Tellus (1983), *35A*, 198–212

West African water vapor variations between recent contrasting Subsaharan rainy seasons

By PETER J. LAMB, *Climatology Section, Illinois State Water Survey, Champaign, Illinois 61820, U.S.A.*

(Manuscript received January 5; in final form June 29, 1982)

ABSTRACT

Investigation is made of the interannual and intraseasonal variability of the southwest monsoon layer's thickness and moisture content over West Africa, and its water vapor supply to this region from the tropical Atlantic, for the Subsaharan (10°–20° N) rainy season of July–September. Results for the very deficient 1968, 1971, and 1972 Subsaharan rainy seasons, whose departures from the 1941–74 mean ranged between -0.78σ and -1.39σ, are compared with those for the near-average rainy seasons of 1967, 1969, and 1975 (-0.27σ to $+0.06\sigma$). The observational base consists of monthly mean rawinsonde data from West African stations and seasonal estimates of the tropical Atlantic near-surface specific humidity field.

Subsaharan drought does not appear to be associated with the northward supply of unusually dry surface air to West Africa from the tropical Atlantic. Over West Africa, the magnitude of the vertically integrated monsoon layer advective water vapor flux tends to be proportional to the layer thickness. The extremely poor 1972 Subsaharan rainy season (-1.39σ) coincided with particularly shallow southwesterly flow across the Gulf of Guinea coast (~5° N); thicker monsoon layers are found characteristic of the less severe 1968 (-0.78σ) and 1971 (-0.88σ) droughts. However, the monsoon layer depth here during the nondrought study years does not always exceed that for drought months. The direction of the low-level water vapor flux above Dakar, a sensitive Subsaharan location (~15° N) on the West African coast, shows a stronger tendency to be from north of west during unproductive Subsaharan rainy seasons (-0.78σ to -1.39σ) than in near-average ones (-0.27σ to $+0.06\sigma$). This suggests the southwest monsoon does not extend as far north along the West African coast during Subsaharan droughts as in more abundant rainy seasons. In contrast to the foregoing Gulf of Guinea results, the monsoon layer over the interior of the Subsaharan zone at ~13° N exhibits minimal variability for the drought study years. The better developed nondrought southwesterly flows here tended to be thicker than those characteristic of most drought months.

1. Introduction

1.1. *Background*

The present author recently identified the tropical Atlantic surface atmospheric and oceanic patterns that coincided with some very deficient and more abundant rainy seasons (i.e., July–September periods) in Subsaharan West Africa (Lamb, 1978a, b). Comparison was made with the 1911–70 average fields given in Lamb (1977). This previous research was undertaken because low-level southwesterly monsoon flow from the tropical Atlantic provides an important moisture source for the westward propagating disturbance lines that give the Subsaharan zone its rain. Subsaharan West Africa and the Atlantic monsoon flow are depicted in Fig. 1. The monsoon flow is in the form of a wedge which decreases in thickness northward from the Gulf of Guinea coast (~5° N), and is overlain by deep tropospheric easterlies (Flohn *et al.*, 1965, Table 9). These easterlies, especially in the midtropospheric layer of maximum speed (Burpee, 1972), probably acquire much of their moisture from the lower southwesterly airstream. The characteristics of the monsoon flow in a given Subsaharan rainy season are determined by the

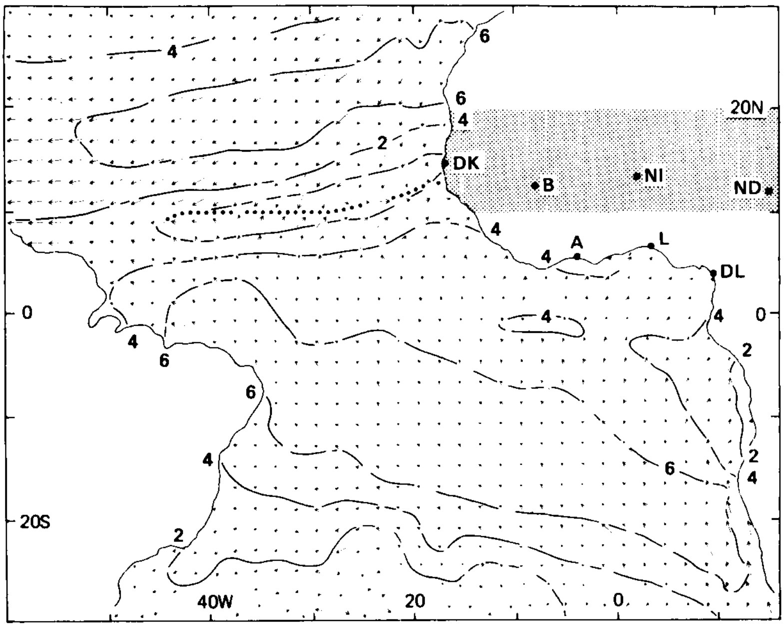

Fig. 1. Orientation map. Arrows and isotachs indicate the 1911–70 resultant wind direction and speed (m s^{-1}) over tropical Atlantic during Subsaharan rainy season (July–September). Dotted line across ocean is discontinuity between northerly and southerly wind directions. After Lamb (1977, Fig. 3). Subsaharan West Africa is shaded. Dots over continent locate the following aerological stations: Abidjan (A), Bamako (B), Dakar (DK), Douala (DL), Lagos (L), Ndjamena (ND), Niamey (NI). See Table 1 for station details.

larger-scale atmospheric circulation and sea–air interaction over much of the tropical Atlantic sector, which further motivated the aforementioned studies.

This earlier work found that the southwesterly surface monsoon flow did not extend as far north along the West African coast during Subsaharan droughts, when the rainfall departed from the 1941–74 mean by -0.58σ to -1.39σ, as in the sixty-year mean circulation pattern (by 200–300 km) or in more abundant (-0.02σ to $+0.96\sigma$) rainy seasons (300–400 km). Similar or slightly larger southward displacements were concurrently characteristic of the following eastern tropical Atlantic surface features—the kinematic axis between Northern and Southern hemisphere trades, the near-equatorial pressure trough, and the zone of maximum sea surface temperature (SST). The location of the pressure trough, which is generally thought to coincide with the area of maximum SST because the trough is a heat trough (e.g., see Ramage, 1974), probably controls the latitude of the kinematic axis and thus athe northward extent of the moist surface southwesterly airflow into West Africa. Although the foregoing displacements are not large, confirmation of the validity and significance is offered by both their internal physical consistency and the very strong northward decrease of Subsaharan rainfall which averages 1–3 mm km^{-1} depending on longitude (Lamb, 1978b). The latter has the important implication that drought-inducing circulation displacements in the meridional direction need not be large. This earlier work also noted that the lower tropospheric mixing ratios recorded over the Subsaharan zone at the height of several very deficient (-0.72σ to -1.39σ) rainy seasons were smaller than during the more productive (-0.02σ) one of 1967 (Lamb, 1978b, Table 2).

The above results suggest that the wedge-shaped, moisture-bearing southwest monsoon flow may not penetrate as far north in West Africa during Subsaharan droughts as in more abundant rainy seasons. This interpretation would seem to be supported by Kidson's (1977) finding that the July–August 850 mb flow over West Africa south of ~8° N was from the east during two severe Subsaharan drought years, whereas it had a westerly component in two wetter years. As a result, there now exists a clear need for a comprehensive investigation of the tropospheric circulation that occurred over West Africa during each of several contrasting modern Subsaharan rainy seasons. Landsberg (1975) has previously stressed the need for such research. It should also usefully complement the currently active enquiry into the mechanism of the well-known palaeoclimatic time-scale variations of North African rainfall (e.g., Kutzbach, 1981).

1.2. *Present study and earlier related research*

The present paper deals with *one* portion of the above topic—the atmospheric water vapor supply to the Subsaharan zone from the tropical Atlantic, via the southwest monsoon flow. Clearly, other processes (e.g., static and dynamic instability mechanisms) contribute to Subsaharan rainfall. However, their investigation should be based on individual rawinsonde soundings; such data were not available to this investigation. This presentation includes estimates of the monsoon layer thickness, and the water vapor content and transport within this layer, for West African aerological stations during the very deficient 1968 (-0.78σ), 1971 (-0.88σ), and 1972 (-1.39σ) Subsaharan rainy seasons. A synopsis of the 1941–81 rainfall variation in Subsaharan West Africa appears in Fig. 2 [see Lamb (1978a, 1982) for full discussions], along with the identification of the study years. Those years mentioned above were selected from the recent period of extended drought on the basis of their rainfall anomaly (Fig. 2) and lower tropospheric mixing ratio (Lamb, 1978b, Table 2) values, and the availability of contemporary tropical Atlantic surface data which ceased with 1972 (Lamb, 1978a). Their results are compared with those for the near-average (relative to the last 40 years) rainy seasons of 1967 (-0.02σ), 1969 ($+0.06\sigma$), and 1975 (-0.27σ) (Fig. 2), years that were chosen because they were the three wettest during the last 15 years. The last 15 years is also the time of best aerological data availability. All of the above study years except 1969 and 1975 were considered in the present author's aforementioned tropical Atlantic surface research. The atmospheric moisture conditions at the surface of the tropical Atlantic adjacent to West Africa are also investigated here for the study years for which the requisite data are available.

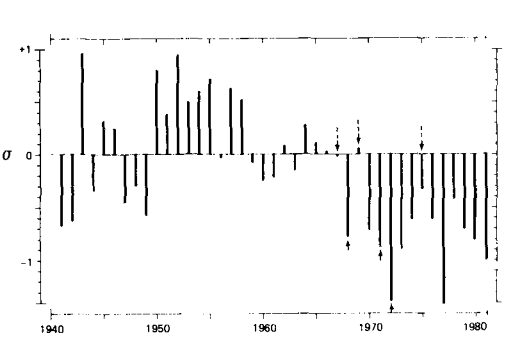

Fig. 2. Time series of yearly average of normalized rainfall departures for 14–20 Subsaharan stations west of 10° E. Ordinate is labelled in standard deviations (σs) from 1941–74 mean. Details of stations and computational procedures used are in Lamb (1978a, 1982). Solid (broken) arrows identify drought (nondrought) study years.

Previous investigations of West African tropospheric water vapor conditions during the Subsaharan rainy season have not had the focus of the present enquiry. The detailed treatment of this topic was initiated by Flohn et al. (1965), using a necessarily incomplete aerological data set for 1957–63. Their attention tended to focus on multi-year average or single year patterns, however, rather than the interannual variability and its relation to Subsaharan rainfall. Furthermore, while the period considered included the relatively productive 1957–58 rainy seasons, it did not contain any drought years (Fig. 2). More recently, Kidson (1977) presented 9-year average streamlines and divergence patterns of the vertically integrated water vapor flux over West Africa during July–August, but incomplete humidity data prevented a comparison of the moisture budgets for abundant and deficient Subsaharan rainy seasons. Finally, neither Flohn et al. (1965) nor Kidson (1977) effectively separated the water vapor regime of the low-level southwesterly monsoon flow from that of the total column, or examined the moisture conditions over the adjacent tropical Atlantic.

2. Observational data

Individual monthly (e.g., August 1968) mean mixing ratios (or specific humidities) and resultant

Table 1. *West African aerological stations used in the present study. Station pressures were computed from 1971–80 data contained in NOAA (1971–80). The parenthetical Bamako information applies only to the 1975 study year; this station was relocated between the 1974 and 1975 Subsaharan rainy seasons*

Station	Country	Latitude	Longitude	Elevation (m)	Average August station pressure (mb)	Observation times (GMT)	Standard isobaric levels (mb) up to 300 mb
Abidjan	Ivory Coast	05° 15′ N	03° 56′ W	7	1013	00 except for 1975 (1200)	1000, 950, 900, 850, 800, 700, ..., 300
Bamako	Mali	12° 38′ N (12° 32′ N)	08° 02′ W (07° 57′ W)	332 (381)	974 (968)	00 except for 1975 (1200)	950, 900, 850, 800, 700, ..., 300
Dakar	Senegal	14° 44′ N	17° 30′ W	24	1009	(1) 00 except for 1975 (2) 1200	Same as Abidjan
Douala	Cameroun	04° 01′ N	09° 43′ E	23	1013	00 except for 1975 (1200)	Same as Abidjan
Lagos	Nigeria	06° 35′ N	03° 20′ E	38	1010	1200	Could be same as Abidjan, but some levels often not available
Ndjamena	Chad	12° 08′ N	15° 02′ E	295	977	00 except for 1975 (1200)	Same as Bamako
Niamey	Niger	13° 29′ N	02° 10′ E	234	985	00 except for 1975 (1200)	Same as Bamako

wind vectors for standard isobaric levels over West African aerological stations were obtained from ASECNA (1968–69, 1971–72, 1975) and by correspondence with regional and national meteorological services for the study years listed above. Table 1 gives pertinent station and data information; the station locations also appear in Fig. 1.

For the surface of the tropical Atlantic, 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 one-degree latitude-longitude square areas. Full details of this data set are given in Hastenrath and Lamb (1977). The present paper utilizes two-degree square July–September averages of sea level pressure and dew point temperature for 1967, 1968, 1969, the 1911–70 mean, and a data set composited for five very deficient Subsaharan rainy seasons (1942, 1949, 1970, 1971, 1972) whose departures ranged between -0.58σ and -1.39σ. The latter is described in Lamb (1978a) and includes the present 1971 and 1972 study years. It is henceforth termed DRY.

Individual monthly rainfall totals for Subsaharan stations were obtained from the Smithsonian Institution (1927, 1934, 1947), U.S. Weather Bureau (1957–65, 1959), ESSA (1966–70, 1967), NOAA (1971–80), and various national and regional Meteorological Services for the entire period of available records.

3. Theory and computational procedures

3.1. *West African tropospheric water vapor*

The mass of water vapor in an atmospheric column of base 1 cm^2, often termed the "precipitable water", is given by

$$P = \frac{1}{g}\int_{p_1}^{p_2} q \, \mathrm{d}p \tag{1}$$

where g is the acceleration due to gravity, q is specific humidity, and p_1 and p_2 are the atmospheric pressures at the bottom and top of an isobaric layer of thickness $\mathrm{d}p$.

The instantaneous horizontal water vapor flux at any location in the atmosphere can be obtained from

$$\vec{w} = \frac{1}{g} q\vec{V} \tag{2}$$

where $\vec{V}$ is the horizontal wind vector, and the flux has dimensions of $(g\,H_2O)$ $(cm\ mb\ s)^{-1}$. When averaged over a period such as a month, the total water vapor flux can be expressed as the sum of two terms

$$\frac{1}{g}\overline{(q\vec{V})} = \frac{1}{g}[(\bar{q}\vec{\bar{V}}) + \overline{(q'\vec{V}')}] \quad (3)$$

where the overbars denote time-averages and the primes instantaneous departures from such averages. The right-hand terms are the advective and eddy components of the total transfer, respectively, with the eddy component being representative of pure time eddies and space-time eddies (i.e., travelling disturbances), but not standing eddies (Hastenrath, 1966).

The water vapor transport in part or all of an atmospheric column is obtained by vertically integrating eq. (3) to give

$$\vec{\bar{W}} = \frac{1}{g}\int_{p_1}^{p_2} [(\bar{q}\vec{\bar{V}}) + \overline{(q'\vec{V}')}]\,dp \quad (4)$$

which has dimensions of $(g\,H_2O)\ cm^{-1}\ s^{-1}$.

The aerological data available to this study were restricted to monthly averages (Section 2). While these permitted the calculation of the advective fluxes in eqs. (3) and (4), the lack of daily rawinsonde observations precluded the estimation of the eddy transports. However, Flohn et al. (1965, Fig. 3, Tables 10–12) have shown that the advective component is nearly identical to the total water vapor transport over West Africa

Table 2. *Intraseasonal and interannual variability of southwesterly monsoon layer above Gulf of Guinea coast (~5°N) for contrasting Subsaharan rainy seasons. J denotes July, A August, and S September. The advective water vapor fluxes and precipitable water contents are vertical integrals with bases of 1000 mb except where accompanied by an asterisk (900 mb) or dagger (950 mb). Observation times were 1200 GMT at Lagos, and 00 GMT at Abidjan and Douala except for 1975 (1200 GMT)*

		Southwesterly monsoon layer												Total tropospheric column		
		Layer top (mb)			Advective water vapor flux direction (degrees)			Advective water vapor flux amount ($g\ cm^{-1}\ s^{-1}$)			Precipitable water (cm)			Precipitable water (cm)		
Station	Year	J	A	S	J	A	S	J	A	S	J	A	S	J	A	S
Abidjan	*Drought*															
	1968	660	728	850	211	233	220	1394	967	882	4.33	3.58	2.33	5.60	5.07	5.36
	1971	750	666	828	212	241	233	1252	1218	966	3.16	3.49	2.50	4.51	4.34	4.92
	1972	834	853	878	217	224	220	923	742	774	2.29	1.99	1.76	4.91	4.36	4.86
	Nondrought															
	1967	809	711	832	218	238	235	1174	1324	914	2.59	3.53	2.34	4.88	4.86	4.84
	1969	800	850	827	206	207	222	974	895	993	2.74	2.11	2.51	5.26	4.90	5.14
	1975	800	783	830	215	239	239	794	893	758	2.58	2.71	2.25	4.55	4.40	4.44
Lagos	*Drought*															
	1968	609	746	885	266*	244*	212*	959*	208*	13*	4.05	2.68	1.69	4.78	4.73	4.72
	1971	765	728	834	273†	272†	—	869†	1019†		2.87	3.07		4.60	4.39	
	1972	835	824	—	259†	257†	—	458†	413†		2.34	2.39		5.02	4.69	
	Nondrought															
	1967	785	651	852	277*	283*	297*	325*	494*	94*	1.23*	3.54	0.57*	3.09*	4.35	3.24*
	1969	824	814	838	—	266*	264*	—	246*	124*	—	2.43	2.18	—	4.57	4.42
	1975			—	—	—	—	—	—		—	—		5.06	4.69	5.02
Douala	*Drought*															
	1968			—	—	—	—	—	—	—	—	—		—	—	—
	1971	700	533	790	265	260	245	995	1171	391	3.73	4.61	2.80	5.29	5.12	5.19
	1972	826	800	825	240	249	275	445	564	450	2.66	3.00	2.78	5.48	5.54	5.85
	Nondrought															
	1967				—	—	—	—	—	—	—	—		—	—	—
	1969			—	—	—	—	—	—	—	—	—		—	—	—
	1975	751	622	660	250	245	261	384	989	587	2.98	4.03	3.79	4.78	4.95	5.09

during July–August, with the eddy flux being an order of magnitude smaller.

The present evaluation of West African advective water vapor transport is for individual stations on a monthly basis (Tables 2, 4, 5). It ultimately used the first right-hand term in eq. (4) to obtain separate vertical integrals for both the southwesterly monsoon layer and the overlying easterly layer. However, since the easterly fluxes were not particularly instructive, they are not presented in this paper. The top of the monsoon layer was taken as the level where the monthly mean zonal wind component (u) became easterly (i.e., <0), which was determined by linear interpolation between the standard isobaric surfaces listed in Table 1. This procedure is not identically equal to obtaining the monthly average of daily monsoon layer thicknesses given by the $u < 0$ criterion, but should provide an adequate index in this regard. It is the only such index presently available. In the case of Dakar (Fig. 1), where the low level flow can be from north of west (Table 4), the basal layer delimited by the above definition is best termed westerly rather than southwesterly, and hence is not necessarily strictly monsoonal. However, the results obtained were still informative (see Section 4.3). The treatment of West African tropospheric water vapor also included the estimation [via eq. (1)] of the average monthly precipitable water in the monsoon and easterly layers above individual stations. While this contains the monsoon layer thickness uncertainty recognized above, the total column and isobaric layer values were not affected by the use of monthly mean specific humidities.

Table 3. *Statistics on march of Subsaharan rainfall during contrasting rainy seasons. Percentages given are averages of those computed for the 20 stations located in Lamb (1978a, Fig. 2). Long-term averages presented and used were derived from all available data for each station. The April–October period (lower panel) receives, on the average, more than 97% of the total annual rainfall (Lamb, 1980, Table 1)*

Percent of long-term monthly average			
Year	July	August	September
Drought			
1968	84	63	78
1971	75	93	68
1972	54	51	50
Nondrought			
1967	91	93	117
1969	127	100	82
1975	165	82	83

Percent of April–October total			
Year	July	August	September
Long-term average	23	38	22
Drought			
1968	24	29	23
1971	22	48	19
1972	20	30	20
Nondrought			
1967	23	35	23
1969	27	37	18
1975	36	31	20

The foregoing calculations were performed separately for July, August, and September of each of the six study years. Because of the lack of some required surface data, the vertical integrations involved had bases of 1000 mb for the coastal stations of Dakar, Abidjan, Lagos (precipitable water only), and Douala, and 950 mb for the inland locations of Bamako, Niamey, and Ndjamena (Table 1, Fig. 1). The lowest and most moist 13–35 mb of the atmospheric column were therefore not included (Table 1). This error source was much larger in the case of the Lagos water vapor transport integrals, for which few wind data were available below 900 mb. As a result, the Lagos results presented here are unfortunately rather inhomogeneous (see Table 2).

3.2. *Tropical Atlantic atmospheric surface moisture*

Data deficiencies precluded the use of a monthly mean time-scale in these computations; seasonal averages were obtained instead. July–September fields of the "10 m" specific humidity over the tropical Atlantic adjacent to West Africa were produced for DRY, the 60-year mean, and the individual years listed in Section 2 (Fig. 3). They have a two-degree square resolution. The specific humidities used were calculated from mean dew points and mean pressures; this procedure was considered to yield a close approximation to the mean specific humidity because of the small

Table 4. *Intraseasonal and interannual variability of lower tropospheric westerly layer above Dakar (~15° N) for contrasting Subsaharan rainy seasons. J denotes July, A August, and S September. The advective water vapor fluxes and precipitable water contents are vertical integrals with bases of 1000 mb. Asterisk indicates top of westerly layer was below 1000 mb*

		Westerly layer												Total tropospheric column		
		Layer top (mb)			Advective water vapor flux direction (degrees)			Advective water vapor flux amount (g cm $^{-1}$ s $^{-1}$)			Precipitable water (cm)			Precipitable water (cm)		
Observation time	Year	J	A	S	J	A	S	J	A	S	J	A	S	J	A	S
00 Z	*Drought*															
	1968	899	925	932	259	289	274	368	258	154	1.56	1.29	1.21	5.32	5.49	5.42
	1971	899	899	957	300	283	323	281	234	55	1.37	1.53	0.71	4.25	4.91	4.47
	1972	898	910	934	293	255	334	336	210	198	1.37	1.33	1.03	4.37	4.66	4.67
	Nondrought															
	1967	878	893	916	242	236	284	522	509	209	2.09	1.88	1.47	5.89	5.99	5.68
	1969	899	915	941	236	243	290	332	226	134	1.67	1.43	1.07	5.40	5.45	5.24
	1975	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1200 Z	*Drought*															
	1968	899	910	*	327	315	*	240	259	*	1.57	1.54	*	5.41	5.59	5.28
	1971	899	926	*	314	301	*	262	146	*	1.44	1.21	*	4.56	4.98	4.33
	1972	891	927	975	275	310	350	333	207	83	1.47	1.17	0.43	4.44	4.60	4.68
	Nondrought															
	1967	891	898	931	260	259	316	308	323	91	1.87	1.82	1.26	5.89	5.89	5.87
	1969	949	949	949	333	250	260	120	87	45	0.84	0.87	0.91	5.00	5.38	5.20
	1975	892	881	949	283	286	300	227	410	42	1.53	1.83	0.83	4.33	4.57	4.38

temporal and spatial variability of pressure and dew point over the tropical oceans (Hastenrath and Lamb, 1977). The humidity fields so obtained were then smoothed with a symmetrical 25-weight filter function derived by R. Bleck. Hantel (1970) has provided a complete discussion of this objective filtering procedure, including a demonstration of its effectiveness. The large-scale features of interest in the present study remain essentially unaltered from the raw to the filtered fields.

4. Results

4.1. *Tropical Atlantic surface atmospheric moisture conditions*

The near-surface specific humidity over the tropical Atlantic adjacent to West Africa is documented in Fig. 3 for the deficient Subsaharan rainy seasons of 1968 (-0.78σ) and DRY (defined in Section 2; rainfall departures ranged from -0.58σ to -1.39σ), and also for the more average rainy seasons of 1967 (-0.02σ) and 1969 ($+0.06\sigma$). This indicates the *surface* moisture content of the southwesterly monsoon flow as it entered West Africa from the tropical Atlantic, together with its upstream genesis, during July–September periods of contrasting Subsaharan rainfall. Fig. 3 also contains, for background information purposes, the 1911–70 mean specific humidity pattern and the location of the kinematic axis between Northern and Southern hemisphere trades for DRY and two individual years. Readers are referred to Fig. 1 for the necessary orientation on the July–September tropical Atlantic surface flow pattern. The 1975 nondrought study year is not represented in Fig. 3 because the requisite data were not available (Section 2). Data deficiencies also precluded the individual treatment of the 1971 and 1972 drought study years in the present context (Lamb, 1978a); the pattern for DRY, to which these years contributed, is offered instead.

The most important implication of Fig. 3 is that Subsaharan drought is probably not (and certainly not necessarily) associated with the northward supply of unusually dry surface air to West Africa from the tropical Atlantic. During the deficient 1968 (-0.78σ) and DRY (-0.58σ to -1.39σ) rainy seasons, for instance, higher than average surface specific humidity characterized the southwesterly monsoon flow as it crossed almost all of the West African coast south of the kinematic axis,

Table 5. *Intraseasonal and interannual variability of southwesterly monsoon layer above interior of Subsaharan zone at ~13° N for contrasting Subsaharan rainy seasons. J denotes July, A August, and S September. The advective water vapor fluxes and precipitable water contents are vertical integrals with bases of 950 mb. Asterisk indicates top of southwesterly layer was below 950 mb. Observation times were 00 GMT except for 1975 (1200 GMT)*

		Southwesterly monsoon layer												Total tropospheric column		
		Layer top (mb)			Advective water vapor flux direction (degrees)			Advective water vapor flux amount (g cm^{-1} s^{-1})			Precipitable water (cm)			Precipitable water (cm)		
Station	Year	J	A	S	J	A	S	J	A	S	J	A	S	J	A	S
Bamako	*Drought*															
	1968	912	*	*	214	*	*	95	*	*	0.69	*	*	5.35	5.22	5.25
	1971	895	899	*	209	190	*	128	39	*	0.91	0.77	*	4.68	4.64	4.22
	1972	916	*	*	186	*	*	90	*	*	0.55	*	*	4.50	4.55	4.34
	Nondrought															
	1967	895	846	*	234	218	*	95	224	*	0.94	1.78	*	—	—	5.44
	1969	899	*	*	207	*	*	119	*	*	0.84	*	*	4.76	5.27	4.78
	1975	881	883	916	218	243	216	227	130	70	1.02	1.02	0.53	4.77	4.65	4.62
Niamey	*Drought*															
	1968	892	894	927	190	190	191	243	192	88	0.85	0.82	0.34	4.22	4.04	3.90
	1971	845	899	*	220	193	*	400	212	*	1.56	0.72	*	4.18	4.10	3.77
	1972	881	871	892	205	213	220	370	281	179	0.95	1.17	0.80	3.92	4.29	3.63
	Nondrought															
	1967	854	827	892	218	235	214	430	498	156	1.40	1.91	0.89	—	—	4.11
	1969	889	874	931	195	203	186	382	266	85	1.02	1.24	0.34	4.88	5.16	4.82
	1975	877	863	919	221	234	191	302	312	110	0.96	1.13	0.43	4.01	3.95	3.51
Ndjamena	*Drought*															
	1968	883	899	899	230	193	220	98	116	35	1.11	0.78	0.70	5.10	4.50	4.12
	1971	873	927	928	223	222	213	106	18	18	0.95	0.32	0.30	3.78	4.13	3.64
	1972	882	899	939	195	210	185	326	72	69	0.91	0.72	0.15	3.91	4.23	3.81
	Nondrought															
	1967	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	1969	880	*	*	200	*	*	166	*	*	1.09	*	*	4.88	4.74	4.57
	1975	882	829	891	207	248	219	300	595	111	0.92	1.56	0.80	4.24	4.21	3.93

including the Gulf of Guinea. The 1968 coastal humidity anomaly in this extended region generally approached + 1 g kg^{-1}, which Fig. 3 (in its entirety) suggests is a reasonably large departure, and can be traced a considerable distance upstream into the southeast trades. The magnitude of this departure feature increased northward from 10° S (Fig. 3) as the air traversed the strong positive SST anomalies identified in Lamb (1978b, Fig. 4). A weaker version of the foregoing pattern characterized DRY. In this case, the positive coastal humidity departures only occasionally approach 1 g kg^{-1} and largely originate within 300–800 km of the coast. This apparently resulted from DRY's warm 10° N–10° S SST anomaly being less pronounced than its 1968 counterpart (Lamb, 1978a, b).

The specific humidity patterns in Fig. 3 for the nondrought years of 1967 (-0.02σ) and 1969 ($+0.06\sigma$) do not contain the features identified above for the deficient 1968 (-0.78σ) and DRY (-0.58σ to -1.39σ) Subsaharan rainy seasons. The results for 1967 are, in fact, essentially the opposite—the surface moisture content of the southwesterly monsoon flow was generally about 0.5 g kg^{-1} below average as it crossed the West African coast south and east of the kinematic axis, an anomaly that can be traced as far upstream as 10° S (Fig. 3) and attributed to abnormally cold SSTs between 10° N–10° S (Lamb, 1978b, Fig. 4). Coastal humidities were near or a little below average during the slightly above normal 1969 Subsaharan rainy season, which is also in contrast to the foregoing drought results.

4.2. *Southwesterly monsoon layer over Gulf of Guinea coast*

The consideration of the onshore southwesterly monsoon flow is expanded here to encompass the

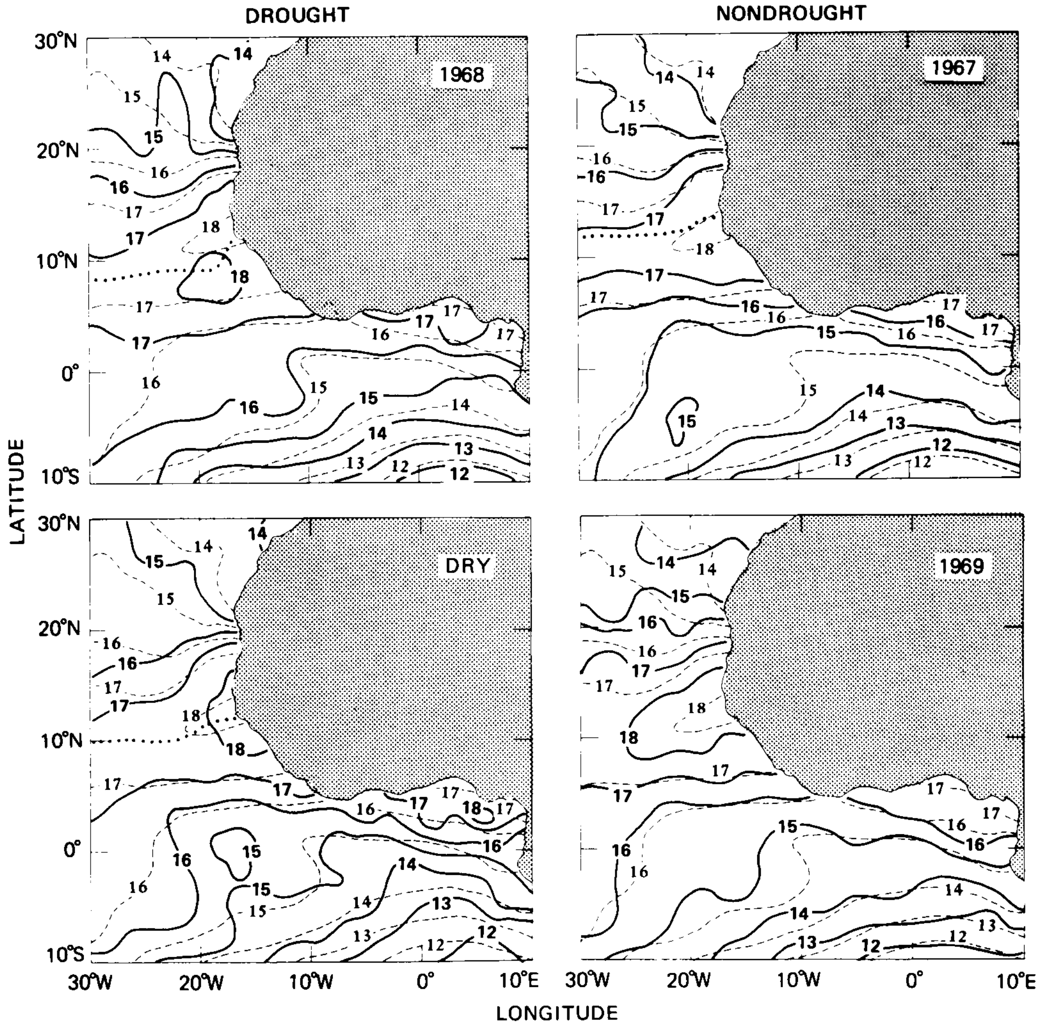

Fig. 3. Eastern tropical Atlantic near-surface specific humidity fields (heavy solid lines, g kg^{-1}) during contrasting Subsaharan rainy seasons (July–September). DRY composite data set is defined in Section 2. Dotted line across ocean is discontinuity between northerly and southerly resultant wind directions for DRY and specified individual years; this information was not available for 1969. Thin broken lines depict 1911–70 mean specific humidity field (g kg^{-1}).

full depth of the layer. Table 2 gives the vertically integrated moisture characteristics of this flow as it crossed the Gulf of Guinea coast (~5° N) during the contrasting Subsaharan rainy seasons of the six study years listed in Section 1. This coastline is sufficiently removed from the Subsaharan zone (10°–20° N) for the coastal monsoon flow to be relatively unaffected by Subsaharan disturbance lines, and instead largely reflect upstream oceanic conditions. The results in Table 2 exhibit considerable and encouraging station-to-station consistency for individual months.

A particularly conspicuous feature of Table 2 is the substantial variation in the monsoon layer thickness over the Gulf of Guinea coast between the three drought study years. At one extreme is the highly deficient 1972 Subsaharan rainy season (Fig. 2; -1.39σ), throughout which the monsoon flow across this coast was rather shallow (generally 125–175 mb) and contained less than half the water vapor in the entire tropospheric column. Table 3 shows that a similar negative anomaly persistence characterized this season's Subsaharan rainfall—monthly amounts were consistently only 50–54% of the long-term average. This reduced, in particular, the normally important August contribution to the annual rainfall total (Table 3). In contrast to 1972, the Gulf of Guinea southwesterly layer was noticeably deeper during July–August of the less severe 1968 (-0.78σ) and 1971 (-0.88σ) Subsaharan drought years (Table 2). This was especially characteristic of July 1968 and August 1971, when the monsoon flow extended to between 530–730 mb and included 67–90% of the column's precipitable water. It is interesting to note that the Subsaharan rainfall during these two months was much closer to the long-term mean than in the other drought months studied (Table 3). Furthermore, the fraction of the 1971 rainfall occurring in August was substantially higher than average, which is in pronounced contrast to the other drought years (Table 3). The Septembers of 1968 and 1971 were characterized by monsoon layers that were much thinner than during the preceding July–August periods, but not quite as shallow as in the particularly dry Subsaharan September of 1972 (Tables 2 and 3).

This tendency for the southwesterly flow across the Gulf of Guinea coast to be less deep in September than in the two earlier months of the Subsaharan rainy season is a rather strong and interesting general feature of Table 2. Despite it, however, the September Subsaharan rainfall is generally very similar to that of July (Table 3).

A further important implication of Table 2 is that pronounced intraseasonal and interannual variations in the monsoon layer thickness above the Gulf of Guinea coast are also characteristic of nondrought Subsaharan rainy seasons (-0.27σ to $+0.06\sigma$). The limited data available for 1967 suggest that the onshore southwesterly flow extended to as high as 650–710 mb in July of this year, and contained up to 70–80% of the total tropospheric water vapor. Subsaharan rainfall was very close to the long-term mean during this month (Table 3), as it was when the Gulf of Guinea monsoon layer was of similar thickness in the aforementioned isolated months (July 1968, August 1971) of otherwise very deficient rainy seasons. In contrast, Subsaharan rainfall was near average in July 1967 and above average in September 1967, despite the Gulf of Guinea monsoon layer being as shallow as in some of the drought years (Tables 2 and 3). There is also some evidence that the southwesterly flow was at least moderately thick during the 1975 rainy season (Table 2). However, this seems to have been characteristic of August and September, months of below average Subsaharan rainfall, as well as the extremely wet July (Table 3). Furthermore, Table 2 suggests that the Gulf monsoon flow during the remaining nondrought study year (1969) tended to be almost as thin, and contained as little moisture (45–55% of column total), as that experienced during the highly deficient 1972 Subsaharan rainy season. There is only weak evidence that the single very wet 1969 month (July, Table 3) was associated with a deeper southwesterly layer than the two subsequent drier months.

The magnitudes of the monsoon layer advective water vapor flux vectors in Table 2 tend to be positively related to the layer thickness. Those for the Subsaharan drought months of July 1968 and August 1971 are therefore relatively large, while rather small vectors characterized the grossly deficient 1972 rainy season (-1.39σ) and, to a lesser extent, the near-average one of 1969 ($+0.06\sigma$). Table 2 does not reveal any significant differences between the monsoon layer advective flux directions of the drought and nondrought study years. The same is true for the precipitable water in the entire tropospheric column over this coastline.

4.3. *Westerly flow across Subsaharan coast*

Table 4 documents the gross moisture characteristics of the lower tropospheric westerly flow above Dakar, a location on the Subsaharan portion of the West African coast close to 15° N (Fig. 1), for the contrasting Subsaharan rainy seasons under study. Fig. 1 indicates that Dakar is located, on the average, close to the northernmost coastal extent of the surface southwesterly monsoon flow. During Subsaharan drought, however, this southwesterly airstream can apparently stay up to 300 km south of Dakar (Fig. 3). Fig. 1 suggests that, should this occur, the lower tropospheric flow above Dakar would likely be from the west or northwest. This implies that of the moisture results in Table 4 (patterned after Table 2), the sector (northwest, west, southwest) of the advective flux direction for the low-level westerly layer may be particularly indicative of circulation changes associated with Subsaharan drought. Because of the strong diurnal wind variation known to occur at low elevations above Dakar, Table 4 contains results for both 00 and 1200 GMT for all possible years; twice-daily soundings were not available for the other West African stations considered in Tables 2 and 5.

As anticipated above, the major difference between the results in Table 4 for the Subsaharan drought and nondrought study years relates to the lower tropospheric advective flux direction. For a given month (e.g., August) and observation time, this direction shows a stronger tendency to be from north of west during Subsaharan rainy seasons that are unproductive (-0.78σ to -1.39σ) than in those near the long-term average (-0.27σ to $+0.06\sigma$). In the latter case, westerly and southwesterly directions are more predominant. Furthermore, Table 4 indicates that no low-level westerly layer could be identified for 1200 GMT of the September 1968 and 1971 drought months. In both cases the 1000 and 950 mb resultant wind vectors were from the northeast, a direction the present data set suggests is often characteristic of shallow flow between the aforementioned basal westerly layer and mid-tropospheric "due easterlies" (from 80°–100°) that usually extend to as low as 800–850 mb over Dakar (not shown). These easterlies reached 900 mb for the two drought Septembers in question. The foregoing results thus appear to be consistent with the present author's earlier finding that the surface southwesterly monsoon flow did not extend as far north along the West African coast during Subsaharan droughts as in more abundant rainy seasons (Lamb, 1978a, b).

Most of the interannual and intraseasonal variations in monsoon layer thickness above the Gulf of Guinea coast for deficient Subsaharan rainy seasons identified in Section 4.2 are not reflected in the much smaller Dakar westerly layer depths (< 10 to 130 mb) given in Table 4. This may partly stem from Dakar's relatively high latitude coastal position (~ 15° N) within the Subsaharan zone and, as already noted, the onshore flow here in these years consequently tending to be from north of west rather than strictly southwest monsoonal. However, since similar Subsaharan results will be presented in Section 4.4 for the interior of the zone at ~ 13° N, the above finding could well be more general. A particularly conspicuous difference between the Dakar and Gulf sets of drought basal layer thickness results is that the 1972 values for Dakar (60–120 mb) are not noticeably shallower than those for the other years. In further contrast to the monsoon airstream at the Gulf of Guinea coast (Table 2), the westerly flow above Dakar during July 1968 and August 1971 does not appear to have been markedly thicker, or to have contained a significantly greater amount of the column's precipitable water, than during the other drought months (Table 4). The fraction of the total tropospheric water vapor in this westerly layer during the drought study years was largely between 22–32%; both the low values and narrow range differ from the earlier Gulf of Guinea results, and reflect the thinner and less variable Dakar basal layer. On the other hand, Dakar's low-level westerly flow exhibits the same general tendency (albeit weaker) to be less deep in September than July–August that characterized the Gulf monsoon layer. This feature is especially characteristic of the drought years in Table 4. An additional similarity between the drought results in Tables 2 and 4 is that the total tropospheric precipitable water was larger in 1968 than 1971–72 at both Dakar and the westernmost Gulf of Guinea station (Abidjan).

The variation of the Dakar basal layer thickness values between the nondrought study years (Table 4) tends to be similar to that documented in Table 2 for the Gulf of Guinea coast, which is in contrast to the drought results discussed above. Such variation includes the 1967 and 1975 layers being moderately thick, which at Dakar (100–130 mb) was also largely confined to July–August, and a rather shallow 1969 layer. The latter was often only 60–70 mb thick at Dakar, and hence no better developed than in the drought months. As already implied, however, the 1969 Dakar results most related to this year's near-average Subsaharan rainfall may be the predominant southwesterly direction of the low-level onshore flow, and not its lack of depth. Table 4 also contains some evidence (00 GMT) that the Dakar westerly layer may have been thicker in the single very wet 1969 Subsaharan month (July, Table 3) than during the subsequent months of average (August) and below average (September) rainfall. The aforementioned tendency for the nondrought years to be characterized by lower tropospheric southwesterly (i.e., monsoonal) flow above Dakar may also help to explain why there is more consistency between the Dakar and Gulf of Guinea nondrought results than their counterparts for the drought study years. During the latter, as noted above, the low-level flow above Dakar tends to be more from north of west, and hence not strictly monsoonal like that crossing the Gulf of Guinea coast.

4.4. *Southwesterly monsoon layer over interior of Subsaharan zone*

The investigation of the southwesterly monsoon flow during the contrasting Subsaharan rainy seasons under study now focuses on the interior of the Subsaharan zone at the relatively southern latitude of ~13° N. Table 5 presents the bulk moisture characteristics of this flow for the three available stations, which are evenly spaced from west to east (Fig. 1). Because of these stations' location in the higher rainfall southern one-third of the Subsaharan zone, their results were expected to be more informative than if history had situated them further north where rainfall is decidedly less abundant. Although Table 5 contains reasonable station-to-station consistency for individual months, this is not as strong as for the more pronounced interannual and intraseasonal variations of Table 2.

Perhaps the most conspicuous feature of Table 5, particularly in view of Table 2's Gulf of Guinea results, is the relative uniformity of the (shallow) monsoon layer thicknesses above a given station for the drought study years. They tend to range between < 25 and ~100 mb, with the layer generally containing only 10–25% of the total tropospheric water vapor. Similar statistics were obtained for Dakar's westerly airstream (Table 4). An especially noteworthy example of the 13° N uniformity is that the southwesterly flow during the extremely deficient 1972 Subsaharan rainy season (-1.39σ) tended to be little, if any, shallower than in the lesser drought years of 1968 (-0.78σ) and 1971 (-0.88σ) (Table 5). Furthermore, this airstream was not especially thick here in the isolated months of near-average rainfall that did occur (Table 3) during the otherwise deficient Subsaharan rainy seasons of 1968 (July) and 1971 (August). These results, which were also found to characterize the low-level westerly flow over the coastal Subsaharan location of Dakar (Section 4.3), are in pronounced contrast to those identified earlier for the Gulf of Guinea monsoon layer. However, one similarity between the 13° N (Table 5) and Gulf (Table 2) drought results is that the total tropospheric precipitable water at their respective westernmost stations of Bamako and Abidjan was larger in 1968 than 1971–72. This was earlier found to be also characteristic of the extreme western Subsaharan station of Dakar (Table 4). In addition, the drought monsoon layer thickness values in Table 5 show the same tendency to be shallower in September than July–August as those for the Gulf (Table 2) and Dakar (Table 4). As for the other locations, however, this difference also occurred in the nondrought study years at 13° N. Interestingly, it is much smaller here, and at Dakar, than along the Gulf of Guinea coast.

In contrast to the foregoing drought results, the variation in the depth of the 13° N southwesterly monsoon flow between the nondrought study years (Table 5) is similar to that evident in Table 2 for the Gulf of Guinea coast. Section 4.3 also found this to be true of the low-level westerly flow above Dakar. At 13° N such variation consists of relatively thick monsoon layers (120–150 mb) during July–August of 1967 and 1975, especially the Augusts, and a much shallower or nonexistent southwesterly flow in August–September 1969 (Table 5). The monsoon layers in the former group tend to be thicker than those characteristic of most of the July and August drought months studied. With the exception of August 1975, they were associated with Subsaharan rainfall that was near or above average, and hence substantially higher than in most of the drought July–Augusts (Table 3). On the other hand, Subsaharan rainfall was almost 20% above the long-term mean in September 1967, despite the monsoon layer here being as shallow as in some of the much drier Septembers (Tables 3 and 5). The southwesterly flow across the Gulf of Guinea coast was of similar relative thickness during this month (Section 4.1). Furthermore, the extremely wet July 1975 (Table 3) does not appear to have been characterized by a monsoon layer that was of comensurate abnormality at 13° N (Table 5), which is again consistent with the earlier Gulf of Guinea findings. However, the 13° N results for the 1969 nondrought study year are in contrast to those discussed immediately above. In this case the anomalously wet month (July, Table 3) experienced southwesterly flow whose depth was greater and more comparable to the same month of the other nondrought years, especially at Bamako and Ndjamena, than characterized the months of average (August) and below average (September) rainfall. As noted earlier, the 13° N monsoon layer was either very shallow or nonexistent during the two latter months. This relatively thick July 1969 basal layer was less evident over the Gulf of Guinea coast (Table 2) and Dakar (Table 4).

The magnitudes of the monsoon layer advective water vapor fluxes in Table 5 tend to be positively related to the layer thickness, as was earlier found to occur above the Gulf of Guinea coast. However, the 13° N values show more evidence of wind speed fluctuations than those for the Gulf, though no significant drought/nondrought differences are apparent in this regard. These comments also apply to the Dakar flux magnitudes in Table 4.

5. Conclusions

In the wake of the widespread publicity given to the Subsaharan drought and famine of the early 1970s, Landsberg (1975) indicated that a "comprehensive diagnostic study of the circulation affecting West Africa" was needed to identify the processes responsible for Subsaharan climatic fluctuations. The present author subsequently contributed to such a line of enquiry in two papers documenting the tropical Atlantic surface atmospheric and oceanic patterns that prevailed during years of very deficient (-0.58σ to -1.39σ departures) and more abundant (-0.02σ to $+0.96\sigma$) Subsaharan rainfall (Lamb, 1978a, b). An extension of this effort has been reported here. The focus was on the West African water vapor variations between recent contrasting Subsaharan rainy seasons, and in particular the low-level moisture-bearing southwest monsoon flow from the tropical Atlantic. The characteristics of this airstream have recently been suggested to be strong determinants of the quality of Subsaharan rainy seasons, both on modern and palaeoclimatic time-scales. For example, Landsberg (1975) asserted that "If the equatorial air masses penetrate in depth northward during the summer (Subsaharan) rainfall is ample, if they do not dry continental Saharan air will prevail. It is essentially a question of the extent and intensity of the (southern) Hadley cell". The following results from Kutzbach's (1981) model simulation of the monsoon climate of the early Holocene are consistent with this view: "Over the African ... land mass ... the low-level cyclonic inflow of air ... (is) stronger at 9000 years B.P. than at present. At the surface, increased southwesterly winds carry moisture into West Africa ... Along 12° N over Africa, the (model) precipitation is about 0.6 cm/day for June to August 9000 years B.P., compared to about 0.55 cm/day now, an increase of 10 per cent ... (This) agrees with palaeoclimatic evidence in Africa ... of enlarged lakes during early Holocene time." Finally, as noted in the Introduction, the research into modern Subsaharan rainfall fluctuations by Kidson (1977) and this author (reference above) was also suggestive of the foregoing mechanism.

With these statements as a backdrop, it is now appropriate to list the following principal conclusions of the present investigation:

(i) Subsaharan drought does not appear to be associated with the northward supply of unusually dry surface air to West Africa from the tropical Atlantic. During the deficient rainy seasons (-0.78σ to -1.39σ) studied, in fact, the southwest monsoon flow across the West African coast (including the Gulf of Guinea) tended to possess higher than average surface specific humidity. Furthermore, this surface airstream was actually less moist during the two near-average (i.e., more abundant) Subsaharan rainy seasons (-0.02σ and $+0.06\sigma$) considered.

(ii) The extremely poor 1972 Subsaharan rainy season (-1.39σ) coincided with a particularly shallow southwesterly monsoon flow across the Gulf of Guinea coast (~5° N). Thicker Gulf monsoon layers were characteristic of the less severe 1968 (-0.78σ) and 1971 (-0.88σ) drought years, and especially their isolated months of better (i.e., 84% and 93% of average) rainfall. However, the depth of the southwesterly airstream above this coastline during the nondrought study years (-0.27σ to $+0.06\sigma$) did not always exceed that obtained for the drought months. For example, the 1969 monsoon flow here tended to be almost as thin, and contained as little moisture, as that experienced during the grossly deficient 1972 Subsaharan rainy season.

(iii) The direction of the advective water vapor flux within the low-level onshore flow above Dakar, a sensitive location (~ 15° N) on the Subsaharan portion of the West African coast, showed a stronger tendency to be from north of west during Subsaharan rainy seasons that were unproductive (-0.78σ to -1.39σ) than in those near the long-term average (-0.27σ to $+0.06\sigma$). In the latter cases, westerly and southwesterly directions were more predominant. Furthermore, no basal layer of onshore flow could be identified over Dakar for occasional drought months. These results seem consistent with the present author's earlier finding that the surface southwesterly monsoon flow did not extend as far north along the West African coast during Subsaharan droughts as in more abundant rainy seasons.

(iv) Unlike the Gulf of Guinea results summarized in (ii) above, the (shallow) monsoon layer over the interior of the Subsaharan zone at ~ 13° N exhibited minimal interannual or intraseasonal thickness variability for the drought study years. In particular, the southwesterly flow here during the especially poor 1972 rainy season (-1.39σ) was little, if any, thinner than in the lesser 1968 (-0.78σ) and 1971 (-0.88σ) drought years. This suggests that the processes responsible for Subsaharan rainfall extremes may be more strongly reflected in the monsoon layer characteristics over the Gulf coast (and perhaps also between 8°–10° N ?) than those occurring as far into the Subsaharan zone as 13° N. In contrast to the foregoing drought results, the variation in the 13° N monsoon layer depth between the nondrought study years (-0.27σ to $+0.06\sigma$) was similar to that identified for the Gulf of Guinea coastline. However, the better developed nondrought southwesterly flows tended to be thicker than those characteristic of most of the drought months. This was true of the single anomalously wet 1969 month [cf (ii) above]. Most of these results were also obtained for the low-level westerly layer above Dakar.

The present investigation has thus provided some confirmation of the earlier ideas and findings concerning the role of the southwesterly monsoon flow for Subsaharan rainfall variability, but complete endorsement cannot be claimed. It is probable that for some aspects, such as the shallow Subsaharan monsoon layer, more definitive and physically instructive results would have emerged from the same analysis of individual rawinsonde observations, had the latter been available. Our future work on this important climate problem will therefore utilize individual soundings (presently being accumulated); it will also be expanded to include treatment of the kinematic processes and static and dynamic instability mechanisms that can stimulate Subsaharan rainfall, in addition to the water vapor related topics considered here. The present results would seem to encourage such further effort.

6. Acknowledgments

Some of this material was first presented at the August 1981 Oxford (U.K.) Symposium on Variations in the Global Water Budget, with the aid of an award from the Legacies Fund of the Royal Meteorological Society and the encouragement of Stanley A. Changnon, Jr. (Chief, Illinois State Water Survey). Most of the research reported above was performed at the University of Adelaide, Australia, using computer programs written by Wence Sulda. The cooperation and comments of Wayne M. Wendland and Stefan Hastenrath, the comments of Kenneth H. Bergman, the computational assistance of Peter Guetter, Phyllis Stone, and Peter Vinzani, and the data provided by West African regional and national meteorological services are also gratefully acknowledged.

Note added in proof

Since this paper was accepted for publication, an evaporation counterpart to Fig. 3 has been produced. It had not been possible to do this earlier, because of logistical problems. Copies of this supplementary figure can be obtained from the author. It was constructed using the same space-time resolution and data set as Fig. 3: the computational procedures followed those employed in the Hastenrath and Lamb *Heat Budget Atlas of the Tropical Atlantic and Eastern Pacific Oceans* (The University of Wisconsin Press, Madison, 1978).

The evaporation figure shows that the occurrence of abnormally moist surface southwesterly monsoon flow across the West African coast south of the kinematic axis during the deficient 1968 and DRY Subsaharan rainy seasons (Fig. 3) coincided with above average evaporation from the extensive 10° N–10° S positive SST anomalies identified in Lamb (1978a, b). In contrast, the relatively dry onshore surface southwesterly monsoon flow during the near-average 1967 Subsaharan rainy season (Fig. 3) was associated with negative evaporation anomalies from some, but not all, of the then much cooler sea surface in the aforementioned area (Lamb, 1978b). In this case, the tendency for negative SST anomalies to suppress evaporation was offset in some areas by positive wind speed departures (Lamb, 1978b). Finally, the 1969 evaporation field was generally near-average between 10° N–10° S, in similarity to the contemporary specific humidity pattern (Fig. 3).

Some of the foregoing evaporation fields, and particularly their relation to SST, wind speed, specific humidity, and sea–air temperature difference anomalies, will be fully treated in a subsequent communication.

REFERENCES

ASECNA. 1968–69, 1971–72, 1975. *Radiosondages-anneé*. Agence pour la Sécurité de la Navigation Aerienne en Afrique et à Madagascar, Dakar.

Burpee, R. W. 1972. The origin and structure of easterly waves in the lower troposphere of North Africa. *J. Atmos. Sci. 29*, 77–90.

ESSA. 1966–70. *Monthly climatic data for the world, 1966–70*. Asheville, N.C.

ESSA. 1967. *World weather records, 1951–60, vol. 5 (Africa)*. Washington D.C.

Flohn, H., Henning, D. and Korff, H. C. 1965. Studies on the water-vapor transport over Northern Africa. *Bonner Meteor. Abhandl. 6*, 36 pp.

Hantel, M. 1970. Monthly charts of surface wind stress curl over the Indian Ocean. *Mon. Wea. Rev. 98*, 765–773.

Hastenrath, S. L. 1966. The flux of atmospheric water vapor over the Caribbean Sea and the Gulf of Mexico. *J. Appl. Meteor. 5*, 778–788.

Hastenrath, S. and Lamb, P. J. 1977. *Climatic atlas of the tropical Atlantic and eastern Pacific oceans*. Madison: The University of Wisconsin Press.

Kidson, J. W. 1977. African rainfall and its relation to the upper air circulation. *Quart. J. Roy. Meteorol. Soc. 103*, 441–456.

Kutzbach, J. E. 1981. Monsoon climate of the early Holocene: climate experiment with the Earth's orbital parameters for 9000 years ago. *Science 214*, 59–61.

Lamb, P. J. 1977. On the surface climatology of the Tropical Atlantic. *Arch. Meteorol. Geophys. Bioklim. B25*, 21–31.

Lamb, P. J. 1978a. Large-scale Tropical Atlantic surface circulation patterns associated with Subsaharan weather anomalies. *Tellus 30*, 240–251.

Lamb, P. J. 1978b. Case studies of Tropical Atlantic surface circulation patterns during recent Subsaharan weather anomalies: 1967 and 1968. *Mon. Wea. Rev. 106*, 482–491.

Lamb, P. J. 1980. Sahelian drought. *N.Z. J. Geogr. 68*, 12–16.

Lamb, P. J. 1982. Persistence of Subsaharan drought. *Nature, 299*, 46–48.

Landsberg, H. E. 1975. Sahel drought: change of climate or part of climate? *Arch. Meteorol. Geophys. Bioklim. B23*, 193–200.

NOAA. 1971–80. *Monthly climatic data for the world, 1971–80*. Asheville, N.C.

Ramage, C. S. 1974. Structure of an oceanic near-equatorial trough deduced from research aircraft traverses. *Mon. Wea. Rev. 102*, 754–759.

Smithsonian Institution. 1927. World weather records (ed. H. H. Clayton). *Smithsonian Miscellaneous Collections 79*.

Smithsonian Institution. 1934. World weather records 1921–30 (ed. H. H. Clayton). *Smithsonian Miscellaneous Collections 90*.

Smithsonian Institution. 1947. World weather records 1931–40 (eds. H. H. Clayton and F. L. Clayton). *Smithsonian Miscellaneous Collections 105*.

U.S. Weather Bureau. 1957–1965. *Monthly climatic data for the world, 1957–65*. Asheville, N.C.

U.S. Weather Bureau. 1959. *World weather records, 1941–50*. Washington, D.C.