Case Studies of Tropical Atlantic Surface Circulation Patterns During Recent Sub-Saharan Weather Anomalies: 1967 and 1968

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ABSTRACT

Sub-Saharan West Africa (10–20°N) receives moisture from the tropical Atlantic via low-level southwesterly flow across the southwestern coast of West Africa. This paper utilizes a large data set to identify the tropical Atlantic (30°N–30°S) surface atmospheric and oceanic patterns for two years when sub-Saharan West Africa experienced anomalous weather. Comparison is made with 60-year (1911–70) average fields.

The following tropical Atlantic surface features were located/centered 300–500 km further south in the deficient sub-Saharan rainy season (July–September) of 1968 than the more abundant 1967 rainy season—the kinematic axis between the Northern and Southern Hemisphere trades, the near-equatorial convergence zone, the near-equatorial pressure trough, the zone of maximum sea surface temperature (SST), the mid-Atlantic maxima of precipitation frequency and total cloudiness, and the center of the North Atlantic subtropical high. Sixty-year mean positions of these features were generally intermediate between the 1967 and 1968 locations. Rainfall was more frequent immediately south of the Gulf of Guinea coast and more abundant along this coast, during the 1968 sub-Saharan drought than in 1967. During the dry July–September 1968, positive SST departures occurred south of 10°N and east of 35°W, with a southwest-northeast oriented negative SST anomaly immediately to the northwest. The opposite SST departure pattern characterized July–September 1967.

The July–September 1968 departures from 60-year average patterns were largely characteristic of April–June 1968. In contrast, the July–September 1967 anomalies showed little evidence of evolving during preceding seasons.

1. Introduction

Discussion of the 1968–74 sub-Saharan drought has generally sought to relate it to anomalies in the large-scale atmospheric circulation. Brief reviews appear in Lamb (1978, henceforth termed L1) and Kidson (1977). Since sub-Saharan West Africa (10–20°N) receives moisture from low-level southwesterly flow across the southwestern coast of West Africa (Flohn *et al.*, 1965, pp. 20–21), sub-Saharan rainfall may be sensitive to variations in the large-scale atmospheric and oceanic conditions at the surface of the tropical Atlantic. Processes occurring over West Africa influence sub-Saharan precipitation more directly, and include the frequency and intensity of disturbance lines (Burpee, 1972; Aspliden *et al.*, 1976), and the position and strength of upper tropospheric divergence in the southern exit region of the tropical easterly jet (Flohn, 1964, pp. 25–33). However, variations in these processes may be related to anomalies in the surface circulation over the tropical Atlantic, with both possibly reflecting a larger scale circulation anomaly.

In a further study of sub-Saharan drought in relation to the large-scale atmospheric circulation, L1 identified the tropical Atlantic surface atmospheric and oceanic patterns of a data set composited for five years which were very dry in sub-Saharan West Africa. Comparison was made with the patterns for a counterpart wet composite data set. The severe sub-Saharan drought year 1968 was excluded from the dry composite because, unlike all other drought years, it possessed enough data to warrant case study treatment (L1).

The present paper therefore gives the results of a detailed study of the tropical Atlantic (30°N–30°S) surface atmospheric and oceanic patterns during and preceding the 1968 sub-Saharan drought. Comparison is made with the patterns for 1967, a very wet year in the western sub-Saharan zone (e.g., Landsberg, 1973, 1975), if not for the region as a whole (L1). At four of the six stations west of 8°W in the 11–16°N belt of West Africa (locations in Fig. 1 of L1), the 1967 rainfall was at least 0.5σ above the 1941–74 mean. Unlike 1967, no zone-wide sub-Saharan "flood" year possessed enough tropical Atlantic marine data to permit case study treatment (L1). Sub-Saharan rainfall variability is examined in L1.

By supplementing the composite patterns of L1 with the case study results contained here, the inquiry into possible relationships between tropical Atlantic surface conditions and sub-Saharan weather anomalies is made

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more general. The need for improved understanding of tropical climatic fluctuations has been frequently stressed of late (e.g., Sawyer, 1974; World Meteorological Organization—ICSU, 1975, pp. 1–6).

2. Observational data

For the tropical Atlantic and eastern Pacific Oceans, individual monthly mean values of various meteorological elements were obtained on magnetic tape from the National Climatic Center, Asheville, N.C., for the period 1911–72 and 1° latitude-longitude square areas. Almost 3.5 million sets of ship observations were available for the area east of 60°W considered here; each set contained 1–16 parameters. Spatial variations in the data amount are indicated in Hastenrath and Lamb (1977a, chart 1). Averages of sea level pressure, surface wind, sea surface and air temperature (SST and AT), total cloudiness and precipitation frequency for 3-month periods of 1967, 1968, and the 60-year (1911–70) mean constitute the basis of the present paper. Subdivision of the year into the January–March, April–June, July–September and October–December quarters, rather than one- or two-month periods, enhanced data stability and permitted concise presentation of results. Choice of the above groupings resulted from the sub-Saharan rainy season being concentrated in July–September (e.g., Jackson, 1961, charts 26–28) and monthly charts showing these quarters to possess distinct patterns.

These marine data were quality controlled when taped, with values beyond physically reasonable limits being excluded. Atmospheric pressure observations made over the open ocean are regarded as less reliable than those made over land. Wind speed was converted from original Beaufort estimates. Verploegh (1967) found wind force data obtained by simple observation to be as accurate as ships' wind measurements. Shipboard measurements of SST and AT are likely to be overestimations (e.g., Saur, 1963; Ramage *et al.*, 1972, p. xi); because of the uncertainty of these errors, however, no corrections were applied. The large-scale departure patterns of SST and AT considered here should be little affected. Fields were smoothed with a symmetrical 25-weight filter function derived by R. Bleck (Hantel, 1970). The large-scale features of interest in the present study remain substantially unaltered from the raw to the filtered fields.

Hastenrath and Lamb (1977a, pp. xi–xii) made a limited investigation of the variability in the above data set for the period 1911–70. Typical standard deviations of individual monthly mean values for 5° squares are 1–2 mb for sea level pressure, 1–2 m s^{-1} for resultant wind speed, 0.5–1.0°C for SST, and 0.1 for total cloud amount. Smaller standard deviations could be expected for coarser time-space resolutions.

Monthly rainfall totals for West African stations were obtained from Smithsonian Institution (1927, 1934, 1947), U. S. Weather Bureau (1957–65, 1959), ESSA (1966–70, 1967), NOAA (1971–74) and various national and regional meteorological services for the entire period of available records up to 1974.

Monthly mean mixing ratios at standard isobaric levels for sub-Saharan aerological stations were acquired from ASECNA (1968, 1970–72) for 1968 and 1970–72, and by correspondence for 1967.

3. Results

a. Wind

Seasonal fields of resultant wind vectors for 2° squares for 1967 and 1968 were expressed as speed and direction departures from 60-year mean patterns. Results are given in Fig. 1. The 60-year mean patterns are presented in Lamb (1977, henceforth termed L2). Direction departures shown in Fig. 1 are limited to those exceeding 30° in areas where the directional steadiness of wind exceeds 40% (L2). They indicate abnormal locations of the chaotic resultant directions of the centers of subtropical anticyclones and the near-equatorial kinematic axis between the Northern and Southern Hemisphere trades (L2), and are henceforth termed "significant direction departures." The South Atlantic area not analyzed in Fig. 1, and also in Figs 3 and 4, possessed poor data coverage.

Sub-Saharan rainfall is concentrated during July–September (Jackson, 1961, charts 26–28), when the features of the tropical Atlantic surface pressure, wind and temperature fields reach their northernmost locations (L2). The most notable wind field anomalies for July–September of 1967–68 occur between 0–15°N and 10–50°W (Fig. 1), and suggest the kinematic axis was located 300–500 km further south during the 1968 drought than in 1967. In July–September 1968, the wind direction discontinuity is 200–350 km south of its mean position, well-defined tongues of strong positive and negative speed departures occur to the north and south of the aforementioned region, and a sizable band of significant direction departures lies along the southern edge of the area where directional steadiness is less than 40% (L2). For July–September 1967, the wind field anomalies between 0–15°N and 10–50°W tend to be the opposite of those for July–September 1968. They include the wind direction discontinuity being up to 200 km north of its average location, negative and positive speed departures lying to the north and south of this discontinuity, respectively, and significant direction departures being more evident north of the sub-40% directional steadiness region than south.

Fig. 2 shows the foregoing contrasts between the July–September wind fields of 1967 and 1968 are reflected in the near-equatorial divergence fields. In particular, the convergence zone is 300–400 km further south during the dry July–September 1968 than in

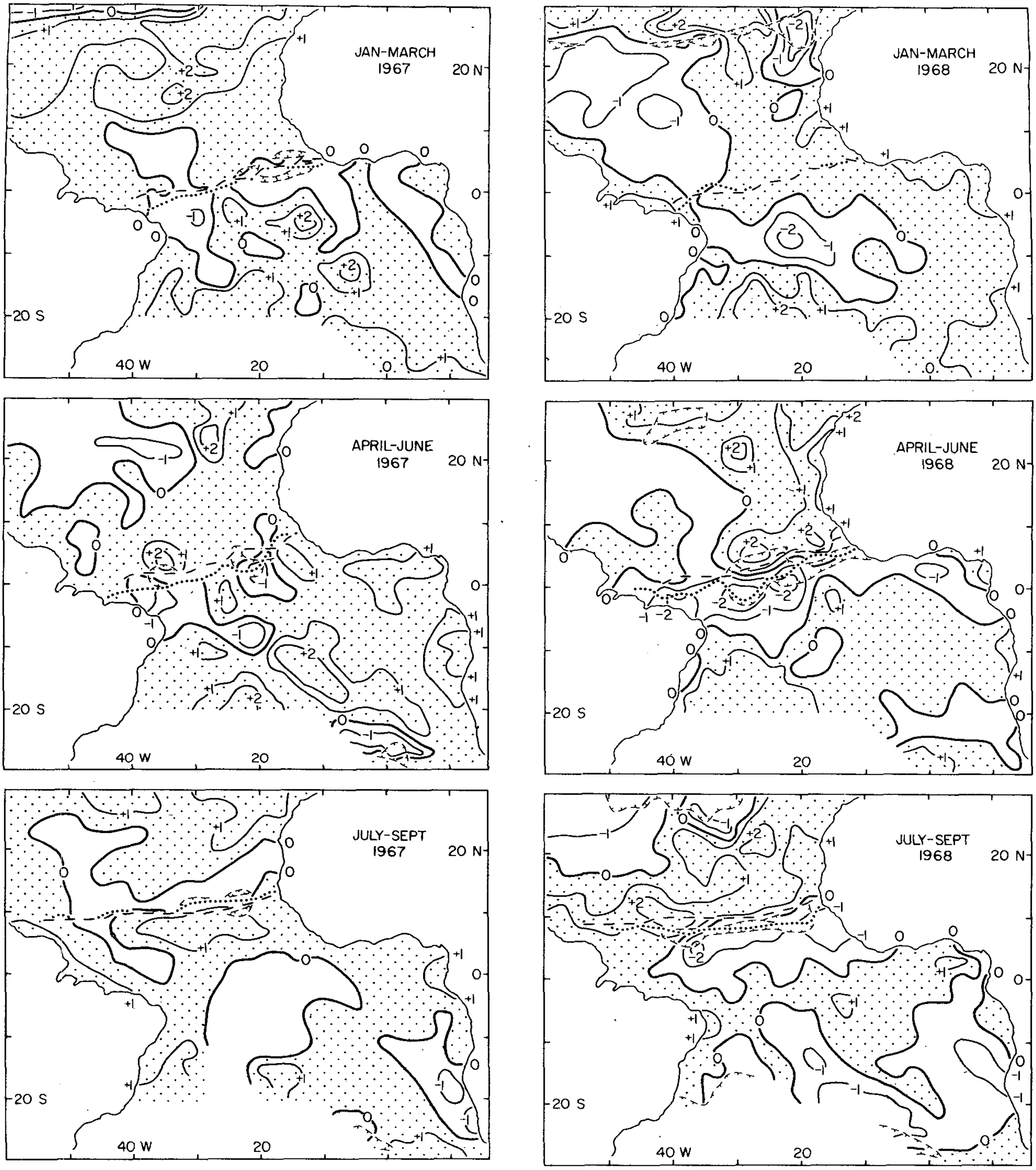

FIG. 1. Seasonal resultant wind fields for 1967 and 1968 expressed as departures from the 1911–70 average patterns. Solid lines are departure isotachs ($\mathrm{m\ s^{-1}}$), positive values shaded; dotted lines locate discontinuity between northerly and southerly resultant wind directions for 1967 and 1968, with broken lines doing likewise for the 60-year mean; barbed lines enclose resultant wind direction departures of more than 30° in areas where the directional steadiness of wind exceeds 40%.

July–September 1967. The 60-year mean convergence zone is centered between these two extremes. A divergence belt immediately equatorward of this convergence zone (Hastenrath and Lamb, 1977b) is weaker and contracted further south in July–September 1968 than July–September 1967.

The wind and divergence anomalies indicating a southward displacement of the kinematic axis in July–

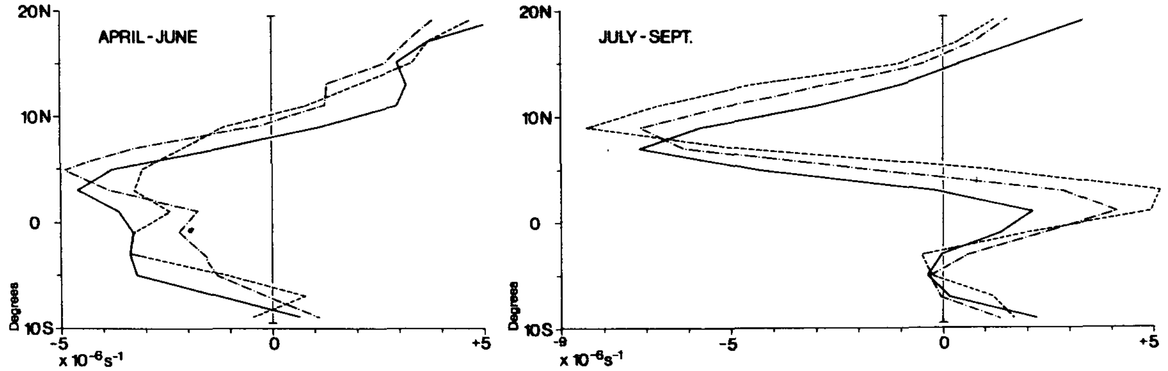

Fig. 2. Seasonal meridional transects of divergence (10^{-6} s^{-1}) for the 10–40°W sector, computed by zonally averaging divergence values for the centers of 2° squares. Solid line is 1968, dashed line 1967, and dot-dashed line the 1911–70 mean.

September 1968, relative to the 60-year mean, first appeared in the preceding April–June (Figs. 1 and 2). In contrast, the northward displacement of the kinematic axis during July–September 1967 did not evolve earlier in the year (Figs. 1 and 2). For April–June 1967, a southward displacement of the kinematic axis similar to April–June 1968 is in fact evident, rather than the opposite which subsequently characterized July–September 1967.

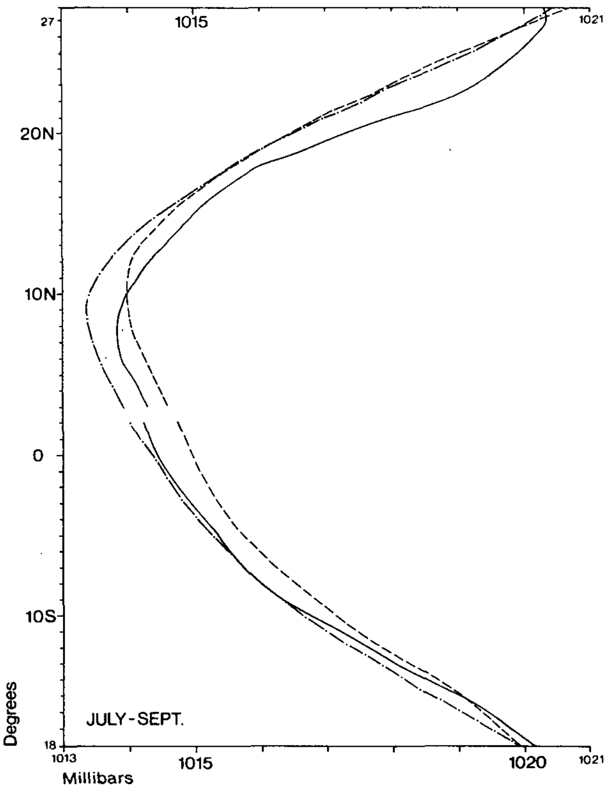

Fig. 3. July–September meridional transects of surface pressure for the north tropical Atlantic (30°N–1°N; 10°W–60°W) and south tropical Atlantic (4°N–20°S; 13°E–52°W). Solid line is 1968, dashed line 1967, and dot-dashed line the 1911–70 mean.

b. Pressure

Seasonal mean pressure values for 1° squares were reduced to meridional transects for the tropical North and South Atlantic for 1967, 1968 and the 1911–70 average. The July–September transects appear in Fig. 3. They contain a value for each degree of latitude, obtained by averaging the pressures for all 1° squares within a zone 4° of latitude in width centered on the latitude concerned.

Fig. 3 suggests the near-equatorial pressure trough was centered about 300–400 km further south in the dry July–September 1968 than in July–September 1967. The 60-year mean trough is centered between these two positions. These trough displacements are consistent with the kinematic axis and convergence zone displacements noted in the previous section. The transects for January–March and April–June (not shown) contain little evidence of the trough displacements for July–September 1967–68 characterizing preceding seasons.

The North Atlantic subtropical high appears to have been centered further south in the dry July–September 1968 than July–September 1967 (Figs. 3 and 1), but not in earlier months. However, results presented in Tanaka *et al.* (1974), Miles and Follard (1974) and L1 suggest that a southward displacement of the center of the North Atlantic high does not accompany all deficient sub-Saharan rainy seasons.

c. Temperature

Seasonal mean fields of SST and AT for 1967 and 1968 were expressed as deviations from their 60-year average counterparts presented in L2. The AT departure patterns virtually replicated those for SST, and therefore are not reproduced; SST anomaly fields appear in Fig. 4.

The SST departure patterns for July–September of 1967 and 1968 are in considerable contrast, with the result that the zone of maximum SST was located 400–500 km further south during the 1968 drought than in 1967. A conspicuous feature of the July–September 1968 pattern is the extensive positive anomaly south of

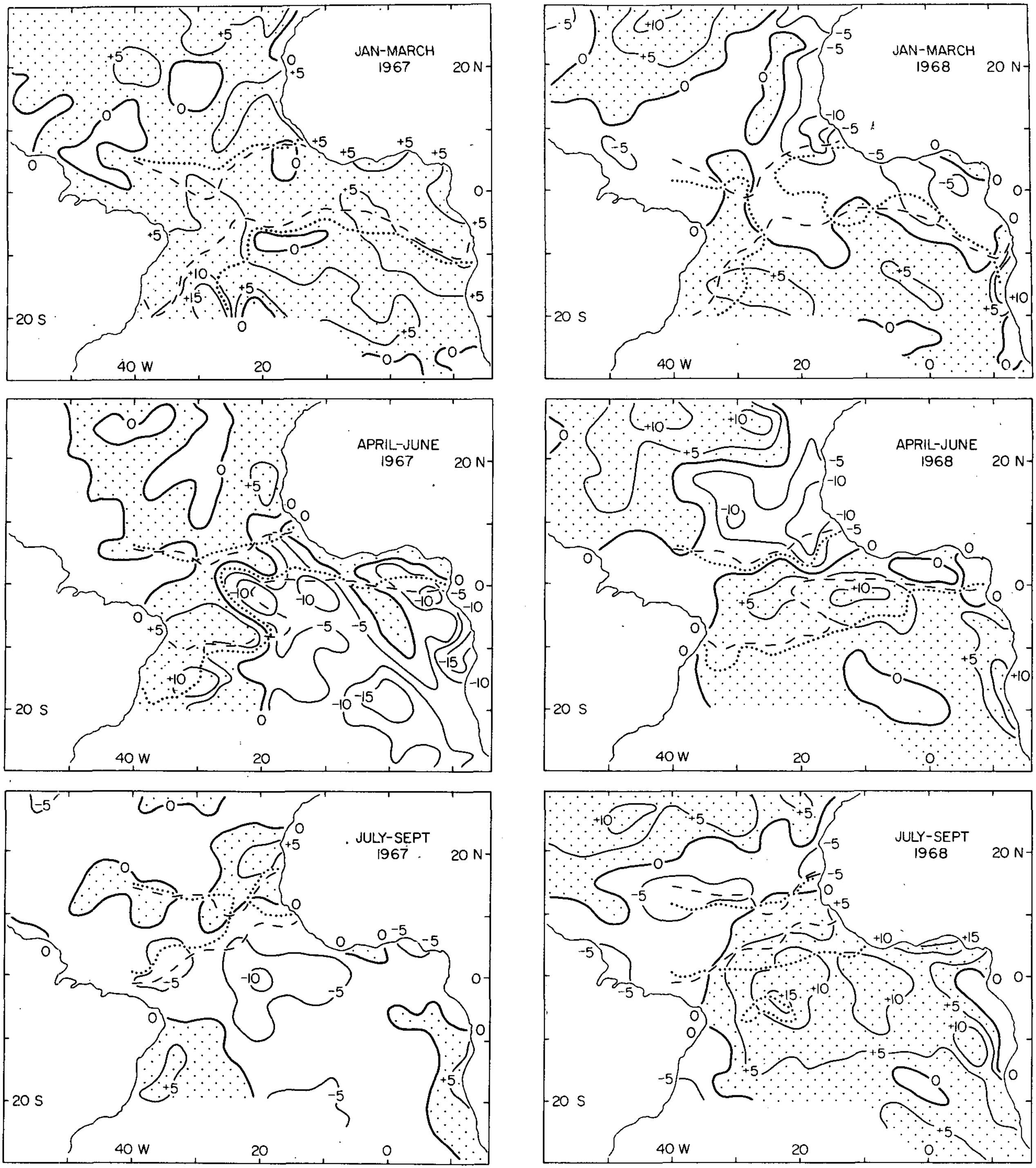

FIG. 4. Seasonal sea surface temperature fields for 1967 and 1968 expressed as departures from the 1911–70 average patterns. Solid lines are departure isotherms (tenths of 1°C), positive values shaded; dotted lines enclose area of maximum sea surface temperature east of 40°W for 1967 and 1968 (>27.0°C for January–March, >27.2°C for April–June, >26.7°C for July–September), with dashed lines doing likewise for the 1911–70 mean.

10°N and east of 35°W. This anomaly is particularly strong in the 0–10°S zone, where departures in excess of +1.0°C occupy large areas in which the annual SST range for the 60-year mean pattern is only 2–3°C (L2). Immediately northwest of this extensive positive anomaly is a southwest-northeast oriented strip of weaker negative SST departures, while a positive anomaly occupies the extreme northwest tropical Atlantic. The foregoing departure pattern for July–September 1968 was accompanied by the zone of maximum SST being displaced about 300 km south of its mean position (Fig. 4).

For July–September 1967 the SST anomaly pattern tends to be the opposite of that for July–September 1968. Important July–September 1967 features include the positive anomalies west of West Africa, and the predominance of negative departures south of 10°N. These negative departures in particular were associated with the zone of maximum SST being displaced about 200 km north of its 60-year mean position during July–September 1967.

Fig. 4 shows that the SST anomaly pattern for July–September 1968 evolved during preceding seasons. The 20°N–10°S departure features, and concomitant southward displacement of the zone of maximum SST, were first completely apparent during the preceding April–

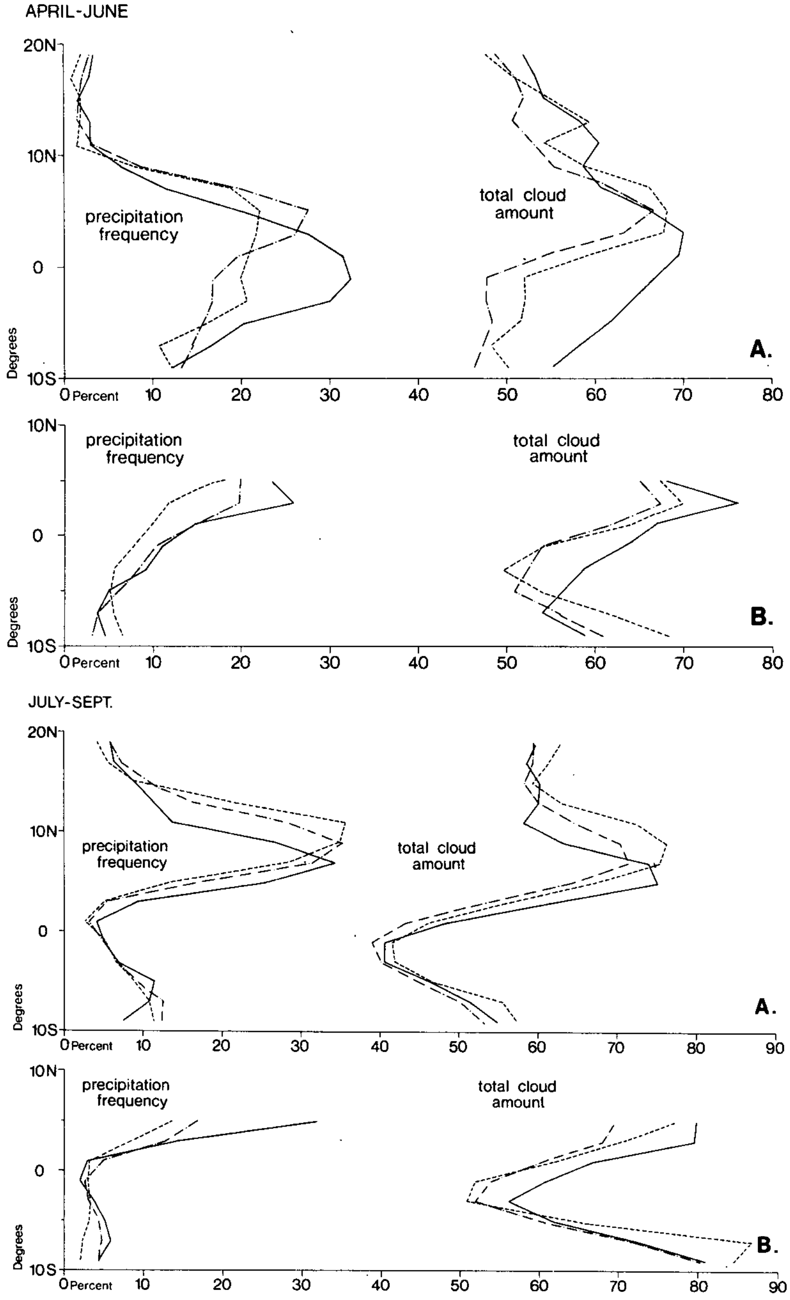

FIG. 5. Seasonal meridional transects of precipitation frequency (left-hand profiles) and total cloudiness (right-hand profiles) for the 10–40°W (a) and 8°E–10°W (b) sectors. Solid line is 1968, dashed line 1967 and dot-dashed line 1911–70 mean.

June. In contrast, negative SST deviations occurred in much of this area during January–March 1968, making the zone of maximum SST irregular and discontinuous. The positive SST departures south of 10°S and in the northwest tropical Atlantic during July–September 1968 had persisted from October–December 1967 (not shown), with equatorward encroachment occurring from January–March to April–June 1968 (Fig. 4).

The SST anomalies noted above for July–September 1967 were partially apparent by the preceding April–June, coinciding with a northward displacement of the zone of maximum SST at some longitudes east of 25°W. In contrast, positive SST departures covered most of the tropical Atlantic during January–March 1967.

A difference between the SST anomaly patterns of July–September 1967 and 1968 particularly foreshadowed during preceding seasons occurs immediately west of West Africa, where moderately strong cold departures prevailed in 1968 in contrast to warm departures of similar magnitude in 1967.

d. Precipitation and cloudiness

Seasonal mean fields of precipitation frequency and total cloud amount for 2° squares for 1967, 1968 and the 60-year mean were zonally averaged for the mid-Atlantic (20°N–10°S, 10–40°W) and Gulf of Guinea (6°N–10°S, 8°E–10°W) ocean areas (Fig. 5).

The zones of maximum precipitation frequency and total cloudiness in the mid-Atlantic (Fig. 5a) were centered about 400 km further south in the deficient sub-Saharan rainy season of July–September 1968 than in July–September 1967. Precipitation frequency and total cloudiness maxima for July–September of the 60-year mean are centered between those for 1967 and 1968. These precipitation and cloudiness displacements are consistent with the kinematic axis, convergence zone and pressure trough displacements noted in preceding sections.

The southward displacement of the mid-Atlantic maxima of precipitation frequency and cloudiness in the dry July–September 1968, relative to the 60-year mean, first emerged during the preceding April–June (Fig. 5a). Earlier sections found that the similar southward displacements of the kinematic axis and convergence zone in July–September 1968 likewise first appeared in April–June 1968. In contrast to 1968, the northward displacement of the mid-Atlantic zones of maximum precipitation frequency and cloudiness during July–September 1967 did not characterize earlier seasons (Fig. 5a). A lack of prior development of July–September 1967 patterns was also apparent for the elements treated in previous sections.

The ocean immediately south of the Gulf of Guinea coast received considerably more frequent rainfall in April–June and July–September 1968 than April–June and July–September 1967 (Fig. 5b). A similar rainfall difference occurred over West Africa south of the sub-Saharan zone, where 1968 generally recorded above average totals, and 1967 near or below average amounts (Table 1). This was most pronounced at Gulf of Guinea coastal locations east of 3°W (Table 1), where 1968 was often the wettest year on record (e.g., Hookey, 1970). However, the coincidence of sub-Saharan drought with abundant rainfall further south in West Africa seems to be unique to 1968 among the recent sub-Saharan drought years, rather than a general rule of behavior (e.g., Tanaka *et al.*, 1975). In contrast to 1968, the 1970–74 sub-Saharan drought was generally a period of below or near average rainfall south of the sub-Saharan zone (Table 1).

4. Summary and discussion

Efforts to explain the recent sub-Saharan drought have generally focused on the possible role of anomalies in the large-scale atmospheric circulation. In a further contribution to this approach, the present study utilized a large data set to identify the tropical Atlantic surface atmospheric and oceanic patterns for two years when sub-Saharan West Africa experienced anomalous weather. The case study results presented here are similar to the composite patterns in L1, thus making the inquiry into tropical Atlantic surface conditions

TABLE 1. April-October rainfall totals (mm) for West African stations south of the sub-Saharan zone with at least 20 years of records. Length of record (years) is in parentheses after the average. Coastal stations are asterisked.

Station	Latitude	Longitude	Average	1967	1968	1970	1971	1972	1973	1974
Lungi*	8°37′N	13°12′W	3475 (98)	3183	2800	3004	2644	2567	2509	2718
Bo	7°57′N	11°46′W	2554 (35)	2441	2458	1889	2118	2414	2226	2271
Kabala	9°35′N	11°33′W	2043 (21)	1967	2652	1766	1736	1987	2061	2071
Odienne	9°30′N	7°35′W	1488 (32)	1355	1453	1436	1578	—	1282	1175
Tabou*	4°55′N	7°22′W	1801 (33)	1306	1980	2196	1860	—	2041	1570
Bouake*	7°44′N	5°04′W	953 (24)	681	1086	818	964	—	860	1002
Abidjan*	5°15′N	3°56′W	1655 (34)	1383	1758	1094	1267	1149	1815	1748
Tamale	9°25′N	0°53′W	1027 (30)	1039	1313	786	1063	984	911	976
Accra*	5°36′N	0°10′W	601 (81)	669	1288	639	706	615	876	842
Lome*	6°10′N	1°15′E	799 (22)	957	1261	1124	818	455	836	913
Cotonou*	6°21′N	2°23′E	1162 (25)	1219	2325	835	885	1135	772	1168
Parakou	9°21′N	2°37′E	1117 (52)	1023	1274	648	1021	864	1331	976
Lagos*	6°35′N	3°20′E	1498 (81)	1451	2475	1505	1188	1275	1386	1190

coinciding with sub-Saharan weather anomalies more general.

The following features of the tropical Atlantic surface atmospheric and oceanic patterns were located/centered 300–500 km further south in the deficient sub-Saharan rainy season (July–September) of 1968 than the more abundant 1967 rainy season: the kinematic axis between Northern and Southern Hemisphere trades (Fig. 1), the near-equatorial convergence zone (Fig. 2), the near-equatorial pressure trough (Fig. 3), the zone of maximum SST (Fig. 4), the mid-Atlantic maxima of precipitation frequency and total cloudiness (Fig. 5), and the center of the North Atlantic subtropical high (Figs. 3 and 1). Sixty-year mean positions of these features are generally intermediate between the 1968 and 1967 locations. Rainfall was more frequent immediately south of the Gulf of Guinea coast (Fig. 5), and more abundant along this coast (Table 1), during the 1968 sub-Saharan drought than in 1967. During the dry July–September 1968, positive SST departures occurred south of 10°N and east of 35°W, with a southwest-northeast oriented negative SST anomaly immediately to the northwest (Fig. 4). The opposite SST departure pattern characterized July–September 1967 (Fig. 4).

Many of the foregoing contrasts between the patterns for the dry July–September 1968 and the wetter July–September 1967 also characterized the comparison of dry and wet composite patterns in L1, albeit with reduced magnitudes.

An ability to forecast the general character of sub-Saharan rainy seasons might allow the effects of future droughts to be reduced by appropriate human and natural resource management. Time series analysis of tropical Atlantic surface data for 1911–72 (not reproduced) did not show extreme rainy seasons to be signaled by, or to represent the culmination of, any long-term atmospheric-oceanic trends. However, preceding sections have shown that the July–September 1968 departures from 60-year average patterns were largely characteristic of April–June 1968 (Figs. 1, 2, 4, 5). Considerable development of the July–September 1968 SST departure pattern occurred by January–March 1968, particularly the cold anomaly immediately west of West Africa (Fig. 4). Some of the dry composite July–September departure features also evolved by the preceding season (L1). Any encouragement this offers for sub-Saharan drought being predictable 3–6 months in advance must be tempered by the fact that the April–June 1967 anomalies included some similarities to those for April–June 1968. The kinematic axis, near-equatorial convergence zone and mid-Atlantic maximum of precipitation frequency were located south of their 60-year mean positions in April–June 1967, as in April–June 1968, rather than the opposite which subsequently characterized the wetter rainy season of July–September 1967 (Figs. 1, 2, 5). Thus, southward displacements of tropical Atlantic surface circulation features in April–June may not always be followed by deficient sub-Saharan rainy seasons.

Relatively small changes in the conditions at the surface of the tropical Atlantic have here been shown to accompany the 1967–68 sub-Saharan weather anomalies. Many of the 1967–68 departures are probably about one standard deviation from 60-year mean values for the same time-space resolution (see Section 2). They are slightly larger than those for the composites in L1. Similarly, displacements of the 1967–68 maxima of convergence, precipitation frequency and total cloudiness from 60-year mean positions (Figs. 2, 5) were generally only equivalent to the 2° latitude resolution employed. However, confirmation of the validity of the foregoing results is offered by the substantial consistency between the departure patterns for the various elements studied. Furthermore, in view of the strong northward decrease of sub-Saharan rainfall—between 12–17°N this averages 2.62 mm km^{-1} along the Atlantic Coast, 1.47 mm km^{-1} at $\sim$3°W, and 0.88 mm km^{-1} at $\sim$8°E (computed from data described in section 2)—the underlying changes in atmospheric and/or oceanic conditions need not necessarily be large.

Hastenrath (1976) found a moderate positive correlation between Caribbean and sub-Saharan rainfall. Accordingly, the tropical Atlantic surface departure patterns for dry and wet sub-Saharan rainy seasons described here and in L1 possess some similarity to those presented by Hastenrath (1976) for Caribbean rainfall anomalies of the same sign.

The results presented above suggest that distinctive SST departure fields accompany the anomalous tropical Atlantic surface atmospheric circulation patterns of extreme sub-Saharan rainy seasons. During the 1968 drought, a displacement of the zone of maximum SST about 300 km south of its 60-year mean position accompanied similar displacements of the kinematic axis, near-equatorial convergence zone, mid-Atlantic maxima of precipitation frequency and total cloudiness, and the near-equatorial trough. This southward shift of the zone of maximum SST resulted from positive SST departures occurring south of 10°N and east of 35°W, and a negative SST anomaly lying immediately to the northwest. Similar SST and atmospheric results were obtained for the dry composite (L1). In contrast, the opposite atmospheric and SST anomalies characterized the wetter rainy season of 1967, and to a lesser extent the wet composite rainy season in L1. This tendency for the SST anomalies south of 10°N and east of 35°W to be the opposite of those immediately to the northwest during sub-Saharan weather anomalies is not a dominant mode of nonseasonal SST variation in the tropical Atlantic (Weare, 1977).

The foregoing coincidence of meteorological and oceanographic departure patterns suggests they may be related. For instance, several authors have considered near-equatorial troughs as heat troughs coinciding with areas of maximum SST (e.g., see Ramage, 1974). In

TABLE 2. Monthly mean mixing ratios (g kg^{-1}) at sub-Saharan aerological stations for the Augusts of 1967–68 and 1970–72.

Standard level (mb)	Dakar (14°44′N; 17°30′W)					Bamako (12°38′N; 8°02′W)					Niamey (13°29′N; 2°10′E)					Ndjamena (12°08′N; 15°02′E)				
	1967	1968	1970	1971	1972	1967	1968	1970	1971	1972	1967	1968	1970	1971	1972	1967	1968	1970	1971	1972
700	8.7	8.0	8.0	7.0	6.8	9.8	9.0	8.4	8.0	7.8	8.8	6.5	8.3	6.8	7.2	8.9	7.3	8.8	7.2	7.2
800	11.5	11.3	11.5	9.5	9.1	13.4	12.3	12.4	11.2	11.4	11.9	9.8	12.2	9.8	11.0	11.4	10.8	12.0	9.9	10.1
850	13.4	13.3	13.0	11.6	10.3	15.3	14.8	14.6	13.1	13.1	14.2	12.2	14.7	11.7	12.9	13.6	12.6	13.6	11.4	11.9
900	15.6	14.8	15.4	13.2	11.9	17.6	17.5	16.2	14.5	15.0	16.3	13.9	17.2	13.4	14.6	14.9	14.8	15.1	13.0	13.6
950	18.0	16.5	17.9	15.0	14.5	18.2	19.2	17.9	16.3	16.9	17.4	15.5	18.6	15.1	16.2	16.8	16.4	16.5	14.7	15.1
1000	19.1	18.8	18.9	17.6	17.2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

view of the kinematic axis and convergence zone experiencing similar displacements to the zone of maximum SST and trough during the contrasting 1967–68 sub-Saharan rainy seasons, the origin of tropical Atlantic SST anomalies is of particular interest. The transport of water vapor into sub-Saharan West Africa may be positively related to the northward extent of the low-level southwest monsoon flow across the West African coast, and hence to the latitude of the kinematic axis over the adjacent Atlantic. Less water vapor was present over the sub-Saharan zone during the height of the deficient 1968 rainy season than in the more productive 1967 one (Table 2), when the eastern Atlantic kinematic axis and zone of maximum SST were 300–500 km further north (Figs. 1 and 4). Furthermore, Table 2 indicates that the August 1967 sub-Saharan mixing ratios also tend to be higher than those for 1971, 1972, and to a lesser extent 1970, the three constituent years of the dry composite in L1 for which upper air data exist. During the dry composite July–September, the eastern Atlantic kinematic axis and zone of maximum SST were likewise located 200–400 km further south than in 1967 (L1).

In addition, Kidson (1977) found the 850 mb flow over West Africa south of ~8°N to be from the east during the sub-Saharan droughts of 1972–73, whereas it had a westerly component in the wetter years of 1959 and 1961. The low-level southwesterly monsoon flow into West Africa decreases in thickness northward from the Guinea coast, where it usually extends to between 850 and 800 mb, and is overlain by easterlies (Flohn *et al.*, 1965, Table 9). Kidson's results may therefore also be consistent with the wedge-shaped, moisture-bearing, southwest monsoon flow not penetrating as far north in West Africa during sub-Saharan droughts as in more abundant rainy seasons.

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