INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **18**: 1261–1271 (1998)

CHANGES IN RAINFALL CHARACTERISTICS IN NORTHERN NIGERIA

AONDOVER TARHULE[1] and MING-KO WOO*
School of Geography and Geology, McMaster University, Hamilton, Ontario, L8S 4K1, Canada

Received 4 November 1996
Revised 27 February 1998
Accepted 2 March 1998

ABSTRACT

This study examines recent changes in several rainfall characteristics in northern Nigeria. The records at 25 locations were analyzed for the occurrence of abrupt changes and trends using the Pettitt and the Mann-Kendall tests. Variables analyzed included annual total rainfall and number of rain days, the dates of onset, termination and duration of the rainy season as well as monthly rainfall, monthly number of rain days and various categories of rainfall above certain intensities.

An abrupt change occurred in the time series of annual rainfall, number of rain days and affected areas north of latitude 11° N. However, the sub-periods prior to and after the change points may be considered to be homogenous. The series of variables related to the duration of the rainy season exhibit no significant trends or jumps. It is concluded that recent changes in rainfall over the Sahel were driven by a reduction in the frequency of rain days of high rainfall intensities during the months of August and September. The fact that the high intensity rainfall does not contribute significantly to crop growth may explain the continuation of agricultural activities in the Sahel despite massive reductions in annual rainfall. © 1998 Royal Meteorological Society.

KEY WORDS: drought; trend; change point; rainfall, annual; rainfall, variables; Nigeria; Pettitt test; rainy season; Sahel

1. INTRODUCTION

Because rain-fed agriculture is the most important mode of employment and food production in West Africa, records of several rainfall variables are used extensively in planning for agricultural and water resources projects. To obtain reliable estimates of the characteristics of rainfall as well as to determine the magnitude of climatic fluctuations, it is necessary that segments of the time series analyzed should be relatively homogeneous. Previous research applied in northern Nigeria was often based on the so called standard climatic normals, or 30-year, non-overlapping periods. Other work analyzed arbitrary periods, sometimes determined solely by the availability of data (Hulme, 1992). These approaches do not consider the possibility of inhomogeneities introduced by significant changes in the rainfall time series such as the positive trends during the 1950s and the onset of a 25-year drought in the late 1960s.

Indices presented by Lamb (1985), Nicholson (1993), and Jones and Hulme (1996) indicate that the onset of the drought was abrupt such that the statistical characteristics of the rainfall series during the drought are significantly different from the pre-drought period. Similarly, Hubert and Carbonnel (1987) and Demaree (1990) demonstrated the existence of possible multiple-stable climatic regimes in some Sahelian rainfall records. Inhomogeneities in climatic series may be introduced by an abrupt change (or 'jump'), by a gradual trend or by a jump superimposed on a trend (Easterling and Peterson, 1995). It is

* Correspondence to: School of Geography and Geology, McMaster University, Hamilton, Ontario, L8S 4K1, Canada; E-mail: woo@mcmaster.ca
[1] Current address: Department of Geography and Planning, University of Jos, Jos, Nigeria.

Contract grant sponsor: Rockefeller Foundation (African Dissertation Internships Award), Natural Sciences and Engineering Council of Canada

CCC 0899–8418/98/111261–11$17.50

important to determine the occurrence and magnitude of such attributes in order to avoid erroneous and inconsistent inferences from the records.

Total annual rainfall at a location is influenced by several variables including the frequency of rain events, the duration of the rainy period and the intensity of rainfall of individual events. Inhomogeneities in the annual rainfall therefore reflect changes in these contributory variables. Adejuwon *et al*. (1990) fitted linear trends to the annual rainfall series of several locations in Nigeria for the entire period of available data which, in some cases, began in 1922. On the other hand, Hess *et al*. (1995) examined trends in the dates of onset, termination and duration of the rainy season in north-eastern Nigeria based on the standard climatic normal periods. Olaniran (1988, 1991) analyzed the fluctuations in the series of rain days of three rainfall categories (low, moderate and heavy intensity), but apart from this, no assessment of the trends and changes in different categories of rainfall intensity in Nigeria appears in the literature.

The objectives of the present study are two-fold: (i) to identify the occurrence of significant statistical change points in the rainfall variables of northern Nigeria and to evaluate trends prior to and after the change point; and (ii) to compare the trends manifested in the sub-series created by the climatic normal periods and by the change point method.

2. STUDY AREA

A large part of northern Nigeria is semi-arid and comprises the Sudan and Sahel savanna bioclimatic regions. The climate is dominated by the rain-bearing, south-westerly tropical maritime and the dry, north-easterly tropical continental air masses. The meeting of these air masses forms a quasi-frontal zone of humidity discontinuity known as the Inter-tropical Discontinuity which migrates across West Africa in response to the relative intensities of the Azores-Libyan and St. Helena sub-tropical pressure systems (Anyadike, 1993). At any location, the rainy season begins when the Inter-tropical Discontinuity has passed overhead northward bound, and ends with its southwards retreat. Between June and September, the Inter-tropical Discontinuity is entrenched to the north of the country and northern Nigeria is under influence of the tropical maritime. These months yield 77–94% of the total annual rainfall for the southern and northern margins of the region. Long-term changes in rainfall during this period therefore govern the changes in the annual total.

3. DATA

Daily rainfall data collected at 25 locations in northern Nigeria for 1931–96 were analyzed. This period encompasses two successive climatic normal periods: 1931–1960 and 1961–1990. The records at five locations started in the late 1930s to early 1940s (see Figure 2 for locations: Potiskum, 1936; Kaduna, 1939; Nguru, 1942; Mokwa, 1943; Yelwa, 1943). For each station, annual series were constructed for the total rainfall, number of rain days, starting date, ending date and duration of the rainy season, while monthly series for the seven months of April–October were constructed for rainfall and number of rain days. Additionally, daily rainfall less than or equal to specified intensity thresholds (5, 10, . . . , 50 mm) as well as the number of rain days for each category were constituted. Missing values were estimated using the median ratio approach, as described by Bradley (1976), from the nearest station with the highest inter-station correlation.

For this analysis, a rain day is any day receiving at least 1 mm of rainfall. Specification of this lower limit avoids uncertainties associated with the recording of very low rainfall (<1.0 mm). The onset of the rainy season is considered to be the first rain day after which there are no dry spells longer than 14 days in-between the subsequent four rain days. Similarly, the season is considered terminated on any rain day followed by a dry spell longer than 14 days during the last four rain days of the year. The duration is the number of days between the termination date and the onset of the rainy season.

4. METHODS

It is hypothesized that the time series for the different rainfall variables contain an abrupt jump which partitions the series into two sub-periods. The non-parametric Pettitt change point test is used to test for the occurrence of the abrupt change. The test is particularly useful when no hypothesis can be made about the location of the change point. It is given as (Pettitt, 1979):

$$K = \max_{1 \leq k \leq N} |U_k| \tag{1}$$

where U_k is equivalent to a Mann-Whitney statistic for testing that two samples ($x_1, x_2, \ldots x_\theta$) and ($x_{\theta+1}, x_{\theta+2}, \ldots x_{\theta+N}$) come from the same population (Demaree and Nicolis, 1990). U_k is calculated from:

$$U_k = 2\sum_{i=1}^{k} M_i - k(N+1) \tag{2}$$

where M_i is the rank of the ith observation when the values $x_1, x_2, \ldots x_N$ in the series are arranged in ascending order. A change point occurs in the series at where U_k attains a maximum. To test for the statistical significance of the change point, the calculated value of K is compared with its theoretical value at probability level α, given as:

$$K_\alpha = [-\ln \alpha (N^3 + N^2)/6]^{1/2} \tag{3}$$

Where a significant change point exists, the series is segmented at the location of the change point. An example of the application of the procedure to the annual rainfall (R_{a}) and number of rain days (D_{a}) at Potiskum is shown in Figure 1. In this study, the annual variables at all locations were tested for the presence of a change point. Subsequent analyses were confined to the sites where the change points occurred. A similar procedure was applied to the total monthly rainfall (R_{m}) and monthly number of rain days (D_{m}) to determine the time of the season most affected by the change in rainfall.

A ratio of the mean values for the segments after and before the change point is used to assess the magnitude of the jump. Expressing the means as a ratio is a useful standardization for comparing variables whose magnitudes vary considerably from station to station.

The Pettitt change point test provides no information about the homogeneity of the sub-periods. For this, the Mann-Kendall ranked τ statistic is used. For each x_i in the series $x_1, x_2, \ldots, x_{\mathrm{N},}$ the number of all subsequent terms whose values exceed x_i is tallied and denoted as n_i. Then, the τ statistic is calculated as:

$$\tau = \frac{4\sum_{i=1}^{N-1} n_i}{N(N-1)} - 1 \tag{4}$$

The significance of the τ statistic is compared with its theoretical value (τ_α),

$$\tau_\alpha = \pm t_\alpha \sqrt{\frac{4N+10}{9N(N-1)}} \tag{5}$$

Here, t_α is the Student-t value at probability level α. For those time series showing no significant change point, the test is applied to the entire series. Then, the magnitude of the trend at time T in the sub-periods is estimated by bT where b is the coefficient obtained from the regression of the variable against time. The statistical significance of b is tested against the null hypothesis of no linear slope ($\beta = 0$) using a t test,

$$t = \frac{|b - \beta|}{\sigma_b} \tag{6}$$

where σ_b is the standard error of b, and the computed t-value is compared with the tabulated Student-t value to test for significance.

5. RESULTS AND DISCUSSION

5.1. Change point in annual series

Figure 2 shows the location of the stations analyzed and the year at which step jumps occurred in annual rainfall (R_a) and number of rain days (D_a). No significant jumps were identified in those variables related to the length of the rainy season (i.e. the dates of onset, termination and the duration). The occurrence of jumps in R_a and D_a is limited to the area north of 11° N with a slight dip towards the east. This region comprises about 35% of the total land mass of the country and is the major cereals and livestock producing zone. After the 1968–74 drought, the Geological Survey of Nigeria designated the region north of Latitude 11° N as a high risk drought region, based primarily on the severity and areal

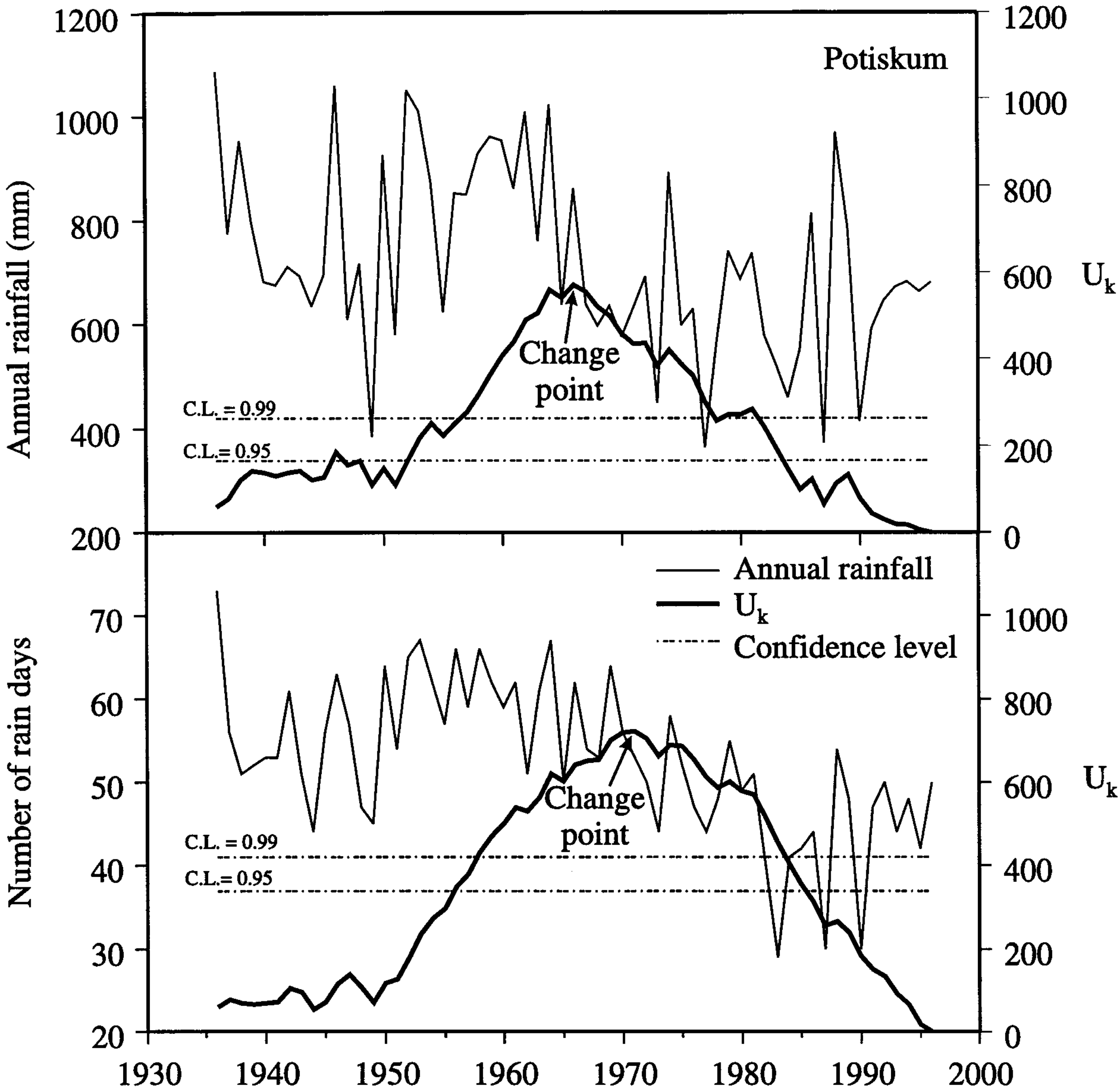

Figure 1. Application of the Pettitt test to the time series of annual rainfall and number of rain days at Potiskum. Thick lines are the calculated U_k statistics (see eq. 1 in text) and the change points are located at max(U_k). Also shown are the confidence limits

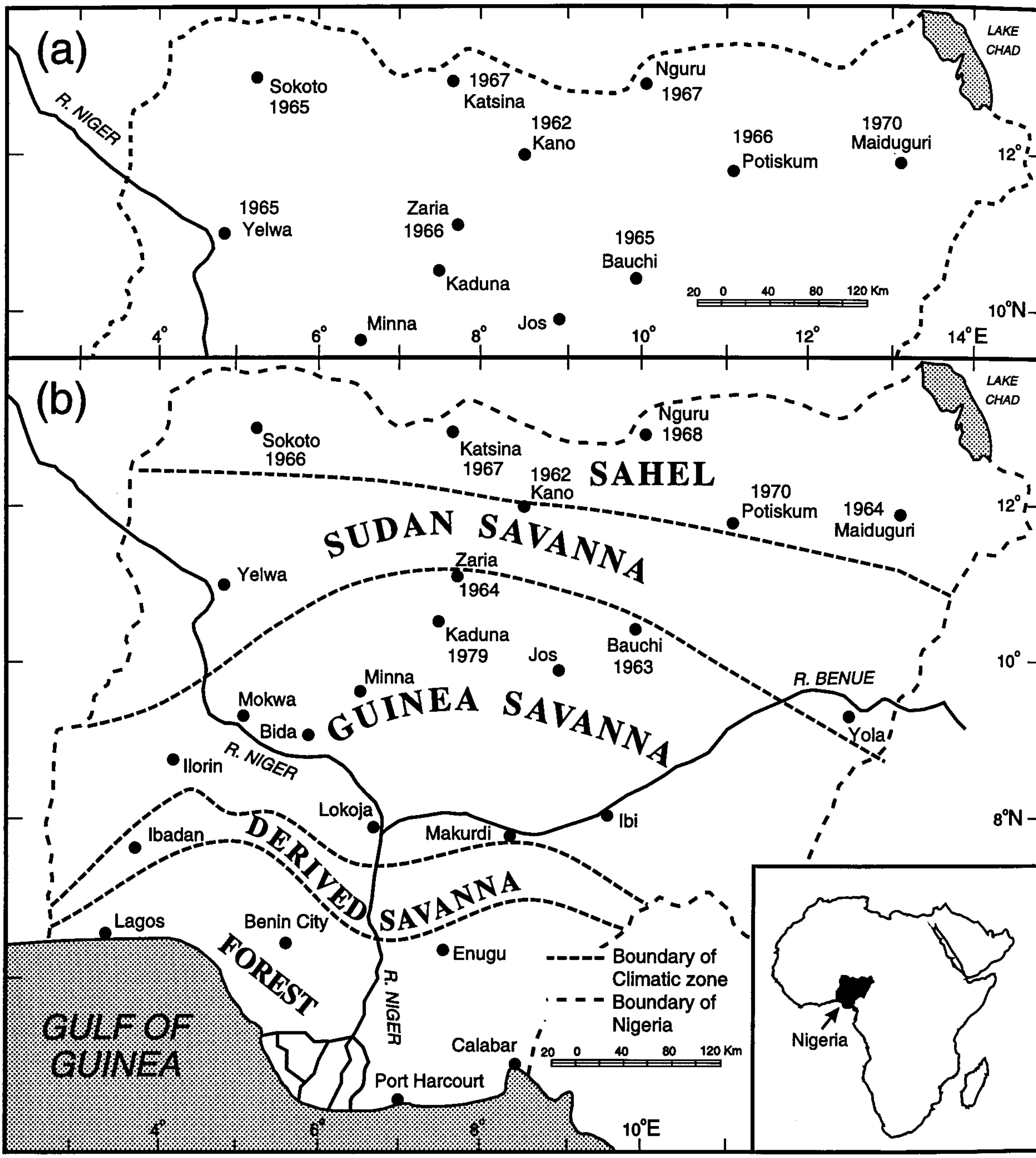

Figure 2. Location of selected rainfall stations and major climatic belts in Nigeria. Also shown are the year of occurrence of change points in (a) annual rainfall and (b) number of rain days. Stations unaccompanied by a year indicate no change point

extent of previous droughts. The area affected by abrupt changes in R_a and D_a corresponds closely with the designated drought region. This finding indicates that the occurrence of a change point can be used as a criterion to distinguish northern Nigeria into sub-regions based on susceptibility to abrupt climatic fluctuations.

The jumps in R_a and D_a occurred between 1962 and 1970 but were not generally coincident, even at the same location. The interval between the change points in R_a and D_a is of the order of 1–2 years except in the northeast where it reaches 4 and 5 years at Potiskum and Maiduguri, respectively. Furthermore, there is no preferred order of occurrence (i.e. the change point in R_a is not necessarily preceded by a change point in D_a). As mentioned previously, the total annual rainfall received at any location depends on the frequency of rain days and the length of the rainy season. Thus, variabilities in the contributory variables at different locations may account for the order of the change points in R_a and D_a. Such variations may also explain the fact that at Kaduna, a change point in the number of rain days is not accompanied by a corresponding change in the total annual rainfall.

5.2. Stationarity of sub-series

The occurrence of statistically significant trends in a series is an indication of non-stationarity. Table I presents the results of the Mann-Kendall τ statistic which tests for the presence of a trend against the null hypothesis of randomness. The sub-periods defined by the occurrence of a change point show no significant negative or positive trends. On the other hand, sub-series based on the standard climatic normal periods produce statistically significant trends at the 0.01 probability level, consistent with the results obtained by Anyadike (1993).

Figure 3 shows the trend lines fitted to the periods prior to and after the change points, as well as to the climatic normal periods. The magnitude of the annual rainfall trends for selected stations after the occurrence of a change point is -1 to -4 mm year^{-1} (Table II), and the hypothesis that $\beta = 0$ cannot be rejected for any of the series. In contrast, based on the second climatic normal period, the annual rate of decline is as high as -8 mm year^{-1}, a value comparable to the results presented by Hess *et al.* (1995). Moreover, all the trends calculated from the second climatic normal period are statistically significant at the 0.05 probability level. Similar results were obtained for the number of rain days (Table II). It is inferred from this that the annual series of total rainfall and number of rain days in northern Nigeria are characterized by an abrupt jump in the mean, and that the periods prior to and after the jump can be considered to be homogeneous. Excessively large trend values arise when the statistical change point is not taken into consideration.

5.3. Magnitude of jump in annual variables

The ratio of the mean of the sub-period after the change point relative to the mean prior to the change point for both annual rainfall and number of rain days is calculated, for several northern Nigerian stations. The stations in Figure 4 are arranged in order of increasing latitude to reflect the latitudinal dependence of rainfall; from the southern-most location of Bauchi (10°22′ N) to Nguru, the most northern (12°56′ N). The general tendency is that in the northern Guinea Savanna, the mean annual rainfall since

Table I. Mann-Kendall τ test for trends for the recent period defined using statistical change point (SCP) and climatic normal period (CNP)

	Annual rainfall		Number of rain days	
Station	SCP	CNP	SCP	CNP
Sokoto	−0.11	−0.32**	−0.19	−0.55**
Katsina	−0.26	−0.36**	−0.26	−0.54**
Kano	−0.23	−0.29**	−0.24	−0.38**
Nguru	−0.33	−0.45**	−0.29	−0.62**
Potiskum	−0.06	−0.30**	−0.27	−0.61**
Maiduguri	−0.22	−0.35**	−0.29	−0.54**
Zaria	−0.12	−0.23	−0.20	−0.21
Kaduna		−0.25	0.12	−0.36**
Bauchi	−0.23	−0.27**	−0.22	−0.28**

* Significant at $\alpha = 0.05$.
** Significant at $\alpha = 0.01$.

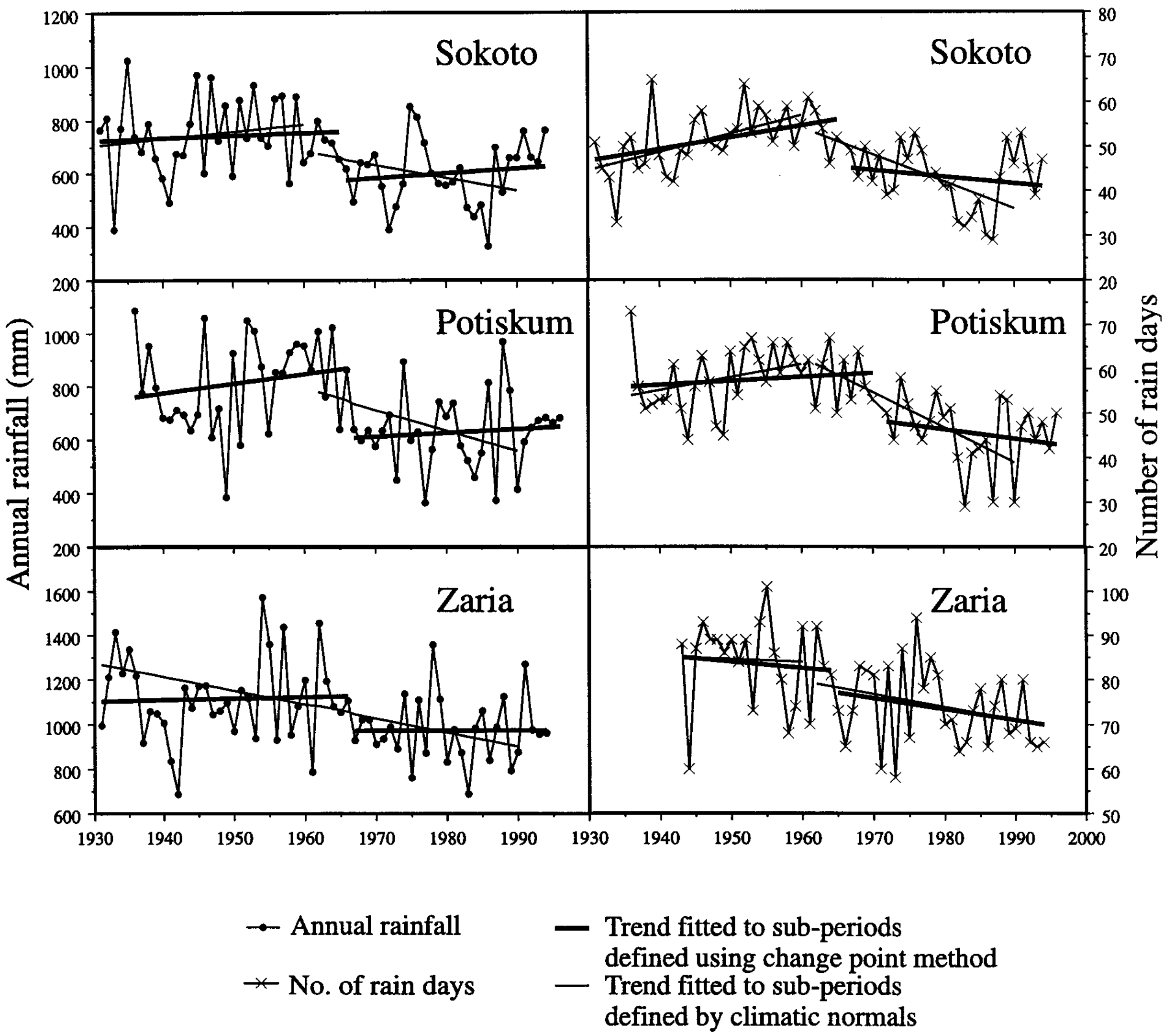

Figure 3. Annual rainfall and number of rain days, trends and step jumps defined by statistical change point for selected stations in northern Nigeria. Trends based on standard climatic normal periods are also shown for comparison

the drought of the late 1960s is about 87% of the pre-drought value. This decreases to 78% in the Sudan and southern parts of the Sahel. At Nguru and Katsina (approximately 13°N) it is only 70%. The number of rain days show similar declines. These ratios demonstrate the severe reduction in annual rainfall over the Sahel.

5.4. Jumps and trends in monthly rainfall series

Table III indicates that the June and July rainfall series contain no significant step jumps. Major jumps occur in the monthly rainfall and number of rain days per month during August and September. Furthermore, the step jumps in August occurred only in the Sahel and Sudan Savanna, while the jump in September was more widespread, reaching as far south as Yelwa and Kaduna (for the number of rain days). The relative magnitude of the jump in the means of the second period for the August and September series is comparable to the annual series, varying between 72 and 84% of the mean of the first sub-period.

Table II. Magnitude of trends in annual rainfall (mm year^{-1}) and number of rain days (days year^{-1}) for sub-periods defined by statistical change point (SCP) and climatic normal period (CNP)

Station	Period[1]	Annual rainfall SCP	Annual rainfall CNP	Number of rain days SCP	Number of rain days CNP
Sokoto	P	0.9	2.6	0.2	0.4 **
	A	−2.2	−4.8*	−0.3	−0.6**
Katsina	P	2.6	2.2	0.1	0.1
	A	−2.5	−8.6**	−0.4	−0.7**
Kano	P	0.5	−1.4	−0.1	−0.1
	A	1.1	−7.3*	−0.3	−0.5**
Nguru	P	−0.6	2.4	−0.1	0.1
	A	−4.2	−8.2**	−0.4	−0.6**
Potiskum	P	3.6	3.9	0.1	0.3
	A	1.4	−7.6*	−0.2	−0.9**
Maiduguri	P	1.6	2.8	0.3	0.4*
	A	−5.0	−8.2**	−0.2	−0.9**

[1] P period prior to the jump; A period after the jump.
* Significant at $\alpha = 0.05$.
** Significant at $\alpha = 0.01$.

The trends after the jump have a magnitude of −1 to −2 mm year^{-1} in August and about −1 mm year^{-1} in September (Table IV). None of these trends are statistically significant. On the other hand, the trends calculated from the climatic normal period are steeper, ranging from −2 to −5 mm year^{-1}. It appears that such large trends are an artifact of arbitrary subdivision of the time series into 30-year periods.

5.5. Jumps and trends in rainfall below specified thresholds

Daily rainfall thresholds at 5 mm intervals (i.e. 5, 10, . . . , 45, 50 mm day^{-1}) were used to derive two sets of time series: (i) total amount of rainfall below a particular threshold; and (ii) number of days with rainfall below a particular threshold. These series were analyzed for jumps and trends. Abrupt reductions (jumps) in the annual amount of rainfall above several intensities are restricted to the Sahel region. However, locations in the Sudan and Guinea Savanna also experienced negative jumps in the number of

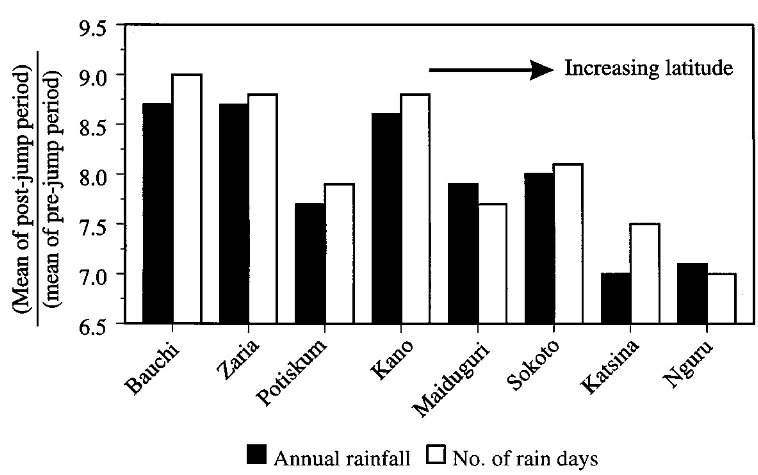

Figure 4. Relative magnitude of jump (indicated by the ratio of mean values for periods after and before the jump) in annual rainfall and number of rain days for selected stations arranged in order of increasing latitude

Table III. Year of occurrence of change points in (a) monthly rainfall, and (b) monthly number of rain days

	Sokoto	Katsina	Kano	Nguru	Potiskum	Maiduguri	Yelwa	Zaria	Kaduna	Bauchi
(a)										
June	–	–	–	–	–	+	–	–	–	–
July	–	–	–	–	–	–	+	+	–	–
August	1967 –	1971 –	1966 –	1967 –	1964 –	1961 –	–	–	+	–
September	1967 –	1967 –	1962 –	1964 –	1964 –	1967 –	1972 –	1967 –	–	–
(b)										
June	–	–	–	–	1969 –	–	–	–	1969 –	–
July	–	1970 –	–	–	–	–	–	–	–	–
August	1965 –	1971 –	1959 –	1968 –	1972 –	1971 –	–	–	–	–
September	1967 –	1962 –	1967 –	1970 –	1976 –	1967 –	1971 –	1967 –	1975 –	–

Note: The years indicate that the change point is significant at 0.05 probability level.
Negative or positive signs (–, +, respectively) indicate the direction of the trend after the occurrence of change point.

rain days above some high thresholds. The magnitude of the trends for each category prior to and after the occurrence of the change point are shown in Figure 5. Of interest are the trends after the change point. Figure 5(b) suggests that the rate of decrease in total rainfall is between -1 and -2 mm year^{-1} for rainfall intensities ≤ 20 mm day^{-1}. This steepens to between -3 and -4 mm year^{-1} at higher intensities (≥ 25 mm day^{-1}). The number of rain days exhibits a similar though more subdued pattern. These findings support the observation of Olaniran (1991), that the recent drought in the Sahel region of West Africa is associated with a large decline in the frequency of moderate and heavy rainfall events during the rainy season. One practical implication is that those activities which are not dependent upon rainfall within the affected intensity ranges may escape the full impact of the drought. This result may explain the relatively mild suffering during the very dry years between 1975 and 1983 noted by Lamb (1983) and Nicholson (1983). Dennett *et al.* (1985) suggested that this was due to the stability of the early season rainfall, among other factors. The relative stability in the low intensity rainfall revealed by this study may have played an important role. This is because low to moderate rain intensities make the most

Table IV. Magnitude of trends in total rainfall and number of rain days in August and September prior to and after the occurrence of a jump as defined by statistical change point (SCP) and climatic normal period (CNP)

		Total rainfall				Number of rain days			
		August		September		August		September	
Station	Period[1]	SCP	CNP	SCP	CNP	SCP	CNP	SCP	CNP
Sokoto	P	–0.1	1.9	–0.5	–0.1	0.1	0.1	0.0	0.1
	A	–1.9	–2.1	0.2	–1.3	–0.1	–0.2**	–0.0	–0.2*
Katsina	P	1.5	3.0	–0.7	–0.5	0.0	0.1	0.0	0.0
	A	–0.7	–4.5**	–0.7	–1.0	–0.0	–0.2**	–0.1	–0.2**
Kano	P	–0.2	–0.2	–0.7	–1.2	–0.0	–0.0	–0.0	–0.0
	A	1.0	–2.1	–0.8	–1.4	–0.1	–0.1	–0.1	–0.2*
Nguru	P	–1.3	–3.4**	–1.2	–1.2	–0.0	–0.1	–0.1	0.0
	A	–1.7	–3.2**	–0.8	–1.3	–0.1	–0.2**	–0.1	–0.2**
Potiskum	P	1.5	3.5	0.1	0.0	0.2	0.3*	–0.0	0.1
	A	–1.9	–3.6**	–1.1	–1.9*	–0.2	–0.3**	–0.1	–0.1*
Maiduguri	P	0.8	1.1	–0.3	–1.9*	0.0	0.1	0.0	0.1
	A	–1.9	–5.3**	–1.8	–2.5*	–0.1	–0.3**	–0.1	–0.2**

[1] P period prior to the jump; A period after the jump.
* Significant at $\alpha = 0.05$.
** Significant at $\alpha = 0.01$.

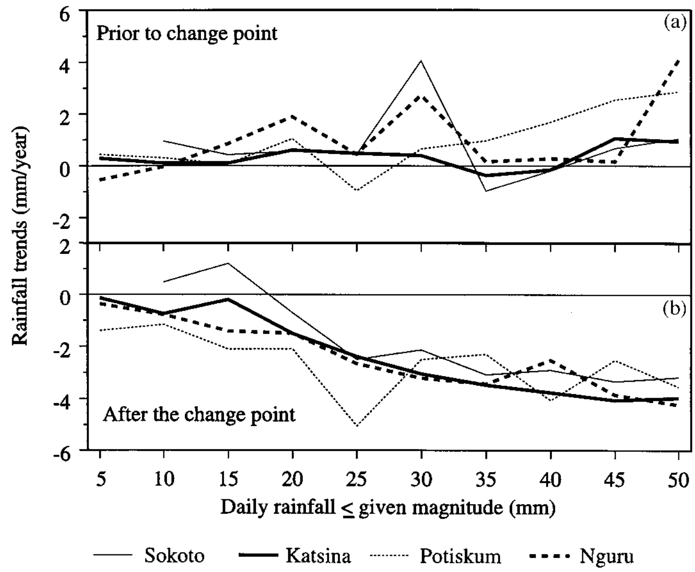

Figure 5. Magnitude of trends in daily rainfall below various thresholds: (a) prior to and (b) after the occurrence of a change point

effective contribution to rain-fed agriculture while high intensity rainfall is responsible for runoff and soil erosion.

6. CONCLUSIONS

(i) The changing point method recognizes a change in the mean of the rainfall series and partitions the series into two segments based on statistical criteria. Across northern Nigeria, the mean rainfall for the period after the change point (which occurred mostly between 1964 and 1972) ranged from 70 to 88% of the pre-drought period. This method is demonstrated to be significantly different from the climatic normal period, which is currently widely used in the English speaking West African countries for assessment of climatic fluctuations.

(ii) Jumps occurred in the series of annual rainfall and number of rain days but not in the variables related to the duration of the season, namely, the dates of onset, termination and duration of the rainy season. Similarly, there were no significant trends in these latter variables, indicating that they played a relatively minor role in the recent decline in Sahelian rainfall.

(iii) After partitioning into sub-periods, many of the apparent trends obtained from the use of the standard climatic normal periods vanish or become muted and the periods prior to and after the change point are stationary.

(iv) Statistically significant trends in annual rainfall were found occurring in northern Nigeria in the period after the change points, amounting to between -1 and -3 mm year^{-1}. Analysis of the monthly data showed that most of this decline was in August and September.

(v) In terms of the rainfall intensity, much of the decline in the high intensity category (≥ 25 mm day^{-1}) occurred after the change point for both rainfall and number of rain days.

(vi) It may be surmised that the widely discussed droughts of the late 1960s resulted primarily from a reduction in the frequency of rain days of high rainfall intensity during the months of August and September.

(vii) The fact that the decline in rainfall occurred during the peak of the rainy season and affected the high intensity rainfall which is not critical to many agricultural activities may explain why these activities continued throughout the region despite the severe reduction in annual rainfall.

ACKNOWLEDGEMENTS

This study was supported by a grant from the Rockefeller Foundation (African Dissertation Internships Award) to Tarhule and funding from the Natural Sciences and Engineering Council of Canada to Woo.

REFERENCES

Adejuwon, J.O., Balogun, E.E. and Adejuwon, S.A. 1990. 'On the annual and seasonal patterns of rainfall fluctuations in sub-Saharan West Africa', *Int. J. Climatol.*, **10**, 839–848.

Anyadike, R.N.C. 1993. 'Seasonal and annual rainfall variations over Nigeria', *Int. J. Climatol.*, **13**, 567–580.

Bradley, R.S. 1976. 'Secular Changes of precipitation in Rocky Mountain States', *Mon. Wea. Rev.*, **104**, 513–523.

Demaree, G.R. 1990. 'An indication of climatic change as seen from the rainfall data of a Mauritanian station', *Theor. Appl. Climatol.*, **42**, 139–147.

Demaree, G.R. and Nicolis, C. 1990. 'Onset of Sahelian drought viewed as a fluctuation-induced transition', *Q. J. R. Meteorol. Soc.*, **116**, 221–238.

Dennett, M.D., Elston, J. and Rodgers, J.A. 1985. 'A reappraisal of rainfall trends in the Sahel', *J. Climatol.*, **5**, 353–361.

Easterling, D.R. and Peterson, T.C. 1995. 'A new method for detecting undocumented discontinuities in climatological time series', *Int. J. Climatol.*, **15**, 369–377.

Hess, T.M., Stephens, W. and Maryah, U.M. 1995. 'Rainfall trends in the North East arid zone of Nigeria 1961–1990', *Agric. Forest Meteor.*, **74**, 87–97.

Hulme, M. 1992. 'Rainfall changes in Africa: 1931–1960 to 1961–1990', *Int. J. Climatol.*, **12**, 685–699.

Hubert, P. and Carbonnel, J.P. 1987. 'Approche statistique de l'aridification de l'Afrique de l'Ouest', *J. Hydrol.*, **95**, 165–183.

Jones, P.D. and Hulme, M. 1996. 'Calculating regional climatic time series for temperature and precipitation: methods and illustrations', *Int. J. Climatol.*, **16**, 361–377.

Lamb, P.J. 1983. 'Sub-Saharan rainfall update for 1982: continued drought', *J. Climatol.*, **3**, 419–422.

Lamb, P.J. 1985. 'Rainfall in sub-Saharan West Africa during 1941–1983', *Zeit. Gletscherkunde. Glazialgeol.*, **21**, 131–139.

Nicholson, S.E. 1993. 'An overview of African rainfall fluctuations of the last decade', *J. Climate*, **6**, 1463–1466.

Nicholson, S.E. 1983. 'Sub-Saharan rainfall in years 1976–80: evidence of continued drought', *Mon. Wea. Rev.*, **111**, 1646–1654.

Olaniran, O.J. 1991. 'Evidence of climatic change in Nigeria based on annual rainfall series of rainfall of different daily amounts, 1919–1985', *Clim. Change*, **19**, 319–341.

Olaniran, O.J. 1988. 'The distribution in space of rain-days of rainfall of different amounts in the Tropics: Nigeria as a case study', *Geoforum*, **19**, 507–520.

Pettitt, A.N. 1979. 'A non-parametric approach to the change point problem', *Appl. Statistics*, **28**, 126–135.