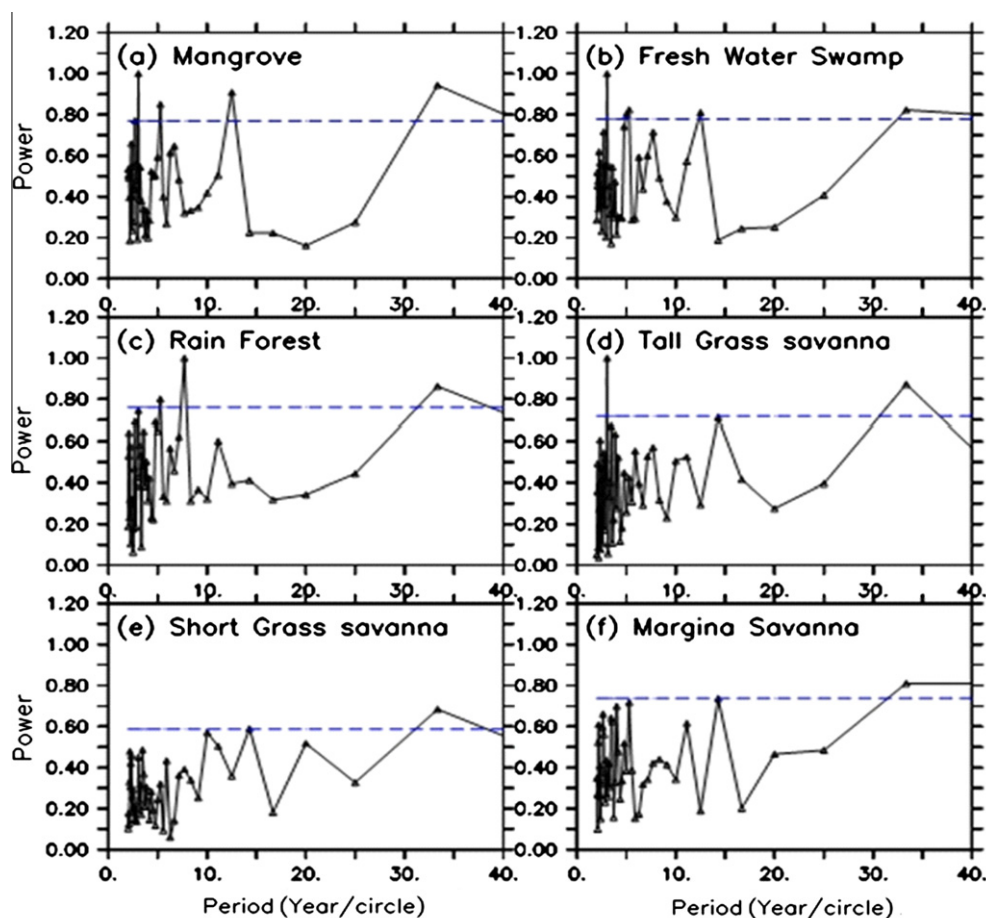


Fig. 11. Periodogram of rainfall series over six ecological zones. (a) Mangrove, (b) Fresh Water Swamp, (c) Rain Forest, (d) Tall Grass Savanna, (e) Short Grass Savanna and (f) Marginal Savanna.

decline in rainfall amount resulted in the southward expansion of the Sahel and declining levels of water in hydro-power generating dams (Kainji, Shiroro and Jebba) which are all located in the middle belt of Nigeria as often widely reported in recent decades (Olaniran, 2002).

Bello (1998) compared the seasonality of rainfall distribution in Nigeria in two periods, 1930–1961 and 1962–1993 which are similar to the WMO reference periods examined here. He found a general reduction in dry season rainfall during 1962–1993 compared to 1930–1961 in agreement with the earlier findings of Adefolalu (1986). According to Adefolalu (1986), locations north of 8°N in the country received over 90% of the total annual rainfall in April–October while for southern stations the proportion of wet season rainfall was 84–88% of the annual total.

Monthly rainfall between 1901 and 2000 showed negative trends for most of the months (10 out of 12 for Nigeria) and zones. The highest significant ($P < 0.001$) decrease in rainfall was observed in the month of June at the rate of 0.54 mm yr^{-1} in the Mangrove zone. Generally, most of the changes are occurring in the months of April, June, August and September. In a related study, a consistent reduction in rainfall of 8 mm yr^{-2} have been linked to reductions in August and September rainfall in the north-east arid zone of Nigeria between 1961 and 1990 (Hess et al., 1995). Devastating flooding events in southern Nigeria has been linked with the progressive increase in August rainfall over the region in the last five decades of the century (Adefolalu, 2007). Others have examined changes in some rainfall characteristics over Nigeria (Olaniran, 1990, 1991; Olaniran and Summer, 1990). They found dominant trend of progressive early retreat of rainfall over

Nigeria and link this with a significant decline of rainfall frequency in September and October. Since 1968, the start of the rains has been getting progressively delayed over southern Nigeria, in agreement with a significant decline in April rainfall (Olaniran, 2002) thereby making southern Nigeria increasingly vulnerable to crop failure.

Spatially, P varied more than four times ($CV = 42.5\%$) as its temporal variation ($CV = 9.4\%$) for 1901–2000 series and this is common to sub-series 1931–1960 and 1961–1990. Hence, the spatial variability seems to be more important in understanding the hydrological processes of this landscape. There may also be the need for detailed analysis of spatial variability in relation to recently available historical land cover (cropland) data in the West Africa. In his review of studies on desertification, Adefolalu (1990) noted that reduced rainfall acts to modulate the initiating factor of desertification. He further reported that Sahelian vegetation of shrub and dry grassland, which was non-existent in Niger State between latitude 9° and 11°N in 1977 occupied between 15% and 20% of that landscape in 1987. The situation in other states in the north of this location could be worse.

The short-wave rainfall cycle with period of 2–3 yr is observed over most of the zones, except over SGS and MS zones. This cycle may be associated with the stratospheric Quasi-Biennial Oscillation (QBO), which is a biennial oscillation of the temperature and zonal wind in the tropical stratosphere (Reed et al., 1961). QBO remains one of the most important components of short-term climate fluctuations, and it is detectable in the surface meteorological elements where their characteristics are reflected in local, regional or global climatic time series, for example in rainfall (Brazdil, 1992;

Mason and Tyson, 1992; Mason and Lindsay, 1993). Lamb (1972) also noted that QBO is related to the southern oscillation, which is the strength of subtropical high belt in both northern and southern hemispheres. The rainfall oscillation with periods of 5–7 yr has a dominant peak in MG, FWS, and RF. This oscillation indicates the influence of tropical sea-surface temperatures, including El Niño–Southern Oscillation events. Studies have shown that 4–6 yr cycles are associated with the El Niño Southern Oscillation (ENSO). The ocean (El Niño) may also cause oscillations of between 3 and 8 yr (WMO, 1985).

The medium-wave rainfall cycles with period 10–15 yr, which have dominant peaks over all the zones (except over RF), may be linked to solar variability. Some studies over Nigeria did not find rainfall cycles with period 10–15 yr in their analysis, possibly because most of the station data used fall within RF zone. The variability of the sun's luminosity has effects on the world climate, including precipitation. This variability is partly measured by the sunspot numbers (Seleshi et al., 1994). Sunspot numbers vary in both long term and short term, the average sunspot cycle lasts 11.1 yr.

The most interesting cycle is the long-wave oscillation with period of about 30 yr. It produces abnormally high and low value in the rainfall series over all the zones, but it is most active over the SGS and MS, where the influence of short-wave cycles is not significant (Fig. 11). Chang-Seng (2007) obtained a similar cycle over Seychelles, and suggested that the 30-yr natural cycle is “tele-connected” to the Atlantic Multi-Decadal Oscillation (AMO) sea surface temperature. Zhang and Delworth (2006) linked the multi-decadal Sahelian rainfall with AMO. The physical mechanism may be related through the processes of the deep ocean thermohaline circulation which distributes heat globally (Zhang and Delworth, 2006; Chang-Seng, 2007).

The comparative analyses of M–K (original and pre-whitened data) and least square regression produced similar results both in magnitude and direction. This may partly due to low and insignificant r_1 in most of the zones and the whole data series of Nigeria. Thus any of the methods is expected to yield satisfactory result in the study area. Finally, the analysis of variability and trends of rainfall series presented here and in previous studies showed that Nigeria landscape was generally drying since the 1970s with the driest decades between 1970 and 1990 of the 20th century. While the south was subjected to widespread flooding and erosion mainly due to increasing rainfall in August and September of the last three decades of the 20th century, reduced rainfall, aggravated by human pressure on fragile ecosystems over northern Nigeria, led to increasing desert encroachment. Long-term rainfall variability in Nigeria has been linked to a combination of factors such as the ITD mechanism, the tropical easterly jet (TEJ), sea surface temperature anomaly (SSTA), biogeophysical feedback mechanism, and the El Niño Southern Oscillation (ENSO) thus making both tropical and extra tropical factors the overall cause of rainfall anomalies in Nigeria (Bello, 1998; Olaniran, 2002; Alli, 2010).

Acknowledgements

The first author was supported by the Alexander von Humboldt Foundation, Bonn, Germany. The second author was partly supported by National Research Foundation, South Africa. Computing facility was provided by the Centre for High Performance Computing (CHPC, South Africa). Comments from the three anonymous reviewers and the Editors are greatly appreciated.

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