Original Research Article

Combining mathematical and statistical algorithms for objectivity in the use of ogive for determining rainfall onset, peak, and retreat dates over Nigeria

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Abstract: The study combined the second-order polynomial and some elements of algebra and trigonometry with the ogive to objectively (mathematically) locate the rainfall onset, peak, and retreat on the ogive, which was visually done. The data used for the investigation are the daily rainfalls of 16 synoptic stations (Ikeja, Calabar, Port-Harcourt, Benin, Ondo, Enugu, Ilorin, Lokoja, Jos, Kaduna, Yola, Kano, Sokoto, Maiduguri, Potiskum, and Nguru) across all the ecological zones of Nigeria. The datasets spanning 50 years (1971–2020) were collected from the Archives of the Nigerian Meteorological Services, Abuja, Nigeria. The ogives were derived from the frequency of rainy days. The peak periods were best detected from the pentad graphs of the rainy-day frequency. The results showed that rainy-day frequency is better than rainfall amount in determining the various rainfall parameters over Nigeria. The second-order polynomial modeled the two curvatures of the rainfall perfectly. The rainy-day frequency in the southern part of the country exhibited double rainfall maxima, while those in the northern part showed a single rainfall maximum. The double rainfall maxima are not peculiar to the southwestern region of Nigeria, as previously widely asserted; they cut across the whole southern region, although the number of days and the depth of the trough between the peaks dimmish from the largest values in the extreme southwest to the least in the extreme southeast. The first rainfall peaks were attained in southern Nigeria in July, except at Ikeja, which was in June. The second rainfall peak was reached in September in all the southern stations. The single peaks were attained in all the extreme northern stations in August and in the other stations south of them in early September. The rainfall onset begins at Ikeja in the extreme southwestern corner of Nigeria around March ending. It spreads eastwards and northwards to cover the entire country by mid-June, reaching Nguru in the northeastern corner. It is generally earlier on the western flank than the eastern flank. Rainfall begins to retreat from the northernmost stations by the third week in September to reach the extreme southern stations between October and early November.

Keywords: rainfall onset; rainfall peak; rainfall retreat; ogive; second-order polynomial; percentage cumulative rainfall; rainy day

1. Introduction

Rainfall onset is the period, at the beginning of the rainy season, when rainfall distribution characteristics have become adequate for crop development, while rainfall retreat is the period, towards the end of the rainy season, when rainfall distribution may no longer sustain crop development[1]. In other words, rainfall onset marks the start of the growing season[2], while its retreat signifies its end. Thus, the growing season was defined by the study of Odekunle[3] as the period of the year during which rainfall distribution characteristics are suitable for crop germination, establishment, and full development. The annual rainfall peak can be taken as the period of highest rainfall, after which the rainfall decreases persistently for many days within a year. Unlike the rainfall onset or retreat that is once a year, the peak rainfall may occur once or twice depending on the

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location of the place over the country. The first is known as a single peak or single maximum rainfall regime, while the second is referred to as a double peak or double maxima rainfall regime[4–6]. The double maxima rainfall regime is confined to the southwestern part of Nigeria between latitudes 4° and 9°N and longitudes 3° and 7°E. The remaining part of the country experiences a single maximum rainfall regime[7]. The space between the double maxima is generally known as the ‘‘Little Dry Season’’ (LDS)[5–7].

The three rainfall seasonal parameters—onset, peak, and retreat—are extremely important in Nigeria's economy, which is located in a typical wet-and-dry climate[8]. The agricultural sector is particularly affected, as about 88% of farmers in the country are smallholders[9] and responsible for 98% of agricultural produce[10], predominantly practicing rainfed agricultural systems[11]. It has been observed that only 1% of Nigeria's cropland is irrigated[12]. In rainfed agricultural systems, the various rainfall seasonal parameters dictate the agricultural calendar and activities, including farmland preparation, selection and mobilisation of crop and seed varieties, planting date, harvesting date, as well as mobilisation of labour and equipment for farm operations[3,11,13]. Information about these seasonal parameters can significantly reduce the risks and costs of re-sowing seeds[11,13].

Rainfall onset, peak, and retreat are experienced at different times in different locations across Nigeria. In general, rainfall onsets usually begin in coastal areas in the south following the apparent movement of the overhead sun away from the equator after the March (spring) equinox towards the northern hemisphere and the concomitant northward movement of the Intertropical Discontinuity (ITD) and its associated moisture-laden wind (monsoon) and air mass (tropical maritime). As the ITD advances further into the hinterland, the rainfall onset continues to spread across the country until it reaches the northernmost part of the country in June. Rainfall retreats usually start in the northernmost part of the country in September, after the September (autumn) equinox and the rapid retreat of the ITD, to reach the coastal area in October ending or early November. In the area of double rainfall maxima, the first rainfall peaks are usually attained between June and July, and the second peak is in September. In the area of the single rainfall maximum, the peaks are attained between August and September[3,5,6,14,15]. However, rainfall onset is often foreshadowed by a succession of isolated showers of uncertain amount, frequency, and intensity and may be accompanied by dry periods of varying duration[16], while the rainfall retreat may also be followed by the same sets of unfavourable rainfall characteristics[3]. The various rainfall seasonal parameters also exhibit significant interannual variabilities[13,17]. For instance, the variability in the rainfall onset date could be up to 70 days interannually[13]. As observed by the studies of Olaniran[18] and Jackson[19], these sets of unfavourable rainfall characteristics adversely affect plant germination and/or growth and are sufficient to destroy the hopes of a normal harvest. Peak rainfall affects many hydrological parameters, including stream or river peak discharge, water table recharge, water reservoir recharge, and channelized debris flows[20].

The foregoing clearly indicates rainfall onset, peak, and retreat as critical determinants of agricultural activities, hydrological processes, and other water-related features in Nigeria. It also shows that the various seasonal parameters exhibit significant interannual variabilities. Thus, the overarching anxieties of farmers in Nigeria are when the growing season is going to be fully established (rainfall onset date) and when it is most likely to be terminated (rainfall retreat). The agriculture and water resources sectors are also concerned about the rainfall peak. Thus, it is pertinent to accurately determine the various seasonal rainfall parameters.

Many methods have been developed and used to determine the rainfall onset, peak, and retreat. As aptly summarised by the study of Odekunle[21], they notably include the Intertropical Discontinuity (ITD)-rainfall model[22,23]; the rainfall-evapotranspiration relation model[24,25]; Markov chain model[26]; percentage cumulative mean rainfall model[3,21,27]; wind shear model[28]; the theta-E technique[29]; vertically integrated moisture transport[30]; the rainfall probability model[3,31]; global daily normalized precipitable water[32]; and the meridional gradient of tropospheric temperature[33]. Of all these existing methods, the percentage cumulative mean rainfall (ogive) is the most widely used. Some of the studies that used this method include Odekunle et al.[1], Odekunle[3,21], Olaniran[18], Ilesanmi[22,34], Adejuwon et al.[35], Recha et al.[36], Guenang and Mkankam[37] and Amekudzi et al.[38]. The strength of this method lies in the fact that it uses rainfall data alone, a readily available direct measurement, rather than some other rainfall-associated factor. As attested to by the study of Olaniran[18], it is accurate because it provides the mean rainfall onset that approximates the mean start of the growing season for all locations in Nigeria. However, as widely used as the method of percentage cumulative mean rainfall model (ogive) has been, to date, the various rainfall seasonal parameters—onset, peak, and retreat—are visually located on the ogive as the first point of maximum positive curvature, the inflection point, and the last point of maximum negative curvature, respectively, in the area of a single maximum rainfall regime. In the area of the double maxima rainfall regime, the onset, first peak, second peak, and retreat are visually located on the ogive as the first point of maximum positive curvature, the first inflection point, the second inflection point, and the last point of maximum negative curvature, respectively[27]. This is highly subjective, as different individuals may pick different points on the ogive for the various rainfall parameters. The more stretched the elongated "s" (i.e., the ogive) is, the less pronounced the curvature and the more difficult it is to accurately locate the points of the various rainfall parameters. Also, the point of inflection, which indicates the rainfall peak, is difficult to locate on the ogive in most cases. This is probably one of the reasons many researchers have used monthly values in the determination of rainfall peak periods. However, the monthly temporal resolution is rather coarse for practical purposes. It is against this backdrop that this study developed a new mathematical approach and combined it with the ogive to objectively locate the rainfall onset, peak, and retreat on the ogive. Therefore, the specific objectives of this study include:

i. determining the rainfall peaks, using daily rainfall frequency in selected climatic stations across Nigeria;
ii. mathematically modeling the first and last curvatures of the percentage cumulative rainfall curve (ogive); and
iii. combining some elements of algebra and trigonometry with the mathematical modeling of the first and last curvatures of the rainfall ogive to locate the rainfall onset and retreat.

2. Study area

The study area is Nigeria, a country situated in the extreme southwestern corner of West Africa, approximately between longitudes 2° and 15°E and latitudes 4° and 14°N. It is bordered by the Republics of Benin to the west, Niger to the north, Chad to the northeastern corner, and Cameroon to the east. The country is bounded by the Atlantic Ocean to the south (**Figure 1**).

The structure of the lower troposphere over the study area is dominated by two main air masses and two associated wind systems, namely, the Tropical maritime (mT) air mass accompanied by south-westerlies also known as the monsoon winds, and the Tropical continental (cT) air mass accompanied by the north easterlies, also known as the Harmattan winds[14,15,39]. The former air mass and its associated winds originate from the southern high-pressure area of the South Atlantic Ocean, passing over the Gulf of Guinea, and entering the country from the southwestern direction, which thus makes it moist. The latter air mass and its associated wind form in the Eurasia-Arabia high-pressure belt enter the country from the north-easterly direction through the Sahara Desert, picking up little or no moisture en-route and thus being dry. The two air streams converge at the surface, where the moisture-laden one forms a wedge under the dry one as a result of variations in their densities. This interface, which is a narrow zone at the earth's surface between the two air streams in the continental area of Nigeria, is called Inter-Tropical Discontinuity (ITD)[39,40]. The surface location of ITD is characterized by zero vorticity air flow, zero meridional mass-momentum flux, strong vertical motion, and a dew point temperature of 15 °C[41–43].

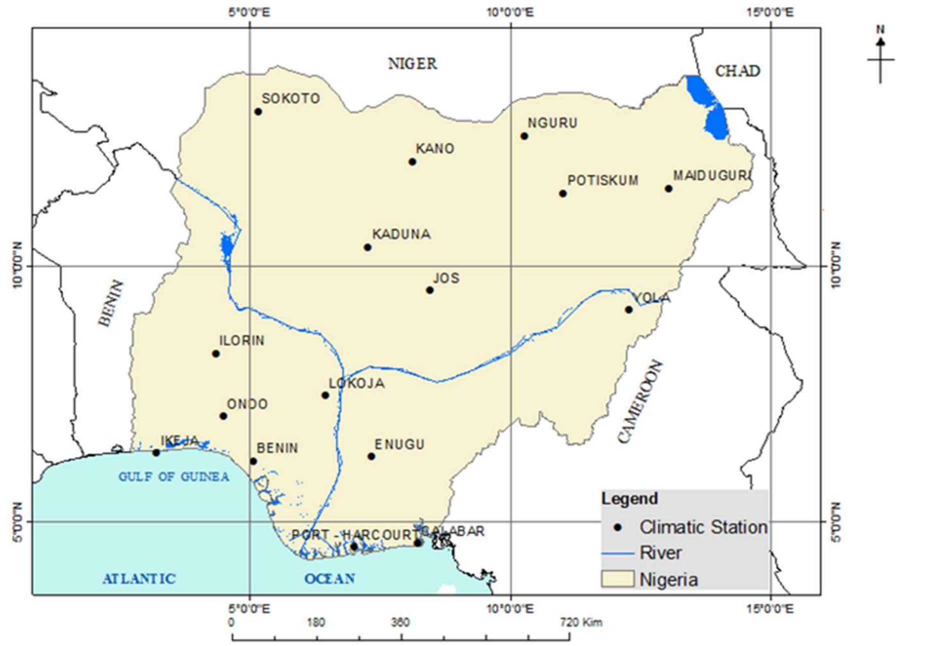


Figure 1. Map of Nigeria, showing the selected rainfall station.

The ITD serves as a reference line for all weather systems and structures in Nigeria. In response to the apparent movement of the overhead sun, the ITD as well as the mT and monsoon winds move from the Guinea Coast to the Sahelian region during the northern summer, bringing the whole country under the moisture-laden air mass and winds to promote frequent rainfall[44]. During the northern winter, the ITD, together with the cT and Harmattan winds, move from the Sahelian region to the Guinea Coast, bringing dry conditions to the whole country[22,39,45,46]. Within the mT and monsoon winds, frequent convection, overturning, and precipitation occur mainly within 4–10 degrees latitude south of the ITD[45,47,48]. Rainfall is favoured within this latitudinal band because the maximum convergence effect of the mT and cT air masses occurs there and the rai-bearing air mass has a sufficient depth (at least, 1500 m)[15]. It is important to note that ITD advances gradually but retreats rapidly[39,45]. Thus, rainfall onsets are experienced when the mT air mass and monsoon winds advance in the summer and cover a location in sufficient depths, while rainfall retreat is experienced in a location when the mT air mass and monsoon winds withdraw from it towards the winter and prevail at limited depths. As a result of the slow advance and rapid retreat of ITD over the continental area of Nigeria, the rainfall onset is gradual while the rainfall retreat is rapid. Also, because the ITD, together with the rain-bearing air mass and winds, advance from the coast into the hinterlands and retreat from the hinterlands to the coast, rainfall onsets commence from the coast and spread northwards, while rainfall retreats start from the northern region and end in the coastal area. The maximum northern limit of the ITD marks the peak of the rainy season as the whole country comes under the influence of the mT air mass and monsoon wind.

The mean annual rainfall ranges from over 3500 mm in Calabar in the south-eastern region of Nigeria to less than 450 mm in Nguru in the north-eastern area of the country. The rainfall distribution over the country exhibits two main regimes: a single maximum rainfall and a double maxima rainfall. In the former, rainfall rises and falls once throughout the year, while in the latter, rainfall rises and falls twice[6]. The significant reduction in rainfall between the two maxima is commonly called "Little Dry Season" (LDS)[7,49]. The mean annual temperature varies between 21 °C and 25 °C on the plateau. It ranges between 23 °C and 29 °C in the southern lowlands and between 24 °C and 33 °C in the north.

3. Methodology

The climatic stations selected to represent Nigeria are Ikeja, Calabar, Port-Harcourt, Benin, Ondo, and

Enugu in the south, and Ilorin, Lokoja, Jos, Kaduna, and Yola, Kano, Sokoto, Maiduguri, Potiskum, and Nguru in the northern part of the country (see **Figure 1**). The data required and used for this study are the daily rainfalls of the 16 selected synoptic climatic stations. The data, spanning 50 years (1971–2020), were collected from the Archives of the Nigerian Meteorological Agency (NIMET), Abuja, Nigeria. NIMET is a federal government agency charged with the responsibility of observing, collating, collecting, processing, and disseminating all meteorological data and information in Nigeria. These data were collected by NIMET using the British Standard rain gauge and a Dines' tilting siphon rainfall recorder. These rainfall data from NIMET had been assessed several times by some previous studies and confirmed their consistency and homogeneity[3,50]. However, there are a few incomplete datasets at some of the stations. These include Ikeja (1976), Ondo (1984 and 2002), Benin (1977), Calabar (2005), Ilorin (1971), Lokoja (1990), Sokoto (2015 and 2017), Kano (1997 and 1998), Maiduguri (1997), and Nguru (2003). These missing data were substituted with the mean of a year preceding and a year following the year of the missing data.

In the percentage cumulative rainfall curve (ogive), the rainfall onset and retreat periods are the first point of maximum positive curvature and the last point of maximum negative curvature, respectively. In the single maximum rainfall regime, the ogive exhibits only two curvatures, with the first being positive and the second being negative. The two alternating curvatures meet or give way to each other at the point of inflection, corresponding to the annual rainfall peak. However, in the double rainfall maxima regime, there are four curvatures. The first is a positive curvature, the second is negative, the third is positive, and the fourth is negative, corresponding to the rainfall onset, "Little Dry Season" onset, "Little Dry Season" retreat, and the rainfall retreat, respectively. Again, in the double rainfall maxima regime, there are two inflection points, corresponding to the first and second rainfall peaks, respectively[7,21,22,27]. Thus, the first curvature that defines rainfall onset in the single maximum rainfall regime terminates at the point of rainfall peak, while the second curvature that defines rainfall retreat begins at the same point of rainfall peak. The first curvature that defines rainfall onset in the double maxima rainfall regime terminates at the point of the first rainfall peak, while the second curvature that defines rainfall retreat begins from the point of the second rainfall peak. As noted earlier, a major challenge with this method to date is its subjectivity in that the various periods are visually located on the ogive.

Next, choose the rainfall parameters that will be used for the computation of the percentage cumulative rainfall (ogive). It has been established that rainy-day frequency is more important to agriculturalists than the amount. For example, five rainy days are more beneficial to crop plants than a single rainy day with the same amount of rainfall[21]. Also, rainy-day frequency is a better signal of the full establishment of the growing season (onset) because the rainy-day frequency can only be high when rainfall has truly commenced and low only when rainfall has retreated. Apart from this, the rainy-day parameter reflects rainfall amount because a rainy day can only be defined using a certain rainfall threshold[21]. Thus, the three seasonal rainfall parameters—rainfall onset, peak, and retreat—were determined in this study using the frequency of rainy days.

The rainfall peaks were first determined and used to mark the end of the first positive curvatures and the beginning of the last negative curvatures on the ogive. The rainfall peaks were determined using the graphs of the mean rainfall that occurred at 5-day intervals throughout the year. Both the rainfall amount and rainy-day frequency were first computed for the pentad graphs. The results showed that the rainfall peaks are clearly discernible using rainy-day frequency but relatively poor with the use of rainfall amount. Thus, the rainfall peaks were determined in this study using the mean pentad graphs of the rainy-day frequency.

The next important step is to define a threshold for a rainy day. According to the World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI)[51,52], a wet or rainy day is a day with rainfall ≥1 mm. This threshold was adopted in this study for the definition of a rainy day.

Thus, all the days with rainfall amounts greater than or equal to 1 mm constitute the frequency of rainy days in this study.

Unlike the rainfall peaks that are clearly discernible on the mean pentad graphs of the rainy-day frequency, however, the onset and retreat periods are not. Thus, the ogive was employed for the determination of the rainfall onset and retreat periods. Nevertheless, given the subjectivity inherent in the use of ogive for this purpose, as pointed out earlier, a new precision method was developed and used to locate the onsets and retreats on the ogive. This was achieved using a second-order polynomial and some elements of geometry and trigonometry, as detailed in the computation procedure in Section 3.1. The second-order polynomial was employed to mathematically model and smooth each of the curvatures, while the elements of geometry and trigonometry were used to determine the point of maximum curvatures on the polynomial curves (see Section 3.1). The various computations were executed using MATLAB software. The computation procedures for the estimation of rainfall onset, peak, and retreat are summarised in the sections that follow.

3.1. Rainfall peaks

i. Calculate the mean rainy-day frequency at 5-day intervals of the year for the 50-year period under investigation;
ii. Plot the graph of the mean rainy-day frequency at 5-day intervals against time through the year, and
iii. Locate the rainfall peak period around the summit of the graph.

3.2. Rainfall onsets and retreats

i. Calculate the mean rainy-day frequency at 5-day intervals for each of the 50-year periods under investigation;
ii. Compute the percentage of the mean rainy-day frequency at 5-day intervals for each year;
iii. Cumulate the percentages of the 5-day mean rainy-day frequency from the beginning of the year to the end of each year;
iv. Eliminate all the zeros in the cumulative 5-day mean rainy-day frequency (rainless pentads) preceding the first rain (rainy pentad);
v. Delete the repetitive pentad values that are more than three consecutive pentads at the beginning of the rain to at most three. This usually happens at the beginning of the rainy season when there are isolated showers, which usually foreshadow the onset of rainfall;
vi. Delete the repetitive pentad values that are more than three consecutive pentads towards the end of the rain to at most three. This usually happens towards the end of the rainy season when there are isolated showers, which usually follow the rainfall retreat;
vii. Compute the mean cumulative percentages of the 5-day mean rainy-day frequency from the beginning of the year to the end of the 50-year period under investigation;
viii. Plot the graph of the mean cumulative percentage against time through the year to obtain the ogive;
ix. Locate the rainy-day frequency peak values already determined above on the graph to determine the beginnings and ends of the first positive and last negative curvatures of the ogive;
x. In the area of the double maxima rainfall regime, the first positive curvature begins from the first rainy-day pentad of the year and ends at the first rainy-day peak, while the last negative curvature begins from the second rainy-day peak and ends at the point where the percentage cumulative rainy day is 100%;
xi. In the area of a single maximum rainfall regime, the first positive curvature begins from the first rainy-day pentad of the year and ends at the point of the annual rainy-day peak, while the last negative curvature begins from the point of the annual rainy-day peak and ends at the point where the percentage cumulative rainy day is 100%;

xii. Model the two curvatures with a quadratic polynomial $Q(x) = fx^2 + gx + h$, where f, g, and h are known in all the cases. The various equations are fully depicted in **Table 1**.

Table 1. The goodness of fit assessment of a second-order polynomial (quadratic function) modeling and smoothing of the first and second curvatures of the percentage cumulative rainy days over Nigeria (1971–2020).

S/N	Station	First curvature		Second curvature	
		Quadratic equation	R^2	Quadratic equation	R^2
1	Ikeja	$y = 0.0411x^2 - 0.2661x + 0.968$	0.9986	$y = -0.073x^2 + 2.7647x + 73.694$	0.9992
2	Calabar	$y = 0.0306x^2 - 0.008x - 0.2354$	0.9995	$y = -0.0601x^2 + 2.8197x + 67.326$	0.9981
3	Port-Harcourt	$y = 0.0298x^2 + 0.017x - 0.1331$	0.9999	$y = -0.0672x^2 + 2.8915x + 68.955$	0.9989
4	Benin	$y = 0.0307x^2 - 0.0199x + 0.0657$	1	$y = -0.0699x^2 + 2.9753x + 68.254$	0.9984
5	Ondo	$y = 0.035x^2 - 0.1147x + 0.0094$	0.9999	$y = -0.0784x^2 + 2.975x + 72.063$	0.9963
6	Enugu	$y = 0.0438x^2 - 0.4409x + 1.1875$	0.9991	$y = -0.0928x^2 + 3.3887x + 70.238$	0.9898
7	Ilorin	$y = 0.0502x^2 - 0.4946x + 1.0584$	0.9985	$y = -0.1341x^2 + 3.5185x + 77.238$	0.9962
8	Lokoja	$y = 0.0392x^2 - 0.0233x - 1.3855$	0.9972	$y = -0.1309x^2 + 4.2184x + 66.516$	0.9972
9	Jos	$y = 0.0551x^2 - 0.2197x - 0.7038$	0.9984	$y = -0.1423x^2 + 3.953x + 72.536$	0.9994
10	Kaduna	$y = 0.055x^2 + 0.0363x - 1.511$	0.9985	$y = -0.1901x^2 + 4.4479x + 74.019$	0.9995
11	Yola	$y = 0.0493x^2 + 0.4015x - 2.5877$	0.9984	$y = -0.1357x^2 + 3.6646x + 75.915$	0.9953
12	Kano	$y = 0.1041x^2 - 0.684x + 1.1772$	0.9998	$y = -0.2112x^2 + 5.9845x + 57.669$	0.9988
13	Sokoto	$y = 0.0997x^2 - 0.8961x + 1.9982$	0.9995	$y = -0.2095x^2 + 6.2117x + 54.039$	0.9975
14	Maiduguri	$y = 0.1062x^2 - 0.2091x + 0.9149$	0.9995	$y = -0.1886x^2 + 5.2982x + 62.641$	0.9995
15	Potiskum	$y = 0.1x^2 - 0.494x + 0.9494$	0.9994	$y = -0.1768x^2 + 5.2396x + 61.234$	0.9998
16	Nguru	$y = 0.1371x^2 - 1.1314x + 2.7253$	0.9988	$y = -0.2173x^2 + 5.2937x + 67.667$	0.9972

Note that all the relationships are significant at 99% level of confidence.

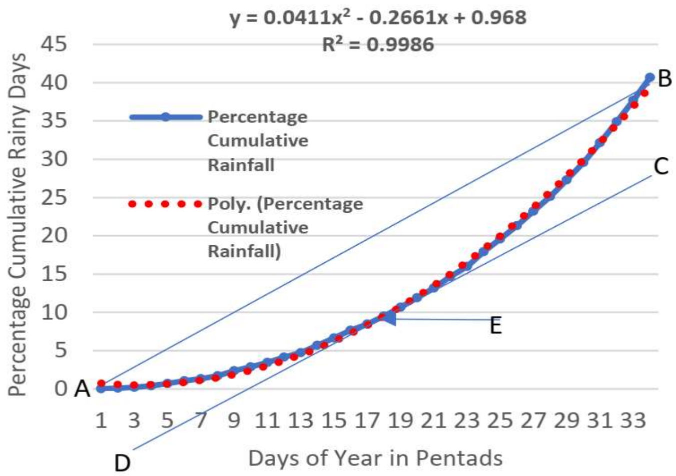


Figure 2. A curvature modelling and first point of maximum positive curvature determination of the percentage cumulative rainy days in Ikeja. Note: Curve AB is a typical first positive curvature of an ogive, line AB is constructed to join the two ends of curve AB, and line CD has the same gradient with line AB (and thus parallel to each other) and is tangential to curve AB at point E (point of maximum positive curvature).

xiii. Join both ends of each curvature with a straight line (e.g., line AB in **Figure 2**);

xiv. Calculate the gradient of the line joining the two ends of each curve and equate it to the gradient of the quadratic curve (dQ/dx) (e.g., the gradient of line CD equals that of line AB and is tangential to curve AC at Point E in **Figure 2**); and

xv. The point of contact of the tangent to the curve is the point of maximum curvature (e.g., point E in **Figure 2**).

The points of the first maximum positive curvature and the last negative curvature on the ogive are the periods of rainfall onset and retreat, respectively.

4. Results

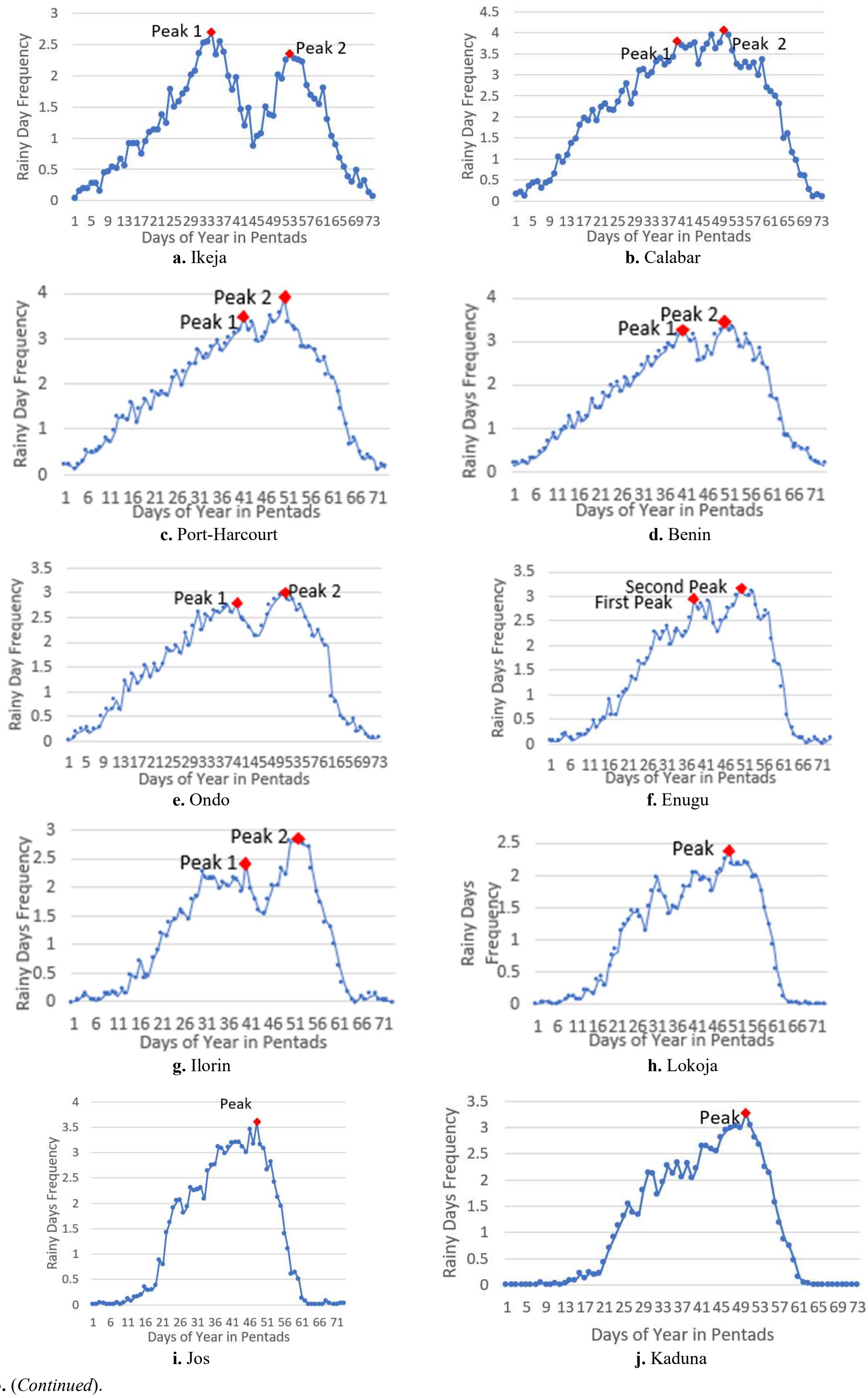
4.1. Mean rainfall peak periods in Nigeria between 1971 and 2020

Figures 3 shows the mean rainfall peak periods between 1971 and 2020 in Ikeja, Calabar, Port-Harcourt, Benin, Ondo, Enugu, Ilorin, Lokoja, Jos, Kaduna, Yola, Kano, Sokoto, Maiduguri, Potiskum, and Nguru, respectively. The results are also summarised in **Table 2**. The results show that the rainy-day frequency of Ikeja, Calabar, Port-Harcourt, Benin, Ondo, Enugu, and Ilorin, which are in the southern part of the country, exhibited double rainfall maxima: 15–19 June and 18–22 September, 10–14 July and 3–7 September, 20–24 July and 3–7 September, 15–19 July and 3–7 September, 15–19 July and 8–12 September, 5–9 July and 3–7 September, and 15–19 July and 13–17 September, respectively. The decreases in the rainy-day frequencies between the two peaks in the various rainfall stations are indicative of the presence of the phenomenon of "Little Dry Season" (LDS) and are most severe at Ikeja, in the extreme southwestern corner of the country. As manifested in the length of the days and the depths of the troughs between the two peaks, the severity of the LDS decreases northward and eastward. The first rainfall peak was first attained in Ikeja, and thereafter, it spread eastward (to Port Harcourt and Calabar) and northward (to Ilorin and Ondo). Generally, in the southern part of the country, the first rainfall peaks were attained when the various stations recorded 41% to 51% of their total annual rainy days. The first rainfall peaks were attained between the first and third weeks of July in all the southern stations except Ikeja, where the peak was attained in the third week of June.

The second rainfall peak was first attained in Benin, Enugu, Port-Harcourt, and Calabar in the eastern part of the country and spread westwards to reach Ondo, Ikeja, and Ilorin. The second rainfall peak was attained in all the stations between the first and third weeks of September when the various stations recorded 71% to 80% of their total annual rainy days. In all the stations experiencing double rainfall maxima, the second peak is the highest peak (primary peak), except in Ikeja, where the first peak is the highest. Also, while it took about five weeks for all the southern stations to attain the first peak, the second peak spread across all the stations within a period of about two weeks.

The rainy-day frequency of Lokoja, Jos, Kaduna, Yola, Kano, Sokoto, Maiduguri, Potiskum, and Nguru, which are in the northern part, showed a single rainfall maximum: 29 August–September 2, 24–28 August, 3–7 September, 3–7 September, 9–13 August, 9–13 August, 14–18 August, 14–18 August, and 19–23 August, respectively. The peaks, which were generally attained between the second week in August and the first week in September, were first attained in the northernmost and easternmost parts of the country and thereafter spread southward. The peaks were attained when the various northern stations recorded 61% to 79% of their total annual rainy days.

The results further show that the rising limbs of the graphs of both the double rainfall maxima and single rainfall maximum regimes display gentle and longer slopes, while those of the declining limbs indicate precipitous and shorter slopes, indicating gradual rainfall onsets and rapid retreat over the country. Also, the peaks indicate sharp peaking, suggesting that the peak periods last only a few days.



a. Ikeja

b. Calabar

c. Port-Harcourt

d. Benin

e. Ondo

f. Enugu

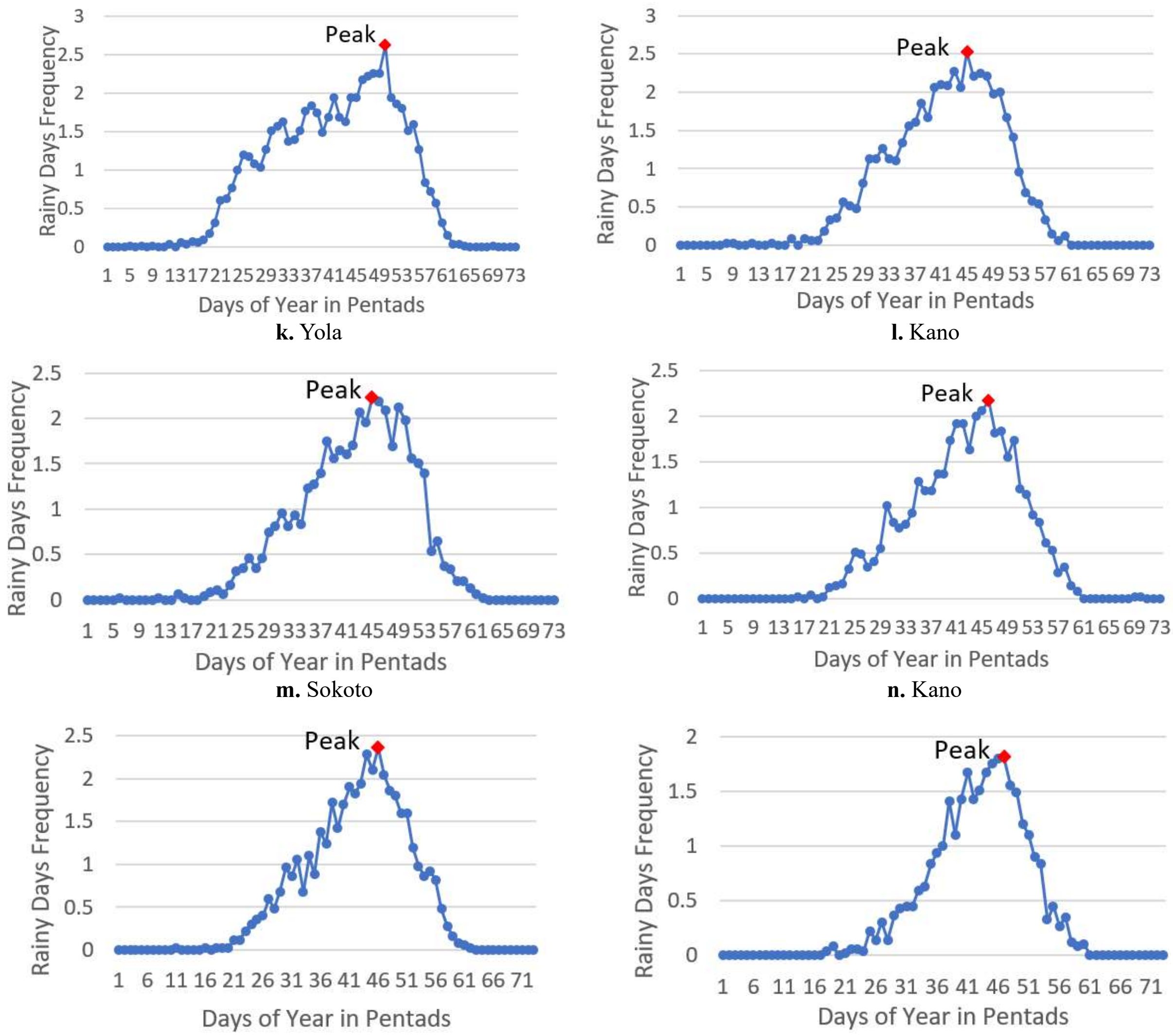
g. Ilorin

h. Lokoja

i. Jos

j. Kaduna

Figure 3. (*Continued*).



k. Yola **l.** Kano

m. Sokoto **n.** Kano

o. Potiskum **p.** Nguru

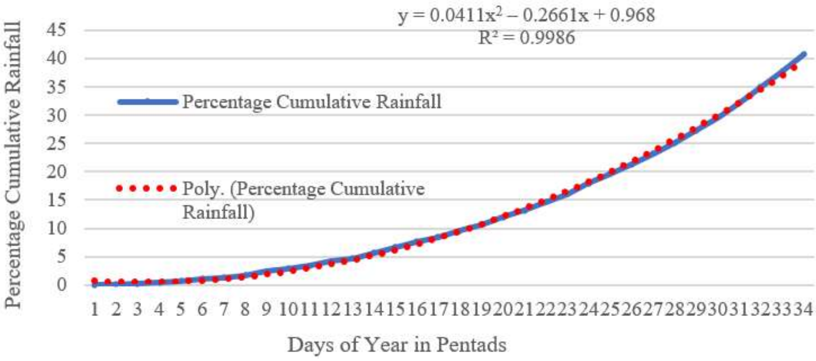
Figure 3. Mean rainfall peak periods in selected climatic stations in Nigeria (1971–2020).

Table 2. Mean rainfall peaks in Nigeria—1971 to 2020.

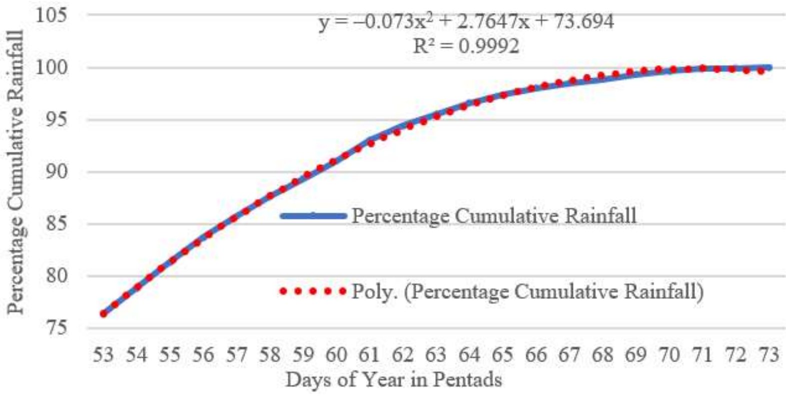
S/N	Station	Peak 1			Peak 2		
		Pentad	**Date**	**Cumulative percentage**	**Pentad**	**Date**	**Cumulative percentage**
1	Ikeja	34	15–19 June	40.67	53	18–22 September	76.34
2	Calabar	39	10–14 July	45.53	50	3–7 September	70.79
3	Port-Harcourt	41	20–24 July	50.48	50	3–7 September	72.19
4	Benin	40	15–19 July	48.57	50	3–7 September	71.50
5	Ondo	40	15–19 July	50.93	51	8–12 September	75.08
6	Enugu	38	5–9 July	41.82	50	3–7 September	73.18
7	Ilorin	40	15–19 July	50.03	52	13–17 September	80.16
8	Lokoja	49	29 August–2 September	71.61	-	-	-
9	Jos	48	24–28 August	76.59	-	-	-
10	Kaduna	50	3–7 September	78.29	-	-	-
11	Yola	50	3–7 September	79.22	-	-	-
12	Kano	45	9–13 August	63.82	-	-	-
13	Sokoto	45	9–13 August	60.68	-	-	-
14	Maiduguri	46	14–18 August	67.93	-	-	-
15	Potiskum	46	14–18 August	66.42	-	-	-
16	Nguru	47	19–23 August	72.21	-	-	-

4.2. Mathematically modeling of the first and last curvatures of the percentage cumulative rainfall curve (ogive)

Table 1 shows the goodness of fit assessment of a second-order polynomial (quadratic function) modeling and smoothing of the first and second curvatures of the percentage cumulative rainy days over Nigeria between 1971 and 2020. The results show that the second-order polynomial modeled the two curvatures perfectly. Apart from the fact that all the relationships are statistically significant at a 99% level of confidence, the values of all the coefficients of determination (R^2) range between 0.9972 and 1. **Figure 4** exemplifies the goodness of fit assessment of the second-order polynomial (quadratic function) modeling and smoothing of the first and second curvatures of the percentage of cumulative rainy days over Ikeja. As can be seen from the graphs, the relationships are perfect to the extent that the polynomial curves lie directly on the two curvatures.



a. First curvature



b. Second curvature

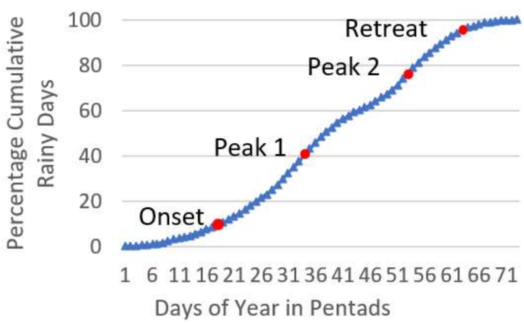
Figure 4. The goodness of fit assessment of a second-order polynomial (quadratic function) modeling and smoothing of the first and second curvatures of the percentage cumulative rainy day in Ikeja (1971–2020).

4.3. Mean rainfall onset and retreat dates in Nigeria between 1971 and 2020

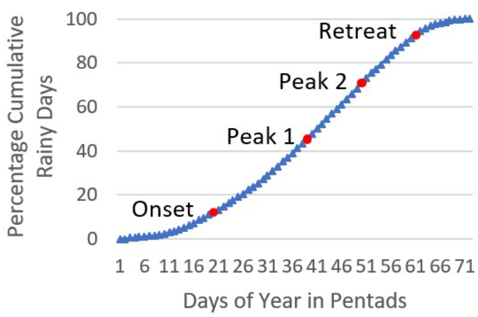
Using the procedure in **Figure 2**, the rainfall onset and retreat dates over Nigeria are depicted in **Table 3**. The mean rainfall onset dates in Ikeja, Calabar, Port-Harcourt, Benin, Ondo, Enugu, Ilorin, Lokoja, Jos, Kaduna, Yola, Kano, Sokoto, Maiduguri, Potiskum, and Nguru were 27–31 March, 6–10 April, 11–15 April, 11–15 April, 6–10 April, 11–15 April, 16–20 April, 11–15 May, 16–20 May, 31 May–4 June, 31 May–4 June, 5–9 June, 31 May–4 June, 15–19 June, 10–14 June, and 15–19 June, respectively. Their corresponding retreat dates were 7–11 November, 28 October–1 November, 2–6 November, 28 October–1 November, 2–6 November, 28 October–1 November, 18–22 October, 8–12 October, 28 September–2 October, 3–7 October, 13–17 October, 18–22 September, 18–22 September, 18–22 September, 18–22 September, and 18–22 September. The results are also depicted in **Figure 5**. As can be seen from the results, the rainfall onset begins at Ikeja in the extreme southwestern corner of Nigeria by March end. It spreads eastwards and northwards to cover the entire country

Table 3. Mean rainfall onset and retreat in Nigeria—1971 to 2020.

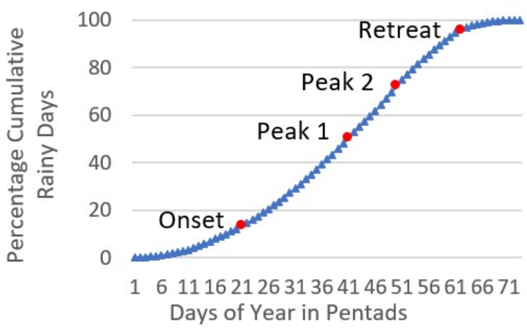
S/N	Station	Onset			Retreat		
		Pentad	Date	Cumulative percentage	Pentad	Date	Cumulative percentage
1	Ikeja	18	27–31 March	9.52	63	7–11 November	95.49
2	Calabar	20	6–10 April	12.01	61	28 October–1 November	92.66
3	Port-Harcourt	21	11–15 April	13.47	62	2–6 November	95.71
4	Benin	21	11–15 April	13.12	61	28 October–1 November	94.41
5	Ondo	20	6–10 April	11.86	62	2–6 November	97.07
6	Enugu	21	11–15 April	8.06	61	28 October–1 November	98.55
7	Ilorin	22	16–20 April	9.10	59	18–22 October	97.05
8	Lokoja	27	11–15 May	17.18	57	8–12 October	94.22
9	Jos	28	16–20 May	16.99	55	28 September–2 October	95.37
10	Kaduna	31	31 May–4 June	19.60	56	3–7 October	96.04
11	Yola	31	31 May–4 June	21.01	58	13–17 October	98.16
12	Kano	32	5–9 June	14.94	53	18–22 September	94.80
13	Sokoto	31	31 May–4 June	11.52	53	18–22 September	94.43
14	Maiduguri	34	15–19 June	18.50	53	18–22 September	93.04
15	Potiskum	33	10–14 June	16.15	53	18–22 September	91.72
16	Nguru	34	15–19 June	12.84	53	18–22 September	94.73



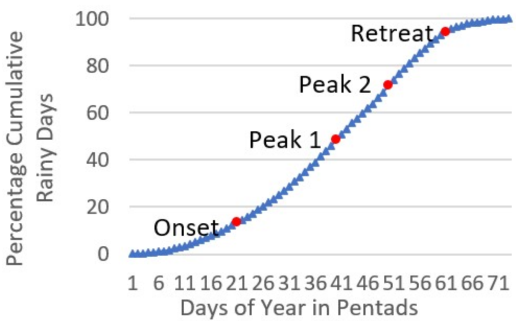
a. Ikeja



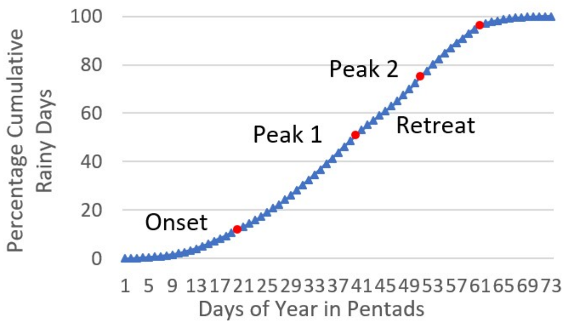
b. Calabar



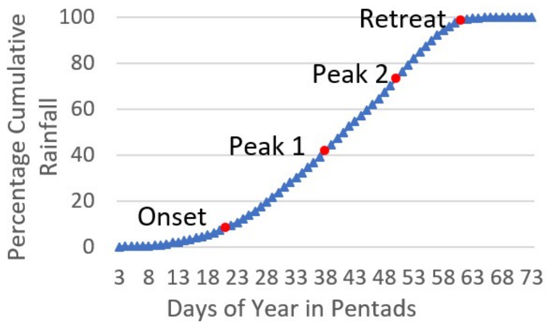
c. Port-Harcourt



d. Benin



e. Ondo



f. Enugu

Figure 5. (*Continued*).

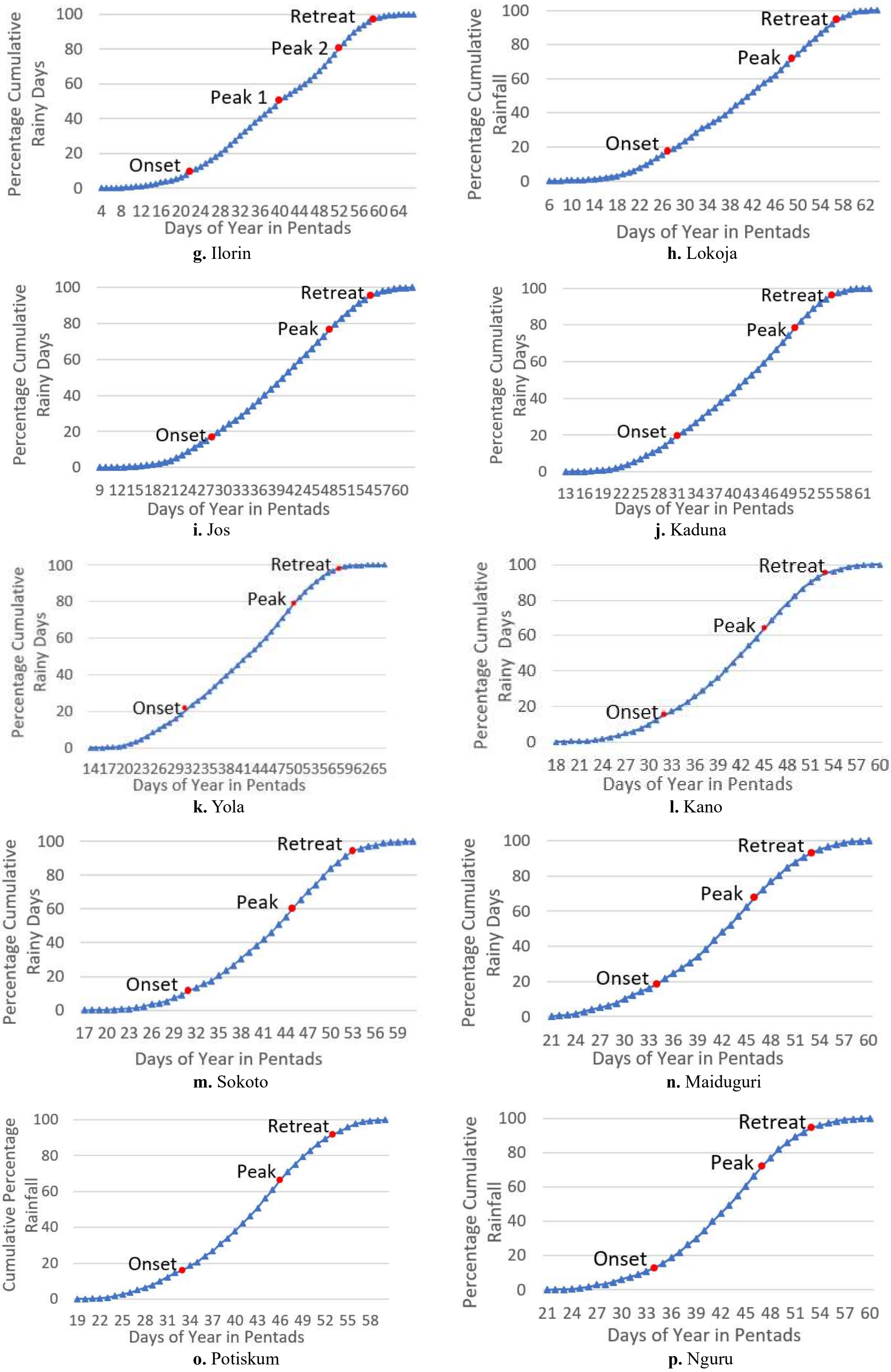


Figure 5. Rainfall onset, peaks, and retreat periods in selected locations over Nigeria (1971–2020).

by mid-June at Nguru in the north-eastern corner. Thus, it takes roughly two and a half months for the rainfall to spread across the country. It is generally earlier on the western flank than the eastern flank. Rainfall onsets are experienced in various locations across the country when about 10% to 21% of the total annual rainy days have been recorded. These percentages are generally lower in southern locations than in the north. Rainfall begins to retreat from the northernmost stations of Nguru, Potiskum, Maiduguri, Sokoto, and Kano by the third week in September to reach the extreme southern stations of Ikeja, Port-Harcourt, and Calabar between October ending, and early November. The rainfall retreats at the various locations when about 91% to 98% of the rainy days have been recorded. Thus, the rainfall retreat takes roughly less than one and a half months from the extreme northern location of the country to reach the south. Again, these results show that the rainfall onset is gradual, taking two and a half months to spread across the country, while the retreat is rapid, taking less than one and a half months to spread across the country.

5. Discussion

The results showed that the rainy-day frequency in the southern part of the country exhibited double rainfall maxima, while those in the northern part showed a single rainfall maximum. Studies have shown that Nigeria has two main rainfall regimes—(a) a single peak or maximum rainfall regime and (b) a double peak or double maxima rainfall regime[5,6]. While rainfall rises and falls once throughout the year in the first type of regime, it rises and falls twice in the second. Various studies suggested that the double maxima rainfall regime and the single rainfall maximum are found in the southern and northern parts of Nigeria, respectively. As observed in this study, the first rainfall peaks were attained in the southern part of the country in July, except at Ikeja, which was in June. The second rainfall peak was reached in September in all the southern stations. The single peaks were attained in all the extreme northern stations in August and in the other stations south of them in early September. Although Iloeje[5] and Odekunle and Adejuwon[6] used monthly rainfall amounts, the various rainfall peak timings observed in the present study agree with their observations.

The trough between that of the double peak is commonly referred to as the LSD[6,7,49]. However, contrary to the name given to this atmospheric phenomenon, the season is not completely rainless but rather a significant decline in both the frequency and amount of rainfall[6,7], further confirming the observations in this study. Previous studies by Adejuwon and Odekunle[7], Omotosho[49], Adefolalu[53] and Adekoya[54] have indicated that the double rainfall maxima phenomenon and the LDS are limited or peculiar to the southwestern part of Nigeria between 4°–9°N and 3°–7°E. While the results obtained in this study further confirm the latitudinal extent of the phenomena over Nigeria, it observed that they cut across the whole southern part rather than being limited to latitudes 3° and 7°E. The earlier studies did not detect the double rainfall peak and LDS eastwards of 7°E because of its low severity over the location and because those studies used rainfall amount which is not as illuminating as rainy days. This study further confirms the observation of Odekunle[21] that rainy day is a better measure of rainfall seasonality parameters.

The two most important factors responsible for the double rainfall peak and LDS over West Africa in general and Nigeria, in particular, are the movements of ITD and its rainfall band and the Sea Surface Temperature (SST) of the Gulf of Guinea[22,39,55,56]. There are significant declines in both the frequency and amount of daily rainfall for a number of weeks halfway through the rainy season in the southern part of the country because, during this time of the year, the ITD and its rainfall band are far away from the location, and there is the anomalously cold SST, which is inhibitory to convection and overturning and thus antagonistic to precipitation formation. The double rainfall peak and LDS cut across the whole southern region because the ITD and its rainfall band were equally far away from the location during the period of the LDS. Although, as observed by Odekunle and Eludoyin[56], the anomalously cold SST is limited to longitudes 8°W to 3°E, the prevailing directions of the mT air mass and monsoon make those passing over longitudes 5°W to 3°E pass over the whole of southern Nigeria.

The results in this study further show that the number of days and the depth of the trough between the two peaks (indicating the severity of the LDS) are most conspicuous at Ikeja, in the extreme southwestern corner of the country but decrease northwards and eastwards. These results further confirm the observation ofOdekunle and Adejuwon[7]. Odekunle and Eludoyin[56] had earlier observed that the SST of the Gulf of Guinea during this time is generally cold, and decreases westwards of latitude 3°E to attain the minimum value between longitudes 2°W and 4°W. Thus, the effects of the anomalously cold SST are expected to be greatest in the west (Ikeja) and diminish eastwards. Again, it is known that air masses undergo thermodynamic transformations along their trajectories. One of the factors determining the extent of the modifications is the distance travelled. Given that the prevailing direction of both mT air mass and the monsoon winds is southwest, the effects of the anomalously cold SST are expected to be greatest in the west (Ikeja) and diminish eastwards and northwards as the mT air mass and the monsoon winds undergo thermodynamic transformations.

As observed in this study, in the southern part of the country, the first rainfall peaks were attained when the various stations recorded 41% to 51% of their total annual rainy days. This further corroborates the observations of Hamilton and Archibold[57] and Ilesanmi[22] that the LDS manifests itself as a decline in both the frequency and amount of daily rainfall for a number of weeks halfway through the rainy season.

Many observations in this study clearly indicate the gradual advance and rapid retreat of the growing season in Nigeria. These include:

- It takes up to five weeks for all the southern stations to attain the first peak, whereas the second peak spread across all the stations within about two weeks;
- Gradual advancement of rainfall onset and rapid retreat;
- The rising limbs of the graphs of both the double rainfall maxima and single rainfall maxima regimes exhibited gentle and longer slopes, while those of the declining limbs indicated precipitous and shorter slopes; and
- Rainfall onset takes roughly two and a half months to spread across the country, and rainfall retreat takes roughly less than one and a half months from the extreme northern location of the country to reach the south.

Of the known mechanisms, theories, and concepts that have been used to account for rainfall characteristics over West Africa in general and Nigeria in particular, the ITD and its associated air masses, winds, and weather systems are the most popularly accepted[22,39,45,46]. As earlier noted in this study, the ITD moves from the coast over Nigeria to the Sahel and vice versa in response to the apparent movement of the overhead sun. It moves from the Guinea Coast to the Sahelian region during the northern summer, bringing the whole country under the moisture-laden air mass and winds that promote frequent rainfall. During the northern winter, it moves together with the cT and Harmattan winds from the Sahelian region to the Guinea Coast to promote dry conditions over the whole country[22,39,45,46]. The ITD and its associated air masses, winds, and weather systems advance gradually but retreat rapidly[45]. Thus, all the characteristics of rainfall listed above, indicating the gradual advance and rapid retreat of the growing season in Nigeria, are driven by the slow advance and rapid retreat of ITD over the continental area of the country.

The results further showed that the second-order polynomial modeled the two curvatures perfectly. Apart from the fact that all the relationships are statistically significant at a 99% level of confidence, the values of all the coefficients of determination also indicated almost 100% degrees of relationship.

The findings in this study also showed that the rainfall onset begins at Ikeja in the extreme southwestern corner of Nigeria around March ending and spreads eastwards and northwards to cover the entire country by mid-June at Nguru in the northeastern corner. It is generally earlier in the western than the eastern flank. Rainfall begins to retreat from the northernmost stations by the third week in September to reach the extreme southern stations between October ending and early November. The ITD begins to advance northwards from the coastal area gradually bringing in the mT air mass and monsoon winds to establish the rainy season (onset). The onset is generally earlier in the western flank than in the eastern flank due to the ITD's orientation, which is approximately WNW-ESE across the country[34,39,58]. Thus, from west to east of the region, it bends southwards. The results obtained in this study also further corroborate the earlier observations of Lélé and Lamb[45] and Nicholson[59] that the long-term annual average isohyetal pattern over West Africa exhibits WNW-ESE alignment. The rapid retreat of ITD after the September Equinox accounts for the rapid retreat from the northernmost stations by the third week in September to reach the extreme southern stations between October ending and early November.

The temporal and spatial spreads of both the rainfall onset and retreat dates observed in this study agree with the earlier observations of Ilesanmi[22,27,34], Olaniran[18], Adejuwon et al.[35], Odekunle[3], Odekunle et al.[1] and Odekunle[21]. However, while some of the rainfall onset and retreat dates observed in this study agree with the findings of the various studies, others are some days to two weeks different (**Table 4**). For instance, the rainfall onset and retreat dates observed in this study are about 1 to 15 days later than those of the previous studies. Although the various studies analysed their datasets over different periods for the same locations, this is not expected to cause differences in the mean periods of rainfall onset and retreat of up to 15 days (three pentads). Also, as observed in **Table 4**, the results of the previous studies over the same locations also differ from one another. These differences are expected because the method used by the present study is objective whereas, the approach used in the previous study is subjective. Also, from personal observation of the rainfall seasonality in the various locations in Nigeria, the results of rainfall onset and retreat dates obtained in this study are the realities. Findings in this study further showed that rainfall onsets are experienced in various locations across the country when about 10% to 21% of the total annual rainy days have been recorded and that these percentages are generally lower in the southern locations than in the north. These figures are similar to those obtained by Odekunle[21] earlier. He also noticed that the various proportions are generally lower in the southern locations than in the north. The rainfall retreats at the various locations when about 91% to 98% of the rainy days have been recorded. Ilesanmi[22] and Odekunle[3] had earlier noted that rainfall retreats all over the country when more than 90% of the rainfall had been recorded.

Table 4. Comparisons of some mean rainfall onset and retreat periods observed in this study with those of some previous studies.

S/N	Station	Rainfall onset period		Rainfall retreat period	
		Present study	Previous studies	Present study	Previous studies
1	Ikeja	27–31 March	28 March[1]	7–11 November	10 November[1]
2	Benin	11–15 April	31 March[1]	28 October–1 November	1 November[1]
3	Ilorin	16–20 April	14 April[1] 15 April[21]	18–22 October	7 October[21] 14 October[1]
4	Kaduna	31 May–4 June	15 May[21] 19 May[1]	3–7 October	22 September[21] 26 September[1]
5	Kano	5–9 June	28 May[1] 4 June[21]	18–22 September	8 September[1] 12 September[21]

6. Conclusion

The study has successfully combined the second-order polynomial and some elements of algebra and trigonometry with the ogive to objectively (mathematically) locate the rainfall onset, peak, and retreat on the ogive. It is shown that rainy-day frequency is better than the rainfall amount in determining the rainfall onset, peak, and retreat over Nigeria. The rainfall peaks are best determined from the rainy-day pentad graphs. The second-order polynomial perfectly modeled the two curvatures of the percentage cumulative rainfall (ogive).

The rainy-day frequency in the southern part of the country exhibited double rainfall maxima while those of the northern part showed a single rainfall maximum. The double rainfall maxima are not peculiar to the southwestern region of Nigeria as previously widely published; it cuts across the whole southern region. The number of days and the depth of the trough between the double rainfall maxima, indicating the severity of the LDS, dimmish from the largest values in the extreme southwest to the least in the extreme southeast. The first rainfall peaks were attained in southern Nigeria in July except at Ikeja which was in June. The second rainfall peaks were reached in September in all the southern stations. The single peaks were attained in all the extreme northern stations in August and in the other stations south of them in early September. The first rainfall peak was attained first in Ikeja and spread eastwards and northwards thereafter. The second rainfall peak was first attained in the eastern part of the country and thereafter spread westwards. The rainfall onset begins at Ikeja in the extreme southwestern corner of Nigeria around March ending and spreads eastwards and northwards to cover the entire country by mid-June at Nguru in the north-eastern corner. It is generally earlier in the western than the eastern flank. Rainfall begins to retreat from the northernmost stations by the third week in September to reach the extreme southern stations between October ending and early November. Rainfall onsets are experienced in various locations across the country when about 10% to 21% of the total annual rainy days have been recorded and these percentages are generally lower in the southern locations than in the north. The rainfall retreats at the various locations when about 91% to 98% of the rainy days have been recorded. The rainfall onset and retreat dates observed in this study are about 1 to 15 days later than those of the previous studies. These are expected because the method used by the present study is objective whereas, the approach used in the previous study is subjective. Also, from personal observation of the rainfall seasonality in the various locations in Nigeria, the results of rainfall onset and retreat dates obtained in this study are the realities.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, TOO; methodology, TOO; software, TOO, AOA, FAA and AAA; validation, TOO, AOA, FAA and AAA; formal analysis, TOO, AOA, FAA and AAA; investigation, TOO, AOA and FAA; resources, TOO and FAA; data curation, TOO, AOA and FAA; writing—original draft preparation, TOO; writing—review and editing, TOO, AOA and FAA; visualization, TOO, AOA and FAA; supervision, TOO and FAA; project administration, TOO;. All authors have read and agreed to the published version of the manuscript.

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