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Characterization of monsoonal rainfall in the Sudano-Sahelian Zone of Northwestern Nigeria

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Abstract: Wavelet transform has been underutilized in characterization of rainfall (Real Onset Dates and Real Cessation Dates) in the study area. This study aims at the characterization of monsoonal rainfall. Daily rainfall data of four stations for the period 1981-2018 were collected from Nigerian Meteorological Agency. The Intra-seasonal Rainfall Monitoring Index (IRMI) was generated and used in determining the RODs and RCDs. The Mann–Kendall test was used to detect trends of the rainfall characteristics. Wavelet transform was used in modelling RODs and RCDs. Findings revealed that RODs vary between stations. There is low (0.3 Spearman's Rank r) correlation between latitudes and Early Cessations (ECs) of rains. The Morlet wavelet analysis revealed that from 1999 to 2018, there were more of EOs and NOs especially in Kano station. We conclude that from 1981 to 2018 there has been a minimal increase in the retreat dates of rainfall in the study area.

Keywords: Cessation, onset, rainfall, Northwestern-Nigeria, Wavelet-transform

INTRODUCTION

The rainy season in the Sudano-Sahelian agro-ecological zone of Northwestern Nigeria, like in other drylands of West Africa, is short and it lasts for only about four to five months in a year (Nouaceur & Murarescu, 2020). Commencements, endings, distributions and amounts of rainfall in the study area have been highly variable in both space and time (Umar & Adamu, 2019). Alternating of a moisture-laden wind from Atlantic Ocean with a dry wind originating from the Sahara Desert derives a cyclic movement of rain-bearing characterized the monsoonal nature of rainfall in the study area (Umar & Adamu, 2019; Ati et al., 2002; Umar et al., 2017). Rainfall characteristics such as Real Onset Dates (RODs), Real Cessation Dates (RCDs), Length of the Growing Season (LGS), and Cumulative Rainfall (CR) are critical factors for sustaining crop productivity in rainfed agriculture especially in this drylands region. Variability in rainfall characteristics poses high risks to sustainable peasant farming. Normal rainfall conditions highly correlate with bumper crop harvest and high yields. Conversely, prolonged dry periods or late onset of a rainy season can lead to crop failures and endanger food security (Odekunle, 2004; Omotosho, 1992).

Determining the RODs of rainfall is crucial to rain-fed farming in the study area because this characteristic is highly related to agronomic activities such as land preparation and crop planting (Oguntunde et al., 2014). It is increasingly acknowledged that very early and delayed planting may damage the cultivated plants and affect farmers' financial welfare. Farmers who are guided by the false onset of rainfall may engage in early planting, and this can lead to the wilting and failure of their crops. False starts of rain, apart from the shortening of LGS, also add to the hardship experienced by farmers who have to replant after the destruction of their initial cultivation (Umar

& Adamu, 2019). Also, farmers who delay in planting may encounter a reduction in the LGS of cultivated crops which affects yields especially for the late-maturing crop varieties. Farmers in the study area are threatened by endemic risks of varying severity that emanate from the uncertainties inherent in the rainfall characteristics of the Sahel zone of West Africa.

Researchers such as Sivakumar (1988) and Stewart (1991) established a significant positive association between the start of rains and the LGS. Thus, earlier onset (EO) most often leads to longer LGS and late onset (LO) is correlated with shorter LGS. There is an understanding that the LGS depends more on rainfall onset than its cessation (Walter, 1967). Crop moisture demand and LGS are the main determinants for crop planting suitability anywhere in the world, and these are also dependent upon RODs and RCDs. Rural households in the dryland of Northwestern Nigeria had been exposed to variety of climate risks such as harvest failure and the death of livestock as a result of droughts resulting from extreme rainfall variability (Umar & Adamu, 2019). Thus, determining monsoonal rainfall characteristics is essential in managing these risks and adapting to climate variability and change. The variability and unreliability of LGS in the study area exacerbate significant risk to agricultural productivity (Stern et al., 1981; Benoit, 1977; Haruna & Murtala, 2019).

Water balance models have been extensively built and employed in determining RODs and RCDs by scholars (Kowal & Knabe, 1972; Walter, 1967; Fasheun, 1983; Samba, 1998; Omotosho et al., 2000; Ati et al., 2002; AGRHYMET, 2005; Usman & Abdulkadir, 2012). We can deduct from these works that, for sure, RODs and RCDs differ from place to place and they can be measured using varieties of quantitative analytical frameworks ranging from simple to complex mathematical equations. Some of the reasons behind the disparity in these frameworks include that scholars differed in the agro-climatological settings in which their models were developed (predominantly tropical Savannas and forests of Australia, Kenya, Burkina Faso, Sothern and Northern Nigeria, etc.). Even models that focus on a single setting may yield different results in calculating RODs and RCDs because scholars differ in the variables they look into while constructing their models. The variables employed in the models' construction include the amount of rainfalls (cumulative rainfall) period for distribution of the amount of rainfall, local crop water requirement, duration of dry spell, crop planting time, etc.

One of these model builders (Usman & Abdulkadir, 2012) proposed the Intra-seasonal Rainfall Monitoring Index (IRMI) model that determines RODs and RCDs of rainfall tried as much as possible to key into real (actual) onset and avoid false start of rain. Correct beginning and ending dates of rains are needed to determine a less risky planting date or planting method, or sowing of less risky types/ varieties of crops in a responsive farming. In this regard, using daily rainfall data that has been reduced or summarized into pentads rainfall amounts, we determined real or actual onset dates using this index equation's that computes RODs, RCDs and CR commencing from the first (1^{st}) of May. The IRMI was adopted because apart from being among the latest, when compared with other models, it is also simple to use and has been specifically developed to be applied in the study area and similar agro-ecological zones.

There is however, the need to go beyond analysing rainfall dates durations/ amounts using the IRMI and incorporate other analytical techniques that explore time series data with the view of revealing rainfall characterization and if a patterned increase or decrease of average values throughout the record (or trend) can be detected and suggest presence or absence of an underlying repeating periodic/seasonal patterns (periodicity) in the data. A state-of-the-art technique in characterization of rainfall behaviour that has been understudied in the study area is wavelet transform (WT). The WT analysis provides a means to assess the most significant frequencies within the time series, in temporal, spatial, and frequency domains including data reduction and signal filtering (Torrence & Compo, 1998; Tiscareno & Hedman, 2018). Its application in various fields has increased rapidly as an alternative to the Fourier Transform (FT) in preserving local, non-periodic, multi-scaled phenomena. (Nouaceur & Muraresc u, 2020). Through the use of WT, it is now possible to get information on amplitude of periodic signals within the time series, and how it varies with time (Ideiao & Santos, 2005).

A wavelet is a short wave-like oscillation with amplitude that begins at zero, increases, and decreases back to zero. Its oscillation function contains both the analysis function and the window. The temporal aspect data/ information is obtained by changing the wavelet over the signal (Merry, 2005). While WTs are mathematical functions that cut up data into different frequency components and then study each segment with a resolution matched to its scale. For the resolution of wavelet analysis, it is considered that low frequencies dominate the entire duration of the signal, whereas high frequencies appear only rarely (from time to time as short interval burst (Nikhila et al., 2014). The Morlet wavelet analysis calculates the correlation between the signal under consideration and a wavelet function $\psi(t)$. Therefore, this study aims at the characterization of monsoonal rainfall in the Sudano-Sahelian Zone of Northwestern Nigeria. The objectives of the research are to determine and examine the RODs and RCDs of rainfall, to establish trends, periodicity and stationary (if any) and explain the overall behaviour RODs and RCDs of rainfall in the study area under the time of review.

METHOD

Study Area

The study area is located between latitudes 12° 00^{i} N to 13° 45^{i} N and Longitudes 3° 30^{i} E to 11° 35^{i} E (Figure 1) (Umar et al., 2017; Danjuma et al., 2020). The climate of the area is tropical wet and dry type coded A_W by W. Koppen. The vegetation comprises of tropical grasslands of Sudan and Sahel Savanna. Agriculture or precisely crop cultivation is the principal economic activity engaged in the study area and it is primarily rain fed. Multitude of food and to lesser extent cash crops such as: millet, sorghum, rice, cowpea, soy beans, wheat, groundnut, maize, cotton, sesame and vegetables are produced by farmers in the area (Umar, 2016; Umar & Adamu, 2018). In terms of agricultural land use, the study area comprises two wide belts of dominant staple cereals, millet and sorghum grown in varying proportions.

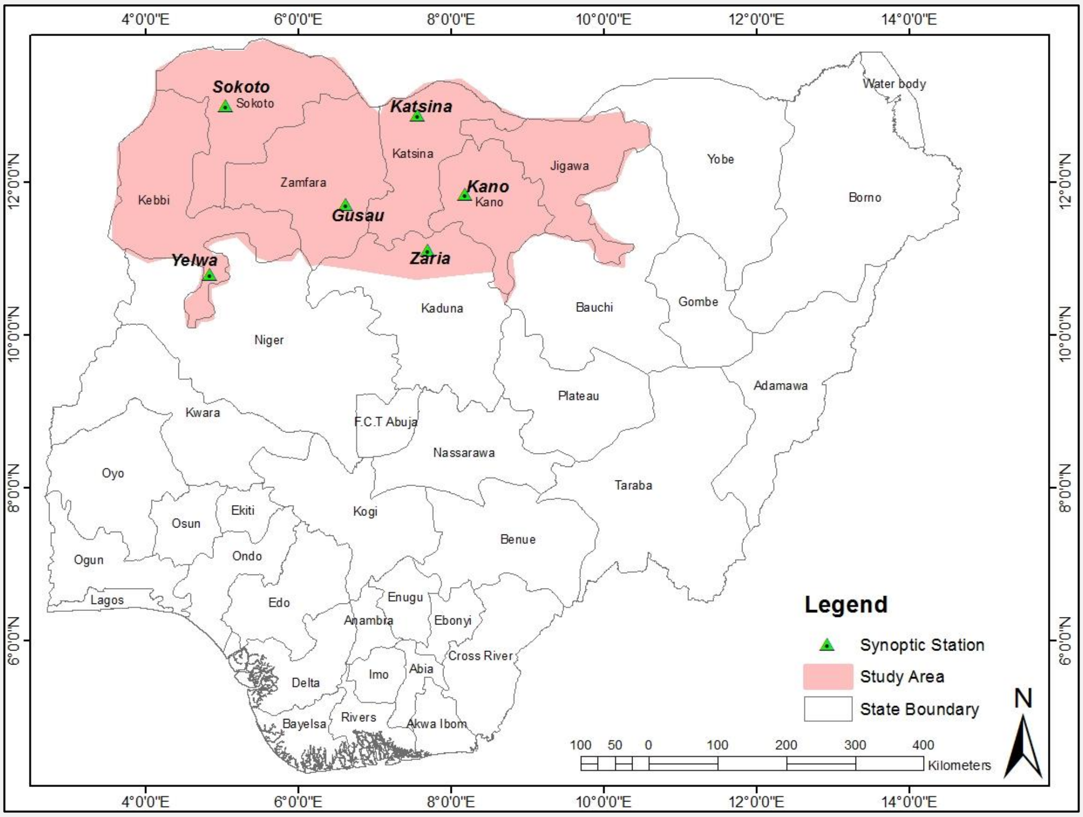

Figure 1. Map of Study Area

Sampling, data and analyses

A purposive sampling procedure was adopted in selecting of four synoptic meteorological stations out of the six of them in Northwestern Nigeria, namely: Gusau, Kano, Katsina, Sokoto, Yelwa and Zaria (Figure 1). The selection was made while giving consideration to stations with longer, consistent, and most reliable daily rainfall records. Historical daily rainfall data of four stations (Gusau, Kano, Katsina and Sokoto) from 1981-2018 were collected from Nigerian Meteorological Agency (NiMet) Head Office, Abuja. The data was analyzed, and IRMI was generated. The analysis was used in determining RODs and RCDs of rainfall in the study area. The first stage of the data analysis involved the computation of pentad rainfall summations which formed the units of analysis of the study. This has been done with the aid of a rainfall pentad calendar. Then IRMI was employed and it generated an index that determines the actual onset and cessation dates on a pentad-by-pentad basis beginning from the 1st May using the equation 1:

$$IRMI = \frac{(Cpt)^2}{(hpt \times Nb \times 100} \quad (1)$$

Where *Cpt* is Cumulative pentad rainfall since May 1; *hpt* is the highest pentad total rainfall since May 1; *Nb* is the number of breaks in rainfall (pentads with less than 5mm of rainfall); and 100 is a factor.

The 'real' start of rains is taken as the pentad within which its index begins to register values ≥ 1 for the first time. The actual or real ending date is calculated when the cumulative pentad rainfall remains the same for two or more consecutive time.

In detection of the trend of RODs and RCDs time series, we employed a non-parametric Mann-Kendall test. This test is widely used because of the advantage that it does not require data to conform to any distribution before it can be used. The equations for the computation of the Mann-Kendall Statistics S, (S) and normalized test statistic Z are as follows:

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^{n-1} \mathrm{sgn}(\mathrm{x_j} - \mathrm{x_k}) \quad (2)$$

$\mathrm{x_j}$ is a time series ranked from i = 1,2,………n-1 and $\mathrm{x_j}$, ranked from $j = i$ +1,2,……….n.

Where:

$$sgn(x_{j\_}x_k) = \begin{cases} +1\ if(x_{j\_}x_k) > 0 \\ 0\ if(x_{j\_}x_k) = 0 \\ -1\ if(x_{j\_}x_k) < 0 \end{cases} \quad (3)$$

The equation for calculation of the variance of S. VAR(S) is:

$$VAR(S) = \frac{n(n-1)(2n-5) - \sum_{i=1}^{m} t_i(t_i - 1)\,(2t_i + 5)}{18} \quad (4)$$

Where n is number of data points; t_i are the ties of the sample time series; and m is number of tied value (a tied group is a set of sample data having same value).

Equation 2 and 3 were then used to compute the test statistics Z. The computation for normalized test statistics Z is given as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} if S > 0 \\ 0 \qquad if S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} if S < 0 \end{cases} \quad (5)$$

A positive Z value indicates an upward trend; a negative value indicates a downward trend, and a zero value indicates no trend. Alternatively, the trend can be determined using computation software applications, such as R-package, SPSS, and PAST3 statistical package. RODs and RCDs were analysed in PAST3 statistical package where an index was generated through transformation (that is by getting the deviation of all the observations from the RODs and RCDs means). The result was interpreted as Table 1.

Table 1. Types of Onset/Cessation

Index	Types of Onset / Cessation
< -1.49	Early Onset/Cessation
-1.49 to 1.49	Normal Onset/Cessation
> 1.49	Late Onset/Cessation

The rest of the computations and modelling transformation analyses such as normality test, autocorrelation, wavelet transformation and etc. were done in the PAST3 statistical package environment.

RESULT AND DISCUSSION

Normality test for RODs and RCDs

Normality test conducted on the distribution of RODs and RCDs (Table 2) reveals that these characteristics are generally not normally distributed because the values of Shapiro-Wilk (W) in the four stations are less than 1. The alphabet N stands for total observations which are 38 in all the stations.

Table 2. Normality test for stations data

Normality Test	Gusau	Kano	Katsina	Sokoto
(RODs) N	38	38	38	38
*Shapiro-Wilk **(W)**	0.9478	0.9217	0.9412	0.9857
p(normal)	0.07542	0.01106	0.06643	0.8994
(RCDs) N	38	38	38	38
*Shapiro-Wilk **(W)**	0.9481	0.9522	0.9412	0.9481
p(normal)	0.07715	0.105	0.06643	0.0772

Variability of RODs

The RODs of rainfall in the study area vary from one station to another. There is this disparity even between stations on the same latitude and within a station from one time to another (see Figure 2). In terms of the association between stations' location with the commencement of rainfall, result reveals that there is a very low (0.07 Spearman's Rank r) correlation between latitudes and EOs. Hence EOs of rain are characteristic features of Kano and Katsina stations where their frequencies of occurrences are both 10 (26.3%) respectively (Table 3).These two stations are on different latitudinal locations. But with regards to longitudinal positions, the two stations are on the more eastward longitudinal parts that is 7.62° East and 8.31° East. Here there is a strong positive (0.8 Spearman's Rank r) correlation between meridians and EO of rains in the study area. Late onset (LOs) of rainfall also recognizes the latitudinal differences to the extent that there is a strongly positive (0.7 Spearman's Rank r) correlation between lines of parallels and LO of rains in the study area where Katsina and Sokoto have 29% and 26.3% frequencies of occurrences respectively.

Table 3. Frequencies and percentages of occurances of rainfall onsets

Station	Early onset (EO)	Normal onset (NO)	Late onset (LO)	Total
Gusau	7(18.4)	25 (83.3)	6 (15.7)	38 (100)
Kano	10 (26.3)	22 (57.9)	6 (15.7)	38 (100)
Katsina	10 (26.3)	17 (44.7)	11 (29.0)	38 (100)
Sokoto	7 (18.4)	21 (55.3)	10 (26.3)	38 (100)
Total	34 (22.4)	85 (56.0)	33 (21.4)	152 (100)

To a large extent, this finding tallies with Amekudzi et al. (2015) who studied variabilities in rainfall onset, cessation and length of rainy season for the various agro-ecological zones of Ghana and found that starts of rainfall follows a latitudinal pattern in Ghana from the forest coastland to savanna hinterlands, and that LO is an associated feature of the savannah zone. On average, RODs commence earlier (21st May) in Gusau (which is situated in the southernmost part of the study area) than in other stations, a difference of 10 days compared to 1st, June the date of the other three stations. This finding has corroborated (Odekunle, 2004) who examined rainfall and length of the growing season in Nigeria and found that rain commences in Kano station around early June.

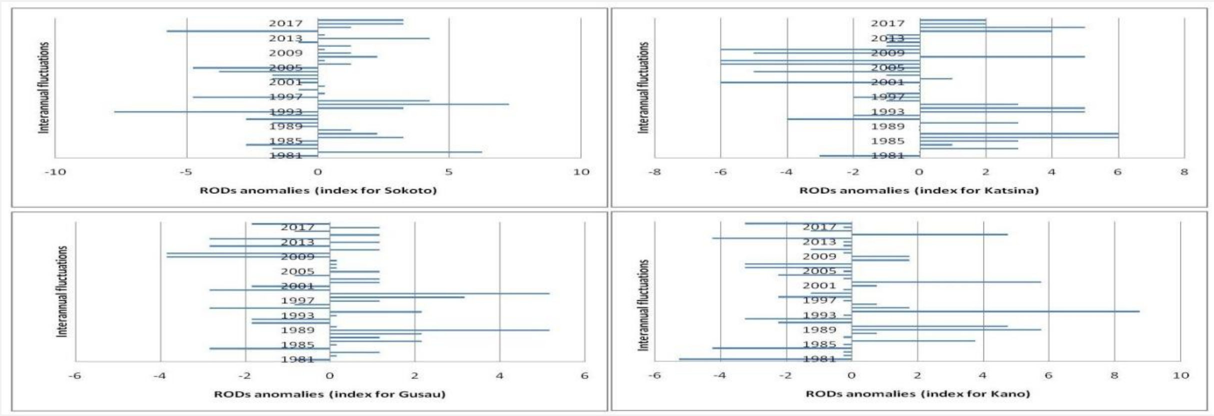

Figure 2. RODs anomalies index in the stations

Variability of RCDs

The RCDs of rainfall contrasted when compared with the RODs in the study area. With regards to the RODs, there is high variability due to occurrences of significant disparity from one station to another (with normal RODs ranging from 83.3% in Gusau, 57.9% in Kano, 55.7% in Sokoto and 44.7% in Katsina) (see Figure 3). There is how ever low variation between stations due to the cessation of rainfall in the study area (with normal RCDs ranging from 79.0% in Katsina, 76.3% in Kano, 60.5% in Sokoto and 57.6% in Gusau). There is low (0.3 Spearman's Rank r) correlation between latitudes and ECs of rains. ECs are, to some extent, characteristic features of Gusau and Sokoto stations where their frequencies and percentages of occurrences are 10 (26.3%) and 9 (23.7),respectively, despite that the two stations are on different latitudes (12° N and 13°N). Katsina and Kano stations that happened to be more eastward longitudes 7.62° to 8.31° East of Greenwich have predominantly NCs with frequencies of occurrences of 79.0% and 76.3% respectively (Table 4).

Table 4. Frequencies and percentages of occurances of rainfall cessations

Station	Early onset (EO)	Normal onset (NO)	Late onset (LO)	Total
Gusau	10 (26.3)	20 (52.6)	8 (21.1)	38 (100)
Kano	6 (15.8)	29 (76.3)	3 (7.9)	38 (100)
Katsina	6 (15.8)	30 (79.0)	2 (5.2)	38 (100)
Sokoto	9 (23.7)	23 (60.5)	6 (15.8)	38 (100)
Total	31 (20.4)	102 (67.1)	19 (12.5)	152 (100)

On average, RCDs of rains are experienced earlier (30st September) in stations such as Katsina, Sokoto and Kano before Gusau with a difference of 10 days (compared to Gusau) where RCDs fall by 10th, October on average. This result has tallied with (Odekunle, 2004) who studied rainfall and length of growing season in Nigeria and found rainfall retreats in Kano station around early second decade of September. As stated earlier, this result did not tally with (Adejuwon, 2006;

Amekudzi et al., 2015) who found specific dates for rainfall cessations across various agro-climatological zones of Ghana.

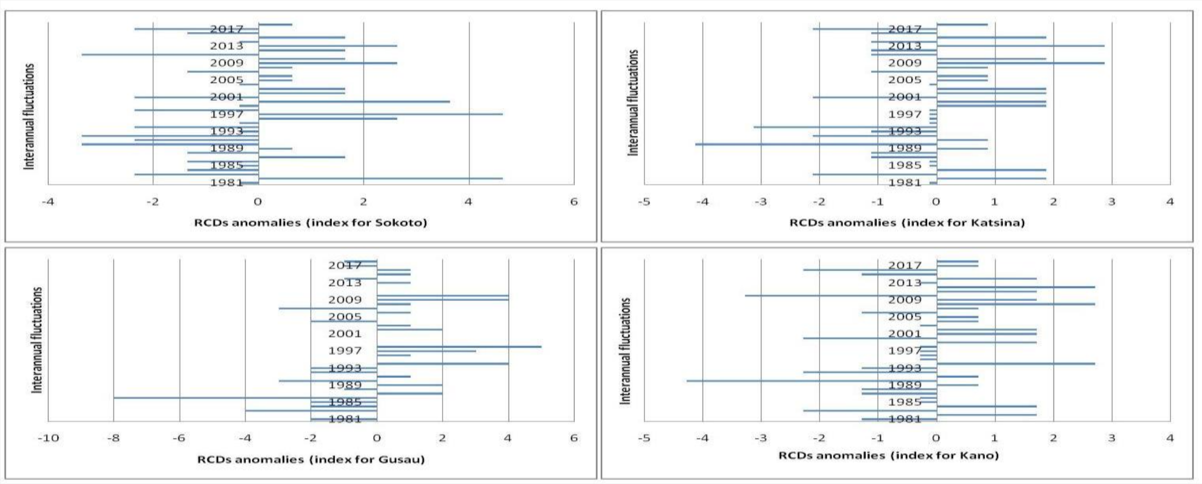

Figure 3. RCDs anomalies index in the stations

Trend, periodicity and stationarity analysis

Trend analysis for the RODs and RCDs time series is relevant in revealing if a change characterized by a smooth, monotonic increase or decrease of average values over the period of record can be detected from the data (Donaire, 2000). Non-normal distribution of the generated RODs and RCDs time series has prompted our use of the Mann-Kendall test to examine the nature of trends in the data because of this test's distribution non-bias. Result shows that at a 95 % confidence level, there is no (statistically significant) trend in RODs and RCDs (Table 5).

Table 5. Mann Kendall test of trend detection for RODs and RCDs

	Gusau	Kano	Katsina	Sokoto
RODs				
S	-80	-48	-94	74
Z	1.01	0.60516	1.1798	0.92442
P (no trend)	0.31249	0.54508	0.23809	0.35527
There is no statistically significant trend				
RCDs				
S	121	102	69	81
Z	1.5301	1.292	0.87115	1.0173
P (no trend)	0.126	0.19637	0.38367	0.30902
There is no statistically significant trend				

The absence of a trend in the dates of commencement and ending of rainfall means inconsequential autocorrelation in the RODs in their annual occurrences. This has been depicted in figures 4, 5 and 6. This situation has been exhibited by random (that is, no trend) data, near zero for all lags (or white noise). Notice how you can see a very slow alternating positive and negative decaying to zero in the lags or an insignificant correlation (less the ±0.5) for all the stations in Figure 4 autocorrelation.

From the preceding, we establish that the RODs are stationary. Stationarity means that the time series does not have a trend, but has a constant variance and no seasonal pattern. The fact that no other lag apart from lag 0 has significant correlation coefficients values suggests absence of underlying repeating periodic/seasonal patterns (periodicity) in the data. The time series in Figure

4 plotted with highest correlation coefficients other than those of lag 0 are that of 0.45 (Katsina at a lag of 1986); 0.4 (Gusau) 0.3 (Kano and Sokoto). The highest correlation coefficient away from 0 lag (coefficient of 1) occurs at a lag of 1986 where the value of r=0.45. This is a typically *white noise* which is an irregular variation that is purely random.

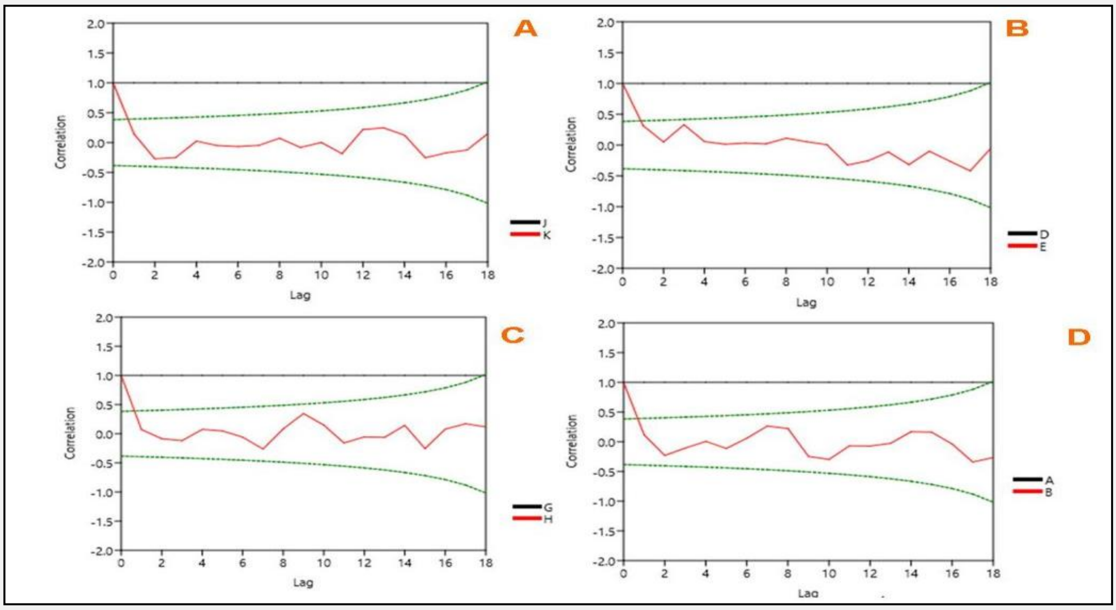

Figure 4. ACF plot for RODs (Sokoto(A); Katsina(B); Gusau(C); Kano(D))

The low variability in the RCDs more that the RODs rules out that RCDs need to undergo autocorrelation computation. They are more typical of white noise than the RODs. It means there is no need to test the autocorrelations of the RCDs as they will show lower significant correlation coefficients in their lags. This type of climatic fluctuation has been characterized as unpredictable and its behaviour cannot be explained or forecasted by models such as Autoregressive Integrated Moving Average (ARIMA).

Morlet wavelet transform

Many systems including rainfall are monitored and evaluated for their characteristics using time signal transformation which is a transformation from the time domain to the frequency domain. The temporal data/ information is captured by changing the wavelet over the signal. For the resolution of Figure 5 and Figure 6 it is thought that low frequencies last for the enduring entire duration of the signal. However, the high frequencies only appear rarely from time to time as short interval burst. This is many a times the case in WTs applications. The Morlet wavelet analysis in Figure 5 calculates the correlation between the signal under consideration and a wavelet function ψ(t).

Figure 5 (A to D) shows the normalized Morlet wavelet power spectrum normalized by |Wn (s)| 2 /σ2. The Y axis (left) is the wavelet scale. The bottom X axis is time (yr). The coloured isolines are at normalized variances of 2, 8, ..., 16. Dark(warm) colours represent high values of the power spectrum and light (cold) colours indicate low values. The thick black contours denote significant areas at the 5% significance level. The dark contour encloses regions of greater than 95% confidence level for a red-noise process with a lag-1 coefficient of 0.72. Cross-hatched regions on either end indicate what has been called the "cone of influence," where edge effects are important (Tiscareno & Hedman, 2018).

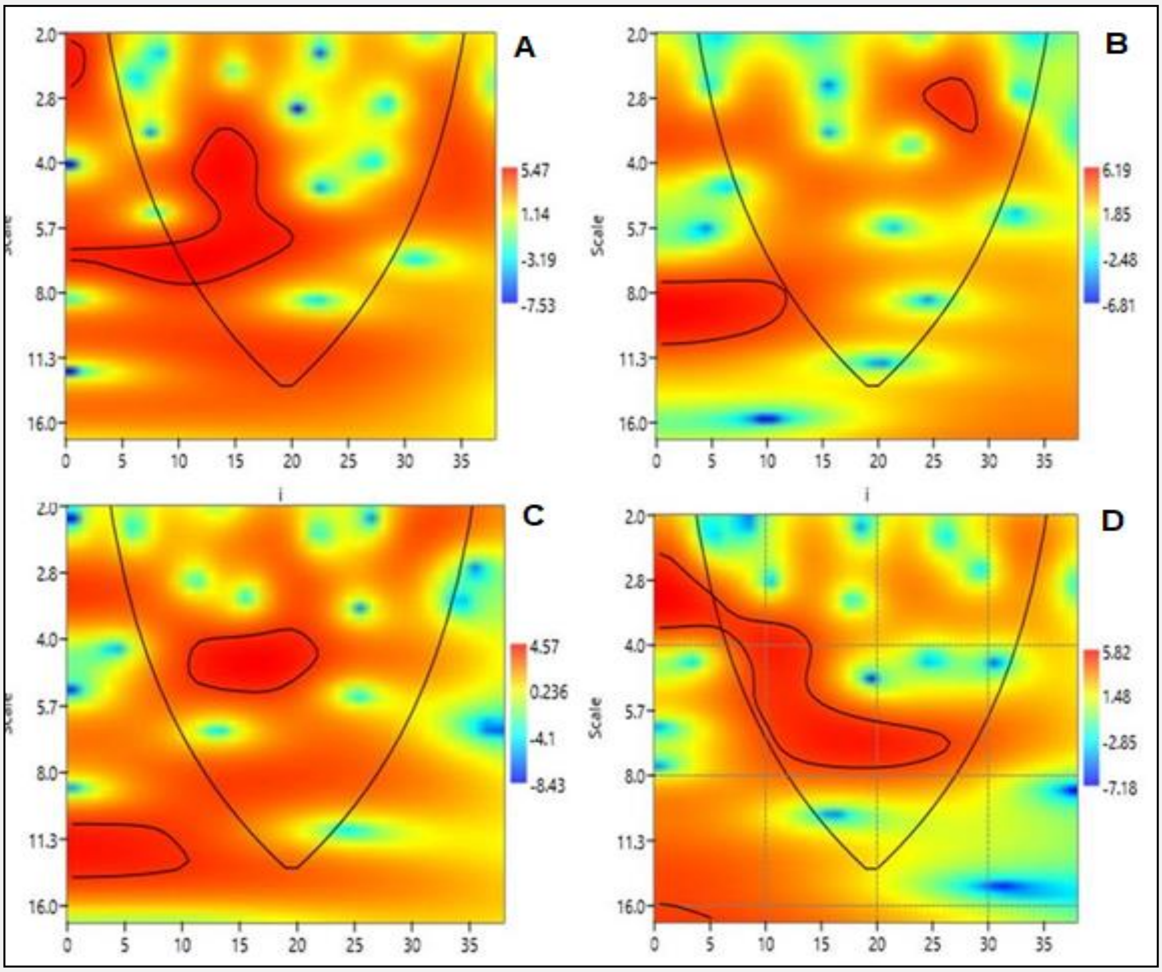

Figure 5. Wavelet power spectrum for RODs (Sokoto(A); Katsina(B); Gusau(C); Kano(D))

In Gusau station, LOs of rainfall were common around 1986 to 1989 and 1997 to 1999 (the two black coloured isolines showed areas at 95 significance confidence level (see Figure 5.C). But from 2008 to 2018, there were more of EOs of rainfall and NOs of rainfall in the station. In Sokoto, there has been interannual variation in the occurrences of RODs. Various types of onsets from EOs to NOs and LOs interchanged with one another from year to year. In Katsina station, LOs of rainfall were common around 1983 to 1987 and 1993 to 1995. But from 2002 to 2011 there were more of EOs of rainfall in the station. In all the stations from 1999 to 2018 there were more of EOs and NOs especially in Kano station (as shown by cold amplitudes). This result corresponds or tallies with (Camberlin, & Diop, 2003) who studied the rainy season characteristics in Senegal and found that time series does not show definite trends during the onset and cessation phases.

All the stations experienced insignificant increase in the LCs of RCDs as shown in Figure 6. This is an indication that from 1981 to 2018 there has been a minimal increase in the retreat dates of rainfall in the study area. In the northernmost stations (Katsina and Sokoto) and one of the southernmost stations, Kano, LCs had been experienced just recently (from around 2006 to 2016). Most of the ECs of rainfall occurred around 1980s in Gusau, Sokoto and to a lesser extent in the other stations. This finding corroborates (Amekudzi et al., 2015), who reported that early cessations are indicated around 1972–1988 for the savannah zone of Ghana.

As Ekpoh & Nsa (2011) reported that studies have shown that most of the droughts that occur in the study area have been found to be associated with LOs and ECs. Our study that make use of WT has corroborated this assertion that to the extent that Wavelet power spectrum for

RODs and RCDs shows that LOs and ECs of rainfall are more common in the northernmost stations, namely: Sokoto and Katsina as shown by Figure 5 and Figure 6 respectively.

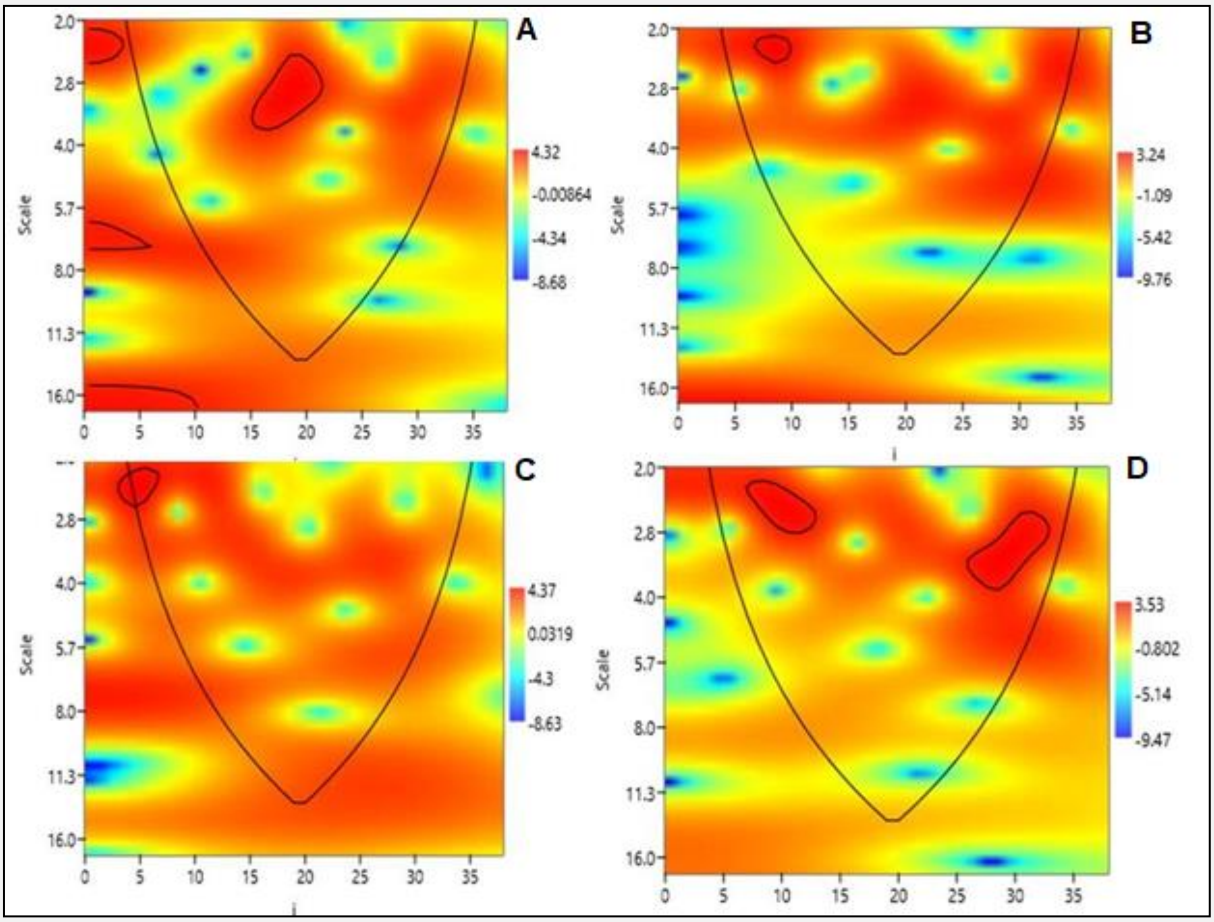

Figure 6. Wavelet power spectrum for RCDs (Sokoto(A), Katsina(B), Gusau(C), Kano(D))

CONCLUSION

This study was aimed at the characterization of monsoonal rainfall in the Sudano-Sahelian Zone of Northwestern Nigeria. Our findings revealed that RODs of rain in the study area vary from one station to another. There is however, a low variation of the RCDs in the study area. There is a low (0.3 Spearman's Rank r) correlation between latitudes and Early Cessations (ECs) of rains. There is no trend in RODs and RCDs. This absence of a trend means insignificant autocorrelation in RODs and RCDs exhibited by random data, near zero for all lags (or white noise, a very slow alternating positive and negative decaying to zero in the lags with an insignificant correlation less the ±0.5) for all the stations. The Morlet wavelet analysis in all the stations revealed that from 1999 to 2018 there were more of EOs and NOs especially in Kano station all the stations experienced insignificant increase in the LCs of RCDs. We conclude that from during the time of review (1981 to 2018) there has been a minimal increase in the retreat dates of rainfall in the study area. This study recommends further studies to focus on exploring intra-annual rainfall characterization with a view of observing its pattern, trends and seasonality or periodicity and if possible coming up with a forecast of these behaviours.

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