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Rainfall Variability in Africa[1]

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ABSTRACT

Time series of annual rainfall for 69 stations in Africa were analyzed for trends and periodicities. Trend analysis showed that most of the annual series indicate some forms of oscillations rather than any particular trend. Use of binomial coefficients to smooth the series indicated positive or negative trends in recent years in 20 series, but only four of these were statistically significant judging by the Spearman rank correlation test. These four stations were geographically distributed within those showing no significant trends.

Assuming the generating process to be purely random, the prominent cycles revealed by the spectral analysis were 2.0–2.5 years and 2.7–3.3 years. In general, the larger observed cycles (3.5–4.4 years, 5.0 years, 6.0–6.5 years, 7.0–8.0 years and 10.0 years) were weak at the 0.05 significance level.

1. Introduction

Significant work has been done in some African countries on trends and periodicities in rainfall. Some of the more recent works are by Wood and Lovett (1974), Rodhe (1974), Bunting *et al.* (1975), Tyson *et al.* (1975) and Rodhe and Virji (1976).

Wood and Lovett (1974) examined sunspot-rainfall relationship for Ethiopia. A cycle of about 10 years was found in Addis Ababa annual rainfall. Rodhe (1974) looked at year-to-year variations in some hydrological parameters (rainfall, runoff and lake level) in Kenya. Periodic fluctuations of some 3–5 years were demonstrated in the annual rainfall data. Tyson *et al.* (1975) observed four cycles in South African annual rainfall. These were 16–20 years, 10–12 years, 3–4 years and the quasi-biennial oscillations. Their analyses showed that there was little evidence that South Africa had undergone progressive desiccation during the period 1880–1972. In the West African annual rainfall, Bunting *et al.* (1975) investigated statistical evidence for trends. No established trends or periods were detected. Rodhe and Virji (1976) observed no definite trend in East African rainfall except in northeastern Kenya where positive trend in recent years was observed. They suggested this to be due to either some local factors or inhomogeneity in the data.

The object of the present study is to examine trends and cycles in the annual rainfall totals for 69 stations in Africa. The locations of these stations are displayed in Fig. 1 and the lengths of the records are given in Table 1. The annual values were extracted from the original monthly records obtained from the various countries through correspondence. No response was received from some countries which have been excluded in the analysis. These include some countries in the Sahel zone (Algeria, Niger, Chad and Egypt), but some stations in the neighborhood of this zone were available. The number of years of observation ranged from 40 to 109. It is realized that some of these series are too short to define a definite long-term trend or analyze the shape of the spectra in detail. The lengths of the records were not the same for all the series examined.

2. Homogeneity

Changes in the site, height, or exposure of raingages may make the rainfall values before and after these changes not comparable. Most of the very old stations may have been affected by one or more of these changes. A trend in a climatological series may arise from such heterogeneity in the data. In this study, homogeneity in the annual rainfall series has been examined by using the run test (Thom, 1966; Siegel, 1957). This is a sensitive non-parametric test. The results of this test indicated no appreciable heterogeneity in the annual rainfall data.

3. Trend analysis

To examine trends in the annual rainfall series, both graphical and statistical approaches have been employed.

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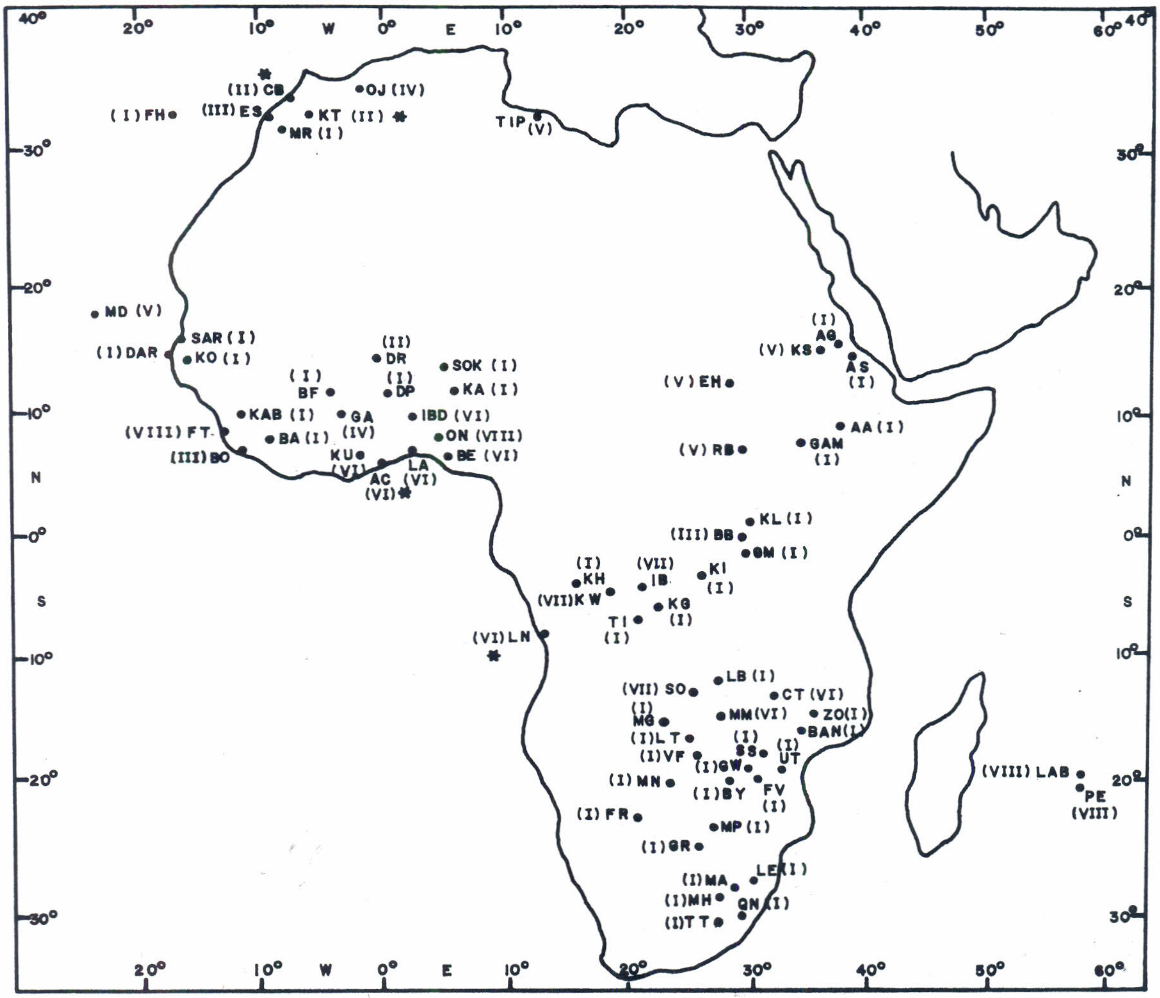


FIG. 1. Location of stations and the spatial distribution of the trend groups. The number in parentheses indicates the observed trend at the station and the asterisk denotes a trend significant at the 5% level. See Table 1.

a. Graphical approach

Under this method, the series were smoothed by binomial coefficients (WMO, 1966) and the resulting series were displayed graphically. The weights used were 0.22 for the ith year, 0.20 for the $i \pm 1$ years, 0.12 for the $i \pm 2$ years, 0.05 for the $i \pm 3$ years and 0.02 for the $i \pm 4$ years. This is a low-pass filter suppressing high-frequency oscillations, and in this case all fluctuations of period shorter than 10 years have been considerably suppressed. The low-pass filtered curves were then classified broadly into eight groups, based only on the length of the records and the graphical representations of the low-pass filtered curves. The generalized trend groups in the rainfall series were (I) generally oscillatory; (II) a general positive trend; (III) a general positive trend followed by negative trend; (IV) a negative trend followed by positive trend; (V) generally oscillatory at the beginning followed by a negative trend; (VI) generally oscillatory followed by positive trend; (VII) positive trend followed by some oscillations; (VIII) negative trend followed by some oscillations.

The station groups are given in Table 1 and some examples of the low-pass filtered curves are shown in Fig. 2. The spatial distribution of the trend groups is given in Fig. 1.

The results from these show 1) that most of the annual series indicated some forms of oscillations rather than any particular trend; 2) none of the stations indicate decreasing rainfall tendency throughout the period of study; 3) positive trends in some recent years at three stations in Morocco to the north of the Sahel zone; 4) seven stations in West Africa to the South of the Sahel zone indicate increasing rainfall tendency in some recent years; 5) decreasing rainfall tendency in some recent years in Sudan; 6) three stations south of the equator indicate increasing rainfall in some recent years [Luanda (Angola), Chipata and Mumbwa (Zambia)].

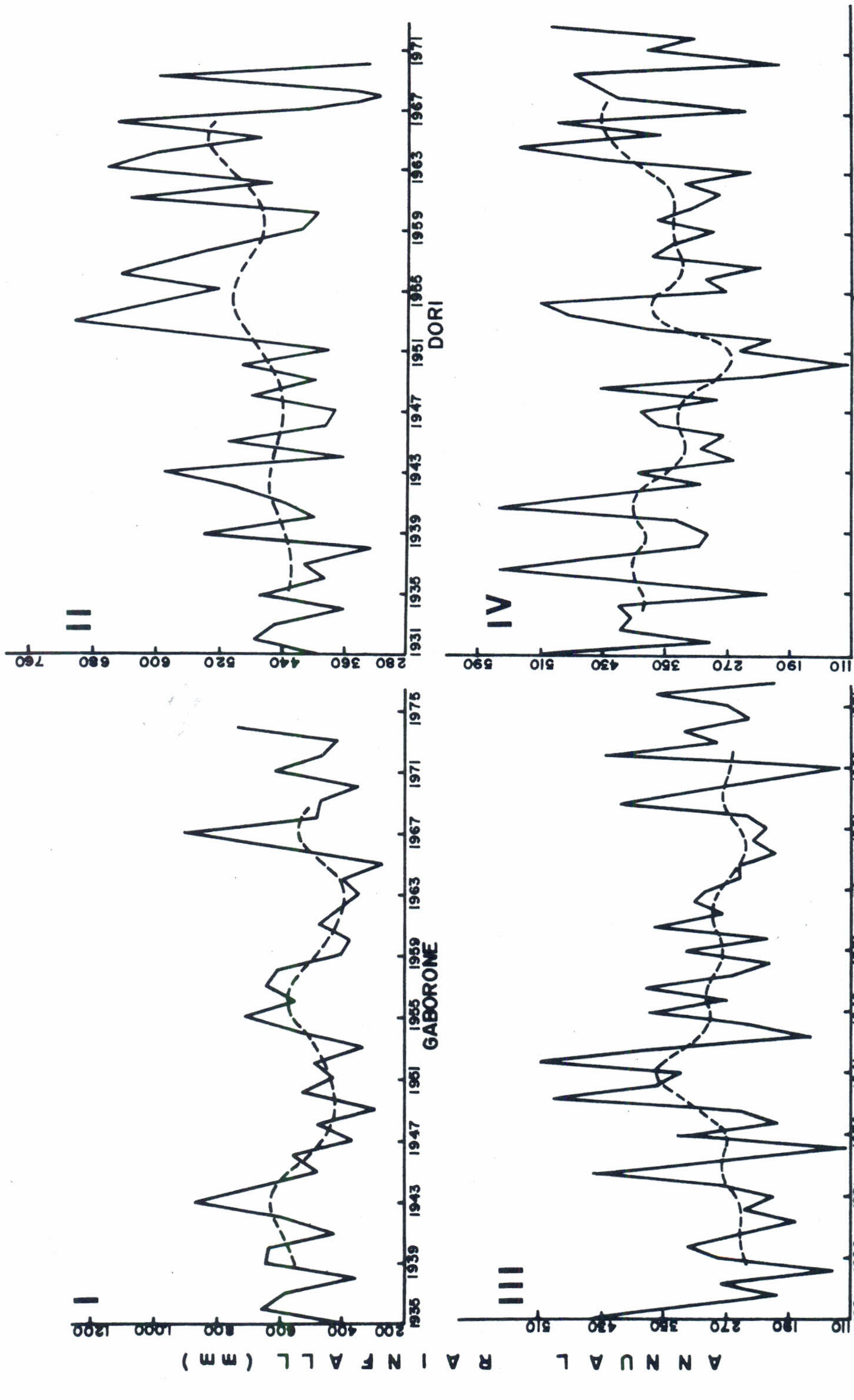
It is however noted that only four trends were found significant by the statistical approach (Section 3b). Three of these stations (Luanda, Cassablanca, and Kasba-Tadla) are in dry climates where year-to-year variability of rainfall is high. The mean annual rainfalls of the three stations are 372, 407 and 423 mm for Luanda, Kasba-Tadla and Cassablanca, respectively. The fourth station (Accra) has an annual mean rainfall of ~788 mm.

b. Statistical approach

It is realized that the visual determination of trends from the smoothed graphs is very subjective depending on individual judgment. An objective statistical method (Spearman rank correlation test) was therefore used to further investigate trends in the annual rainfall data. The presence of some form of trend in climatological data may be ex-

TABLE 1. Country and stations, symbols of stations, location of station, elevation, length of record, and the type of trend observed from smoothed graphs.

Country and station	Station symbol	Location	Elevation (m)	Record length	Trend type
Morocco					
Marrakech	MR	30°37′N 08°02′W	468	1921–73	I
Cassablanca	CB	33°34′N 07°40′W	62	1921–73	II
Kasba-Tadla	KT	32°26′N 06°16′W	503	1921–73	II
Essaouira	ES	31°31′N 09°47′W	15	1921–73	III
Oudja	OJ	34°47′N 01°57′W	468	1921–73	IV
Madeira Island					
Funchal	FH	32°41′N 16°46′W	58	1921–70	I
Cape Verde Island					
Mindalo	MD	16°53′N 25°00′W	2	1921–70	V
Senegal					
Dakar	DAR	14°44′N 17°30′W	27	1897–1973	I
St. Louis	SAR	16°01′N 16°27′W	4	1903–73	I
Kaolack	KO	14°08′N 16°04′W	6	1919–73	I
Sierra Leone					
Baru	BA	07°59′N 10°52′W	185	1913–74	I
Kabala	KAB	09°35′N 11°33′W	463	1913–74	I
Bonthe	BO	07°32′N 12°30′W	7	1913–74	III
Free Town	FT	08°37′N 13°12′W	20	1913–74	VIII
Upper Volta					
Diapaga	DP	12°04′N 01°47′E	308	1931–70	I
Banfora	BF	10°38′N 04°46′W	460	1931–70	I
Dori	DR	14°02′N 00°03′W	276	1931–70	II
Gaoua	GA	10°02′N 03°11′W	333	1931–70	IV
Ghana					
Accra	AC	05°36′N 00°10′W	68	1901–73	VI
Kumasi	KU	06°43′N 01°36′W	287	1904–73	VI
Nigeria					
Kano	KA	12°03′N 08°32′E	476	1905–73	I
Sokoto	SOK	13°01′N 05°15′E	351	1910–73	I
Ibadan	IBN	07°26′N 03°54′E	234	1905–73	VI
Lagos	LA	06°33′N 03°21′E	19	1892–1973	VI
Benin	BE	06°19′N 05°36′E	79	1906–73	VI
Ondo	ON	07°06′N 04°50′E	287	1906–73	VIII
Libya					
Tripoli	TIP	32°52′N 13°13′E	80	1916–74	V
Ethiopia					
Argodat	AG	15°33′N 37°53′E	626	1922–73	I
Addis Ababa	AA	09°02′N 38°45′E	2324	1902–73	I
Gambella	GAM	08°17′N 34°38′E	—	1905–73	I
Asmara	AS	15°17′N 38°55′E	2326	1903–73	I
Zaire					
Kinshasha	KH	04°19′S 15°19′E	282	1931–73	I
Lubumbasi	LB	11°39′S 27°29′E	1260	1931–73	I
Kindu	KI	02°57′S 25°55′E	497	1931–73	I
Zaire					
Goma	GM	01°41′S 29°14′E	1552	1931–73	I
Tshikapa	TI	06°24′S 20°51′E	521	1931–73	I
Kananga	KG	05°53′S 22°25′E	654	1931–73	I
Butembo	BB	00°08′S 29°16′E	1840	1931–73	III
Ilebo	IB	04°20′S 20°33′E	465	1931–73	VII
Kikwit	KW	05°02′S 18°48′E	518	1931–73	VII
Rwanda					
Kigale	KL	01°58′N 30°07′E	1491	1927–73	I
Rhodesia					
Victoria Falls	VF	18°06′S 25°50′E	1062	1905–72	I
Fort Victoria	FV	20°04′S 32°52′E	1096	1889–1972	I
Umtali	UT	18°58′S 32°40′E	—	1889–1972	I
Bulawayo	BY	20°09′S 28°37′E	1343	1887–1972	I
Salisbury	SS	17°50′S 31°01′E	1491	1891–1972	I
Gwelo	GW	19°27′S 29°51′E	1428	1899–1972	I
Malawi					
Zomba	ZO	16°05′S 35°07′E	653	1914–70	I
Bandanga	BAN	15°25′S 35°19′E	—	1914–70	I
Angola					
Luanda	LN	08°51′S 13°14′E	74	1901–70	VI
Botswana					
Gaberone	GR	24°40′S 25°55′E	983	1935–75	I
Mahalapye	MP	23°05′S 26°48′E	991	1935–75	I
Maun	MN	19°59′S 23°25′E	945	1935–75	I
Francistown	FR	21°13′S 27°30′E	1001	1935–75	I
Lesotho					
Qachas Nak	QN	30°07′S 28°42′E	—	1896–1970	I
Maseru	MA	29°17′S 27°30′E	1530	1919–70	I
Teyaneng	TT	30°09′S 27°28′E	—	1896–1970	I
Mohales Hoek	MH	29°09′S 27°44′E	—	1896–1970	I
Leribe	LE	28°53′S 28°03′E	—	1889–1970	I
Mauritius					
Labourdoness	LAB	20°04′S 57°35′E	—	1862–1970	VIII
Pemplemousses	PE	20°26′S 57°30′E	—	1862–1970	VIII
Sudan					
Kassala	KS	15°28′N 36°24′E	500	1931–73	V
En-Hamud	EH	12°42′N 28°26′E	565	1931–73	V
Rumber	RB	06°48′N 29°42′E	418	1931–73	V
Zambia					
Mongu	MG	15°15′S 23°09′E	971	1904–70	I
Livingstone	LT	17°52′S 25°15′E	748	1904–70	I
Mumbua	MM	14°59′S 27°04′E	905	1904–70	VI
Chipata	CT	13°38′S 32°35′E	1018	1904–70	VI
Solwezi	SO	12°11′S 26°23′E	1339	1904–70	VII


I
GABORONE
II
DORI
III
ESSAOUIRA
IV
OUJDA
ANNUAL RAINFALL (mm)

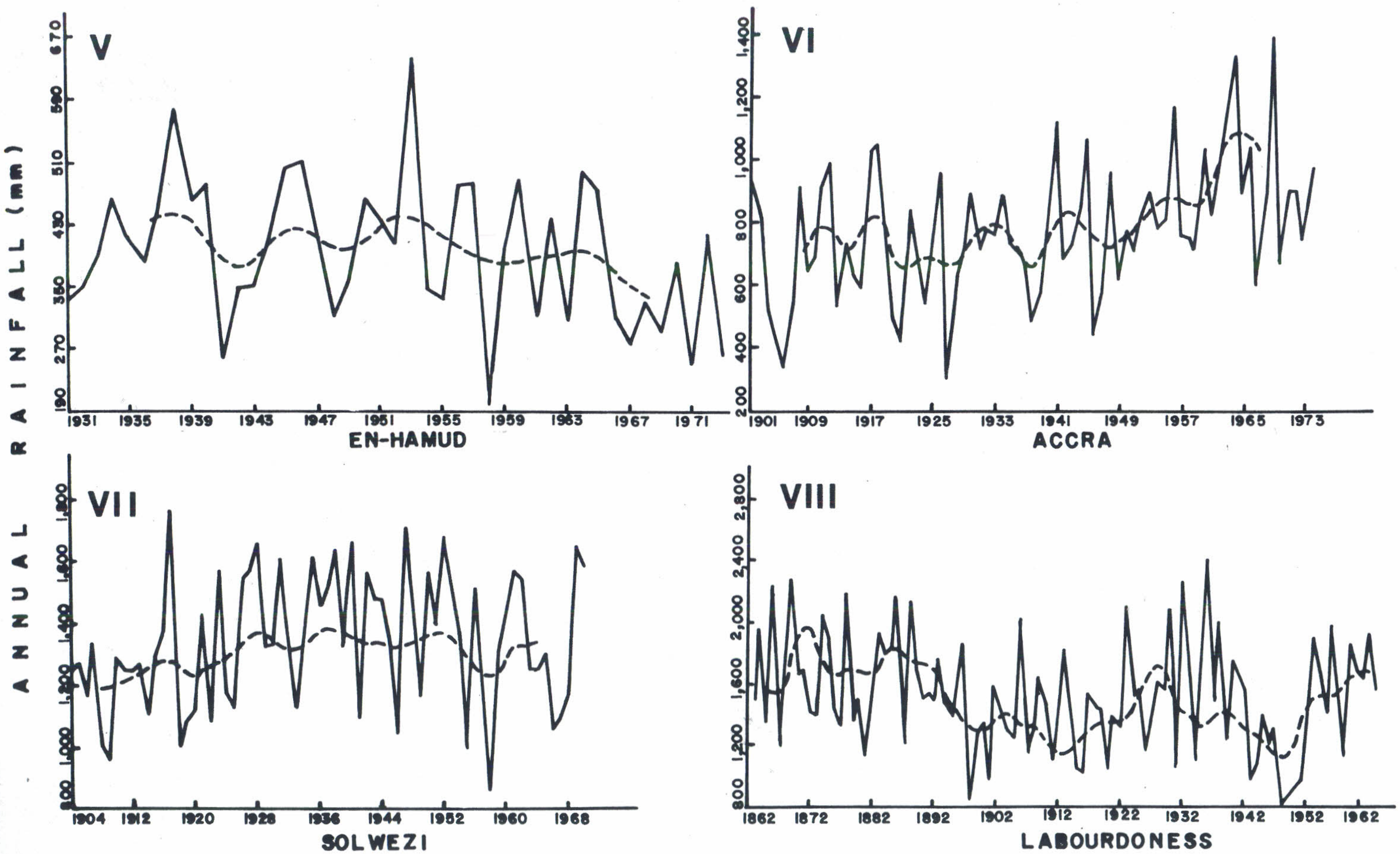


FIG. 2. Some examples of the low-pass filtered curves: (I) generally oscillatory; (II) a general positive trend; (III) positive followed by negative trend; (IV) generally negative followed by positive trend; (V) generally oscillatory, then negative trend; (VI) generally oscillatory, then positive trend; (VII) positive trend, then some oscillations; (VIII) negative trend, then some oscillations. The solid lines are the original series, the dashed lines the smoothed series.

amined by the use of rank correlation methods (WMO, 1966).

These tests are robust and the departures from the Gaussian normal distribution will not be of serious concern. They do not assume that the trend in question is linear. In the present study, Spearman rank correlation test has been applied to all the unsmoothed annual rainfall series. The Spearman rank correlation Γ_s is calculated from

$$\Gamma_s = 1 - \frac{6 \sum_{i=1}^{N} di^2}{N(N^2 - 1)}, \quad (1)$$

where $di = k_i - i$, k_i is the rank of the series X_i and N the total number of observations.

For $N > 8$, the value of Γ_s is tested for significance by computing the statistic t defined by

$$t = \Gamma_s\left(\frac{N - 2}{1 - \Gamma_s^2}\right)^{1/2}. \quad (2)$$

The t-value is compared with the probability points of Student's t-distribution with $N - 2$ degrees of freedom.

At 0.05 significance level, the rank test indicated significant trend only at Luanda, Accra, Cassablanca and Kasba-Tadla. The Spearman rank correlation coefficient was equal to 0.32, 0.42, 0.28 and 0.35 at Cassablanca, Kasba-Tadla, Luanda and Accra, respectively. The smoothed graphs indicated positive trends in recent years at these four stations.

Large-scale variation in rainfall is mainly controlled by the large-scale atmospheric circulations. Lamb (1966) examined rainfall patterns in Africa between 1961 and 1965 and observed excess rainfall in most parts of the tropics and a deficiency in the arid and semi-arid zones between 10–15° and 30° north and south. Also observed after 1961 were the rising levels of Lake Victoria and other lakes in the equatorial Africa. He noted that the world changes of rainfall, temperature and general circulation patterns since 1960 were comparable in magnitude to the changes which took place in or about the 1890's. In this study, the run test showed that there was no appreciable heterogeneity in the rainfall series, and the spatial distribution of the four stations indicating significant positive trends in the recent years formed no particular pattern. In general, the stations adjacent to these four showed no significant trends, making it difficult to give climatological reasons for the observed trends. Hence the major rain-generating functions in the lower latitudes (e.g., excursions of the ITCZ) have not been examined.

4. Spectral analysis

In spectral analysis, both Parzen (1961) and Blackman-Tukey (1958) procedures of estimation of spectra have been applied. Maximum time lags were chosen as large as possible but less than one-third of the total number of years of record. This was to achieve satisfactory resolution in the spectrum. At least three different time lags were applied to reduce the risk of picking up of high power.

In general, successive differencing can be used to eliminate polynomial trends both in the mean and variance (Granger and Hatanaka, 1964). In this study, a difference filter given by the equation $y_t = X_t - X_{t-1}$ has been used. This is a high-pass filter. The significance of the observed spectral peaks was tested at both 0.01 and 0.05 significance levels. The generating process was assumed to be purely random (white-noise).

The time series analysis of the unsmoothed data revealed the following features:

1) Lag-one correlation was negative at most stations, having large negative values at some stations, this being indicative of short-period oscillations.

2) Spectral analysis results indicated that there were some cycles in the annual rainfall series. The major cycles showing up were 2.0–2.5 years and 2.7–3.3 years. In general, longer cyles were also present in the series but these cycles (3.5–4.4 years, 5.0 years, 6.0–6.5 years, 7.0–8.0 years, or 10.0 years) were not significant at the 0.05 significance level.

5. Conclusions

There have been speculations and study as to whether the climate is changing. The Sahel drought of late 1960's and early 70's attracted a lot of world attention. Lamb (1974) suggested that the general circulation of the atmosphere is slowly changing, resulting in an equatorward shift of the principal climatic belts. Some past studies on rainfall trends in certain regions of Africa have revealed no established trends in the annual rainfall series (Bunting *et al.*, 1975; Landsberg, 1975). Tyson *et al.* (1975) observed that the tendency for occurrence of any trend in South African rainfall decreased with the increase in the length of records. Rodhe and Virji (1976) observed no significant trends in East African rainfall except in the dry northeastern Kenya. They attributed the observed increasing tendency to inhomogeneity or some local factors.

Results of the present trend analysis have shown that most of the annual series examined indicated generally an oscillatory characteristic without significant trend. Positive or negative trends observed from the smoothed graphs in the recent years were declared insignificant by a statistical test except in four stations. The four series indicated increasing rainfall tendency in the recent years. However, it was noted that the stations indicating significant trends were near those indicating no significant trends and their spatial distribution formed no particular pattern. This made it difficult to give a climatological explanation for the observed trends in the annual rainfall series; hence no attempt was made to examine the general circulation parameters on which rainfall greatly depends. It is possible for such trends to arise from some local factors, but there is a feeling that the positive trends in the recent years are part of long-period oscillations which could not be determined here due to the limited data available. An overall impression is that rainfall over Africa is oscillatory in time.

On assuming the generating process to be purely random, the prominent cycles in the annual rainfall were 2.0–2.5 years and 2.7–3.3 years. These cycles have been detected in some past studies over certain parts of Africa (Rodhe, 1974; Rodhe and Virji, 1976; Tyson *et al.*, 1975; Landsberg, 1975). Quasi-biennial oscillations have been found in many meteorological data particularly in long temperature records (Landsberg *et al.*, 1959, 1963). Some larger cycles (3.5–4.4 years, 5.0 years, 6.0–6.5 years, 7.0–8.0 years or 10.0 years) also appeared. But, in general, these were not significant at 0.05 significance level with the assumption of white-noise hypothesis. However, it has been noted that some of the series were too short (40 years) to analyze the shape of the spectra in detail or to detect very large cycles.

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