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WEST AFRICAN RAINFALL DEFICITS AND SEA SURFACE TEMPERATURES

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ABSTRACT

Comparisons between years of below average rainfall over West Africa, sea-surface temperatures (SST) over the Atlantic Ocean and the world ocean, and latitudinal positions of the Inter Tropical Convergence Zone (ITCZ) over the Atlantic Ocean show that the relationships depend mainly on the rainfall anomaly patterns. The well-known SST dipole (cold northern ocean and warm equatorial and southern ocean) is only apparent during those August months with below average Sudano–Sahelian rainfall and above average Guinean rainfall (rainfall type '−/+') and an abnormal southward position of the ITCZ. In contrast, those August months that experience rainfall deficits over the whole of West Africa (rainfall type '−/−') are associated with warm SST anomalies over the eastern Pacific Ocean, cold persistant SST anomalies over the equatorial Atlantic Ocean and a more northward position of the ITCZ. Those patterns first appear in northern spring before the Sahelian rainy season.

The composite SST differences for the '−/+' and '−/−' rainfall types computed with August or July–September amounts have a good resemblance with each other. Comparison of results related to the reverse July–September rainfall patterns (the '+/−' and '+/+' patterns) during the 1950s shows that the SST anomalies were globally colder when, on average, the Sahelian rainy seasons experienced significant excesses while the Guinean little dry seasons were more marked.

KEY WORDS West African rainfall SSTs ITCZ Anomalies

1. INTRODUCTION

West African rainfall is linked to the south-west monsoon circulation during summer because of the particular geometry of the West African continent, which increases the strong sea–land contrasts westwards of about 20°E. Rainfall depends mainly on three factors: the water vapour content in the tropospheric layers, the condensation nucleus charge and the presence of local convergences and ascents in humid air masses. The low-level water vapour originates from the Atlantic Ocean (Hastenrath and Lamb, 1977; Lamb, 1983; Leroux, 1983; Cadet and Nnoli, 1987), and from evaporation–transpiration processes over the land (Monteny, 1985). Nucleus charge is not only associated with microphysical cloud processes but also with the diffusion of aerosols by regional and large-scale circulations (Prospero and Carlson, 1972; Ben Mohamed and Frangi, 1986; Prospero and Nees, 1986). Convergences and ascents are linked to disturbances, such as easterly waves and squall lines, which result first from interactions between planetary or regional-scale phenomena, and second from the more complex meso-scale dynamics (Rennick, 1976; Reed *et al.*, 1977; Riehl, 1979; Song and Frank, 1983). Moreover because of the low latitudes (less than 18°N), mean flows play an important role (Newell *et al.*, 1972) so that oceanic and continental surface conditions (SST, albedo, soil wetness and vegetation, surface roughness) can influence the climatic evolution and particularly the rainfall variability on monthly and seasonal time-scales (Charney *et al.*, 1977; Walker and Rowntree, 1977; Nicholson, 1982; Sud and Smith, 1985; Folland *et al.*, 1991). Some diagnostic investigations have focused on the relationship between Sudano–Sahelian rainfall anomalies and large-scale flows over West Africa on these time-scales. In particular, it is well established that abnormal drought conditions (wet conditions) over the Sahel are linked

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to decreases (increases) of the intensity of convergence at 850 hPa, of divergent circulations (Hadley type and Walker type), and of the tropical easterly jet at 100–200 hPa, whereas the African easterly jet strengthens (weakens) (Newell and Kidson, 1984; Fontaine and Janicot, 1992).

Other diagnostic studies (Lamb, 1978; Hastenrath, 1984; Folland *et al.*, 1986; Lough, 1986; Palmer, 1986; Hastenrath, 1988; Semazzi *et al.*, 1988; Wolter, 1989; Lamb and Peppler, 1990) and some recent model simulations (Ward *et al.*, 1990; Druyan, 1991) have also examined the statistical links between Sahelian rainfall indices and sea-surface temperature (SST) fields. The main conclusion from these investigations is that Sahelian rainfall deficits are associated with a typical structure of SST anomalies: warm anomalies over equatorial and southern parts of the Atlantic Ocean and more extensively over the Indian Ocean and the southern parts of the Pacific Ocean; cold anomalies over northern areas of the Atlantic and Pacific Oceans. It should be noted here that the Atlantic pattern is part of the global SST difference between the two hemispheres and that this later pattern appears to be correlated significantly with Sahelian rainfall mainly because of the presence of decadal variations in the two time series (Folland *et al.*, 1986). Some climate simulations show, however, that the Atlantic fields could be linked directly to the Sudano–Sahelian rainfall variability because abnormally high SSTs throughout southern areas tend to reduce surface pressures and the subsequent water vapour flow into the West African continent (Druyan, 1991). The strong persistence of SST anomalies is another point of interest, which has been used by the UK Meteorological Office to improve the statistical predictability of Sahelian rainfall anomalies during the summer rainy season (Ward *et al.*, 1990; Folland *et al.*, 1991).

To document the relationships between SST anomaly fields and West African rainfall anomalies, this note will take into account rainfall information not only over the Sahelian belt (typically between the 100 mm and 400 mm totals of annual rainfall), but over the whole of West Africa. Annual, seasonal, and monthly rainfall anomaly fields are organized into large-scale patterns (e.g. Nicholson, 1981, 1986; Janowiak, 1989; Olaniran, 1991; Janicot, 1990, 1992). We focus on the August rainfall patterns for three major reasons. First this month is the peak of the rainy season along the Sahelian belt and of the little dry season on the Guinean coast: during August, the ITCZ reaches its most northern position over the Atlantic Ocean and the African continent, while the strongest gradients of rainfall between the Sudano–Sahelian belt and the Sahara desert are experienced. Second, August rainfall patterns allow us to take into account the intensity and/or the duration of the little dry season that normally occurs on the Guinean coast during this month: rainfall amounts relative to the end of the first rainy season (July) or to the beginning of the second one (September) are then occulted. Third, the rainfall variability in August is closely associated with the variability that affects seasonal and annual rainfall amounts on the Sahelian and Guinean areas. Two major patterns are considered here: August months in which rainfall anomalies of the same sign extend over the whole area (from the Guinean coastline to the Sahelian belt); August months in which rainfall anomalies are of the opposite sign north and south of about 10°N. These different large-scale patterns clearly demonstrate that diagnostic analyses which seek to clarify the statistical links between SSTs and African rainfall must not consider only the sole occurrence of 'dry Sahel/wet Sahel'. Since recent years have shown that abnormal dry rainy seasons and abnormal dry months of August were more frequent than wet ones north of 10°N (Janicot, 1992), we shall consider two rainfall patterns: (i) a large drought pattern ('type −/−') when negative anomalies are encountered over the whole of West Africa; and (ii) a contrasted rainfall pattern ('type −/+') when simultaneously negative anomalies extend north of 10°N and positive anomalies occur south of 10°N. The meteorological and oceanographic conditions associated with these patterns are obviously different; in consequence diagnostic analyses that take into account the whole West African continent might be useful in helping to clarify many aspects of the links between SST fields and tropical rainfall anomalies.

Our main goal is to examine the relationships between recent rainfall anomaly patterns over West Africa, quasi-global and Atlantic patterns of SST anomalies, and the latitudinal excursion of the ITCZ over the Atlantic. However, the relationships between SSTs and the reverse rainfall anomaly patterns ('+/+' and '+/−' types) that occurred during the 1950s (the wettest recent period over the Sahel) will be investigated for providing some elements of comparison, but this paper presents only an introduction to this difficult problem.

2. DATA AND METHODS

West African rainfall totals were obtained from ORSTOM (more than 1000 stations) for the period 1948–1974, ASECNA (1975–1978), AGRHYMET and NOAA (1980–1985), data for 1979 being unavailable. The available stations were not well distributed over the continent and an objective analysis of the data set led to the computation of mean values over small areas (1° latitude by 4° longitude). The data set contains more than 100 basic areas over the whole of West Africa north of the Equator and west of about 23°E, and is precisely described by Janicot (1990, 1992).

The world ocean SST data came from the National Meteorological Center (see Reynolds and Gemmil, 1984). The data consists of more than 100 thousand ship and buoy measurements per month, which were objectively analysed over the 60°N–40°S domain. The version used consists of 180 monthly SST anomaly fields over the area 40°N–40°S, 100°W–100°E on a 2° x 2° grid for the period January 1970 to December 1984. To better document SST variations in the Atlantic Ocean and the ITCZ migration, two other data sets were used. Monthly SSTs over the tropical Atlantic Ocean (30°N–20°S on a 2° x 2° grid; 1964–1990 period) from the FOCAL data set (Servain *et al.*, 1985) and weekly ITCZ positions at 28°W (1971–1990 period) from Citeau and Demarcq (1990). The compression of the SST information has been performed by principal component analysis (rotated and unrotated) and computations of regional indices carried out to exhibit spatio-temporal modes of SST variability and associate them with the two West African drought patterns. Only the first loading pattern and the associated time-series of a varimax rotated solution applied to FOCAL SSTs are presented.

The overall common period (1971–1984) is obviously rather short but very interesting since only the two drought patterns (types '−/−' and '−/+') are encountered during August (the peak of the tropical rainy season and of the Guinean little dry season), which accounts for numerous recent seasonal droughts (Dennett *et al.*, 1985). Moreover the period is well documented (Semazzi *et al.*, 1988) and short enough to limit the influence of trends in both SST and rainfall series. This allows us to test whether the SST relationships using only the Sahelian rainfall series are different when taking into account (i) the whole of West Africa and particularly the two drought patterns, and (ii) a period marked by a reduction of mean annual rainfall and interannual variability compared with the long-term mean (Nicholson, 1986). The composite SST anomalies were calculated using the whole length of data for the respective data set: the '−/−' composite includes 1970.

In addition we carried out similar analyses using July to September mean data in order to identify the relationships between the SST anomaly patterns and the rainfall types (Janicot, 1990) on a seasonal base. Moreover, using the monthly historical sea-surface temperature data set version 3 (MOHSST3) further back than 1970 (Bottomley *et al.*, 1990) we include some 'wet' Sahel rainfall types (which occurred mainly during the 1950s) to compare with results for the recent dry period. MOHSST3 contains monthly SST anomalies (1856–1990) from a base climatology for 1951–1980 over as many 5° x 5° latitude–longitude grid squares as are available (Folland *et al.*, 1991).

Statistical connections were analysed compositing the SST anomalies for the two sets of years and testing the average values for a significant difference from the mean using the Student's *t*-test.

3. RESULTS

3.1. Tropical SSTs and West African drought patterns

For the recent period 1970–1984, the rainfall type '−/−' occurred in August 1970, 1972, 1974, 1975, 1976, 1978, 1981, 1982, and 1983; the rainfall type '−/+' occurred in August 1971, 1973, 1977, 1980 and 1984. The average SST anomaly fields are shown in Figure 1 for the rainfall type '−/−' and Figure 2 for the rainfall type '−/+'. Three months were selected (April, June and August) to focus on the seasonal evolution of the statistical connection. It appears that links between SST and West African rainfall anomalies are not only evident on a seasonal time-scale. Before a typical global drought (the '−/−' August pattern), cold Atlantic SST anomalies in northern spring (Figure 1(a)) are replaced in June by warmer temperatures over southern parts of the Atlantic Ocean but cold SSTs persist over equatorial areas in June (Figure 1(b)) and into August

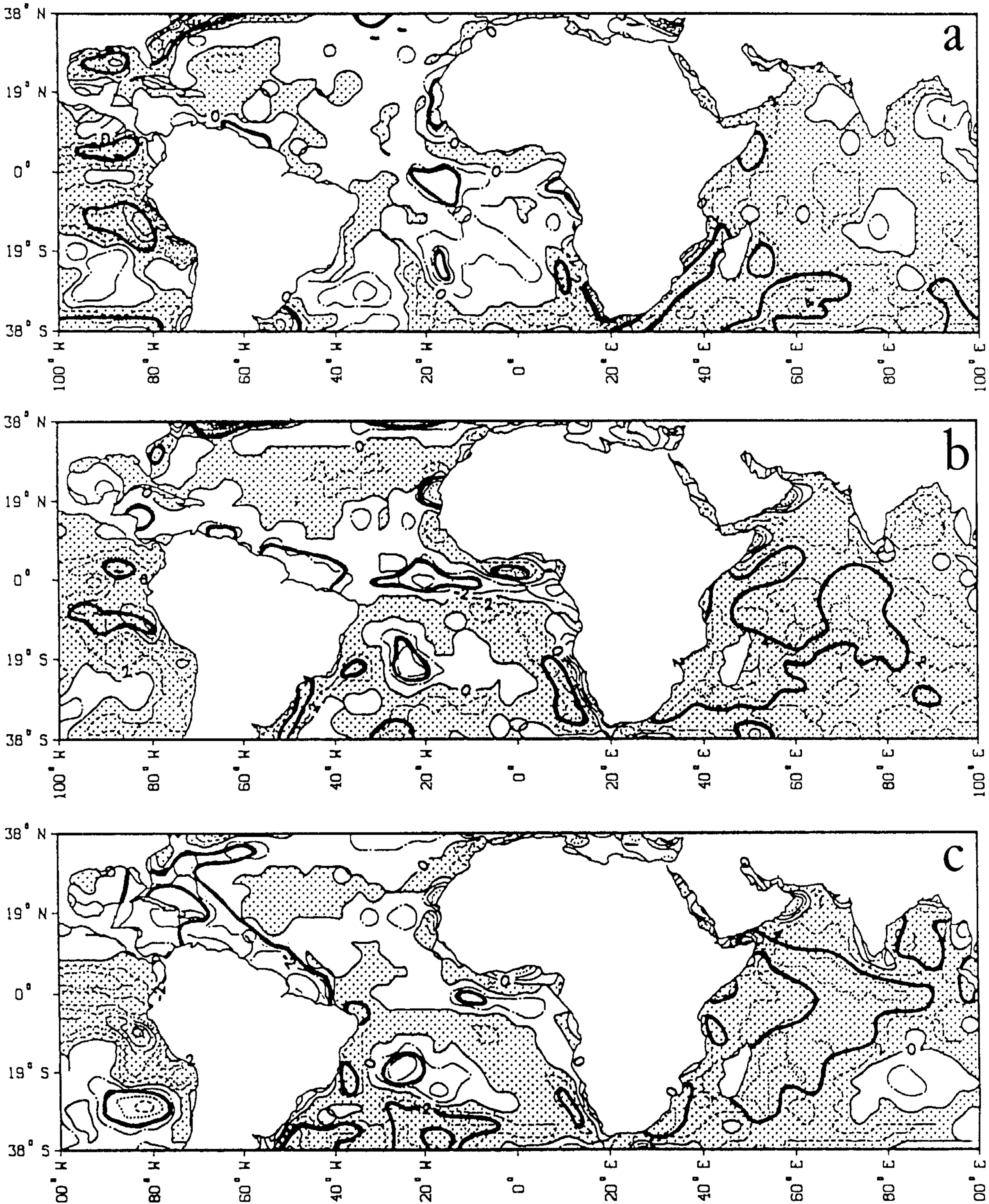


Figure 1. Composite fields of tropical SST monthly anomalies (from the 1970–1984 mean) for those August months of rainfall type '–/–' (1970, 1972, 1974, 1975, 1976, 1978, 1981, 1982, and 1983): April (a), June (b), and August (c). Isothermal intervals are of 0·2°C, dot shading indicates positive areas; areas significant at the 10 per cent level are enclosed by heavy lines

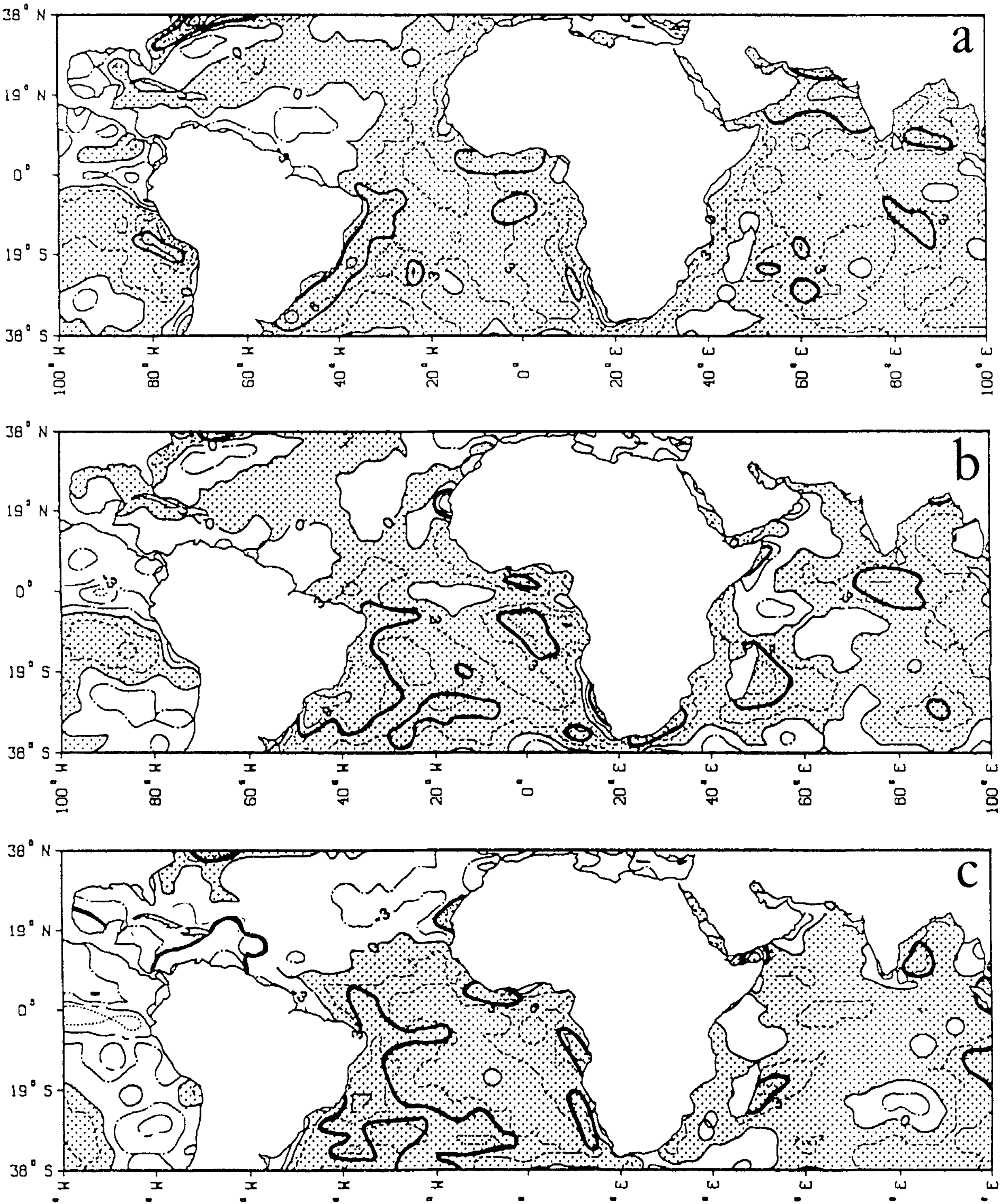


Figure 2. Composite fields of tropical SST monthly anomalies (from the 1970 to 1984 mean) for those August months of rainfall type '−/+' (1971, 1973, 1977, 1980, and 1984): April (a), June (b), and August (c). The interval is of 0·3°C, dot shading indicates positive areas; areas significant at the 10 per cent level are enclosed by heavy lines

over the Gulf of Guinea. The Pacific coast of South America exhibits some persistent warm anomalies, except south of about 25°S where an area of significant cold SSTs is present during August (Figure 1(c)).

In many areas the April and August SST anomalies are both of the same sign: negative values over a large part of the equatorial Atlantic, positive values over the eastern Pacific (north of 25°S) and the Indian Ocean (Figure 1(c)). This statement underlines the importance of April and possibly earlier months' patterns for the seasonal evolution of summer conditions. The spatial coherency of Atlantic SST anomalies weakens over the eastern parts and SSTs become warmer over the 5°N–15°N latitude belt west of the African coastline, while the Indian Ocean and the Equatorial Pacific become less warm. This pattern is consistent with the ENSO mode of global SST variability: positive anomalies over the eastern Pacific (more particularly near the Peruvian coast) and simultaneously negative anomalies, linked to a strengthening of the equatorial upwelling in the equatorial Atlantic (Cadet and Garnier, 1988). It is, however, difficult to establish a direct and strong connection between the Pacific warming associated with the Southern Oscillation and the Sahelian rainfall because no clear statistical link can be found (Stoeckenius, 1981) except for a weak but coherent signal during major events (Ropelewski and Halpert, 1987; Fontaine, 1990).

As illustrated in Figure 2(a), during April of type '$-/+$' years, warm SST anomalies extend across the Atlantic, more particularly in the Gulf of Guinea, and are very persistent from April to August except over the northern parts. It should be noted also that eastern Pacific waters experience cold anomalies. During August (Figure 2(c)) an Atlantic thermal dipole becomes obvious north and south of a line joining Guyana and Senegal; this pattern also persists into September along with an SST warming around the Cape Verde Islands and the Gulf of Guinea (not shown). There is no clear spatial coherency of SST anomalies over the Indian Ocean, but the equatorial Pacific exhibits cold waters during April (Figure 2(a)). Those results are very interesting since, as pointed out by Ward *et al.* (1990), global SST anomalies do not change drastically between June and the end of the Northern Hemisphere summer, but the beginning of the Northern Hemisphere spring can experience some significant modifications of SST patterns. April and May would appear to be of importance to August rainfall anomalies over West Africa.

It is clear (Figure 1 and 2) that the northern parts of the Atlantic exhibit cold SST anomalies in both West African August drought months. This fact is in accordance with recent diagnostic and simulation studies (Semazzi *et al.*, 1988; Ward *et al.*, 1990; Druyan, 1991; Folland *et al.*, 1991) that do not distinguish between the two rainfall types. The large drought pattern (type '$-/-$' in Figure 1) has a stronger global signal than the contrasted drought pattern (type '$-/+$' in Figure 2), but the contrasted mode (type '$-/+$' in Figure 2), is more consistent with these earlier findings: presence of an abnormal warming over large parts of the Indian Ocean and the southern Atlantic associated with cold anomalies over the northern parts of the Atlantic Ocean and the eastern parts of the equatorial and south Pacific. Analysis of all monthly SST patterns (not shown) sets up another point: anomaly fields linked to the type '$-/-$' outline an in-phase evolution of global SST, warmings or coolings becoming relatively stable in the beginning of the Northern Hemisphere spring; in contrast, SST patterns associated with the '$-/+$' rainfall mode are not coherent before the summer. Moreover it should be noted that the SST anomalies of eastern equatorial areas of the Pacific Ocean associated with the ENSO–anti-ENSO mode are different: in type '$-/-$', SST anomalies are warm since the beginning of the Northern Hemisphere spring (April in Figure 1(a)); in type '$-/+$' they are cold in June (Figure 2(b)).

All these results provide some evidence that sub-Saharan dry occurrences are associated with more than one global and Atlantic SST anomaly pattern, a feature consistent with Janowiak (1989), Semazzi *et al.* (1988) and Wolter (1989), and with the existence of several rainfall anomaly patterns over West Africa.

3.2. West African drought patterns and the Tropical Atlantic

3.2.1. SST anomaly patterns. To better document the relationship between the rainfall patterns and Atlantic SSTs in August, similar composites were computed with the FOCAL data set. These data are more accurate than Reynolds and Gemmil's (1984) data over this ocean because they have not been filtered so much. Figure 3(a–c) presents the values of the *t*-test computed on the differences between the SST composites '$-/+$' and '$-/-$' in April, June, and August: positive (negative) values show areas where warmer (colder)

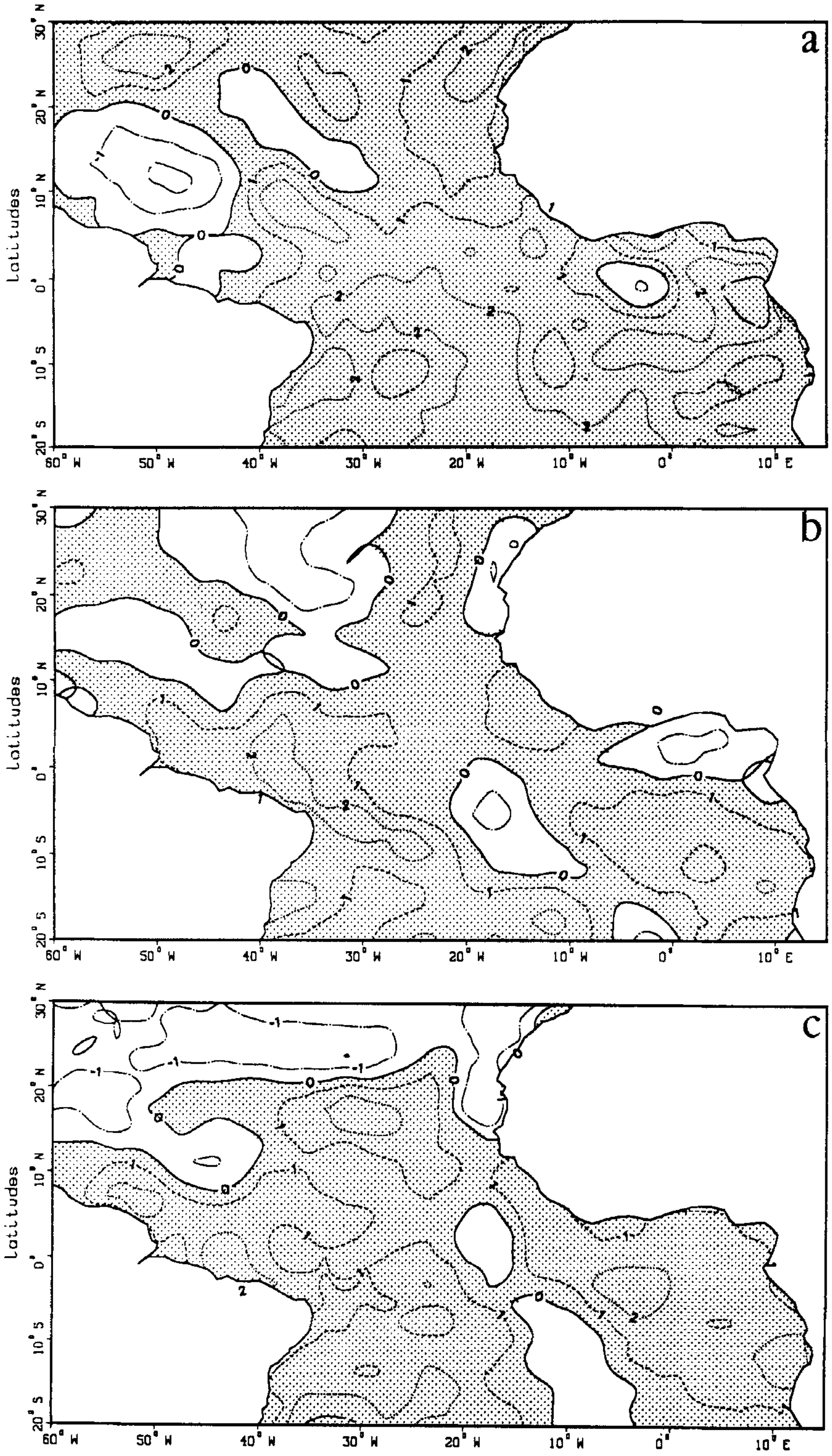


Figure 3. SST composites with Student's *t*-test values for the '−/+' minus '−/−' August rainfall patterns: (a) April, (b) June, and (c) August. Values greater (lower) than +1·8 (−1·8) can be judged significant at the 10 per cent level

SSTs are encountered during '$-/+$' rainfall patterns; values greater (lower) than $+1{\cdot}8$ ($-1{\cdot}8$) can be judged significant at the 10 per cent level.

During April and June (Figure 3(a and b)) the patterns exhibit large positive SST differences with values greater than 2 (lower than -2) all over the domain except some negative values north of Guyana in April. During August (Figure 3(c)) the SST differences are positive (negative) south (north) of about 15°N–20°N. That is consistent with aforementioned results, in particular the thermal dipole in Figure 2(c) (cold northern areas contrasting with abnormal warm temperatures south of a Guyana–Senegal separating line in type '$-/+$') and with recent diagnostic investigations and simulations (Ward *et al.*, 1990; Druyan, 1991) although the coverage of the FOCAL data does not allow us to determine the existence of warm anomalies south of 20°S and more precisely over the 20°S–44°S, 40°W–10°E area reported by Druyan (1991). The seasonal evolution of all monthly composite fields (not shown here) indicates a relative stability of SST anomaly patterns from March to August and shows that the SST dipole arises during those August months that exhibit the contrasted rainfall pattern, mainly because of strong cold anomalies offshore of Mauritania.

Principal component analyses of Atlantic SSTs (Lough, 1986; Quilfen, 1987; Nicholson and Nyensi, 1990; Bigot, 1991) identify in-phase variations over the whole tropical domain on the first eigenvector and, on the second, a pattern with SST anomalies in the northern parts opposite to those in equatorial and southern areas: this dipole is clearer when the boreal summer period (July–September) only is considered and is consistent with Lamb (1978) who first identified this pattern in relation to July–September rainfall anomalies and with Hastenrath (1984) who used July–August anomalies.

Figure 4 shows the time evolution of this SST dipole (Servain, 1991) based on the difference between a northern tropical Atlantic index (28°N–5°N) and a southern one (5°N–20°S). Months of August featuring types '$-/-$' (circles) and '$-/+$' (points) show that the two rainfall patterns are not clearly separated when we examine their successive occurrences in relation to this Atlantic dipole index: the strongest values occur in 1976 ('$-/-$') and in 1980 ('$-/+$'); the weakest ones in 1972, 1974 ('$-/-$') and in 1973, 1984 ('$-/+$'). This failure is due to the fact that this interhemispheric index does not take into account the equatorial signal (apparent in Figures 2 and 3) linked to the equatorial upwelling partly induced by the low-level monsoon flow over the eastern Atlantic (Hastenrath and Lamb, 1977). The rotated (varimax) principal component analysis

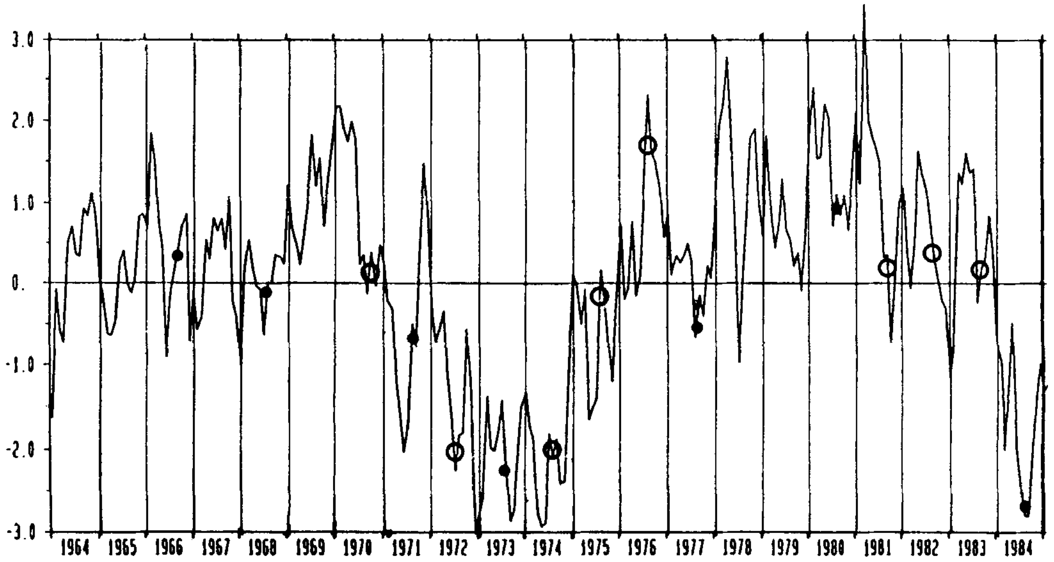
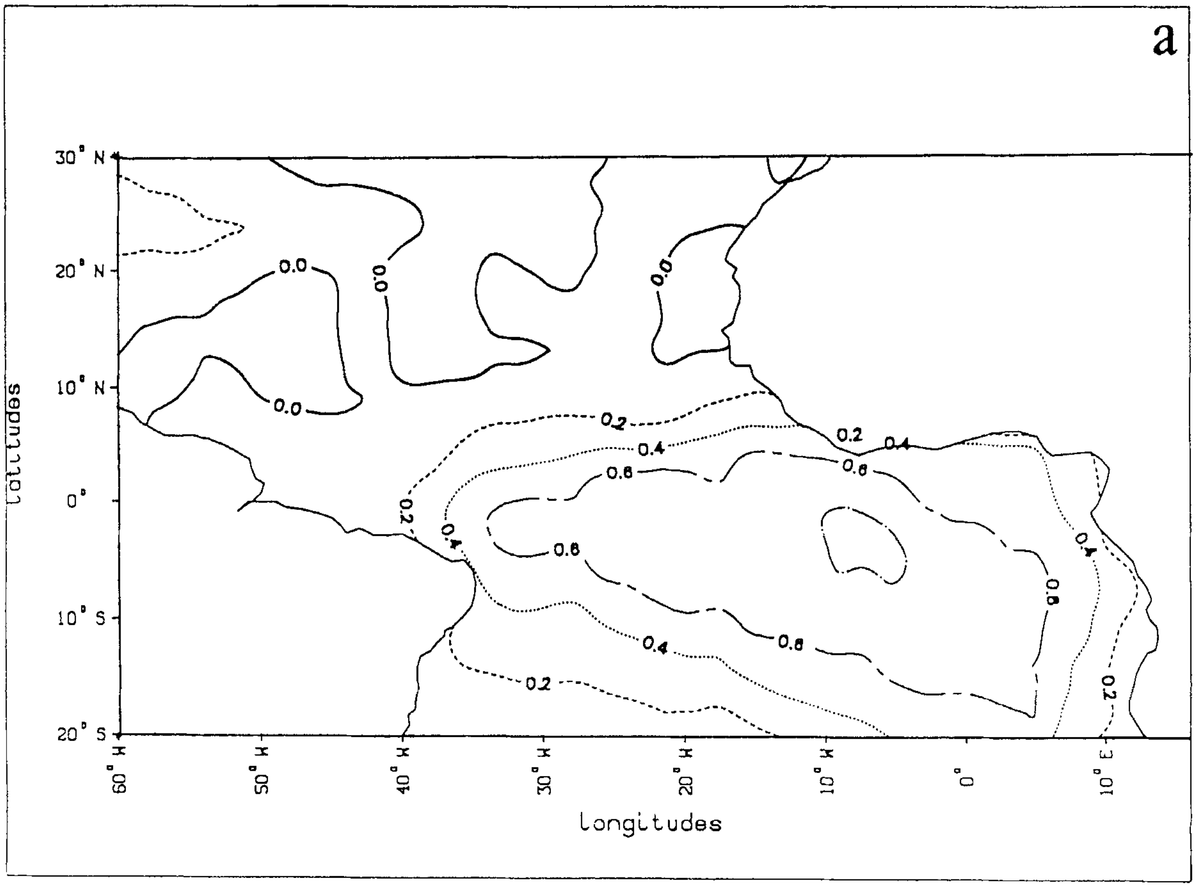


Figure 4. Time series of the monthly Atlantic dipole and August rainfall patterns occurrences. The Atlantic dipole index (Servain, 1991) is based on the difference between two mean values: monthly SST averaged between (i) 28°N and 5°N, and (ii) 5°N and 20°S (in standard deviations). Circles and points represent, respectively, the '$-/-$' and '$-/+$' rainfall occurrences



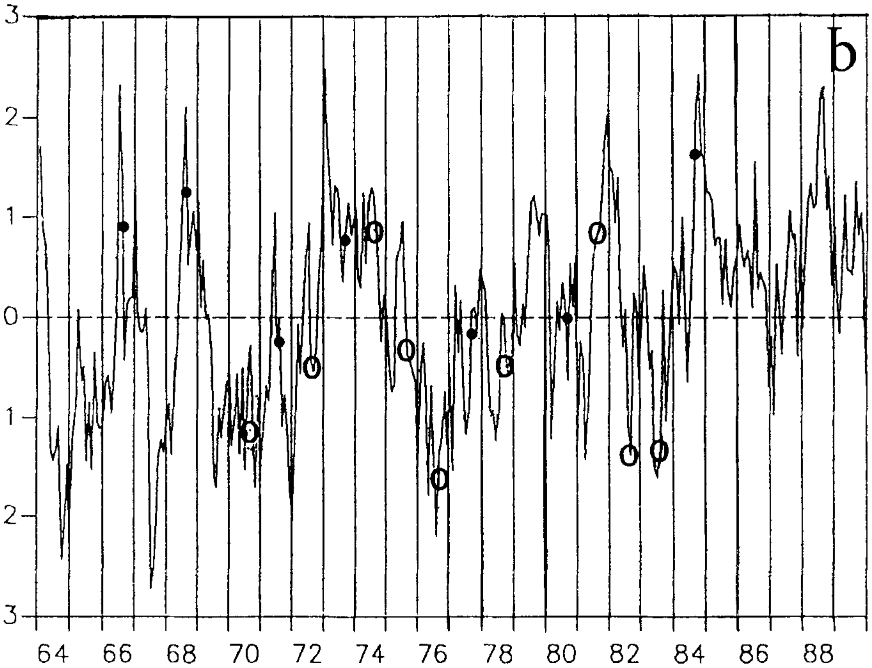


Figure 5. First loading pattern (a) and first time series (b) (EOF with varimax rotation, 23 per cent of variance) computed from the FOCAL 1964–1989 data set (monthly anomalies) and August rainfall patterns occurrences. Circles and points represent, respectively, the '−/−' and '−/+' rainfall occurrences

performed on monthly Atlantic SST anomalies from January 1964 to December 1989 emphasizes this signal on the first axis (22·6 per cent of the variance in Figure 5(a)) and as illustrated in Figure 5(b), the two West African rainfall patterns are better differentiated than with the interhemispheric signal: modes '−/−' (circles) are generally associated with weak values (cold anomalies in the Gulf of Guinea) with the exception of 1974 and 1981; modes '−/+' (points) appear to be linked to positive values (warm anomalies) or values very near the average in 1971 and 1977. These observations emphasize the importance of SSTs in the central and eastern parts of the equatorial Atlantic to future diagnostic investigations because they suggest a possible link with the seasonal migration of the ITCZ.

3.2.2. ITCZ latitudinal positions. The latitudinal positions of the ITCZ at 28°W in the Atlantic appear to be different during abnormal dry or wet years over the Sahel (Guillot *et al.*, 1986; Citeau *et al.*, 1989). These studies have shown that unusually wet years are linked to a strong and early northern ITCZ migration over the central equatorial Atlantic; below average rainfall years exhibit the reverse pattern. Moreover a 'slow' migration as in 1972, 1973, 1982 and 1983, is often followed by an abnormally dry rainy season, but a 'quick' migration, as in 1974 or 1985, tends to precede an abnormally wet rainy season. It is clear that the two West African rainfall patterns ('−/−' and '−/+') show different seasonal migrations of the ITCZ (Figure 6). This difference is particularly evident during two periods: in March–April (before the beginning of the northern shift) and in June–September during the tropical rainy season.

Comparison with the 1971–1989 mean values shows that the '−/−' rainfall occurrence is associated with a less southern position (1·5°N) of the ITCZ in northern winter, an earlier northern movement (from the end of February) and a more northern position during August (9°N). This suggests that global West African dryness is not only due to southward shifts of ITCZ positions but also to dynamic phenomena, such as those discussed in Newell and Kidson (1984) and Fontaine and Janicot (1992).

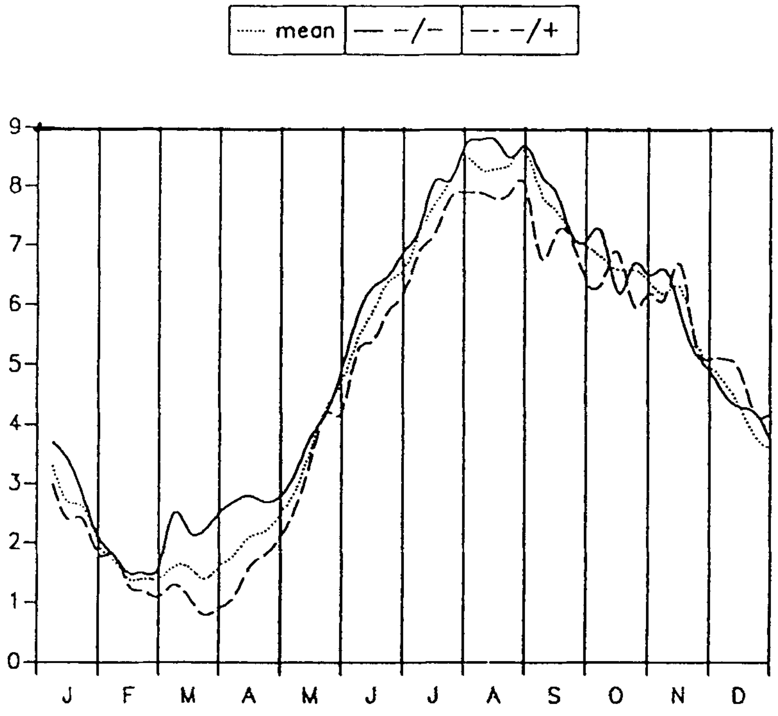


Figure 6. Time series of the ITCZ latitudinal position at 28°W: 1971–1989 mean values (dotted line), '−/−' composite (solid line) and '−/+' composite (broken line)

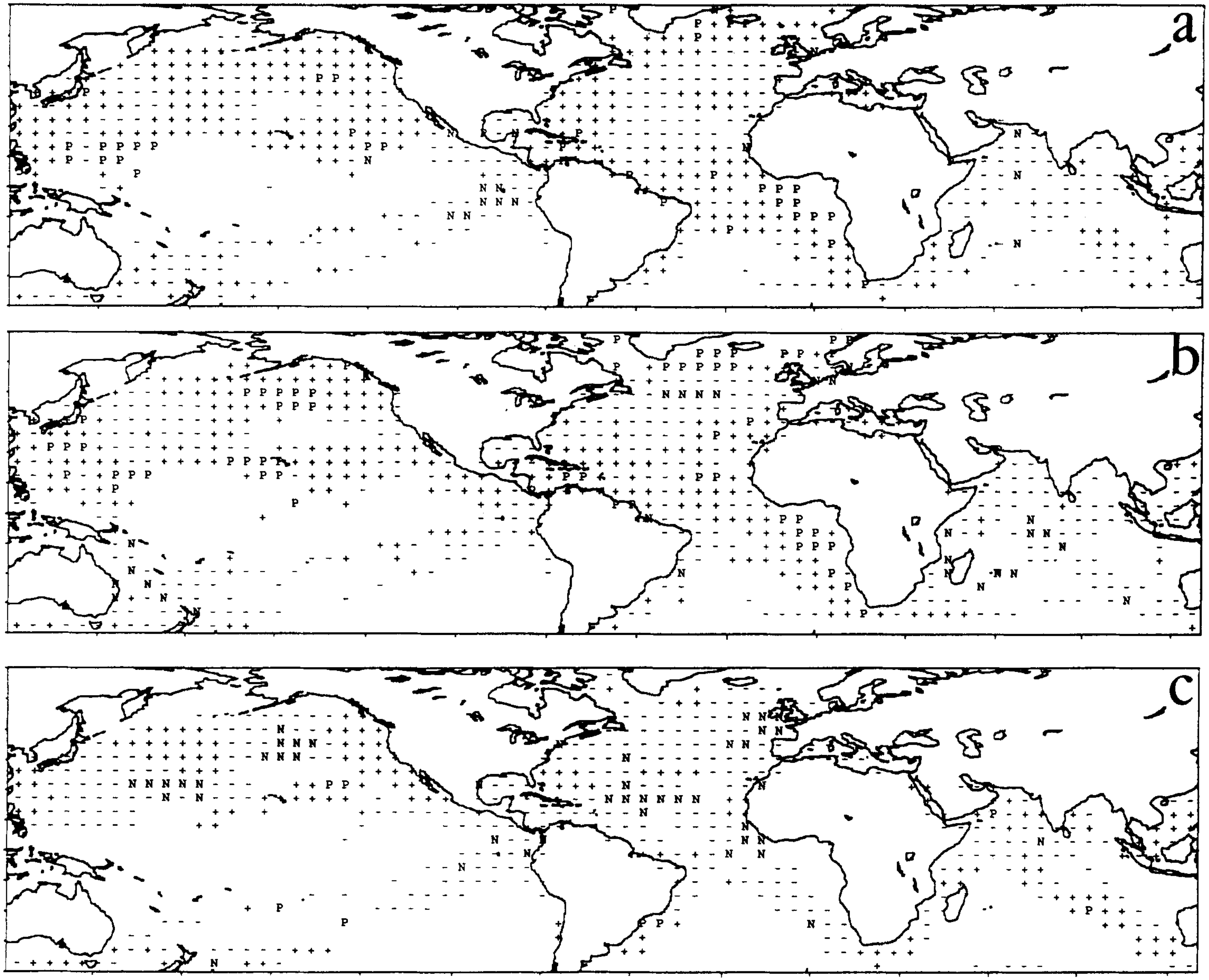


Figure 7. SST composites with Student's t-test values for (a) the '$-/+$' minus '$-/-$' August rainfall patterns, (b) the '$-/+$' minus '$-/-$' July–September rainfall patterns, (c) '$+/-$' minus '$+/+$' July–September rainfall patterns. Results are displayed in a matrix form: blanks indicate 5° × 5° squares where composite differences could not be computed; '+' and '−' show the sign of the composite differences; 'P' and 'N' replace '+' and '−', respectively, when a value exceeds the statistical significant level at $P = 0{\cdot}1$

In contrast the '$-/+$' rainfall occurrence is associated with a more southern position of the ITCZ (less than 1°N at the end of March) and to reduced northern excursion (8°N in August). The differences between the concurrent composite positions of the ITCZ during '$-/-$' and '$-/+$' occurrences are coherent during the first three-quarters of the year: from the last week of March to the second of April they are statistically significant at the 1 per cent significant level. The above results should, however, be confirmed over longer and/or wetter periods (section 3.3).

Based on the Atlantic SST patterns (Figure 1 and 2) and the seasonal excursions of the convergence zone at 28°W (Figure 7) it appears that during '$-/-$' rainfall occurrences the more northern position of the ITCZ in April is associated with cold SST anomalies in the equatorial Atlantic (Figure 1(a)). During '$-/+$' rainfall occurrences the more southern position of the ITCZ is in agreement with warm SST anomalies (Figure 2(a)). Furthermore, a less northward migration of the ITCZ in July–August of '$-/+$' years is linked to warm anomalies over the Gulf of Guinea. This suggests that in the mid-summer of years with above average rainfall south of 10°N (without any little dry season) there is a reduced northward position of convergence–convection zones associated with the intertropical front over West Africa.

3.3. Relationships between global SST anomalies and rainfall patterns during 'dry' and 'wet' periods

In order to better document the relationship between West African rainfall types and SST patterns, three additional composite analyses were performed according to Janicot's typings on the 1948–1985 period (Janicot, 1990).

(i) A composite analysis of August rainfall anomalies in '$-/-$' (1953, 1970, 1972, 1974–1976, 1978, 1981–1983) and '$-/+$' (1960, 1963, 1966, 1968, 1971, 1973, 1977, 1980, 1984, 1985) rainfall occurrences (referenced as AUG$-/-$ and AUG$-/+$).

(ii) A composite analysis of July–August–September (JAS) rainfall anomalies in '$-/-$' (1970–1973, 1975–1978, 1981–1983) and '$-/+$' occurrences (1959, 1960, 1962, 1963, 1965, 1966, 1968, 1974, 1980, 1984, 1985): the years 1948 ($-/-$) and 1949 ($-/+$) were not included because of too many gaps in the SST files). These composites will be respectively referenced as JAS$-/-$ and JAS$-/+$.

(iii) A composite analysis of July–August–September rainfall patterns '$+/+$' (1951–1953, 1955, 1957) and '$+/-$' (1950, 1954, 1956, 1958, 1961), which occurred during the wettest recent period over the Sahel (the 1950s): they will be respectively referenced as JAS$+/+$ and JAS$+/-$. Results relative to the same patterns in August (AUG$+/+$ and AUG$+/-$) are not reported because AUG$+/+$ occurs only in 1962.

Figure 7(a–c) shows the Student's t-values computed on the SST composite differences between AUG$-/+$ and AUG$-/-$ (Figure 7(a)), JAS$-/+$ and JAS$-/-$ (Figure 7(b)), and JAS$+/-$ and JAS$+/+$ (Figure 7(c)). These results are displayed in a matrix form: blanks indicate 5° x 5° squares where composite differences could not be computed, '$+$' and '$-$' the sign of the differences, and 'P' and 'N' replace '$+$' and '$-$', respectively, when a value exceeds the statistical significant level at $P=0{\cdot}1$. Comparison of results related to the AUG and JAS Sahelian dry patterns (Figure 7(a) and 7(b)) shows a rather good similarity: in relation to the AUG$-/-$ or JAS$-/-$ rainfall patterns, SSTs during AUG$-/+$ or JAS$-/+$ occurrences are colder in the Indian Ocean (and over some northern parts of the Atlantic Ocean) and warmer over the other oceanic regions (mainly over the North Pacific and the equatorial and South Atlantic). Although the intertropical Atlantic SST dipole is more evident when only August rainfall patterns are taken into consideration (Figure 7(a)), the SST differences associated with JAS rainfall amounts (Figure 7(b)) are as a whole slightly more significant. This indicates that links between SST anomalies and West African rainfall patterns are more accurate on a seasonal time-scale.

Comparisons between SST anomalies during abnormally dry and wet rainy seasons over the whole of West Africa (JAS$-/-$ and JAS$+/+$) or during the two contrasted rainfall patterns (JAS$-/+$ and JAS$+/-$) are not reported because the results essentially reflect the significant trends that affect SST series on global and regional scales (Folland *et al*., 1986; Palmer, 1986; Bottomley *et al*., 1990; Ward *et al*., 1990).

Despite many gaps, results relative to the JAS '$+/-$' minus '$+/+$' composite difference (Figure 7(c)) are more interesting. They show a clear predominance of negative values. In relation to JAS$+/+$ occurrences this indicates a relative cooling of the global ocean in August when JAS rainfall anomalies over Sahelian (Guinean) areas are positive (negative). The SST composite anomalies from the long-term mean separately computed during the JAS+/+ and JAS−/− events (not shown) are consistent with this feature: in JAS+/+ warm anomalies over the Atlantic Ocean (mainly in northern areas) and the eastern equatorial Pacific are encountered; in JAS+/−, some warmer than normal temperatures are also present in the northern tropical Atlantic, but the equatorial and southern parts of the Atlantic Ocean, the eastern equatorial Pacific and the Indian Ocean exhibit coherent cold anomalies. The Atlantic SST dipole is more evident during the two contrasted rainfall types and tends to reverse between JAS−/+ and JAS+/−.

4. CONCLUSION

During the recent drought period in the Sahel, examination of West African rainfall fields shows that anomalies tend to be organized into two patterns: years in which rainfall anomalies of the same sign occur over the whole of West Africa; years in which rainfall anomalies are of the opposite sign north and south of 10°N. This diagnostic investigation has taken into consideration these spatial patterns. It appears that the SST variability in the eastern equatorial Pacific is a major signal during the 1970–1984 period, partly because of the two large ENSO events of 1972 and 1982–1983. Thus a '−/−' (a '−/+') rainfall anomaly pattern is associated with warm (cold) anomalies over the eastern equatorial Pacific. Our findings also confirm the importance of the thermal dipole on a global scale according to Folland *et al.* (1986) especially for the '−/+' rainfall pattern, and suggest that tropical Atlantic SSTs play an important role in the occurrence of rainfall patterns on an interannual time-scale. Over the tropical Atlantic, an August month with a '−/−' rainfall pattern is, on average, preceded by cold anomalies over large parts of the basin before June, the cooling persisting in the Gulf of Guinea into August. In contrast, months of August characterized by the '−/+' pattern are associated with warm anomalies before June and then with the development of an asymmetrical structure about a Guinea–Senegal line (cold anomalies in northern parts and warm anomalies over equatorial and southern parts). The latter pattern (the thermal dipole) is in good accordance with the most recent diagnostic studies and numerical simulations, which, however, take into consideration only the simple alternative 'dry Sahel/wet Sahel'. Another main feature of our results is the potential influence of SSTs on the arrangement of semi-permanent near-equatorial atmospheric features (association between the equatorial surface divergence induced by the cross-equatorial flow, the cold Ocean and the convection, Hastenrath and Lamb (1977)). Thus, a more southern (northern) position of the ITCZ during March–April and July–August is associated with a '−/+' ('−/−') rainfall pattern in August. Furthermore an abnormal southern position is associated with abnormally warm SSTs in the Gulf of Guinea. We suggest that this tends to weaken the normal meridional shift of the ITCZ and to maintain it south of its mean seasonal position. There is hence some new evidence to suggest that equatorial Atlantic SSTs and the northward migration of the ITCZ system (including the intertropical front over West Africa) are associated and can control some (but not all) continental rainfall anomaly patterns.

Results relative to the most recent wet period in the Sahel (during the 1950s) allow us to take into consideration the two other July–September (JAS) modes of rainfall variability over West Africa: JAS+/− and JAS+/+. In relation to the SST patterns that occur during JAS+/+ seasons, the SST composites relative to the JAS+/− occurrences provide some evidence of a relative cooling of the global ocean in August, mainly in equatorial and southern areas. This is consistent with a reversing of the Atlantic dipole between the two contrasted rainfall anomaly patterns: schematically, cold (warm) SST anomalies north of 10°N in the tropical Atlantic and warm (cold) SST anomalies in its equatorial and southern parts tend to occur during JAS−/+ (JAS+/−) rainfall patterns.

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REFERENCES

Ben Mohamed, A. and J. P. Frangi, 1986. 'Results from ground based monitoring of spectral aerosol optical thickness and horizontal extension: some specific characteristics of dusty Sahelian atmospheres', *J. Clim. Appl. Meteorol.*, **25,** 1807–1815.

Bigot, S. 1991. 'Variabilité et téléconnexions de l'océan Mondial entre 40°N et 40°S', *La Veille Climatique Satellitaire*, **36,** 29–42.

Bottomley, M., Folland, C. K., Hsiung, J., Newell, R. E. and Parker, D. E. 1990. *Global Ocean Surface Temperature Atlas GOSTA*, Joint Meteorological Office/Massachusetts Institute of Technology Atlas, Printed by HMSO, London, 20 pp, 313 plates.

Cadet, D. and Garnier, R. 1988. 'L'Oscillation Australe et ses Relations avec les Anomalies Climatiques Globales', *La Météorologie, VII*, **21,** 4–18.

Cadet, D. L. and Nnoli, N. O. 1987. 'Water vapour transport over west Africa and the Atlantic Ocean during Summer 1979', *Q. J. R. Meteorol. Soc.*, **113,** 581–602.

Citeau, J. and Demarcq, H. 1990. 'Position de la zone intertropicale de convergence le long de 28°W et température de surface de l'océan', *Veille Climatique Satellitaire*, **32,** 2–7.

Citeau, J., Finaud, L., Cammas, J. P. and Demarcq, H. 1989. 'Questions relative to ITCZ migrations over the tropical Atlantic Ocean, sea surface temperature and Senegal river runoff', *Meteorol. Atmos. Phys.*, **41,** 181–190.

Charney, J. G., Quirk, W. J., Chow, S. H. and Kornfield, J. 1977. 'A comparative study of the effects of albedo change on drought in semiarid regions'. *J. Atmos. Sci.*, **34,** 1366–1385.

Druyan, L. M. 1991. 'The sensitivity of Sub-Saharan precipitation to Atlantic SST', *Climatic Change*, **18,** 17–36.

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

Folland, C. K., Palmer, T. N. and Parker, D. E. 1986. 'Sahel Rainfall and worldwide sea temperatures, 1901–85', *Nature*, **320,** 602–607.

Folland, C. K., Owen, J., Ward, M. N. and Colman, A. 1991. 'Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods', *J. Forecast.*, **10,** 21–56.

Fontaine, B. 1990. '*Etude comparée des moussons indienne et ouest africaine: caractéristiques, variabilité et téléconnexions*', 2 vols, Université de Bourgogne and CNRS, Dijon.

Fontaine, B. and Janicot, S. 1992. 'Wind field coherence and its variations over West Africa', *J. Climate*, **5,** 512–524.

Guillot, B., Lahuec, J. P., Citeau, J. and Bellec, B. 1986. 'Les climats de l'Afrique de l'ouest et du nord-est du Brésil: Recherche de téléconnexions', *La Veille Satellitaire*, **N11,** 18–37.

Hastenrath, S. 1984. 'Interannual variability and annual cycle: mechanisms of circulation and climate in the tropical Atlantic sector'. *Mon. Wea. Rev.*, **106,** 1280–1287.

Hastenrath, S. 1988. '*Climate and circulation of the Tropics*, Company Atmospheric Sciences Library, D. Reidel, Dordrecht/Boston/Lancaster/Tokyo, 455 pp.

Hastenrath, S. and Lamb, P. J. 1977. 'Some aspects of circulation and climate over the eastern equatorial Atlantic', *Mon. Wea. Rev.*, **105,** 1019–1023.

Janicot, S. 1990. '*Variabilité des précipitations en Afrique del'ouest et circulation quasi-stationnaire durant une phase de transition climatique*', PhD thesis, University of Paris 6, Paris.

Janicot, S. 1992. 'Spatio-temporal variability of West African Rainfall, Part I: regionalisation and typings', *J. Climate*, **5,** 489–497.

Janowiak, J. E. 1989. 'An investigation of interannual rainfall variability in Africa', *J. Climate*, **1,** 240–255.

Lamb, P. J. 1978. 'Case studies of tropical Atlantic surface circulation patterns during recent sub-Saharan weather anomalies: 1967 and 1968, *Mon. Wea. Rev.*, **106,** 482–491.

Lamb, P. J. 1983. 'West African water vapor variations between recent contrasting Subsaharan rainy seasons, *Tellus*, **35A,** 198–212.

Lamb, P. J. and Peppler, R. A. 1990. 'West Africa', in Glantz, M. H., Katz, R. W. and Nicholls, N. (eds), *Teleconnexions: Linkages between ENSO Worldwide Climate Anomalies and Societal Impacts*, Cambridge University Press, Cambridge, 1990.

Leroux, M. 1983. '*Le climat de l'Afrique tropicale*', 2 vols, Champion, Dijon.

Lough, J. M. 1986. 'Tropical Atlantic Sea Surface Temperature and Rainfall Variations in Subsaharan Africa', *Mon. Wea. Rev.*, **114,** 561–570.

Monteny, B. A. 1985. 'Importance of the tropical rain forest as an atmospheric moisture source', *Proceedings ISLSCP Conference*, 2–6 December 1985, Roma.

Newell, R. E., Kidson, J. W., Vincent, D. G. and Boer, G. J. 1972. '*The General Circulation of the Tropical Atmosphere and Interactions with Extratropical Latitudes*', Vol. 1, MIT Press, Cambridge, MA, 258 pp.

Newell, R. E. and Kidson, J. E. 1984. 'African mean wind changes between Sahelian wet and dry periods', *J. Climate*, **4,** 27–33.

Nicholson, S. E. 1981. 'Rainfall and atmospheric circulation patterns during drought periods and wetter years in West Africa', *Mon. Wea. Rev.*, **109,** 2191–2208.

Nicholson, S. E. 1982. *The Sahel: a Climatic Perspective*, Club du Sahel, Committee for Drought Control on the Sahel, CILSS, OECD, 80 pp.

Nicholson, S. E., 1986. 'The spatial coherence of African rainfall anomalies: interhemispheric teleconnections'. *J. Clim. Appl. Meteorol.*, **25,** 1365–1381.

Nicholson, S. E. and Nyensi, R. S. 1990. 'Temporal and spatial variability of SSTs in tropical Atlantic and Indian Oceans', *Meteorol. Atmos. Phys.*, **42,** 1–17.

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

Palmer, T. N. 1986. 'The influence of the Atlantic, Pacific and Indian Oceans on Sahel rainfall', *Nature*, **322,** 251–253.

Prospero, J. M. and Carlson, T. N. 1972. 'Vertical and areal distribution of Saharan dust over the west equatorial North Atlantic Ocean', *Journal of Geophys. Research*, **77,** 5255–5265.

Prospero, J. M. and Nees, R. T. 1986. 'Impact of the North African drought and El Niño on mineral dust in the Barbados trade winds', *Nature*, **320,** 735–738.

Quilfen, Y. 1987. '*Variabilité de l'atmosphère atlantique tropicale et interactions avec l'océan*', Thesis, Université de Bretagne Occidentale Brest.

Reed, R. J., Norquist, D. C. and Recker, E. E. 1977. 'The structure and properties of African wave disturbances as observed during phase III of GATE', *Mon. Wea. Rev.*, **105,** 317–333.

Rennick, M. A. 1976. 'The generation of African waves', *J. Atmos. Sci.*, **10**(33), 1955–1969.

Reynolds, R. W. and Gemmil, W. H. 1984. 'An objective global monthly mean surface temperature analysis', *Trop. Ocean Atmos. News.*, **23,** 4–5.

Riehl, H. 1979. '*Climate and Weather in the Tropics*', Academic Press, London, 611 pp.

Ropolewski, C. F. and Halpert, M. S. 1987. 'Global and regional scale precipitation and temperature patterns associated with El Nino/Southern Oscillations', *Mon. Wea. Rev.*, **115,** 1606–1626.

Semazzi, F. H., Metha, V. and Sud, Y. C. 1988. 'An investigation of the relationship between sub-Saharan rainfall and global sea surface temperatures', *Atmos. Ocean*, **26,** 118–138.

Servain, J. 1991. 'Simple climatic indices for the tropical Atlantic Ocean', *J. Geophys. Res.*, **96**(C8), 15137–15146.

Servain, J., Picaut, J. and Busalacchi, A. J. 1985. 'Interannual and seasonal variability of the tropical Atlantic Ocean depicted by sixteen years of sea surface temperature and wind stress', in *Coupled Ocean–Atmosphere Models*, Elsevier, Amsterdam, pp. 211–237.

Song, J. L. and Frank, W. H. 1983. 'Relationship between deep convection and large-scale processes during GATE', *Mon. Wea. Rev.*, **111,** 2145–2160.

Stoeckenius, T. 1981. 'Interannual variations of tropical precipitation patterns', *Mon. Wea. Rev.*, **109,** 1233–1247.

Sud, Y. C. and Smith, W. E. 1985. 'The influence of surface roughness of deserts on the July circulation: a numerical study', *Boundary-Layer Meteorol.*, **4,** 383–398.

Walker, J. and Rowntree, P. R. 1977. 'Effect of soil moisture and rainfall in a tropical model', *Q. J. R. Meteorol. Soc.*, **103,** 29–46.

Ward, M. N., Folland, C. K., Maskell, K., Rowell, D. and Colman, A. 1990. 'Understanding and predicting seasonal rainfall in subsaharian Africa'. *WMO, Tropical Meteorology Research Programme Report Series*, **36,** 157–161.

Wolter, K. 1989. 'Modes of tropical circulation, Southern Oscillation, and Sahel rainfall anomalies', *J. Climate*, **2,** 149–172.