A STUDY OF CLIMATIC VARIABILITY IN NIGERIA BASED ON THE ONSET, RETREAT, AND LENGTH OF THE RAINY SEASON

O.J. OLANIRAN

Department of Geography, University of Ilorin, Nigeria

AND

G. N. SUMNER

Department of Geography, St. David's University College, Lampeter, Dyfed. U.K.

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ABSTRACT

The long-term variability of rainfall conditions in Nigeria in terms of the onset, retreat, and length of the rainy season has been analysed, using pentad data for the period 1919–1985. Data were grouped into four areas, arranged in a south–north transect; the Coastal, Guinea-Savanna, Midland and Sahelian Zones. The series for retreat of rainfall showed evidence for quasi-triennial and quasi-6-year oscillations, while that for rainy season length displayed quasi-biennial and quasi-triennial oscillations. No consistent spectral peaks emerged for changes in the date of onset of the rainy season. There is spatial coherence in variation in the date of the retreat of rainfall over the whole country, whilst for the date of onset of the season spatial coherence is limited to southern Nigeria (Coastal and Guinea-Savanna Zones). Northern Nigeria (Midland and Sahelian Zones) and southern Nigeria (Coastal and Guinea-Savanna) emerge as distinct areas in terms of spatial coherence in the variation of the length of the rainy season. There is also evidence for a secular change in the date of the retreat of rainfall for the whole country during the period 1939–1985, and in the date of onset of rainfall for southern Nigeria for 1968–1985.

KEY WORDS Nigerian rainfall Rainfall periodicity Rainfall trends Rainfall fluctuations

INTRODUCTION

Moist south-westerly winds bring rainfall into Nigeria from the tropical Atlantic Ocean across the Gulf of Guinea coast. At the surface this moist airstream can penetrate beyond Nigeria as far as the southern fringes of the Sahara Desert near latitude 20° N. Figure 1 shows that this south-west monsoon flow decreases in thickness northwards from the Gulf of Guinea. It is overlain by a hotter and drier north-easterly airstream, which originates from above the Sahara. Globally, the zone at the surface which separates the south-westerlies from the north-easterlies has been variously called the Inter Tropical Convergence Zone (ITCZ), the Inter Tropical Front (ITF) and the Inter Tropical Discontinuity (ITD), or simply the Equatorial Trough dependent upon the varying emphases placed on cloud and precipitation development or temperature and humidity contrasts. In Nigeria, and in this study, stress must be laid upon the moisture discontinuity across the zone, so that the term ITD is preferred.

Areas to the north and to the immediate south of the ITD are virtually rainless, the first because the air mass is dry and if any cloud exists at all it is of a high cirriform nature, and the second, because only slight cumuliform development can occur by day. Rainfall thus occurs in zones C and D in Figure 1, at a considerable distance south of the surface location of the ITD. In these zones conditions favour the development of clouds of considerable vertical extent. Zone E, to the south of these again, is characterized by extensive stratiform development, and consequently reduced rainfall.

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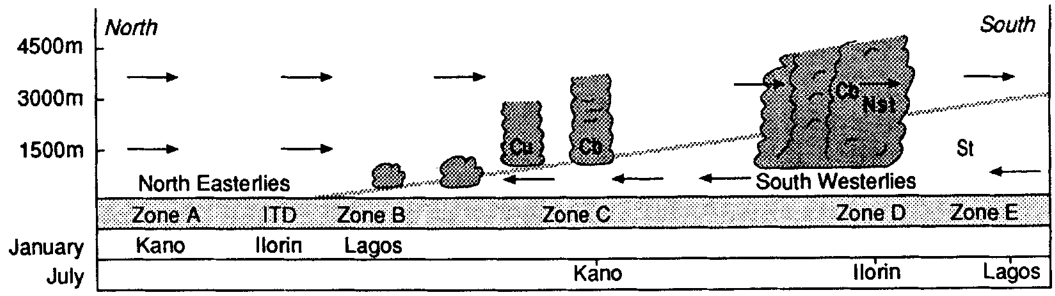

Figure 1. The ITD and the weather zones in an idealized atmospheric cross-section from south to north over Nigeria (from Ojo (1977))

The position of the ITD fluctuates seasonally, causing movement in the areas affected by the zones of different cloud and precipitation development. Between January/February and August there is a net northward advance of the zones as the ITD moves northwards, with a corresponding retreat south again from about the end of August. When the ITD is at its most northward extent in July/August, beyond Nigeria's northern border, zone-E weather affects an area extending a short way inland from the coast, producing what is known as the intramonsoonal period in this area.

Although seasonal variation in rainfall occurrence in Nigeria may appear initially to be a simple matter, as outlined above, it is still characterized by a high degree of variability in terms of:

(i) the times of onset and retreat of rainfall over the different areas of the country:
(ii) the length of the rainy season;
(iii) total rainfall during the rainy season;
(iv) rainfall frequency.

All previous studies of climatic change in West Africa using rain-gauge data have been based on total annual rainfall (e.g. Ayoade (1973), Kowal and Kassam (1975), Klaus (1978), and Nicholson (1980) or annual and monthly rainfall series (Gregory, 1983; Hutchinson, 1985; Dennett *et al.*, 1985). Elsewhere, however, some effort has been concentrated on analyses of the onset of specific shorter-term phenomena, for example, of spring weather in Britain (Davis, 1972), or of the monsoon over India (Subbaramayya and Bhanu Kumar, 1987). This study attempts, therefore, to look at periodicities, trends, and fluctuations in the precipitation climate of Nigeria based on the rainfall attributes (i) and (ii) above, and using short-term (pentad) data for as long a data record as possible.

METHODS OF STUDY

Determination of times of onset, end, and duration of the rainy season

The dates of the onset, duration, and retreat of the rainy season have been determined according to the method outlined by Ilesanmi (1972). This involves, first, computing the percentage of the mean annual rainfall occurring for each 5-day interval (pentad), and second, accumulating and plotting the computed percentages throughout the year. The time of onset of the rainy season is then taken to be the first point of maximum curvature on the plotted graph, provided that this date is not followed by a dry spell of 10 days or more. The time of cessation of the rainy season is similarly the last point of pronounced negative curvature on the graph, provided again that it is not preceded by a dry spell of 15 days or more. The total duration of the rainy season is the time interval between these two. An evaluation of Ilesanmi's method in relation to other techniques of determining the onset of rainfall has been undertaken by Olaniran (1983a).

DATA

Daily rainfall data for the 21 stations shown in Figure 2 have been collected for the period 1919–1985, and although data availability varied from one station to another, the stations chosen possess a long record of

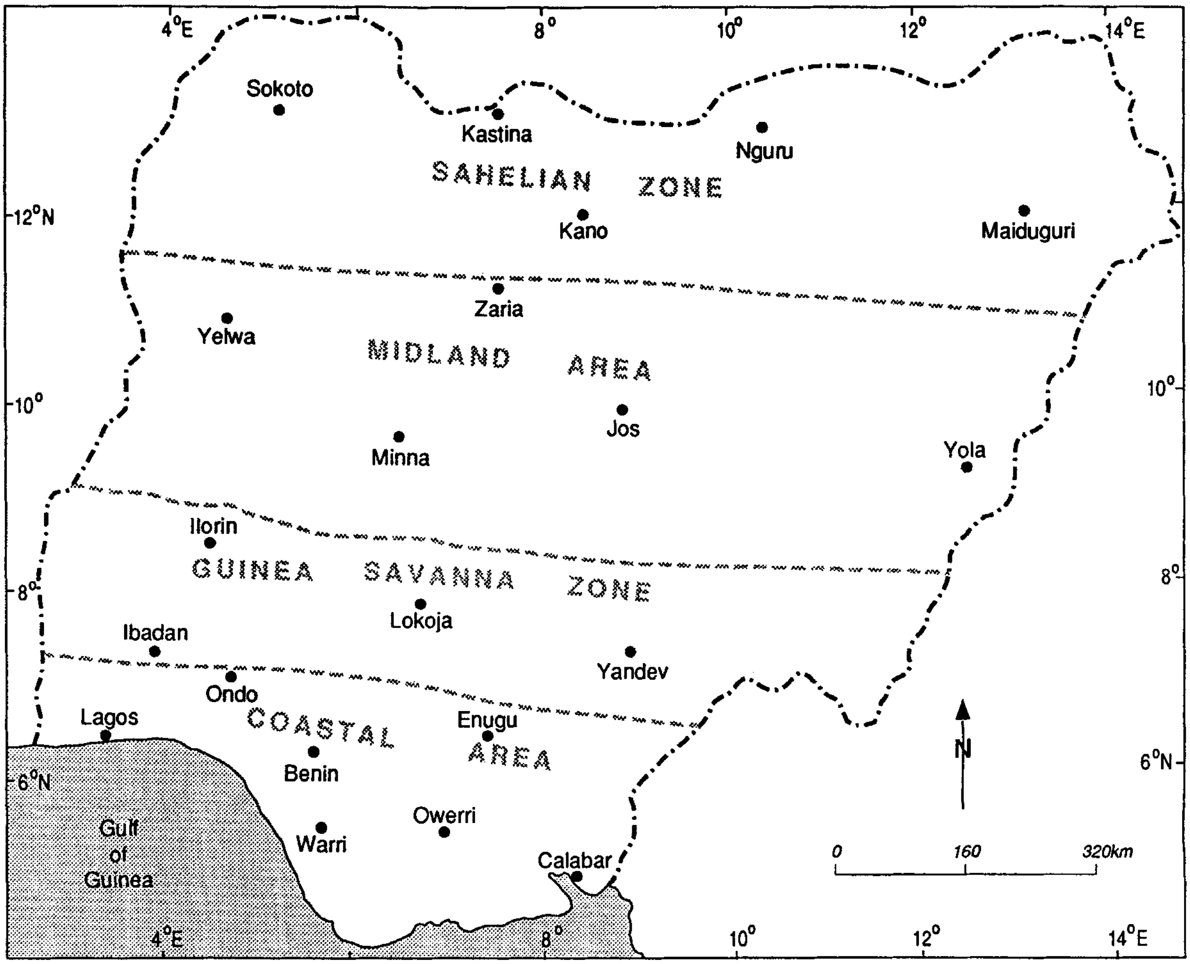

Figure 2. Map of Nigeria showing the data collection stations and geographical regions

data, and, as well, are, as far as possible, evenly distributed throughout the country. These data were then subjected to the elementary analysis described above. These 21 stations have been grouped into four areas, reflecting areas of differing physical control on the climate, based on the study by Olaniran (1987). These areas are:

(i) the Coastal Zone, dominated by tropical maritime (mT) air for most of the year;

(ii) the Guinea-Savanna zone, where mT air dominates for about 7 months, but with tropical continental (cT) air for the remaining 5 months;

(iii) the Midland Zone, which is predominantly highland, where the cT air mass dominates, but where the topography effectively extends the length of the humid period, due to localized convection and orographic effects (Olaniran, 1983b);

(iv) the Sahelian Zone, where the cT air mass predominates, and the mT air mass invades for between only 3 and 5 months at most (Olaniran, 1983b).

Using the criteria laid down originally by Ilesanmi (1972), and described briefly above, mean dates for the onset and retreat of the rainy season were obtained for each of these four zones, and also subsequently for rainy season duration. Using the available data, a maximum of between four and seven stations appear in each zone. The area means were based on a minimum of five sites for the Coastal Zone, three for the Guinea-Savanna and Midland Zones, and four for the Sahelian Zone. In the Midland and Guinea-Savanna zones, the start of the continuous data record was delayed, so that only for the Coastal and Sahelian Zones did the effective data record match the complete series, 1919–1985. Therefore, in the Midland Zone the effective record was from 1922 to 1985, and in the Guinea-Savanna Zone, from 1939 to 1985.

For certain years, even these minimum thresholds of sites could not be realized, so that, within the data periods specified above, 3·5 per cent of data were missing for the Coastal Zone, 2·8 per cent missing for the Guinea-Savanna Zone, 4·2 per cent missing for the Midland Zone, and 3·7 per cent for the Sahelian Zone. Estimates of dates for the years with missing values were determined using multiple regression equations based on latitude, longitude, and elevation (see Olaniran (1984)). The problem of missing data was more serious prior to 1940 than in the post-1940 period when all the stations had been established. In the ensuing analysis, therefore, greater reliability may be assigned to cycles and trends which are post-1940, than for the period before 1940.

Mean dates of the time of onset and cessation of the rainy season have been calculated for the duration of the effective data period, as outlined above. These appear in graphical form for each of the four zones in Figure 3 (a and b). A summary of overall mean dates is presented in Table I. A similar sequence of graphs for each area for rainy season duration appears in Figure 3c. Each graph expresses the time of occurrence (for dates) or duration as a deviation in whole days about the mean for the whole period. Positive deviations indicate years with an early onset or late end to the rainy season, or longer than average durations, whilst negative deviations connote years with a late onset, early end, or shorter than average duration.

DATA ANALYSIS

Each series relating to onset, cessation, or duration of the rainy season has been analysed for periodicities, fluctuations, and trends using power spectra and low-pass filter techniques, and the Mann–Kendall (τ) rank statistic.

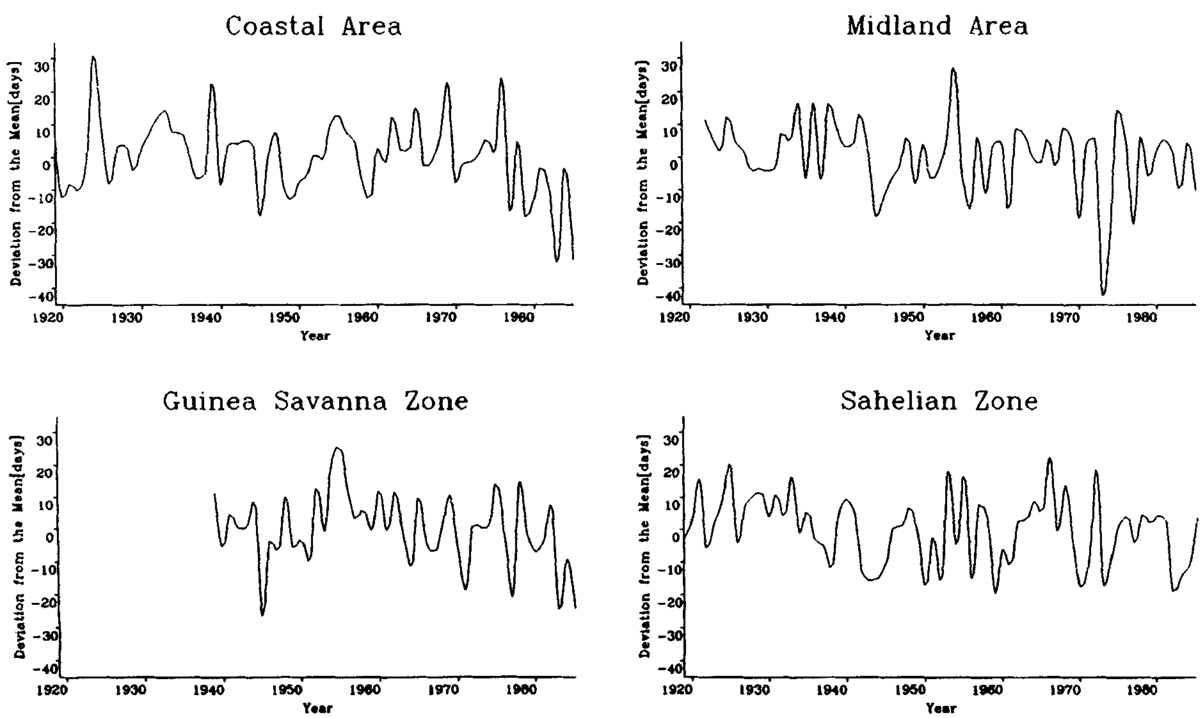

Figure 3. (a) Variation of onset of rainfall in Nigeria (1919–1985)

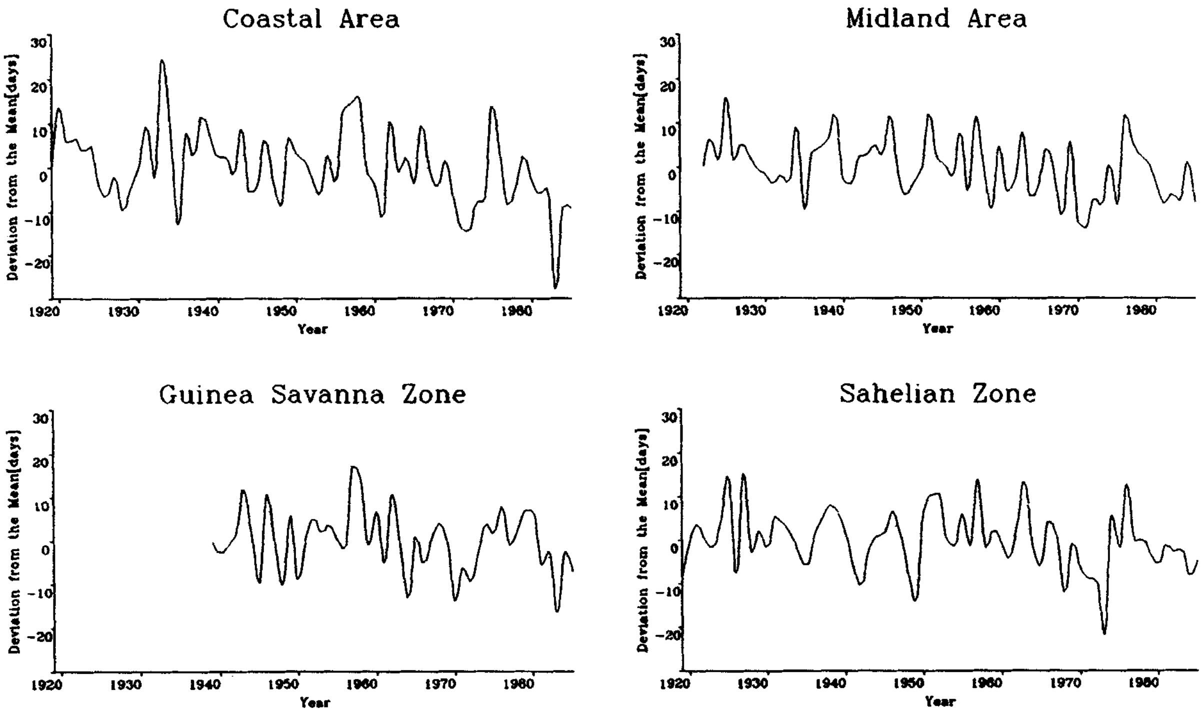

Figure 3. (b) Variation of retreat of rainfall in Nigeria (1919–1985)

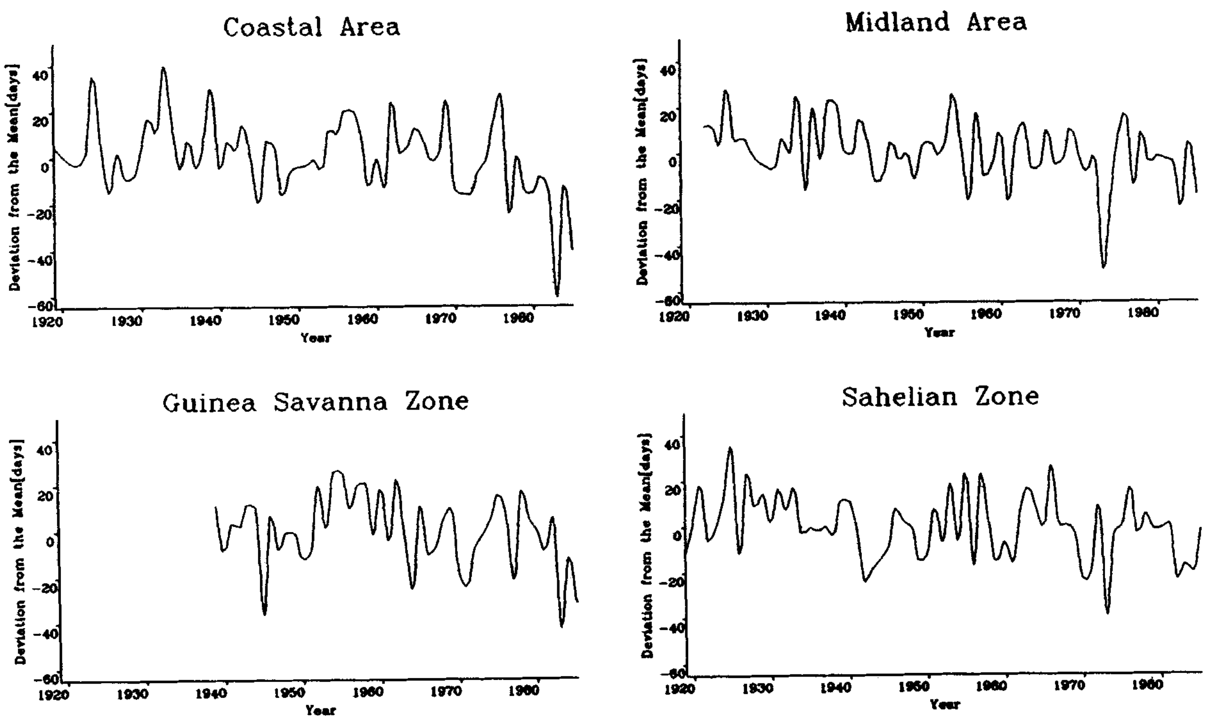

Figure 3. (c) Variation of length of rainy season in Nigeria (1919–1985)

Table I. Summary of the characteristics of the rainy season in Nigeria. The limits in parentheses correspond to the 95 per cent probability level

Area	Mean date of onset	Mean date of retreat	Mean duration (days)
Coastal	March 26 (± 3)	Nov. 1 (± 2)	220 (± 4)
Guinea-Savanna	April 16 (± 3)	Oct. 17 (± 2)	184 (± 5)
Midland	May 11 (± 3)	Oct. 3 (± 2)	145 (± 4)
Sahel	June 15 (± 3)	Sept. 20 (± 2)	97 (± 4)

Power spectrum analysis

Each series was subjected to power spectrum analysis using a maximum lag of 30, but subject to the condition that oscillations greater than one-third the number of years in each series will be rejected even if found to be statistically significant (see Mitchell *et al.* (1966), Flocas and Giles (1984)), so as to protect against spectra of a possibly spurious nature. Tests of significance in this study were as described by Mitchell *et al.* (1966), with the null hypothesis continuum determined at the 95 per cent probability level. The analysis utilized the ASPECT software, developed by the University of Warwick, adopting the Bartlett window conforming to the spectral analysis as described by Mitchell *et al.* (1966).

The low-pass filter technique

The application of filter analysis to meteorological data has been discussed by Panofsky and Brier (1958), Mitchell *et al.* (1966), and Craddock (1968).

Each of the rainfall departure series was subjected to a low-pass filter using nine weighting factors, which conform to binomial coefficients: 0·22 for the central year (i), 0·20 for the years ($i \pm 1$), 0·12 for the years ($i \pm 2$), 0·05 for the years ($i \pm 3$) and 0·02 for the years ($i \pm 4$). This filter has a response function that is equal to unity at infinite wavelengths but decreases asymptotically to zero with decreasing wavelengths. The response of this filter is approximately given by the equation:

$$R(f) = \cos^n \pi f \tag{1}$$

where $R(f)$ is the frequency response, f is the frequency, and n is the appropriate length of the moving average. The method of constructing the weights of this filter has been detailed by Mitchell *et al.* (1966).

To avoid loss of terms corresponding to $0{\cdot}5\,(k-1)$, where k is the number of filter weights at the beginning and end of the filtered series, Vines (1982) suggested adding the average value of the unfiltered series $0{\cdot}5\,(k-1)$ times at the beginning and end of the unfiltered series. This results in a filtered series having the same number of terms as the original series. This approach was followed in this study and the possible edge effect of this approach on the filtered series should be noted.

The Mann–Kendall (τ) statistic

Trend refers to the monotonic increase or decrease in average value between the beginning and end of a time series (Giles and Flocas, 1984). Although the trends in climatic data are seldom linear (Mitchell *et al.*, 1966), the linear regression method has been used to search for trends in many climatic time series (e.g. Ayoade (1973), Hutchinson (1985), and Subbaramayya and Bhanu Kumar (1987)). In testing for non-randomness against trend, Mitchell *et al.* (1966) suggested the use of either Mann-Kendall (τ) or Spearman (r) rank statistics. The Mann–Kendall statistic was applied in this study.

In view of the assertion by Winstanley (1973) that rainfall will decline over the Northern Hemisphere part of the tropics from 1930 to 2030, and consistent with the discussion on data quality above, the secular trend in the deviation series was first investigated for the period 1939–1985. The two subperiods for which trends were also investigated are 1939–1967 and 1968–1985. The latter period was selected to embrace the serious drought episode which has afflicted Sahelian West Africa since the late 1960s (Lamb, 1980), with the latter period determining the former.

RESULTS

Periodicities in the onset, retreat, and duration of the rainy season

Before subjecting all the regional series to spectral analysis, their non-randomness and conformity to the Gaussian normal distribution was tested. All the regional series were found to be non-random using the lag-one serial correlation (r_1) test as discussed by Mitchell *et al.* (1966). The frequency distribution of each of the rainfall deviation series was tested for normality using Fisher's coefficient of skewness (v_1) and kurtosis (v_2), compared with their standard errors (s.e.). The only series not found to satisfy these conditions were those for the date of onset and duration of the rainy season in the Midland area. Both these series could be normalized by the application of $\log_{10}$-square correction. Finally, in order to obtain smooth spectral estimates all series were detrended using the transformation:

$$X_t \mapsto X_t - \alpha - \beta t' \tag{2}$$

as provided for in ASPECT. In this transformation the coefficieints α and β are fitted by the least-squares method to the mean values over each period of the time series.

The periods corresponding to the significant spectral peaks in the detrended series at the 95 per cent probability level are listed in Table II, and in Table III the proportion of the variance accounted for by the significant quasi-periodic oscillations are presented. The results in Table II show that a quasi-biennial oscillation with periodicities of 2·4–2·7 years applies to the dates of onset series in Coastal, Guinea-Savanna, and Midland areas, but fails to occur in the Sahelian Zone. Further groupings of oscillation periods occur at 3·2–3·9 years in the Coastal, Guinea-Savanna, and Sahel Zones, and at 4·1–4·8 years in the Coastal, Midland, and Sahel Zones, although taken together, these two groups form a long continuum across the whole country. A further group of oscillations between 6·0 and 6·7 years appears for areas inland from the Guinea-Savanna Zone, but not in the Coastal Zone. No spectral peak therefore, is common to all four zones, although all are common to three, but in different combinations.

In contrast to periodicities in the dates of onset of the rainy season, the power spectra for dates of the retreat of rainfall show two oscillations which are consistent over the whole country: at 3·2–3·3 years, and at 5·7–6·3

Table II. Yearly periodicities corresponding to spectral peaks, significant to the 95% level

Area	Yearly periodicities			
Onset of rainy season				
Coastal	2·7	3·2	4·1, 4·8	
Guinea-Savanna	2·7	3·3		6·7
Midland	2·4		4·1	6·0
Sahel		3·9	4·6	6·7
Retreat of rainy season				
Coastal		3·2	4·1	6·0
Guinea-Savanna	2·7	3·2		5·7
Midland	2·3, 2·7	3·3	4·4	6·3
Sahel	2·4	3·2		6·3
Duration of the rainy season				
Coastal	2·7	3·2	4·8	6·0
Guinea-Savanna	2·7	3·2		6·3
Midland	2·5	3·2	4·1	
Sahel	2·3, 2·8	3·2	4·0, 4·6	6·0

Table III. Percentage of total variance explained by various spectral peaks

	Oscillation with peak at (years)				
Onset of rainy season					
Region	2·4–2·7	3·2–3·9	4·1–4·8	6·0–6·7	
Coastal	21·3	6·4	3·8		
Guinea-Savanna	15·0	26·7		6·3	
Midland	19·5		9·9	5·1	
Sahel		4·9	6·5	1·5	
Retreat of rainy season					
Region	2·3–2·4	2·7	3·2–3·3	4·1–4·4	5·7–6·3
Coastal			18·4	3·0	9·5
Guinea-Savanna		51·5		6·5	5·0
Midland	28·4	20·5	1·7	3·7	5·7
Sahel	26·0		11·4		16·5
Duration of the rainy season					
Region	2·3–2·8	3·2	4·0–4·8	6·0–6·3	
Coastal	17·0	24·0	6·9	7·7	
Guinea-Savanna	33·5	19·2		4·3	
Midland	20·6	3·1	8·9		
Sahel	34·6*	4·9	5·4	1·2	

* Two combined oscillations.

years. There is also a 2·3–2·7-year cycle, but this is absent in the Coastal Zone, and evidence for a 4·1–4·4-year cycle in two zones: Coastal and Midland.

Similar periodicities also emerge for the rainy season duration series, but in the case of the quasi-2-year and quasi-3-year periodicities, apply more generally over the whole country. The quasi-2-year cycle ranges from 2·3 to 2·8 years, whilst the quasi-3-year cycle is the same in all zones: 3·2 years. There is continued evidence to support the further two ranges of cycles which emerged for both onset and retreat series, although these do not apply across the whole country. There is a 4·0–4·8 year oscillation, which is absent only from the Guinea-Savanna Zone, and further, a 6·0–6·3-year cycle, absent from the Midland Zone.

Four distinct cycles emerge from the power spectra analysis illustrated in Figure 3 and Table II. In approximate terms their ranges cover quasi-2-year, quasi-3-year, quasi-4-year, and quasi-6-year periods. Of particular interest is the quasi-biennial oscillation (QBO) which has emerged for the date of onset of rains in the Coastal, Guinea-Savanna and Midland Zones, and for the date of retreat of rains in Guinea-Savanna, Midland and Sahel Zones. It is present in all zones for rainy season duration. Subbaramayya and Bhanu Kumar (1987) also found evidence of this oscillation in the dates of onset of the summer monsoon for the six regions of India considered by them, while Ayoade (1973) has earlier found evidence that the QBO is a common feature in the annual rainfall series for 42 stations in Nigeria itself. Jagannathan and Bhalme (1973) for India, Landsberg (1975) for Dakar, Senegal, and Klaus (1978) for West Africa as a whole, have all reported evidence of strong spectral bands of 2·0–2·9 years for annual rainfall series. Although the QBO is best developed in the tropics, it occurs world-wide (see Oladipo (1987)). In addition, the QBO is often linked to an oscillation averaging 2·2 years, as displayed by tropical stratospheric winds, or the 26-month cycle in the ultraviolet flux of the sun (Tabony, 1979; Oladipo, 1987).

A quasi-triennial oscillation has been found in this study to be common to all regional series, except for the dates of onset of rainfall in the Midland Zone (Table II). Oscillations of a similar order have been found in the drought series of the interior plains of North America (Oladipo, 1987), Indian drought indices (Bhalme and Mooley, 1983), East African annual rainfall series (Rodhe and Virji, 1976) and in West African rainfall series (Ayoade, 1973; Klaus, 1978). This oscillation is close to that of the Southern Oscillation (SO), which possesses a modal peak in the 3–5-year range (see Rodhe and Virji (1976)). This range also includes the quasi-4-year cycle, identified for some zones in each of the series being considered, and may further indicate that it would be

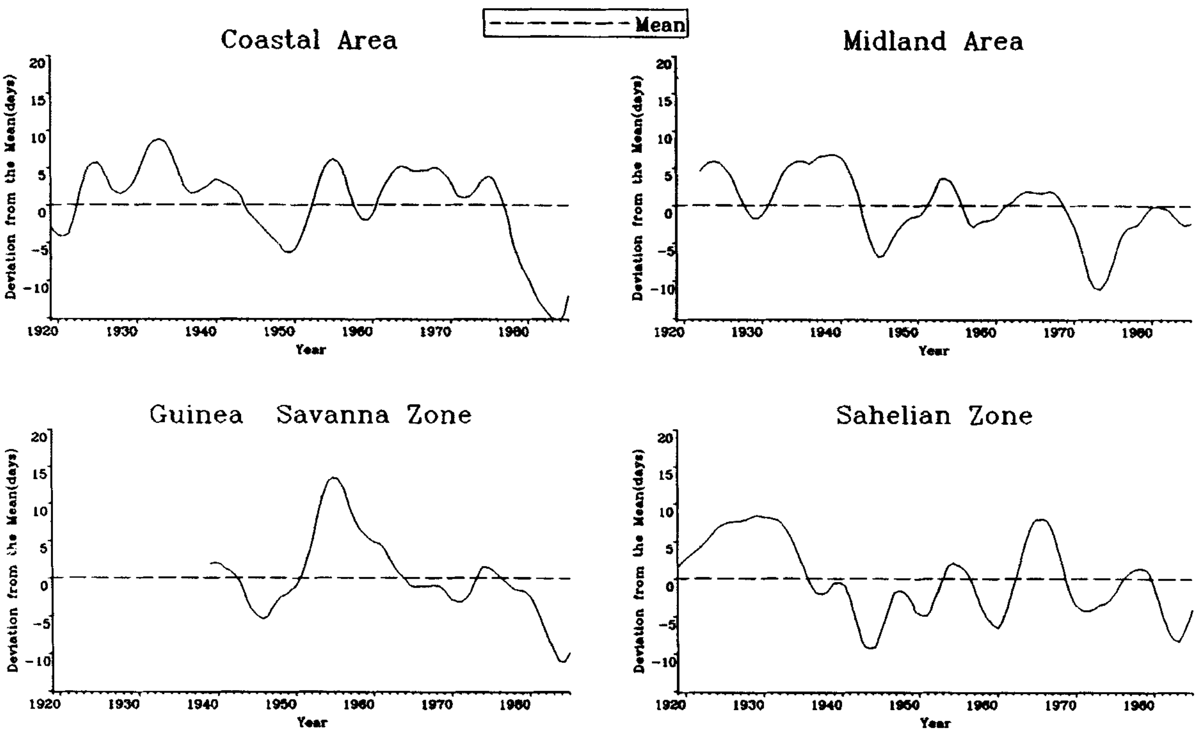

Figure 4. (a) Variation of onset of rainfall in Nigeria smoothed by a low-pass filter

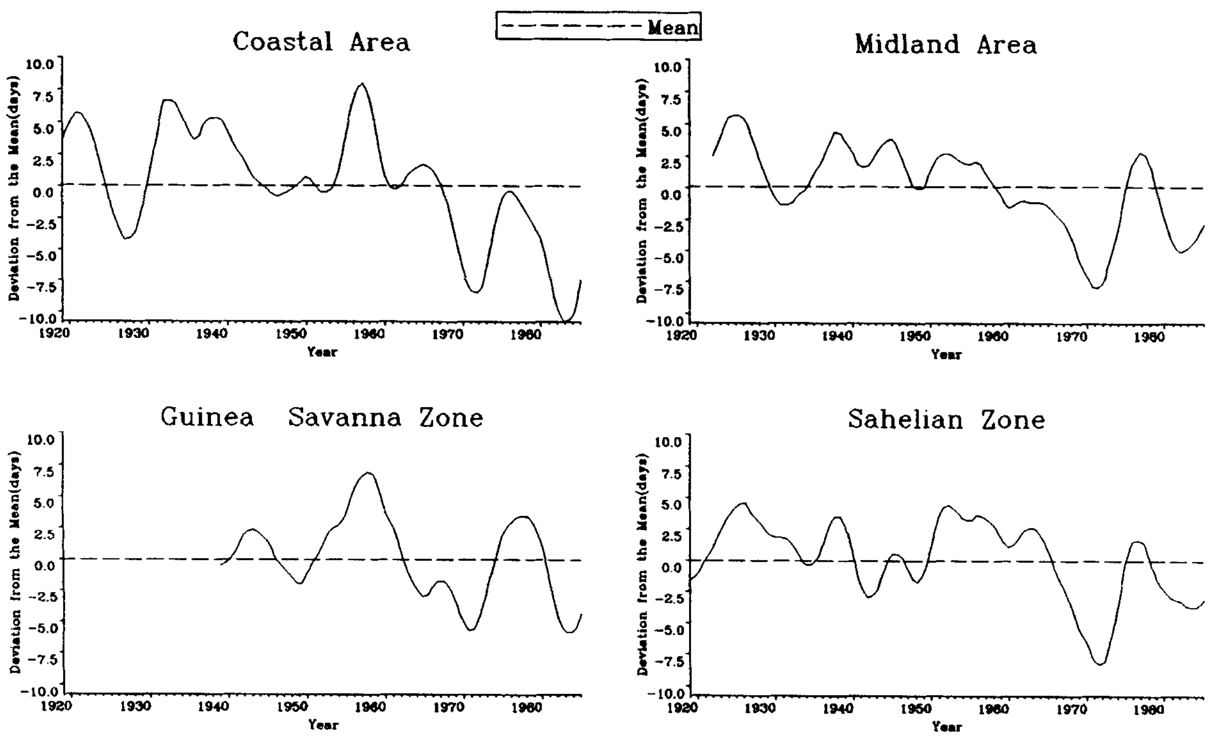

Figure 4. (b) Variation of retreat of rainfall in Nigeria smoothed by low-pass filter

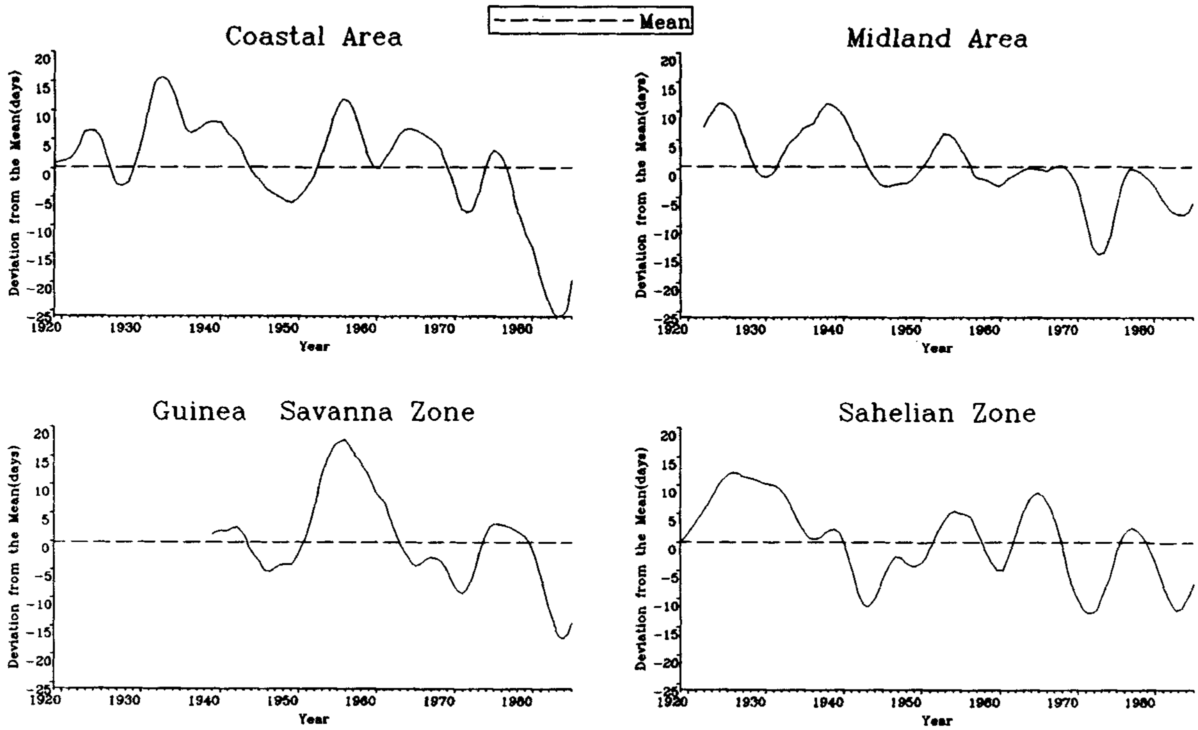

Figure 4. (c) Variation of length of rainy season in Nigeria smoothed by a low-pass filter

appropriate to merge the two ranges. This would be particularly appropriate when considering the series for dates of onset of the rainy season, as referred to above. A quasi-4-year cycle in itself has rarely been reported for rainfall data, although Ayoade (1973) found some evidence for it in Nigerian annual rainfall series. More commonly, it has been isolated for temperature series. It has, for example, been reported for annual temperature series in the Prairie provinces of Canada (Georgiades, 1977) and for Greece (Flocas and Giles, 1984).

The next important spectral peak in the series is the quasi-6-year oscillation, displayed in all series and all zones, with the exception of the series for dates of onset in the Coastal Zone, and for duration in the Midland Zone. Subbaramayya and Bhanu Kumar (1987) also found evidence of peaks between 6 and 8 years in the series for the onset of the Indian summer monsoon for many areas in that subcontinent. Cycles of this order may be produced by the interaction of the single sunspot cycle with longer term cycles, for example, the Bruckner cycle of 35 years, or the lunar cycle of 18·6 years (Vines, 1982, 1986).

Although the quasi-periodic oscillations discussed above are statistically significant they account for small amounts of the variance, especially the quasi-triennial and higher oscillations (Table III). The temptation to use them for prediction purposes should therefore be resisted. In fact, as noted by Rodhe and Virji (1976), many attempts in such directions have failed to produce useful forecasts. However, the results of the spectral analysis will be useful in helping our understanding of the physical processes which influence the fluctuations in the timing and duration of rainfall events in West Africa. For example, the results of spectral analysis as presented in this study will serve to strengthen the belief of extra-terrestrial influences on climatic fluctuations, as noted by Landsberg (1975).

Fluctuations in the onset, retreat, and duration of the rainy season

Fluctuations in the dates of onset and retreat, and duration, of the rainy season for the four zones of Nigeria are shown in Figure 4. Fluctuations in annual rainfall conditions in sub-Saharan West Africa have been examined by Oguntoyinbo and Richards (1977) for stations selected along a south–north transect in Nigeria, for the Sudan Savanna part of Nigeria (the Sahel Zone in this study) by Kowal and Kassam (1975), and for the subtropical part of West Africa (between 10° and 20° N) by Lamb (1980, 1982). Based on these studies, the periods, 1924–1931, 1943–1945, 1947–1950, 1968–1974, 1977, and 1979–1981 have been identified as times of widespread drought, while 1950–1958 and 1959–1967 recorded above-average and near-average rainfalls, respectively. The fluctuations in Figure 4 are discussed with these sequences in mind.

The peak periods of delayed onset of rainfall during the 1940s shown in Figure 4a are not perfectly in phase for the four zones: being centred on 1943–1944 in the Sahel, on 1945 in the Midland and Guinea-Savanna Zones, but on 1948–1949 in the Coastal Zone. On the other hand, the peak periods of delayed onset of rainfall associated with the widespread droughts, reported in the literature for the period 1968–1974, seem to occur at about the same time in the different zones, except, again, in the Midland Zone. In the Sahel, where it is most pronounced, it is centred on 1970–1974, on 1972–1974 in the Midland Zone, but on 1970–1972 in the two southern zones. The curves in Figure 4a also show that the delayed onset of rainfall in the early 1970s was greatest in the Midland area, and pronounced in the Sahel Zone, but was generally small in the two southern zones. The figure also shows that the peak period of delayed onset of rainfall in the early 1980s is centred on 1983–1984 in the Coastal Zone, but on 1983 in the rest of the country, while its intensity is most pronounced in the two southern zones.

Figure 4a further shows that there is also some correspondence between periods of early or about normal onset of rainfall and the broad times of average or above-average rainfall reported in the literature. Thus, the above-average rainfall of 1950–1958 reported in the literature, is associated with an early onset of rainfall with peaks centred on 1954–1955 in the two southern zones, on 1953 in the Midland area, and on 1954 in the Sahel. The near-average rainfall for the 1960s, reported in the literature for subtropical West Africa, is shown in Figure 4a to be associated with a near-normal date of onset of rainfall in the Guinea-Savanna and Midlands areas during much of that decade, but with an early onset of rainfall in the Coastal and Sahel areas, with a peak centred on 1965–1966 in the Sahel.

The results of a simple linear correlation between the raw, unfiltered data (Table IVa) show that, for adjacent areas, the greatest degree of interregional coherence (association) for fluctuations in the dates of the onset of the rainy season between 1939 and 1985 is between the Coastal and Guinea-Savanna Zones. Between these two zones the correlation (r) reached 0·655, whilst lower values apply elsewhere ($r = 0·317$ between the Midland and Guinea-Savanna Zones, and 0·354 between the Midland and Sahel Zones). All correlation coefficients were significant at better than the 5 per cent rejection level, but r-squared values reach 42·9

Table IV. Interzonal correlations in rainy season characteristics. Significant levels: 5 per cent $r = 0·300$; 1 per cent, $r = 0·370$

Area	Coastal	Guinea-Savanna	Midland	Sahel
a) Onset of rainy season				
Coastal	1·000	0·655	0·305	0·192
Guinea-Savanna		1·000	0·317	0·112
Midland			1·000	0·354
b) Retreat of rainy season				
Coastal	1·000	0·595	0·343	0·324
Guinea-Savanna		1·000	0·484	0·255
Midland			1·000	0·682
c) Duration of rainy season				
Coastal	1·000	0·730	0·519	0·350
Guinea-Savanna		1·000	0·410	0·215
Midland			1·000	0·526

per cent for the two southern areas, and only 10·1 per cent and 12·5 per cent respectively between adjacent zones further north.

In contrast to the dates of onset of rainfall series, the degree of interzonal association for the retreat of rainfall series, and between these and the above and below-average rainfall periods identified earlier, is comparatively high (Figure 4b). The marked rainfall deficit reported in the literature for the period 1947–1950 is associated with an early retreat of rainfall in the Guinea-Savanna Zone, with the peak centred on 1949, on 1947–1948 in the Midland Zone, and on 1948 in the Sahel Zone, while the Coastal area experienced normal times of retreat of rainfall around this time (Figure 4b). All four areas experienced a notably early retreat of rainfall in the early 1970s, with the peak centring on 1970–1972, and also in the early 1980s, centring on 1983 for the two southern zones, on 1981 for the Midland Zone, and on 1982–1983 in the Sahelian Zone.

The above-average rainfall of 1950–1958 reported for sub-Saharan West Africa, is associated with a late retreat of rainfall in all four areas, and the peak centred on 1956 in the Coastal area, 1957 in the Guinea-Savanna Zone, on 1951–1956 in the Midland area, and on 1951–1958 in the Sahel Zone. On the other hand, there are pronounced regional differences in the pattern of retreat of rainfall during the 1960s when subtropical West Africa experienced near normal rainfall conditions. The time of retreat of rainfall was normal only in the Coastal Zone. Kowal and Kassam (1975) on the basis of their analysis of annual rainfall fluctuations for the Sahel, projected that conditions would be wet towards the end of the 1970s. This projection has been realized, but with the above-average rainfall associated with a delayed retreat rather than with an advanced time of onset, of the rainy season (Figure 4a and b).

The interzonal correlations between adjacent areas for the time of retreat series reveal comparatively high coefficients: 0·595 between the Coastal and Guinea-Savanna areas; 0·484 between the Guinea-Savanna and Midland areas; and 0·682 between the Midland and Sahel Zones (Table IVb). When compared to interzonal correlations for the dates of onset of the rainy season the coefficients show a consistently high degree of association (r-squared, 35·4 per cent, 23·4 per cent and 46·5 per cent) across the country, indicating a much higher and more uniform degree of spatial coherence. Only between the two southern zones was the degree of association poorer than was the case for the date of onset series.

Finally, the plots of yearly variation in rainy season duration (Figure 4c) show that a high degree of association exists between the two southern zones, and a less pronounced one between the two northern zones. A linear correlation of $r = 0{\cdot}730$ (r-squared, 53·3 per cent) exists between Coastal and Guinea-Savanna areas, and of $r = 0{\cdot}526$ (r-squared, 27·7 per cent) between the Midland and Sahel Zones. Between the Midland and Guinea-Savanna Zones, however, $r = 0{\cdot}410$ (r-squared, 16·8 per cent). These figures suggest that in terms of spatial coherence in rainy season duration the country may be divided into two halves, northern and southern, embracing on the one hand, the Coastal and Guinea-Savanna Zones, and on the other, the Midland and Sahel areas.

Nicholson (1980) analysed the nature of fluctuations in annual rainfall for subtropical West Africa and reported a strong coherence in variation throughout the region from the southern fringe of the Sahara to 10° N. In the light of the results obtained in this study it seems this conclusion should be modified, at least in terms of the three rainy season characteristics under study. Such characteristics are in themselves, as well as the amount of rainfall, important determinants of the efficacy and usefulness of the rain falling during the rainy season. In particular, therefore, it is important to note that whilst the degree of spatial coherence in terms of the time of onset of the rains is strictly limited to the south of the country (the Coastal and Guinea-Savanna areas), that of the date of retreat of the rains is apparently strong throughout the country. The combined effect of these two variations is that, for rainy season duration, the south (Coastal and Guinea-Savanna) and to a lesser degree, the north (Midland and Sahel), represent two separate regions.

Such variation in the integrity of the areas may be explained in terms of the mode of advance and retreat of the rain-producing mechanisms. Specifically, the ITD invades from the south at the beginning of the rainy season in a highly irregular manner, in a series of surges, stagnations, and retreats. On the other hand, its net final retreat at the end of the rainy season is far more regular (Adejokun, 1966; Oguntoyinbo and Richards, 1977). This differential pattern of advance and retreat of the ITD, and possibly the enhancement of rainfall-producing processes by the highlands, for example the Midland area, have combined to determine the pattern of variations in the dates of onset, retreat and duration of the rainy season.

Trends in the onset, retreat, and duration of the rainy season

The three sets of regional series were next examined for secular changes using the Mann–Kendall (τ) rank statistic. The results obtained are shown in Table V. These suggest that the observed trends in the time of onset of the rainy season between 1939 and 1985 are, statistically, not significantly different from a randomly fluctuating series. The same conclusion may be reached for the period 1939–1967. However, for the 1968–1985 period there was a significant delay in the onset of the rainy season in the two southern areas, the Coastal and Guinea-Savanna Zones. One possible explanation of this might be that the irregular south to north advance of the ITD was limited to southern Nigeria during this period. Oguntoyinbo and Richards (1977) cited such a case for 1971.

The same statistic applied to the series for the times of retreat of rainfall suggests, cautiously (at the 90 per cent level), that, with the exception of the Guinea-Savanna area, Nigeria experienced a relatively early retreat of the rains throughout the period 1939–1985. For the Coastal and Midland areas this trend is significant at the 99 per cent and 95 per cent levels, respectively. Subdividing the data further, for the entire 1951–1985 period, the negative trend was statistically significant to the 99 per cent level for the Sahel area, and at the 90 per cent level in the Guinea-Savanna area. The data presented in Table VI support this view. Thus, while on average the time of retreat of rainfall was normal or about normal throughout the whole country during the period 1939–1950, for the period 1981–1985, the time of retreat of rainfall southwards was on average earlier by about 11 days in the Coastal Zone, 7 days in the Guinea-Savanna Zone, 6 days in the Midland Zone and 4 days in the Sahel.

The largely insignificant trend isolated for the Guinea-Savanna Zone for the times of retreat of rainfall, could result from intrazonal differences in rainfall fluctuation patterns. Oguntoyinbo (1981) mapped the rainfall anomaly for Nigeria for the period 1969–1973, and only the Guinea-Savanna Zone was found to show evidence of significant intrazonal variation. The results of rainfall correlation with time for the period 1931–1960 for 42 stations in Nigeria, carried out by Ayoade (1973), provide a similar pattern, while Nicholson (1980) reported similar intrazonal variations in the pattern of rainfall fluctuations for the Soudano–Guinea (Guinea-Savanna Zone in this study) and the Sahelo-Sahara zones of West Africa. Areal averages obtained for a region in which intrazonal variations are strong will result in comparatively obscure general trends.

For the series for rainy season duration, only in the Coastal area is there any evidence for a statistically significant trend through the period 1939–1985 (Table Vc). This is probably due to the highly significant

Table V. Trends in the times of onset and retreat of the rainy season, and in duration, using the Mann–Kendall (τ) rank statistic. Significance levels are indicated: 90 per cent (+), 95 per cent (*), 99 per cent (**)

Area	1939–1985	1939–1967	1968–1985
a) Onset of rainy season			
Coastal	−0·1638	0·0345	−0·4248*
Guinea-Savanna	−0·1563	−0·0197	−0·3464*
Midland	−0·0546	−0·0049	−0·1765
Sahel	−0·0194	0·0788	−0·0327
b) Retreat of rainy season			
Coastal	−0·2877**	0·0148	−0·1373
Guinea-Savanna	−0·1193	−0·0197	−0·0980
Midland	−0·2359*	−0·1576	0·1111
Sahel	−0·1933+	−0·0394	0·0458
c) Duration of rainy season			
Coastal	−0·2359*	0·0591	−0·2941+
Guinea-Savanna	−0·1637	−0·0099	−0·1765
Midland	−0·1434	−0·0493	−0·1111
Sahel	−0·0675	0·1527	−0·0196

Table VI. Deviation from the mean of dates of retreat of rainfall in Nigeria, 1939–1985 (positive values indicate late retreat, and negative, early retreat)

Period	Coastal	Guinea-Savanna	Midland	Sahel
1939–1950	1·2	0·3	1·6	−1·3
1951–1960	3·1	4·8	2·2	3·9
1961–1970	−0·3	−2·4	−2·8	−0·7
1971–1980	−4·0	1·2	−1·9	−3·2
1981–1985	−11·3	−7·0	−5·7	−3·8

trends in the times of onset and retreat of rainfall in this zone (Table Va and b) for 1968–1985 and 1939–1985, respectively.

These results show that there was no secular change in the time of onset of rainfall for the four areas during the period 1939–1985, other than that in the two southern areas during recent years, 1968–1985. The analysis of monthly rainfall series for the Sahel for the period 1941–1983 by Dennett *et al.* (1985), and for the period 1943–1982 for the Gambia by Hutchinson (1985) also indicated a lack of coherent secular changes in the timing of onset of rains. Both found that the June monthly rainfall (the month of normal onset of rainfall in the Sahel) did not change significantly during these periods.

In contrast to this lack of change in the timing of onset of rainfall, the results presented here show that the time of retreat of rainfall became progressively earlier during the 1939–1985 period. The studies of Gregory (1983), Dennett *et al.* (1985), and Hutchinson (1985) on the fluctuations of monthly rainfall in the Sahel also suggest this. Gregory (1983) found that rainfalls in the Sahel in August and September were reduced more during the period 1961–1980 when compared with 1931–1960. Dennett *et al.* (1985) and Hutchinson (1985) found for the Sahel and the Gambia, respectively, that August and September monthly rainfalls declined consistently during the period 1941–1983 (1943–1982 for the latter). To this can now be added that Nigeria experienced a progressively earlier retreat of rainfall between 1939 and 1985.

DISCUSSION—CHANGES IN THE REGIONAL CLIMATOLOGY

According to Winstanley (1973), the climatic zones in the Northern Hemisphere slowly shifted northward for about a century until around 1930, but since then there has been a southward movement, and thus, reduced rainfall, in the Sudano–Sahelian region of West Africa, and other similar regions. Winstanley expected this southward movement to continue until around 2030, and considered the variations as a part of a 200-year cycle. Lamb (1973) also expressed the opinion at the time that the phenomena giving rise to the Sudano–Sahelian drought have a long history and that the drought was not likely to disappear in the near future. Similarly, Bryson (1973) was pessimistic about the return of the monsoon rains to the region during this century. A long run of dry years was therefore indicated from a number of quarters at that time. Since then there has been a greater awareness of the magnitude of the impact of human activity through increases in global atmospheric carbon dioxide. Just what impact these effects have had or will have on any trend, is still open to question at the present time, although Bryson (1973) at the time explained the persistence of drought over sub-Saharan Africa in terms of the equatorward displacement of the subtropical highs, brought about by just such an increase in the amount of carbon dioxide and particulate matter in the atmosphere since the 1940s, resulting in an increase of temperature at the Earth's surface of the order of 0.1°C. Such a temperature increase, Bryson noted, may displace the latitude of the subtropical highs equatorwards by about 15 km, and thereby reduce the poleward advance of the ITD from the Gulf of Guinea coast.

Other workers, however, have suggested that the increasing aridity and unreliability of rainfall in sub-Saharan Africa is due to causes, initially at least, unrelated to the position of the latitudinal climatic belts. Nicholson (1980, 1981) suggested that the persistence of drought over the region is not due to large-scale displacements of the ITD, but rather to factors which inhibit rainfall activity behind (to the south of) the ITD. These factors may assume the form of changes of stability and vertical motion (Kidson, 1977) or variable convective activity, due to changes of sea-surface temperature and wind strength (Lamb, 1978, 1980). Newell and Kidson (1984) have further emphasized the importance of subsidence in the lower and middle atmosphere during the Sahelian rainy season, and have indicated an association between the strength of the mid-tropospheric easterly jets north and south of the Equator, the magnitude of the horizontal wind shear and the intensity of the temperature gradient.

Regardless of cause, however, the view that drought conditions are liable to continue for some time in sub-Saharan Africa has been re-emphasized in recent studies (e.g. Gregory (1983), and Hutchinson (1985)), and although the idea has occasionally been challenged during the intervening years (e.g. Landsberg (1975), and Bunting *et al.* (1976)), some researchers are reasserting earlier conclusions in the light of more recent evidence (e.g. Dennett *et al.* (1985)). Lamb (1982), for example, has confirmed the persistence of drought conditions over sub-Saharan Africa for the period 1941–1981.

This study has confirmed the drying trend in terms of the timing and duration of the rainy season in Nigeria. On the whole, the country has experienced progressively earlier retreats of rainfall southwards at the end of the rainy season during the period 1939–1985. This is perhaps best explained in terms of an early and/or rapid withdrawal southward of weather associated with zones C and D (see Figure 1), the wettest parts of the ITD. If there is a strong extratropical cooling over the Northern Hemisphere, as hypothesized by Winstanley (1973), this may lead to an equatorward displacement of climatic zones, with the result that the subtropical high pressure areas will block the northward advance of the ITD. Data presented by Oguntoyinbo and Richards (1977) showed that the northernmost limit reached by the ITD progressively decreased at between 0·5° and 1° latitude per annum from 1969 to 1973, from 21·5° N to 19·5° N. They further noted that the rate of retreat of the ITD was particularly rapid in 1971 and 1972 (7° of latitude between September and October 1972). They did not, however, report any corresponding southward displacement of the ITD at its southern limit during this period. Lamb (1983) subscribes to the hypothesis of a restricted northward advance of the south-west monsoon in West Africa in years of Sahelian drought, a view also supported by Hastenrath (1984).

An increase in the intensity of the subtropical high will also block the northwards movement of the ITD (Stranz, 1978). Stranz presented data of mean deviations of air pressure to show that the anomalous rainfall of the period 1970–1972 over the Sahel was characterized by higher than usual pressure over North Africa, where the subtropical highs are normally situated. The strong easterly winds which develop on the southern flank of the Saharan High in such circumstances take up more dust into the atmosphere and thereby inhibit precipitation processes, as well as block the northward movement of the ITD.

CONCLUSIONS

The long-term variability of rainfall conditions in West Africa has usually been examined in terms of the annual or monthly rainfall series. In this study the analysis of variability has been taken further and examined in terms of periodicities, fluctuations, and trends in the onset, retreat, and duration of the rainy season, based on Nigerian data for the period 1919–1985. Mean dates for the onset and retreat of the rainy season in each area illustrate the progressive invasion of the rains inland from the coast between late March and mid-June, and their retreat in the reverse direction between mid- to late September and early November. A notable deterioration in the dates of onset and retreat of the rains has been identified, with a statistically significant trend towards progressively later dates of onset of the rains in the south of the country between 1968 and 1985, and towards progressively earlier dates for retreat of the rains over the whole of Nigeria, from 1939 to 1985.

The mean dates and durations calculated for four zones in the country (Coastal, Guinea-Savanna, Midland, and Sahel) exhibit evidence for quasi-2-year, quasi-3-year, quasi-4-year, and quasi-6-year oscillations. These results would be useful in helping our understanding of the physical processes which influence the fluctuations in the timing and duration of rainfall events in West Africa.

Little evidence was found of spatial coherence for dates of onset of rainfall between the different areas in Nigeria, and there is a notably persistent decay of association with increasing distance. The variation in timing of the retreat of rainfall, however, is much more consistent over the whole country, as reflected in higher and more consistent interzonal correlations. The implication then is that a later or earlier retreat of rainfall which begins in the Sahel will similarly be experienced by the other three regions to the south. In the case of the onset of rainfall, because associations are limited only to southern Nigeria, any early or delayed onset of rainfall which begins in the Coastal area will only normally be shared by its immediate neighbour to the north, that is, the Guinea-Savanna Zone.

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