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Characteristics of African rainfall — An update

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सार— 1901 से 1990 तक की अवधि में प्रत्येक वर्ष इल निनो (ई.एन.) अथवा न्यूनतम दक्षिणी दोलन (एस ओ) अथवा पूर्वी भूमध्यरेखीय प्रशांत समुद्र सतह के उष्ण (डब्ल्यू) या शीत (सी) लहरों के प्रभाव से प्रभावित अथवा इनमें से किसी के संयोग से उत्पन्न प्रभाव से प्रभावित अथवा इन सभी से अप्रभावित (नॉन-इवेन्ट्स) विशेषता वाला रहा है। दक्षिणी अफ्रीका को छोड़कर जहां इल निनो वर्षों के दौरान मामूली सूखे की स्थिति पाई गई है अफ्रीका के किसी भी क्षेत्र में किसी भी प्रभाव के संयोग के फलस्वरूप इसी महत्वपूर्ण अनुकूल संबंध का पता नहीं चला है जबकि भारतीय ग्रीष्मकालीन मानसून वर्षा के साथ एंन्सो प्रभावित वर्षों और सूखे की घटनाओं के बीच सुसंयोग का पता चलता है।

विशिष्ट क्षेत्रों में प्रत्यंतरों की तुलना कऱने पर क्षेत्रों में आमतौर पर सामंजस्य की कमी पाई गई है। प्रत्येक क्षेत्र के प्रत्यंतरों को सकारात्मक अथवा नकारात्मक रूप में वर्गीकृत किये जा सकने वाले वर्षों में प. अफ्रीका, पू. अफ्रीका और द. अफ्रीका के बीच सभी प्रकार के दूर संयोजन पाए गए तथा महाद्वीपीय स्तर पर बाढ़ों या सूखा की घटनाओं की अधिकता पाई गई और न ही भूमध्यरेखा एवं उपोष्णकटिबंधों में प्रतिकूल प्रत्यंतरों की प्रचुरता पाई गई है।

पाँच वर्षों के निरन्तर मानों से प. अफ्रीका और पू. अफ्रीका (बेमेल प्रावस्था) में ~24 वर्षों और द. अफ्रीका से ~17 वर्षों के औसत अंतरालों पर सकारात्मक प्रत्यंतरों के ऐसे दीर्घ मध्यांतरों का पता चला है जिनके पहले या बाद में सूखे की घटनाएं लम्बे अंतरालों पर घटी हैं। यह अफ्रीका में वर्षा की भिन्नता का आधारभूत लक्षण प्रतीत होता है।

ABSTRACT. Each year during 1901-1990 was characterized as having an El Nino (EN) or Southern Oscillation minimum (SO) or warm (W) or cold (C) waters in east equatorial Pacific sea surface or any combination of these, or none (non-events). In contrast to Indian summer monsoon rainfall which showed a very good association between ENSOW type years and droughts, none of the African regions showed any significant, consistent relationship with any combination, except S. Africa where a slight bias for droughts was observed during El Nino years.

When departures in specific regions were compared, often there was lack of coherence within regions. For years when departures in every region could be classified as positive or negative, all type of teleconnections between W. Africa, E. Africa and S. Africa were seen and no preponderance was observed for continental scale floods or droughts, nor for opposite departures for equator and subtropics.

Five-year running averages indicated long intervals of positive departures preceded or followed by long intervals of droughts, with average spacings of ~24 years for W. Africa and E. Africa (but phases not matching) and of ~17 years for S. Africa. This seems to be a basis feature of African rainfall variability.

Key words — El-Nino, African rainfall, Inter hemispheric teleconnections, Quasi biennial oscillation, Quasi triennial oscillations.

1. Introduction

Rainfall in the African continent is highly variable. However, some regional coherence is reported, broadly in Sahel, E. Africa and South Africa, though the rainfall variability in these three regions is very different from each other (Hulme, 1992). Droughts in Sahel affect a broad area including the entire northern hemispheric part of Africa (Nicholson, 1980) while some major rainfall anomalies are reported to occur simultaneously throughtout Africa (Nicholson, 1986a) and even global teleconnections have been demonstrated (*e.g.* Stoeckenius, 1981 and references therein). Nicholson (1986a) observed a certain degree of interhemispheric connectivity but strongest spatial associations were within the northern hemisphere (Sahel) and within equatorial and South Africa. Also there seemed to be two preferred configurations *viz.* precipitation of the same sign over all the continent and, opposite signs between tropical and subtropical latitudes. For South Africa, Tyson (1986) showed an oscillatory pattern of ~18 years periodicity and reported that Sahel and Kalahari had synchronous wet and dry spells while equatorial latitudes and S. Africa had opposite rainfalls. Relationship with ENSO (El Nino/Southern Oscillation) have also been reported. Dyer (1979) reported SO influence on rainfall in limited areas of South Africa. Rodhe and Virji (1976) showed that East African rainfall had spectral peaks at 2-2.5, 3.5 and 5-5.5 years. As these peaks are similar to those with the SO index, Nicholson and Entekhabi (1986) conducted a detailed power spectrum analysis of African rainfall series by Blackman-Tukey and Fourier methods. The analysis revealed quasi-periodicities clustered in four bands at 2.2-2.4, 2.6-2.8, 3.3-3.8 and 5.0-6.3 years, common throughout equatorial and southern Africa but only weakly evident in northern Africa. A cross-spectral analysis with SO index showed a strong influence and coherence in the QBO range of 2.2-2.4 years for rainfalls in southern Africa and Parts of the equatorial regions. For equatorial region, higher rainfall was reported to be associated with low SO index, while for other regions where an SO influence could be demonstrated, higher rainfall was reported to be associated with high SO index. Janowiak (1988) reported that positive rainfall departures in equatorial E. Africa and negative departures in S. Africa followed ENSO events. Lindesay and Vogel (1990) gave historical evidence for SO-rainfall relationship in S. Africa.

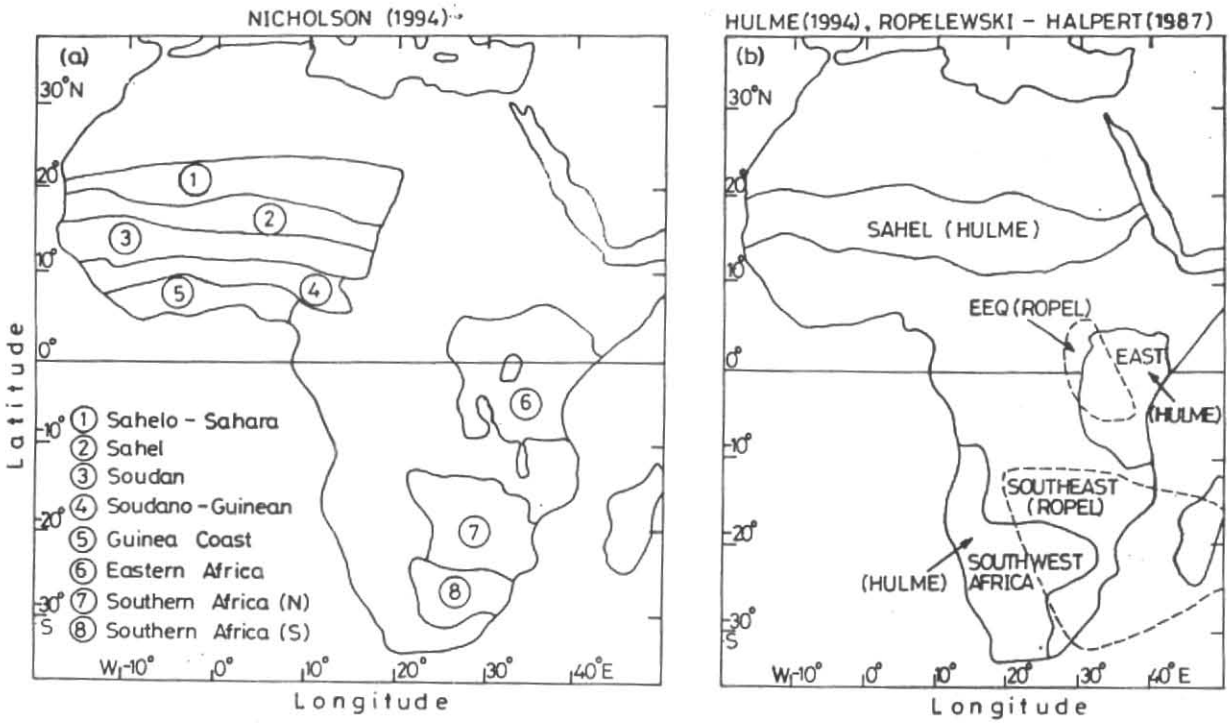
The SO index minima are associated with El Ninos (warm water episodes along the Peru-Ecuador coast) as also with SST (warmer waters) in the EEP (Eastern Equatorial Pacific). As such, workers have generally used only one of these indices for studying ENSO relationships. For example, Rasmusson and Carpenter (1983) and Ropelewski and Halpert (1987) used El Nino years as ENSO episodes. Shukla and Paolino (1983) used Darwin pressure while, Kiladis and Diaz (1989) used SST and SO index and Ropelewski and Halpert (1989) used SO index. Khandekar and Neralla (1984) and Mooley and Paolino (1989) used the SST anomalies over the Eastern Equatorial Pacific. However, El Ninos, SO minima and warm SST (EEP) do not always seem to synchronize. Deser and Wallace (1987) examined these events and concluded that El Nino events "occurred both in advance of the subsequent to major negative swings of the Southern Oscillation" and that EN and SO "are more loosely coupled than other studies would imply". Recently, we examined these events for the last 120 years and characterized each year as having an El Nino (EN), or Southern Oscillation minimum (SO), or eastern equatorial Pacific SST maxima (warm events W) or minima (cold events C) or any combination of these, or none of these (non-events). We found that for Indian summer monsoon, unambiguous ENSOW was a very favourable combination for association with droughts. In this note, we propose to examine the behaviour of African rainfall during the various categories of years as also regional coherences and teleconnections, using 90 years (1901-1990) data.

2. Data

For categorizing the years, we used El Nino data from Quinn *et al.* (1987) where they mention the years, *at the beginning of which* El Nino had already developed or was developing and also mention its strength depending upon the SST anomaly along Peru-Ecuador coast (>2.9°C, strong; 2.0- 2.9°C, moderate, <2.0°C weak). For Southern Oscillation index (SOI), we used values from Wright (1977, 1984 and further private communication), and also Tahiti minus Darwin (T-D) mean sea level atmospheric pressure (Parker, 1983 and further values from Meteorological Data Reports). For eastern equatorial Pacific SST, we used data from Wright (1984), Angell (1981) and further private communications from them. Rainfall data for Africa were obtained from Nicholson (1986, 1993, 1994) in the form of standardized annual rainfall departures for eight regions (Fig.1a), five in West Africa (Sahelo-Sahara, Sahel, Soudan, Soudano-Guinean and Guinea coastal regions) and three in Eastern and Southern Africa (Eastern Africa, Southern Africa-North and Southern Africa-South regions). These were supplemented by similar data for Sahel, East Africa and Southwestern Africa (Fig.1b) given by Hulme (1992, 1994) as also for Equatorial East Africa and Southeast Africa given by Ropelewski and Halpert (1987). Just for comparison, Indian summer monsoon data were obtained from Parthasarathy *et al.* (1992).

3. ENSO Relationship

Fig. 2 shows a plot of the SO and SST indices in the upper part, followed by the various rainfall series for (a) 1900-1945 and (b) 1945-1990. For each year, the rectangles (fifth row) show whether the year had an El Nino (EN), Southern Oscillation minimum (SO), and warmer waters (W) or colder waters (C) in the eastern equatorial Pacific. Whenever El Nino existed, the symbols S, M, W at the top of the rectancle indicate the strength (Strong, Moderate, Weak) of the El Nino. For the SO indices, minima are shaded black and maxima are shown hatched, while for SST, maxima (temperature increases W) are shown black while minima (temperature decreases C) are shown hatched. For the rainfall, increases exceeding 0.5σ are shown black and



Figs. 1(a&b). (a) Eight regions of Africa used for rainfall analysis by Nicholson (1994). (b).Three regions of Africa (Sahel, East Africa and Southwest Africa) used by Hulme (1994) and two regions (East Equatorial and Southeast Africa) used by Ropelewski and Halpert (1987)

decreases below -0.5σ are shown hatched. The smooth lines are five year moving averages. Most of the rainfalls are annual (Jan-Dec) averages, except for Equatorial East Africa (Oct-April next year), Southeast Africa (Nov-May next year) and Southwestern Africa (July of previous year-June). The big full circles show the maxima of the 5-year moving averages and the triangles show the minima. The circled numbers show the spacing (in years) between successive maxima (big full circles).

Figs. 3, 4, 5 show the rainfall status in the different regions during years of different categories. Rainfall was divided into six categories *viz.* severe floods (full triangles, > 0.99σ) mild floods (open triangles, 0.50 to 0.99σ), small positive deviations (+, 0 to 0.49σ), small negative deviations (-, 0 to -0.49σ), mild droughts (small circles, -0.50 to -0.99σ) and severe droughts (big circles, < -0.99σ). In what follows, the acronyms EN, SO, W etc. are used in their literal sense. Thus, EN means El Nino existed. So means the Southern Oscillation Index (T-D) had a minimum. W or C means equatorial eastern Pacific SST was warm or cold. ENSO means El Nino existed and (T-D) had a minimum simultaneously, and so on Fig. 3 shows events (years) where El Nino was involved. There were 13 unambiguous ENSOW (El Nino in the beginning of the year, and SO and W in the middle of the year) and another 13 ambiguous ENSOW (El Nino in the beginning of the year but SO and/or W in the early or later part of the year, not in the middle), 2 ENSO, 3 EN and 3 ENC. The symbols I and II refer to the first and second years when El Ninos occurred in two successive years (1918-19, 1925-26, 1930-31, 1940-41, 1957-58, 1982-83). The first 8 rainfall columns refer to those of Nicholson (1994), where the first 5 refer to west Africa and are expected to show similar results between themselves. This is, in general true and on many occassions, all these show positive or negative extremes. But the extremes are not always of one sign for any type of years. For example, for Sahel, amongst the first 13 (unambiguous) ENSOW, 3 showed severe droughts (big circles), 2 showed mild droughts (small circles), 2 were -, 4 were +, 2 were mild floods (open triangles) and there were no severe floods. Thus, 5 were droughts, 6 were normal and 2 were floods, not a very encouraging distribution. Thus, considering all the regions, from the 13 events, 6 or 7 were normal and the rest were distributed more or less equally between droughts and floods, basically indicating random distributions. In

Fig. 2. SO and SST indices, our classification of every year (ENSOW etc.) with S, M, W, showing strength strong, moderate, weak of the El Nino and rainfall departures in various African regional series. For SO, minima are shown black, maxima hatched. For SST, maxima are shown black, minima hatched. For rainfall, extremes (0.5σ or more) are shown black for floods and hatched for droughts. Smooth thick lines are 5-year running averages. Triangles show minima and big full circles show rainfall maxima. Circled numbers represent spacings (in years) between successive maxima (a) 1901-1945, (b) 1945-1990

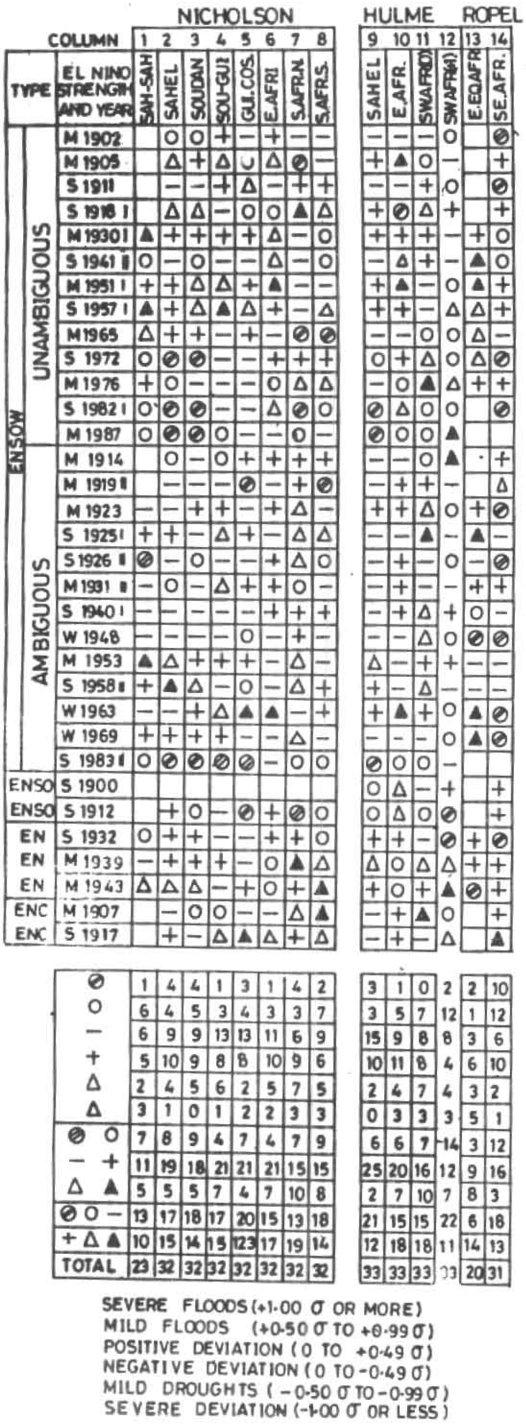


Fig. 3. Rainfall status in the various African regions used by Nicholson (1994, col. 1-8), Hulme (1994, col. 9-12) and Ropelewski and Halpert (1987, col. 13-14) and All India Summer monsoon given by Parthasarathy *et al.* (1992) (our column 15). Symbols + and Δ represent positive departures and - and 0 represent negative departures, for unambiguous, ambiguous and other type of events, all involving El Ninos (EN)

contrast, the last (15th) column of Fig. 3 for the Indian summer monsoon shows 12 droughts, 1 normal and no floods, indicating an excellent correlation between unambiguous ENSOW and Indian droughts. The 9th (Sahel), 10th (E. Africa) and 11th (SW Africa) columns refer to rainfall series of Hulme. The 12th column is for data of 11th column (SW Africa) one year later. Columns 13 and 14 refer to East equatorial Africa and SE Africa (data of Ropelewski and Halpert).

For the 13 ambiguous ENSOW (El Nino in the beginning of the year but SO or W not in the middle of the year), neither the All India summer monsoon nor African rainfall and ENC events. For all events involving EN, the statistics is as shown at the bottom of Fig. 3. In a maximum of 33 events, half or more seem to be in the normal (+, -) category for all African regions and from the rest, roughly equal numbers are for floods and droughts. Only for SE Africa (column 14), there is a slight bias for droughts. If El Ninos are considered as equivalent to low SO indices, the finding of Nicholson and Entekhabi (1986) that for equatorial region (E. Africa), higher rainfall (floods, triangles) was associated with low SO index (El Ninos) does not seem to be fully borne out. For example, for column 6 (E. Africa), column 10 (E.Africa) and column 13 (Eq. E. Africa) the numbers for droughts and floods are respectively 4, 7; 6, 7; 3, 8. Thus, slight bias for floods is indicated but the presence of some droughts and lots of normals is disconcerting. In general, an inverse relationship between low SO (El Nino) and high rainfall (floods) in equatorial regions or a positive relationship between low SO (El Nino) and low rainfall (droughts) in S. Africa is not well established. Therefore, a prediction based on the same may prove misleading and hazardous.

An interesting aspect is the differences in the various South African series. The differences could be because of different geographical regions (within South Africa). But the difference between column 11 and 12, both referring to Southwestern Africa (Hulme, 1994) is revealing. Nicholson (1994) mentions that the four north-most zones of West Africa (column 1,2,3,4) have a high sun rainfall maximum in August while Guinea Coast (column 5) has two rainy seasons separated by a relatively dry period during the high-sun season. Eastern Africa (column 6) has in most areas two rainy seasons during the year. Thus, for all these, the annual rainfall, defined as for January to December, is appropriate. However, for all parts of South Africa, there is a single rainfall season during the high-sun period, which is November to February. Thus, annual rainfall (Jan-Dec) will have only a part of the maximum (Nov-Dec) in one year and rest (Jan-Feb) in the next year! Nicholson and Entekhabi (1986) are aware of this fact but have still used and presented Jan-Dec as annual rainfall (Nicholson, 1994) and justify the same on several grounds (Nicholson, 1985) including the

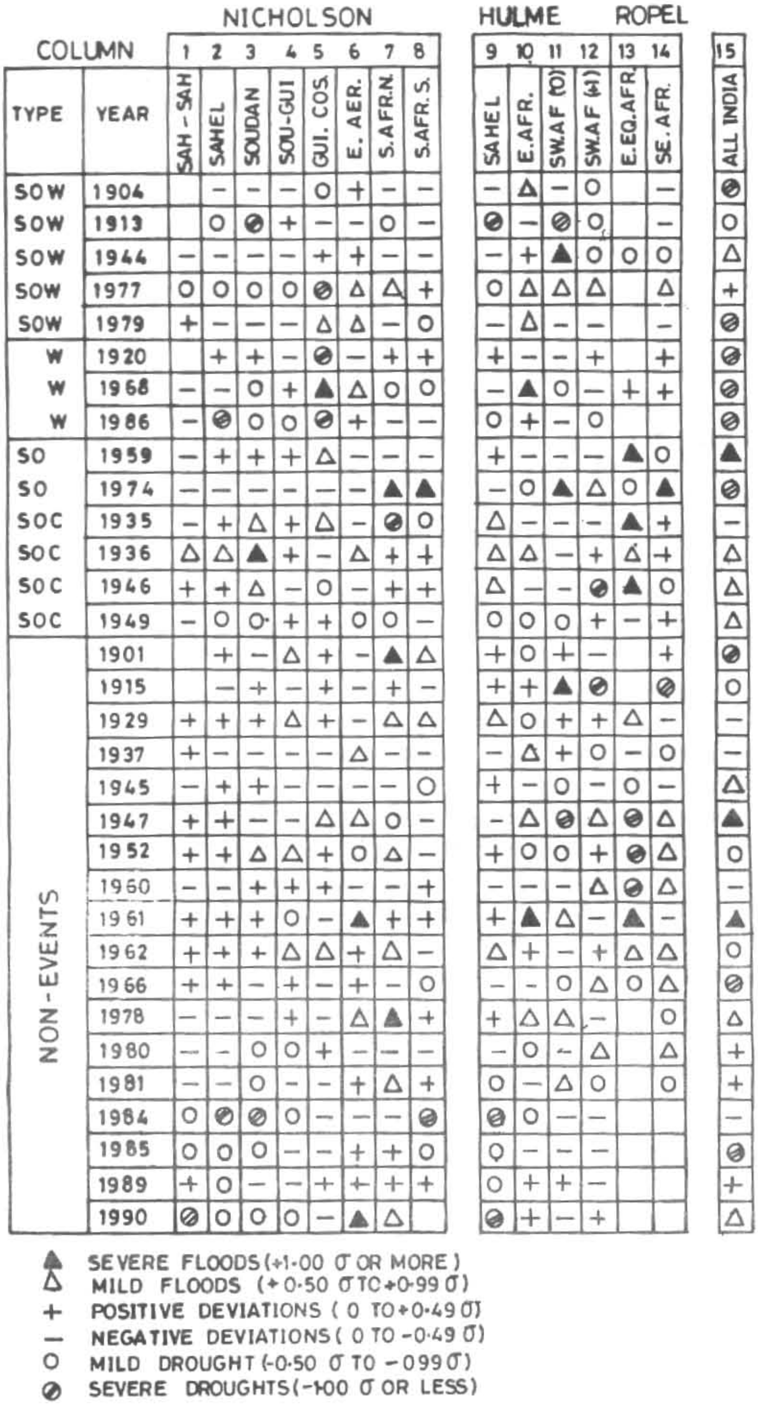


Fig. 4. Same as Fig. 3, for events involving SO and/or W and SOC and, non-events

high correlation between calendar year and "agricultural" year rainfall totals as also because numerous previous studies of rainfall in southern and eastern Africa have used calendar-year data (*e.g.* Ogallo, 1979; Rodhe and Virji,

COLUMN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	NICHOLSON								HULME				ROPEL		
YEAR	SAH-SAH	SAHEL	SOUDAN	SOU-GUI	GUI. COS	E. AFR	S.AFR N	S AFR S	SAHEL	E.AFR	SWAF(O)	SW.AF(+1)	E.EQ.AFR	SE.AFR	ALL IND
1903		O	+	+	O	+	O	⊘	−	+	O	−		Δ	+
1906		▲	▲	+	−	Δ	−	+	▲	▲	−	▲		Δ	+
1908		−	−	+	−	+	−	O	+	Δ	O	▲		Δ	Δ
1909		+	Δ	▲	+	−	−	▲	▲	+	▲	−		−	+
1910		O	−	+	Δ	−	−	−	−	−	−	−		−	Δ
1916		+	+	Δ	+	+	O	O	−	+	⊘	O		−	▲
1921	O	−	−	+	+	⊘	Δ	+	−	⊘	+	O		⊘	+
1922	−	+	+	+	−	−	⊘	O	Δ	−	O	Δ	Δ	Δ	+
1924	+	+	Δ	Δ	+	O	−	+	+	O	O	▲	⊘	▲	+
1927	Δ	▲	▲	+	−	−	O	O	Δ	−	O	−	⊘	O	−
1928	+	−	Δ	Δ	+	−	−	−	+	O	−	+	O	+	O
1933	Δ	Δ	Δ	Δ	▲	−	−	O	Δ	O	⊘	Δ	O	+	▲
1934	−	−	+	−	+	−	−	▲	+	O	Δ	−	O	−	Δ
1938	−	+	+	−	−	−	−	+	+	−	O	Δ	−	▲	Δ
1942	−	O	−	O	−	−	−	Δ	−	+	−	+	⊘	Δ	▲
1950	Δ	▲	▲	O	O	−	−	Δ	Δ	−	+	−	−	−	+
1954	+	▲	Δ	Δ	+	−	+	−	Δ	−	+	Δ	−	▲	+
1955	+	Δ	Δ	Δ	Δ	−	Δ	Δ	+	−	Δ	+	+	Δ	Δ
1956	Δ	+	+	−	−	−	+	Δ	Δ	−	+	−	Δ	+	▲
1964	−	+	Δ	+	−	+	O	O	Δ	+	O	O	O	O	Δ
1967	−	+	+	+	−	Δ	+	Δ	+	Δ	Δ	O	▲	O	+
1970	O	−	−	−	−	+	⊘	O	−	+	O	+	−	+	▲
1971	O	O	O	O	−	−	−	+	O	−	+	Δ	⊘	Δ	+
1973	O	⊘	⊘	O	−	−	−	+	⊘	O	O	▲	+	▲	Δ
1975	O	−	−	−	−	−	+	Δ	−	−	Δ	▲	−	▲	▲
1988	+	−	+	−	+	Δ	+	Δ	−	+	▲	+			▲

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
⊘	0	1	1	0	0	1	2	1	1	1	2	0	4	1	1
O	5	4	1	4	2	1	4	7	1	5	9	4	4	3	0
−	6	7	6	6	13	16	13	3	6	10	4	6	5	3	1
+	5	8	8	9	8	5	5	6	9	7	5	6	2	6	10
Δ	4	2	7	6	2	3	2	7	7	2	4	5	2	7	7
▲	0	4	3	1	1	0	0	2	2	1	2	5	1	5	7
⊘ O	5	5	2	4	2	2	6	8	2	6	11	4	8	4	1
− +	11	15	14	15	21	21	18	9	15	17	9	12	7	9	11
Δ ▲	4	6	10	7	3	3	2	9	9	3	6	10	3	12	14
⊘ O −	11	12	8	10	15	18	19	11	8	16	15	10	13	7	2
+ Δ ▲	9	14	18	16	11	8	7	15	18	10	11	16	5	18	24
TOTAL	20	26	26	26	26	26	26	26	26	26	26	26	18	25	26

▲ SEVERE FLOODS (+1·00 σ OR MORE)
Δ MILD FLOODS (+0·5 σ TO +0·99 σ)
+ POSITIVE DEVIATION (0 TO +0·49 σ)
− NEGATIVE DEVIATION (0 TO −0·49 σ)
O MILD DROUGHTS (−0·50 σ TO −0·99 σ)
⊘ SEVERE DROUGHTS (−1·00 σ OR LESS)

Fig. 5. Same as Fig. 3, for cold (C) events only

1976; Tyson, 1980; Tyson *et al.*, 1975). However, Hulme (1992, 1994) used Jan-Dec for Sahel and E. Africa but July-June for Southwestern Africa, with each year in the table referring to the end of the rainfall year. Thus, the values

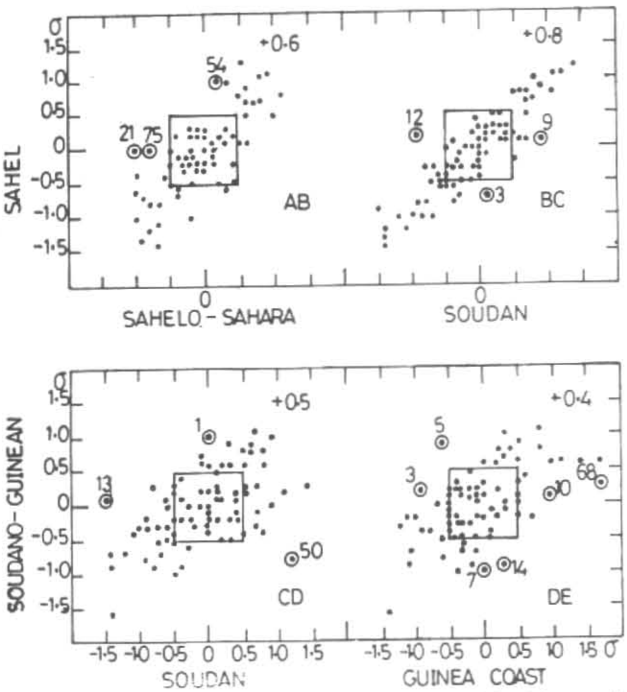


Fig. 6. Correlations in West Africa, Sahel *versus* Sahelo-Sahara and Soudan (upper part) and Soudano-Guinean *versus* and Guinea Coast (lower part). The squares mark the ±0.5σ limits. Correlation coefficients are indicated

used in our coloumn 11 for SW Africa refer to an interval starting about 6 months prior to the January of El Nino year, ending about 6 months later to the January of El Nino year, while values used in column 12 refer to an interval one year later. The fact that column 12 shows droughts, normals, floods as 14, 12, 7 while column 11 shows 7, 16, 10 indicates that El Nino effects are seen better (if at all) several months after the El Nino has evolved. The results for SE Africa (column 14) *viz.* 12, 16, 3 substantiate this fact as these data by Ropelewski and Halpert (1987) refer to November to May (next year).

Fig. 4 shows rainfall patterns for year when there was no El Nino. For the 5 SOW (*i.e.* T-D was minimum and SST was warm), 3 W and 2 SO (in all 10) events, the numbers of droughts, normals and floods show that even though normals are predominant, West Africa is slightly biased for droughts, Guinea Coast is unbiased, East Africa is slightly biased for floods and S. Africa is almost unbiased, again not in full conformity with the expectations outlined by Nicholson and Entekhabi (1986).

A curious group is of the 4 SOC (T-D minima, with cold SST) events. Here, the effects of SO minima and C (cold events) are expected to be contrary. So, no pattern is expected and none is seen.

The most interesting group is of non-events. For these 18 non- events, no extreme rainfalls are expected. In general, only (+,-) *i.e.* small deviations are expected to prevail and do seem to prevail. But some extremes are also seen. Some of these droughts (circles) in the bottom part of Fig. 4 are because of thes severe prolonged droughts in West Africa in the 70's and 80's. If only the 11 events up to 1966 are considered, W. Africa shows mostly normal rainfall and East Africa and South Africa show many droughts and floods, indicating that factors other than El Nino, SO minima or warm Pacific waters are affecting the rainfalls considerably in these areas.

Finally, Fig.5 shows rainfall during the C (cold) events *i.e.* events when the equatorial eastern Pacific waters were colder than normal. These events also coincide with SO indices maxima and all La Ninas are included here. For All India summer monsoon rainfall (column 5), there is a preponderance of floods. However, for the African regions, more than half are normal rainfall events. In general, the biases in Africa are not clear-cut or profuse.

In conclusion, in contrast to the All India summer monsoon rainfall which shows many droughts associated with ENSOW (El Ninos, with T-D minima and SST maxima) and floods with C, the African rainfall shows only slight biases, indicating very loose relationship, in agreement with our earlier results (Kane, 1989) for some regions in Africa and certainly not useful for any reliable predictions. Occurrences of severe widespread droughts or floods during some of the events in Figs. 3 to 5 seem to be by chance coincidence. This also applies to the 1982-83 severe widespread droughts, attributed to the 1982/83 strong ENSO event, as Nicholson and Entekhabi (1986) say, "rightly or wrongly".

4. Spatial coherence and interhemispheric teleconnections

Whereas a meaningful relationship with EN (El Nino), SO (T-D minima), W, C (warm or cold SST) seems to be ruled out for most of the regions, Figs. 2 to 5 do show some relationship between rainfall extremes in the various regions.

(A) *Annual rainfalls*

An interesting feature seen in Fig. 2 is the occurrences of rainfall maxima (or minima) with a spacing of 2-3 years, more for some regions than for others. This is the quasiperiodic behaviour in the 2-3 year band (Quasi-biennial Oscillation) studied by Tyson *et al.* (1975), Ogallo (1979), Nicholson and Entekhabi (1986) amongst others and will be discussed by us later. Another interesting aspect is the simultaneous occurrences of the extremes in several regions. A simple way of establishing coherence is by studying the correlations.

Fig. 6 shows a plot of the annual rainfall departures of one region *versus* another in W. Africa. The squares in the middle of each plot show the ±0.5σ limits. The rainfall in Sahel seem to be well-correlated (+0.6 or more) with those

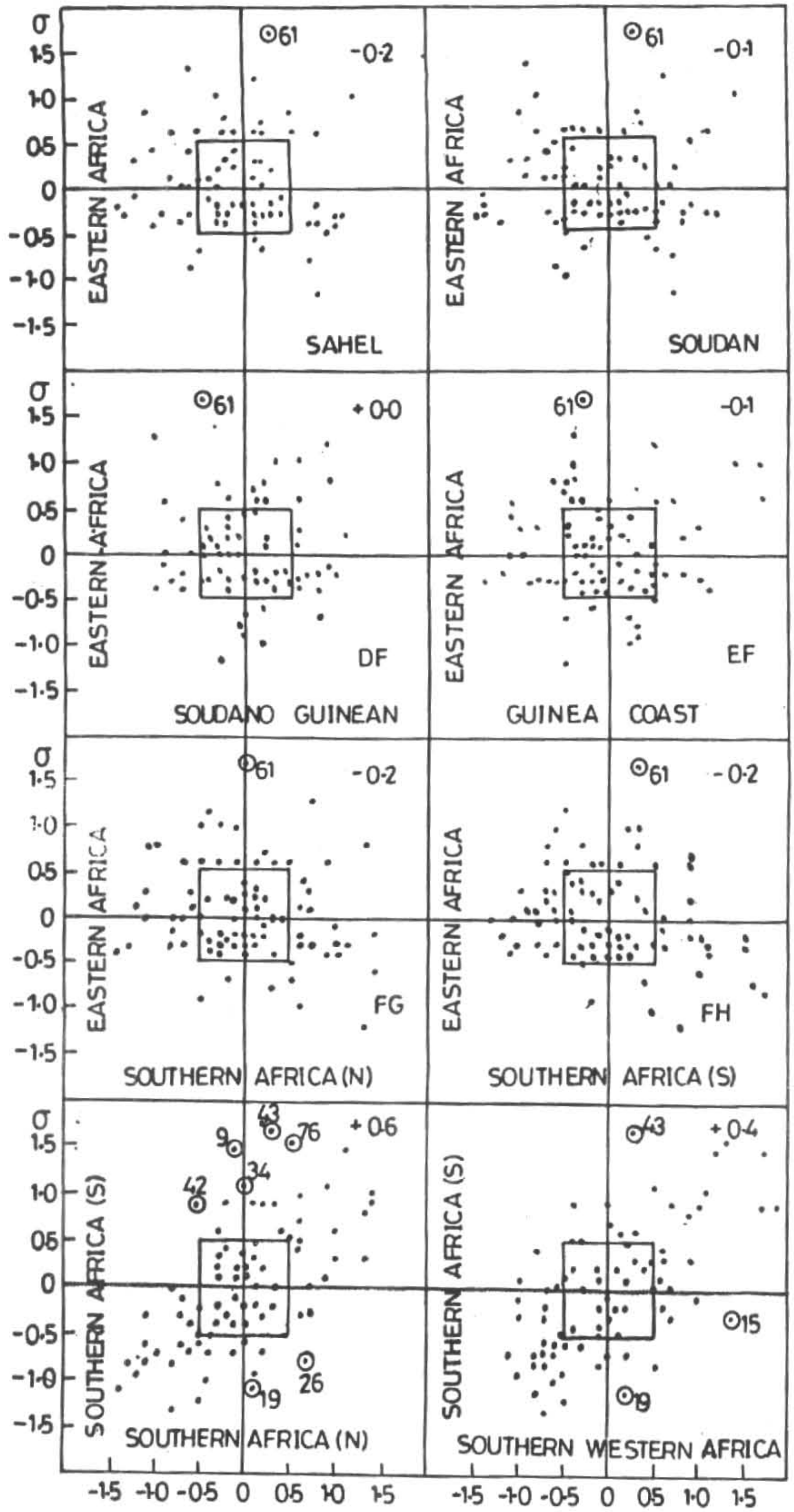


Fig. 7. Same as Fig. 6, for Eastern Africa *versus* Sahel, Soudan, Soudano-Guinean, Guinea Coast, Southern Africa (N) and Southern Africa (S) and Southern Africa (S) *versus* Southern Africa (N) and Southwestern Africa

for Sahelo-Sahara in the north and Soudan in the south. Some notable nonconformities are the droughts in Sahelo-Sahara in 1921, 1975 and in Soudan in 1912 and the floods in Soudan in 1909 when Sahel showed only normals rainfall and the floods in Sahel in 1954 when Sahelo-Sahara showed only normal rainfall. Down below, Soudano-Guinean has positive but low correlations (+0.5 or less) with Soudan in the north and Guinea Coast in the south, with nonparallelism in many years. Thus Guinea Coast and its vicinity has many features dissimilar to its northern neighbours, a fact already known (*e.g.* Nicholson, 1994).

Fig. 7 (upper half) shows similar plots for E. Africa *versus* Sahel Soudan, Soudano-Guinean and Guinea Coast. All correlations are near zero, indicating an overall lack of relationship. In the lower half, E. Africa shows poor relationships with S. Africa (North and South), while S. Africa (South) is well correlated with S. Africa (North) and moderately correlated with SW Africa. The correlations may have been partly destroyed because of the use of "calendar" year for E. Africa and S. Africa (North and South) by Nicholson (1994), while SW Africa refers to July-June (Hulme, 1994).

Simple correlation analysis is rather a crude way of getting an overall picture. Nicholson (1980, 1986a,b) used an elaborate linear correlation method to assess the similarity of annual departure maps for the years 1901 to 1973 and obtained six basic anomaly types of rainfall patterns. These can be reduced to four basic pattern *viz.*(*i*) negative departures all over the African continent (*ii*) positive departures all over the continent, (*iii*) negative departures in the equatorial region but positive departures in the northern and/or southern subtropics (*iv*) positive departures in the equatorial region but negative departures in the northern and/or southern subtropics. Nicholson (1980) gave a list of years which could be classified into one of the six anomaly types. Later, Nicholson (1986a) gave similar lists of six anomaly types (1 to 6) for North Africa as also for the whole African continent and later (Nicholson, 1986b) for Africa south of the equator. Unfortunately, the anomaly type numbers 1 to 6 in all these publications do not represent the same type. For example, in Nicholson (1986a, Table 2), Anomaly type1 represents uniformly negative departures (years 1973, 1972, 1971 etc.) for North Africa but in Table 3, similar uniformly negative departures (years 1973, 1972, 1971 etc.) for the whole African continent are listed under Anomaly Type 3. Later, in Nicholson (1986b), Table II lists the subnormal rainfall (strong negative departures), South Africa as Type 1. In any case, we compared these lists and reproduce the same in our Table 1.

While arriving at this classification, correlations as low as +0.3 have been used. As such, the selection cannot possibly be regorous but only indicative. In our Table 1, we have underlined years which were seen in at least two regions (from N. Africa, whole continent or S. Africa) and hope that at least these would be truly representative of the

TABLE 1

Years classified as four basic types (i) to (iv) as obtained from Nicholson (1986a,b)

Type	North Africa [Nicholson (1986a) Table 2]	Continent [Nicholson (1986a) Table 3]	South Africa [Nicholson (1986b) Table II]
	Type 1	Type 2	Type 1
(*i*) Uniformly negative	73, 72, 71, 70, 49, 48, 42, 40, 26, 19, 13, 7	73, 72, 71, 49, 48, 42, 40, 19, 13	73, 66, 64, 60, 59, 49, 33, 30, 28, 27, 24, 22, 8, 3
	Type 4, 6	Type 4	Type 4
(*ii*) Uniformly positive	57, 55, 54, 51, 43, 33, 29, 24, 17, 9, 6, 5, 1	67, 63, 61, 60, 57, 50, 34, 25, 17	67, 63, 57, 50, 42, 34, 17, 9
	Type 2	Type 3	Type 2, 3
(*iii*) Negative at equator Positive in subtropics	58, 56, 53, 52, 50, 46, 36 , 22	58, 56, 55, 54, 53, 52, 43, 18	56, 55, 53, 43, 40, 39, 36, 29, 25, 23, 21, 20, 18, 11, 7, 1
	Type 5, 3	Type 1, 5, 6	Type 5, 6
(*iv*) Positive at equator, Negative in subtropics	68, 63, 47, 44, 41, 37, 31, 14	70, 68, 66, 65, 47, 44, 41, 37, 35, 31, 26, 22, 12, 3	70, 68, 65, 51, 47, 45, 44, 41, 37, 35, 31, 16, 14, 12, 5

anomaly type. Also, for any of these years, homogeneity within the region is expected. The data in Figs. 2 to 5 were examined to check this classification.

In Table 2 (North Africa) and Table 3 (African continent) of Nicholson (1986a), some years in the beginning of each row showed very high correlations between years and type. As such, these years were expected to be prominent examples of that type. For example, the years 1971, 1972, 1973 were mentioned as best representative of continental droughts and years 1934, 1963, 1967 as of continental floods. For each region, we gave our own category rating *viz.* P, N, M depending upon whether all locationis in the same region gave positive (P), negative (N) or mixed (M) rainfall departures. By this convention, the years 1971, 1972, 1973 mentioned by Nicholson as continental droughts should be NNN (Negative departures in all regions). Instead, we observed that these were NNM, NPM and NMM. Similarly, the years 1934, 1963, 1967 mentioned by Nicholson as continental floods should be PPP (positive departures in all regions). Instead, we observed these were MNM, MPM and MPM. It is obvious that the classification of years into the various types of anomalies made by Nicholson is very general. Hence, we attempted a rigorous classification taking into account the actual annual rainfall departures for each region (W. Africa, E. Africa and S. Africa) for each year. The 3 letter classification (*e.g.* NNM) can have 27 categories (P or N or M for each of the 3 regions). It was interesting to note that only one year (1936) was a PPP *i.e.* positive departures simultaneously in all the regions. Also,

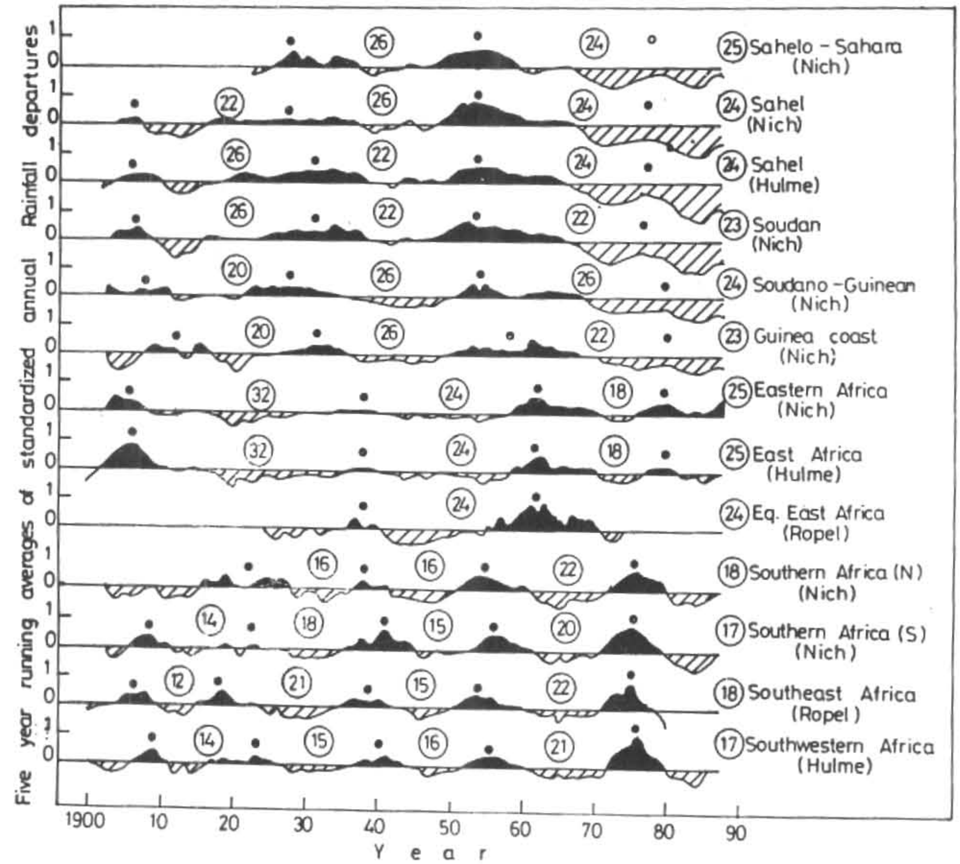


Fig. 8. Five-year running averages of the various African rainfall series. Positive departures are shown black and negative departures are shown hatched. Big full circles show maxima and circled numbers show spacings (in years) between successive maxima, while squared numbers indicate average spacing for each series

only 1983, 1984 qualified as a NNN, *i.e.* simultaneous negative departures in all regions. Almost half the number of years had mixed patterns (noncoherence) inside more than one region simultaneously, probably due to local circulations interfering with teleconnections. Out of 90 years, there were only 20 years when every region was coherent in itself. (Readers interested in Tables giving these details can obtain the same from the author, on request). Thus, teleconnections are not very frequent and several types are involved (positive as well as negative relationships between various regions at different times). This leads to low overall correlations and one is tempted to suspect that it is indicative of overall randomness, though the four basic configurations suggested by Nicholson (1986a) *viz.* (1) negative departures or (2) positive departures over most of the continent, (3) negative departures in low latitude tropics but positive elsewhere and (4) positive departures in the low latitudes but negative elsewhere, may as well be there.

The seasonality of rainfall considerably from one region to another. Also, some regions seem to have Quasi-biennial variations, which may not be of the same nature (amplitudes, phases and even periods) in all regions. Both these factor would tend to dilute coherences between region. To eliminate the effects of these factors and to bring out longterm coherences, five-year running averages were evaluated.

(B) *Five-year running averages*

Fig. 8 shows a plot of the 5-year running averages of the various rainfall series. Positive deviations are shown black and negative deviations are shown hatched. Fig. 9 shows plots of rainfall in one region *versus* another. Compared to Fig. 6 and 7, the ccrrelations in Fig. 9 are better. Sahelo-Sahara, Sahel and Soudan are very well correlated while Soudano Guinean and Guinea Coast are less correlated. Surprisingly, the correlations of E. Africa with W. Africa and S. Africa are still poor.

Overall correlations between any two series can be poor for various reasons. For example, both the series may be random, or any one of them may be random, or, both may have regular periodicities of but with dissimilar characteristics. In Fig. 8, one can see that the black (or hatched) portions appear simultaneously within the same region but not simultaneously for different regions. The black full circles in Fig. 8 mark the positions of rainfall maxima and the circled numbers represent the spacing (in years) between successive maxima. As can be seen, the spacing is 22-26 years for the W. African region, yielding an average spacing

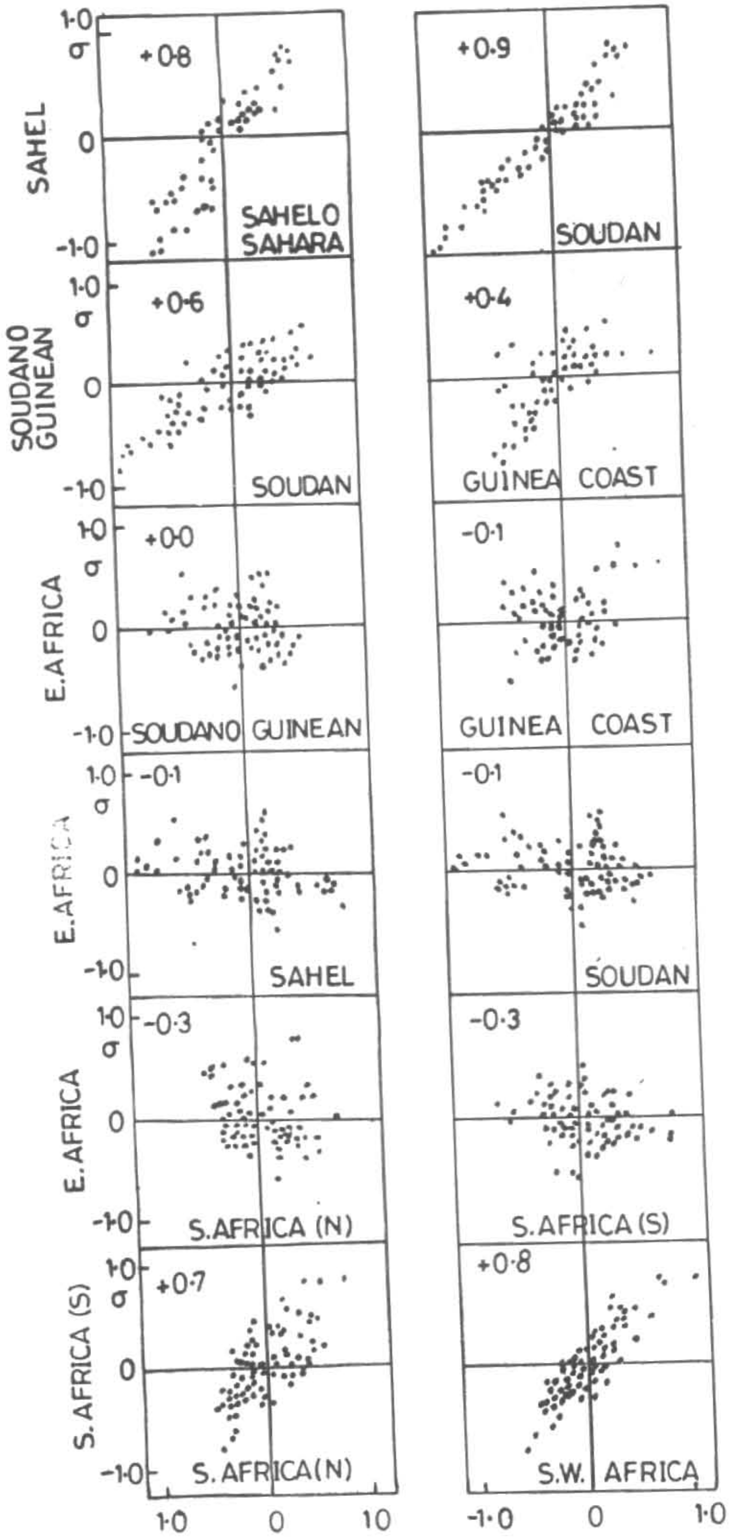


Fig. 9. Correlations between regions, using 5-year running averages

(squared numbers) of 23-25 years. For E. Africa, the spacing is more irregular, in a range of 18-32 years, while the average spacing to 24-25 years. For S. Africa also, the spacing is irregular, in a wide range 12-22 years, and the average spacing is 17-18 years. Eventhough W. Africa and E. Africa have roughly the same average spacing (~ 24 years) between the successive maxima, the correlation is almost zero; because the maxima of one do not occur simultaneously with the maxima or minima of the other. Instead, the occurence is shifted, *i.e.* out of phase. It seems to us that the interhemispheric coherence or anticoherence is more like a chance coincidence of maxima or minima belonging to different periodicity structures in different regions. It may be interesting to study these periodicities by themselves.

5. Periodicities and predictions

Trends and periodicities in African have been studied since long *e.g.* by Bunting *et al.* (1976) for W. Africa, Rodhe and Virji (1976) for E. Africa, Tyson *et al.* (1975) for S. Africa, Ogallo (1979), Nicholson and Entekhabi (1986) for various parts of Africa. Whereas no significant trends were detected in any part of Africa (upto about 1965), significant quasi-periodicities have been reported clustered in the bands 2.2-2.4, 2.6-2.8, 3.3-3.8, 5.0-6.3 years (Nicholson and Entekhabi, 1986) for about 70 years data upto 1973. Kane and Trivedi (1986) analysed the data for various locations in the world and reported significant periodicities for some African regions, notably Sahel and South Africa, for data upto mid 70's. Since then, some regions (*e.g.* W. Africa) have suffered drastic changes like prolonged droughts. Therefore, we conducted a power spectrum analysis for all the series reported by Nicholson (1994) and one series of Hulme (1994) for Southwestern Africa. We used the method of Maximum Entropy Spectral Analysis (MESA, Burg, 1967; Ulrych and Bishop, 1975) which detects spectral peaks very accurately. Since amplitude estimations are not reliable in MESA (Kane and Trivedi, 1982), we obtained the peaks T_k (k=1 to n) from MESA and used the same in the expression:

$$f(t) = A_0 + \sum_{k=1}^{n} [a_k \text{ Sin } (2\pi t/T_k) + b_k \text{ Cos } (2\pi t/T_k)] + E$$

$$= A_0 + \sum_{k=1}^{n} r_k \text{ Sin } (2\pi t / T_k + \phi_k) + E \qquad (1)$$

where $f(t)$ is the observed time series and E is the error factor. The parameters A_0, (a_k, b_k) and their standard errors were estimated by conducting a Multiple Regression Analysis (MRA, Bevington, 1969). From these, one can obtain the amplitudes r_k and their standard error σ. which is common to all r in this methodology. Amplitudes exceeding 2σ are significant at a 95% (a priori) confidence level.

Fig. 10 shows the plots of the amplitudes of the various periodicities detected in the various annual rainfall series. The hatched portion represents the 2σ (a priori) limit. The two bottom plots are for the SO (Southern Oscillation) index and for SST (Sea-Surface Temperature in the eastern equatorial Pacific). The following may be noted:

(1) All rainfall plots show significant QBO (Quasi-biennial Oscillations) and it is tempting to assume that these are related to the QBO of the SO index and SST. However, the periodicities are not matching exactly. Whereas periodicities at or need 2.10, 2.34, 2.70 seem to exist in all plots, their relative proportions are different for different plots. Since we had only annual values of rainfall available for analysis, the values of QBO periodicities are not expected to be very accurate. For SO and SST, the accuracy is better we could use 3-monthly averages. Periodicities in QTO (Quasi-triennial Oscillations) and larger range are also observed *viz.* 3.0, 3.2, 3.4, 3.5, 3.6, 3.7 and 3.8 years. Here again, more than one are seen in almost every plot and comparison with 3.6 years of the SO index and SST becomes dubious. We have not carried out a cross-spectra and coherence analysis as the earlier results of Nicholson and Entekhabi (1986) had already suggested that SO had a strong influence (coherence in the QBO range) only in South Africa. Our results in section 3 (ENSO relationship) have already demonstrated the fragility of these relationships.

(2) Periodicities in the larger ranges are also noticed, notably at <u>4.1</u>, <u>4.2</u>, <u>4.6</u>, <u>4.7</u>, <u>4.8</u>, 5.1, <u>5.7</u>, <u>5.8</u>, <u>5.9</u>, 6.1, <u>6.4</u>, <u>6.5</u>, <u>7.3</u>, <u>7.6</u>, <u>7.7</u>, <u>8.2</u>, <u>8.3</u>, <u>9.2</u>, <u>9.3</u>, <u>9.6</u>, 10-12 & 13-15 years. Here again more than one appear in each plot but in different proportions in different plots. Hence, comparison with similar peaks in SO or SST becomes dubious. It is tempting to attribute the 10-12 year band to sunspot cycle, for the Sahel region and South Africa. However, for southern Cape, Tyson (1981) suggests that the 10-11 year oscillation may be forced by longitudinal changes in the position of the first ridge of standing wave 3, which may oscillate with a similar quasi-periodicity.

(3) For W. Africa (except Guinea Coast), E. Africa and S. Africa (except S. Africa, South), peaks seem to occur at 27-32 years. For Sahel, Guinea Coast and S. Africa, peaks appear at 17-19 years. In the SO index, there is a peak at 19 years while SST has 20 years. A comparison of SO, SST with S. African rainfall is tempting.

(4) In W. Africa, there are significant peaks in the larger periodicity region (50-90 years). These are mainly due to the positive rainfall departures during the 50's, followed by the large droughts during the 70's (Fig. 8) and hence, are not very meaningful.

Whereas many of these peaks seem to be highly significant, their occurrence in large numbers is frightening. MRA probably inflates significant by over-fitting. The irregular spacings in Fig. 8 are also due to this multiplicity. Again, there is no guarantee that these peaks would persist in future

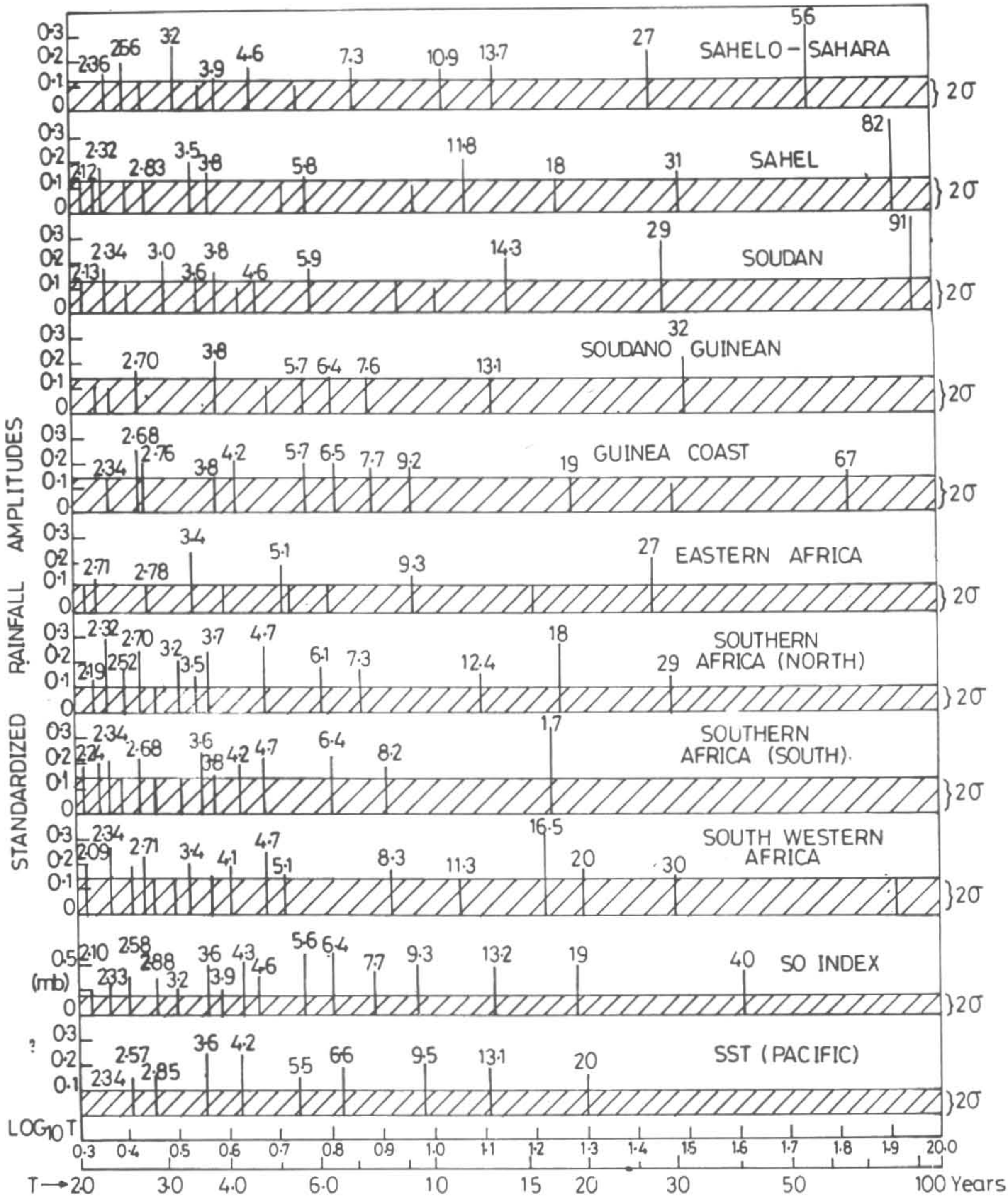


Fig. 10. Maximum Entropy Spectral Analysis (Amplitudes *versus* periodicities) for various rainfall series in Africa as also for SO and SST indices. Hatched portion indicates 2σ(a priori) limit

with the same relative proportions. Even for the SO index, Wright (1977) demonstrated that the spectra varied considerably for the four intervals 1851- 1882, 1881-1912, 1911-1942 and 1941-1972. Similar changes could have occurred for the rainfall series and may occur in future. As such, prediction possibilities seem to be bleak. Using a 7-year running mean of annual Senegal river runoff, Faure and Gac (1981) demonstrated a 30-year cycle in Sahelian rainfall and predicted a return to wetter conditions by 1985, which did not come true. In our paper (Kane and Trivedi, 1986) also, the prediction for Sahel failed. For northeast part of S. Africa (data of Dyer and Tyson, 1977) we had predicted below average rainfall for 1982-87, which seems to have come true. It would thus seem, that amongst all these series, S. Africa has the best chance of having some prediction potential. Since the last drought occurred during early 80's, the next drought could be around 2002-05 and the present should be a period of excess rain.

The peaks shown in Fig. 10 were obtained by analysing annual values. When 5-year running averages were analysed, all peaks near and below 5 years disappeared, those up to 7 years had amplitudes reduced but all other (9 years and more) remained intact. This gives us confidence that the signals are not false.

6. Conclusions and discussion

Characterizing each year during 1901-1990 as having an El Nino (EN) or a Southern Oscillation index minimum (SO) or warm (W) or cold (C) waters in the eastern equatorial Pacific or any combination of these or none (non-events), the annual rainfall departures for various parts of Africa were examined to check whether annual rainfall extremes were related to any particular combination. It was noticed that the rainfall extremes in most of the regions were unrelated to any combination, except for slight bias for droughts in S. Africa in El Nino years, where, out of 31 El Nino years, 16 had normal rainfall, 12 had droughts and 3 had floods. In contrast, for All India summer monsoon rainfall, amongst 33 El Nino years, 11 had normal rainfall, 17 had droughts and 5 had floods.

Regarding coherence and teleconnections, Nicholson (1986a,b) reported coherences within each of W. Africa, E. Africa and S. Africa. We checked this with correlation analysis. In W. Africa, Sahel was well correlated with Sahelo-Sahara and Soudan; but Soudano-Guinean and Guinea coast had lesser correlations. E. Africa was poorly correlated with W. Africa or S. Africa while within S. Africa, correlations were moderate. For teleconnections, Nicholson (1986a,b) used an elaborate correlation method and identified four basic patterns *viz.* negative or positive departures all over the continent and negative or positive departures in the equatorial region associated with positive or negative departures in the subtropics. To check it or a yearly basis, we chose 4 regions Sahelo-Sahara, Sahel, Soudan and Soudano-Guinean (Leaving out Guinea Coast) to represent W. Africa (data of Nicholson, 1994), E. Africa data from Nicholson (1994), Hulme (1994) and Ropelewski & Halpert (1987) to represent E. Africa (3 series) and data for South Africa north and South (Nicholson, 1994), Southwestern Africa (Hulme, 1994) and Southeast Africa (Ropelewski and Halpert, 1987) as the four series representing S. Africa. We noticed, however, that amongst 90 years (1901-1990), only one year (1936) had floods and only two years (1983, 1984) had droughts over the whole continent. Teleconnections, if any, were scarce.

The seasonality of rainfall differs considerably in different parts of Africa. Also short-term local circulation patterns could cause differences and dilute teleconnections. To eliminate the effect of these factors, 5-year running averages were evaluated and each was considered as belonging to the central year (*e.g.* average of 1902, 1903, 1904, 1905, 1906 was considered is belonging to 1904). The four basic patterns proposed by Nicholson were not the predominant ones, neither were any others, indicating that teleconnections were rare, more like random chance coincidence.

The plots of 5-year averages showed quasi-regular patterns with long intervals of positive departures followed or preceded by long intervals of negative departures. The spacing between maxima was irregular; but W. Africa and E. Africa had an average spacing of 24 years. However, their maxima rarely tallied, giving an overall correlation of almost zero between West and East Africa. For S. Africa, the average spacing was 17 years. Thus, the overall correlation between S. Africa and E. or W. Africa was bound to be almost zero.

A power spectrum analysis of the various series showed significant periodicities in several bands *viz.* Quasi-biennial, Quasi-triennial, 4-6, 7-9, 10-12 years and more. Some of these matched with periodicities in SO and SST. In the large range, West and E. Africa and some parts of S. Africa had peaks in the 27-32 year range while Sahel, Guinea Coast and all of S. Africa had peaks in the 17-19 years range. In each region the plethora of peaks makes interpretation and forecasting difficult. Nevertheless, excess rains during 1990-2000 and droughts around 2002-05 seem likely in S. Africa. Tyson (1991) has reviewed the past and present conditions and future scenarios for climate change in S. Africa.

Atmospheric conditions related to known examples of teleconnections have been studied by several workers. For example, Krueger and Winston (1975) and Kanamitsu and Krishnamurti (1978) have documented individual years of contrasting rainfall departures (droughts *versus* floods or normal) and studied the associated tropical circulations. Kraus (1977) showed the spatial coherence of subtropical droughts, specially for the 1972 event, when droughts occurred not only in Sahel and Sudan but also the borders of the Indian desert and in Central America, and were accompanied by lower temperatures in the southern subtropics and higher temperatures in the Atlantic. It is interesting to note that the global drought years mentioned by Kraus (1977) *viz.* 1971-72, 1940-41 and 1913-14 and the more recent event of 1982-83 were all associated with El Ninos, which has probably resulted into the popular belief (in our view, unsubstantiated) that all El Ninos cause global droughts! Interactions between tropical and midlatitude circulation patterns have been suggested by many workers (*e.g.* Krueger and Winston, 1974). Regarding the rainfall variability, a common mechanism invoked is the excursion of ITCZ (Inter Tropical Convergence Zone). However, Nicholson (1986a) challenges the same on several grounds, particularly in Southern Hemisphere Africa where much of the rainfall seems to be linked with midlatitude systems (*e.g.* Harangozo and Harrison, 1983). Instead, Nicholson (1986a) emphasized the roles of Hadley circulation and its antithesis, the Walker circulation through their variations in location and intensity, which was confirmed in the comparative study for continental drought and wet years (1972 and 1967) by Kanamitsu and Krishnamurty (1978). Other factors like tropical zonal flow also seem to play an important role in affecting the rainfall in Sahel (*e.g.* Newell and Kidson, 1984) and in southern Africa (*e.g.* Harangozo and Harrison, 1983). For S. Africa, Tyson (1984) compared circulation patterns for extended dry and wet spells, confirmed the role of both low latitutde and midlatitude forcing and suggested that the variations in the atmospheric field of motion at the 500hPa level are responsible for the interannual rainfall variability. Various combinations of all these factors could possible yield all the rainfall patterns (teleconnections) we have located in various years. However, none of these seem to be predominant or long-lasting and seem to be very much akin to random occurrences.

In contrast, the periodic structures seen in the various rainfall series seem to be on firmer, realistic grounds. Nicholson and Entekhabi (1986) did observe peaks in the range 16-25 years but desisted from discussing the same on the grounds that the resolution at low frequencies was very poor (in the Blackman- Tukey and Fourier methods they used) and the length of the series (73 years) was too small. In our plots, irregular peaks with average spacings of ~ 24 years in W. Africa and E. Africa (but phases unmatched) and ~ 17 years in S. Africa were noticed. These would naturally give teleconnections of all varieties, which would thus lose much of their physical significance while the real thing may be the different periodic structures. If true, a search would be necessary for pinpointing the origins of these periodicities. For the Subsaharan African rainfall, Lamb (1978), Lough (1986), Druyan and Hastenrath (1991), Janikot (1992) and many others have discussed the role of tropical Atlantic sea surface temperatures. Folland *et al.* (1991) demonstrated that Sahel droughts were associated with cool northern ocean and warm southern ocean, including Indian ocean (Fontaine and Bigot,.1993). It needs to be explored whether these ocean temperatures have any periodicity near 24 years.

For equatorial and southern Africa, Nicholson and Entekhabi (1987) studied relationship with sea surface temperatures along the southwestern coast of Africa. For southern Africa, Tyson (1981) showed that the extended wet spells of the quasi 18-year oscillation occurrred in association with (a) increased pressure in the region of the subtropical ridge of the first zonal standing wave in the 500-hPa surface in the southern hemisphere, (b) eastwards displacement of weakening of the Indian Ocean high and (c) a probable lowering of pressure over the subcontinental interior. Mason (1990, 1995) invoked the temporal variability of sea-surface temperature around S. Africa. These phenomena should then have a 18-year periodicity. It is interesting to note that the SO index and SST have periodicities near 16 years. To us, it seems that the secrets of the African rainfall may lie in the origins of these long periodicities. Hulme (1992) points out (*i*) land cover changes (deforestation etc.) (*ii*) global ocean circulations associated with SST and (*iii*) changing composition of the global atmosphere as major causes of the different interannual variability of Sahel, E. Africa and SW Africa. It remains to be checked whether any of these exhibit long-term periodicities.

Regarding regional coherence, Nicholson and Palao (1993) report that the entire Sahel cannot always by treated as homogeneous and Sahel, West Coast and Guinea Coast can be considered homogeneous only for periods exceeding 7 years. In E.Africa also there is considerable heterogeneity, specially in the eastern horn (Beltrando and Camberlin, 1993).

Acknowledgements

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