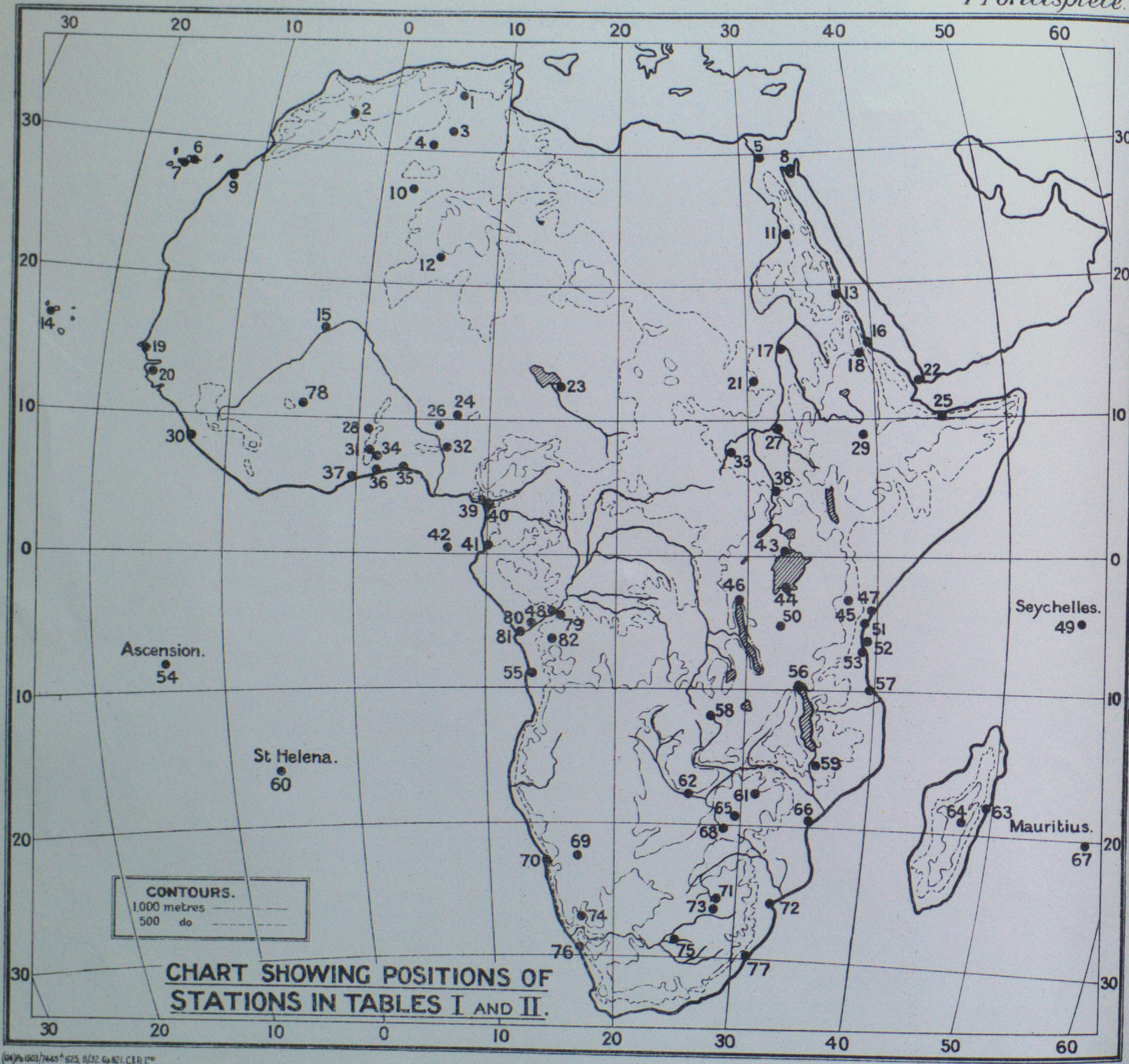

CHART SHOWING POSITIONS OF STATIONS IN TABLES I AND II.

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A STUDY OF THE ATMOSPHERIC CIRCULATION OVER TROPICAL AFRICA

By C. E. P. BROOKS, D. Sc. and S. T. A. MIRRLEES, M.A.

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A STUDY OF THE ATMOSPHERIC CIRCULATION OVER TROPICAL AFRICA

§ 1—INTRODUCTION

In the collecting of data for the extension over the period 1921–30 of the well known publication of the Smithsonian Institution entitled *World Weather Records*, considerable discrepancies were found to exist in the values of mean pressure, reduced to mean sea level, at neighbouring stations in tropical Africa. In order to examine these discrepancies, a map of the distribution of pressure at mean sea level was prepared, embodying all available data. Some difficulties in drawing the isobars were examined by reference to the prevailing wind directions, and this process gradually led to a general study of the atmospheric circulation over tropical Africa in different seasons, the results of which are set out below. Further, owing to the great elevation of many of the stations, it was found that the circulation was not intelligible if consideration was limited to conditions at sea level, and charts were drawn also for the equipotential surface of 1000 dynamic metres, which is equivalent to 1022 metres at the equator and 1021 metres in latitude 30°.

The choice of this plane of reference may require some explanation. It was desired to employ the isobars in the free air as equivalent to the stream lines of the air at that height, and this could only be done if the isobars were drawn along an equipotential surface. There was also the practical consideration that the representation of heights in dynamic metres greatly facilitated the pressure reductions.

The method of reduction employed was the same as that employed in the preparation of the tables for the *Réseau Mondial*. It is based on an expansion of the formula $p_0 = pe^{\frac{z}{KT}}$ and assumes that the temperature decreases upwards at the rate of 0·5°C. per 100 metres and that the average relative humidity is 50 per cent.

§ 2—PRESSURE DATA

The list of stations for which data were employed, with their latitudes, longitudes and heights (in metres) is shown in Table I. In this table column 5 gives the pressures for the year, reduced to mean sea level for the heights shown in column 4. These figures were plotted on a large-scale map, together with a number of resultant winds (see § 3). At stations above 1000 metres in elevation, a second series of pressure values is given, showing the pressure reduced to a height of 1000 dynamic metres. Smooth isobars were then drawn for every millibar, and corrected annual means were read off from the resulting map. These corrected figures are shown in column 6. The values for January, April, July and October were then adjusted by applying a correction equal to the difference between the two columns 5 and 6, and these corrected figures are shown in columns 7 to 10.

It is believed that in the majority of cases the correction was necessary because of the inaccurate determination of the height of the station, and approximately the same correction would therefore apply throughout the year. In other cases the discrepancies may have been due in part to anomalous temperatures, and here the assumption of constancy is not justified to the same extent, but within the tropics the annual variation of temperature is not usually very great.

For Egypt and the Nile Valley only a skeleton selection of stations was employed, as it was possible to make use of the excellent maps recently published by the Survey Department at Cairo.[1] These maps also include a very large number of resultant winds, from which the stream lines of the air could be drawn with great ease.

[1] Cairo, Survey Dept. Atlas of Egypt. Meteorological maps, text and charts. [1928].

TABLE I—PRESSURE AT MEAN SEA LEVEL AND AT 1000 DYNAMIC METRES

	(1)	(2)		(3)		(4)	(5)	(6)	(7)	(8)	(9)	(10)
No.	Station	Position				Height	Year		Jan.	April	July	Oct.
		Lat.		Long.			Obs.	Corr.				
		°	′	°	′	metres	mb.	mb.	mb.	mb.	mb.	mb.
1	Touggourt	33	1 N.	5	56 E.	69	1014·5	1016·0	20·6	13·6	13·2	16·7
2	Ain Sefra	32	56	2	42 W.	1074	15·0	15·0	20·3	12·9	11·2	16·0
							* 900·6	900·6	901·5	897·7	901·9	901·3
3	Ouargla	31	9	4	56 E.	154	1015·8	15·3	23·1	11·3	12·3	14·5
4	El Goléa	30	36	3	2 E.	380	15·0	14·8	18·8	12·4	11·4	15·0
5	Helwan	29	52	31	20 E.	116	14·0	14·0	18·9	13·5	08·3	14·9
6	La Laguna	28	28	16	20 W.	547	17·7	17·7	20·9	17·3	16·8	15·9
7	Izaña	28	19	16	30 W.	2367	17·4	17·4	22·3	17·2	14·2	17·2
							902·9	902·9	905·0	901·5	903·2	902·7
8	Tor	28	14	33	37 E.	2	1011·6	11·6	17·2	11·4	05·3	12·3
9	Cape Juby	27	57	12	56 W.	7	16·9	16·9	19·8	16·3	15·7	16·4
10	Insalah	27	1	2	21 E.	280	12·3	13·0	20·7	10·9	08·9	13·1
11	Aswan	24	2	32	53 E.	100	11·6	11·6	17·7	10·8	05·8	11·7
12	Tamanrasset	22	36	5	36 E.	1380	13·3	12·2	18·6	09·2	08·0	12·2
							901·2	901·2	902·5	899·0	900·5	901·1
13	Port Sudan	19	37	37	13 E.	6	1009·9	09·9	14·5	10·0	04·6	10·4
14	St. Vincent	16	54	25	4 W.	11	14·2	14·2	15·4	14·2	14·3	13·3
15	Timbuctoo	16	43	2	52 W.	250	09·9	10·9	15·5	08·9	09·4	10·6
16	Massawa	15	37	39	24 E.	19	10·0	09·1	13·3	08·8	04·9	09·6
17	Khartoum	15	37	32	33 E.	390	08·3	08·3	12·1	06·0	07·3	07·0
18	Addi Ugri	14	53	38	49 E.	2022	07·4	08·1	08·7	06·7	09·4	08·5
							897·8	898·8	898·6	898·4	899·4	899·2
19	Dakar	14	40	17	26 W.	32	1012·4	12·4	13·0	11·5	13·3	12·1
20	Bathurst	13	27	16	36 W.	2	12·0	12·0	12·6	12·1	12·0	11·4
21	El Obeid	13	11	30	14 E.	569	09·4	09·4	12·3	07·3	08·8	08·1
22	Perim	12	39	43	26 E.	61	08·5	09·7	14·8	10·2	03·4	11·3
23	Kasseri am Logona	12	5	15	0 E.	295	09·0	09·0	13·8	07·8	10·2	07·9
24	Kaduna	10	32	7	25 E.	637	13·0	10·0	11·1	08·0	11·3	09·7
25	Berbera	10	22	45	2 E.	11	10·2	10·2	15·7	10·3	04·1	11·9
26	Zungeru	9	45	6	5 E.	131	10·1	10·0	09·5	08·1	11·8	10·2
27	Malakal	9	35	31	37 E.	394	09·1	08·1	07·9	05·8	10·5	09·1
28	Basari	9	15	0	50 E.	404	20·9	10·5	09·8	08·8	13·1	11·3
29	Addis Ababa	9	2	38	45 E.	2450	07·3	08·0	09·7	05·7	07·6	08·3
							897·2	897·9	899·2	896·6	897·2	898·2
30	Freetown	8	30	13	14 W.	68	1012·3	12·3	11·7	11·4	14·3	12·4
31	Bismarckburg	8	12	0	34 E.	710	07·9	10·5	09·0	09·1	12·7	10·8
32	Lokoja	7	48	6	44 E.	70	09·1	09·6	09·2	07·6	11·2	09·9
33	Wau	7	42	28	3 E.	440	08·5	08·5	09·1	06·3	09·6	08·5
34	Atakpame	7	32	1	8 E.	380	13·6	10·6	09·3	09·7	13·0	10·2
35	Lagos	6	27	3	24 E.	4	11·1	10·7	09·9	09·5	12·9	11·0
36	K'peme	6	13	1	32 E.	4	10·6	10·8	08·8	09·2	13·3	10·9
37	Accra	5	12	0	12 W.	24	09·8	11·1	09·9	09·5	14·1	11·2
38	Mongalla	5	11	31	47 E.	448	08·0	08·5	07·3	07·5	10·7	08·6
39	Kamerun	4	5	9	45 E.	12	09·7	09·9	08·0	09·3	12·7	09·9
40	Duala	4	3	9	41 E.	8	10·2	10·1	08·5	08·8	12·6	10·2
41	Libreville	0	23	9	26 E.	35	13·3	13·0	12·3	11·5	15·4	13·0
42	St. Thomas	0	20	6	43 E.	5	11·9	12·9	11·5	11·4	16·0	13·0
43	Entebbe	0	5 N.	32	29 E.	1171	10·5	10·0	08·4	09·4	12·0	09·1
							899·0	899·0	897·9	898·7	900·4	898·2
44	Neuwied	2	0 S.	33	2 E.	1194	1009·4	10·1	09·0	10·0	12·2	08·7
							899·3	899·1	898·1	898·8	900·7	898·5

* At stations over 1000 m. in elevation the second line of figures gives the pressure reduced to a height of 1000 dynamic metres.

TABLE I (*Cont.*)—PRESSURE AT MEAN SEA LEVEL AND AT 1000 DYNAMIC METRES

No.	Station (1)	Position Lat. (2) °	Position Lat. (2) ′	Position Long. (3) °	Position Long. (3) ′	Height (4)	Year Obs. (5)	Year Corr. (6)	Jan. (7)	April (8)	July (9)	Oct. (10)
		°	′	°	′	metres	mb.	mb.	mb.	mb.	mb.	mb.
45	Moshi	3	19	37	22 E.	1162	1015·3	11·0	07·4	10·3	15·6	08·5
							*899·5	899·9	897·4	899·3	902·8	898·5
46	Usumbura	3	21	29	32 E.	800	1007·8	08·9	08·2	08·2	10·5	07·6
47	Mombasa	4	3	39	40 E.	15	11·7	13·4	11·6	11·4	16·6	13·9
48	Brazzaville	4	17	15	16 E.	320	12·8	12·8	11·8	11·2	16·4	12·1
49	Seychelles	4	37	35	27 E.	5	11·9	11·9	11·5	10·5	12·9	12·8
50	Tabora	5	1	32	49 E.	1222	10·0	10·0	08·3	09·2	11·9	06·7
							898·7	898·9	898·0	898·7	901·0	897·7
51	Tanga	5	4 S.	39	7 E.	27	1014·1	13·3	10·5	11·3	16·6	14·2
52	Zanzibar	6	10	39	11 E.	22	14·2	13·9	10·6	12·3	17·9	14·7
53	Dar es Salaam	6	29	39	18 E.	8	13·6	14·0	11·2	12·1	17·9	14·8
54	Ascension	7	56	14	25 W.	17	14·4	14·4	13·4	12·3	16·5	15·2
55	Loanda	8	49	13	13 E.	58	13·3	13·3	11·6	11·2	16·7	13·9
56	Tandala	9	23	34	14 E.	2051	18·0	11·5	09·0	11·1	16·6	10·0
							899·2	899·4	897·5	899·2	902·7	898·7
57	Lindi	10	0	39	44 E.	82	1014·1	14·1	10·5	12·0	18·5	14·5
58	Elizabethville	11	39	27	28 E.	1236	09·8	09·8	06·7	10·1	16·0	06·6
							898·8	898·8	896·6	899·2	902·4	897·2
59	Zomba	15	23	35	18 E.	955	1012·4	12·8	07·6	13·1	19·6	10·8
60	St. Helena	15	57	5	40 W.	602	15·1	15·1	13·5	13·6	17·4	15·4
61	Salisbury	17	48	31	5 E.	1468	11·9	12·7	08·8	13·3	20·2	09·9
							901·0	901·2	897·4	901·9	905·9	899·9
62	Livingstone	17	51	25	51 E.	960	1012·7	11·7	06·3	12·9	19·1	08·4
63	Tamatave	18	9	49	26 E.	4	15·9	15·9	10·7	14·1	21·0	17·4
64	Tananarive	18	55	47	32 E.	1375	14·6	14·6	09·8	13·1	21·4	14·7
							902·2	902·5	899·0	901·5	906·7	902·9
65	Gwelo	19	27	29	49 E.	1412	1014·1	12·9	07·8	16·9	20·6	09·9
							901·0	901·0	897·6	904·6	905·8	899·6
66	Beira	19	50	34	51 E.	7	1015·8	15·2	09·5	15·0	22·1	14·5
67	Mauritius	20	6	57	33 E.	55	15·9	15·9	11·1	13·5	20·8	17·8
68	Bulawayo	20	9	28	35 E.	1340	13·0	13·0	07·2	14·2	20·9	10·1
							901·2	901·2	897·2	902·2	906·2	900·0
69	Windhoek	22	34	17	6 E.	1665	1009·6	12·6	04·8	13·4	20·2	10·2
							901·8	901·6	896·2	902·5	906·1	900·3
70	Walfish Bay	22	56	14	30 E.	3	1014·6	14·4	11·7	12·8	18·4	14·3
71	Pretoria	25	46	28	13 E.	1400	15·2	15·8	08·5	17·1	24·2	13·4
							902·9	903·0	899·4	904·1	907·8	901·8
72	Lorenzo Marques	25	58	32	30 E.	59	1017·3	17·3	12·4	17·6	22·8	17·0
73	Johannesburg	26	11	28	4 E.	1806	17·3	16·0	09·6	17·3	23·9	13·8
							903·4	903·1	898·9	904·3	908·0	901·7
74	Kuibis	26	44	16	54 E.	1308	1013·6	13·9	07·4	13·4	22·4	12·3
							901·9	901·4	897·6	900·9	905·9	901·3
75	Kimberley	82	42	24	47 E.	1202	1014·3	17·3	09·5	18·5	26·9	14·9
							906·0	904·5	899·0	904·3	908·0	902·0
76	Port Nolloth	29	14	16	51 E.	5	1017·2	15·2	11·4	14·3	19·6	15·0
77	Durban	29	53	31	4 E.	15	18·0	18·0	13·7	17·9	23·1	17·5

* At stations over 1000 m. in elevation the second line of figures gives the pressure reduced to a height of 1000 dynamic metres.

§ 3—WIND DATA

In addition to these Egyptian data, which cover the area from the Mediterranean to the equator, resultant winds were obtained chiefly from three other sources[2]. Resultants for a few additional stations were computed from the original observations, and these are shown in Table II. For the winds over the oceans,

TABLE II—RESULTANT WIND DIRECTIONS

No.	Station	Lat.		Long.		Direction			
						Jan.	April	July	Oct.
		°	′	°	′	°	°	°	°
	Sahara	various *				—	—	264	46
78	Bobo Dioulasso . .	11	8 N.	4	13 W.	62	195	204	193
25	Berbera	10	22 N.	45	2 E.	56	45	236	65
48	Brazzaville . . .	4	17	15	16 E.	232	243	250	225
79	Kimuenza † . . .	4	19	15	23 E.	244	253	237	250
	Kimuenza ‡ . . .					259	137	233	256
80	Vivi	5	45	13	30 E.	236	252	257	239
81	Banana	5	58 S.	12	27 E.	224	197	223	227
52	Zanzibar . . .	6	10	39	11 E.	33	175	174	174
82	San Salvador . . .	6	17	14	53 E.	244	214	234	253
59	Zomba	15	23	35	18 E.	85	77	76	44
61	Salisbury . . .	17	48	31	5 E.	58	105	106	73
62	Livingstone . .	17	51	25	51 E.	77	97	100	104
64	Tananarive . . .	18	55	47	32 E.	87	98	103	89
65	Gwelo	19	27	29	49 E.	70	114	113	74
68	Bulawayo . . .	20	9	28	35 E.	86	124	129	84
73	Johannesburg . . .	26	11	28	4 E.	9	—	41	—
74	Kuibis	26	44	16	54 E.	314	322	331	315

* See *London, Meteorological Office, Geophysical Memoirs*, No. 48, 1929.
† Surface Winds.
‡ Upper Winds.

use was made of the wind roses on the " Pilot Charts " issued by the U.S. Hydrographic Office; in the trade-wind regions these showed such definite directions that it was possible to insert the resultant by inspection. For the Red Sea, we utilised the wind roses in the *Meteorological Charts of the Red Sea*, published by the Meteorological Office, London, 1895.

Some valuable resultants of winds at a height of 1000 metres in the free air were obtained from a paper by L. J. Sutton[3], and results of occasional ascents in other districts from an Admiralty chart.[4] These were entered in their appropriate places on the charts for 1000 dynamic metres. The following resultants at 1000 metres were derived from some unpublished data in the Meteorological Office.

Resultant wind at 1000 m. (degrees).

	Jan.	April	July	Oct.
Kamaran I. (Red Sea) . .	165	144	332	340
Berbera	70	Var.	235	80

[2] Lyons, Sir Henry: Presidential address . . 1917. The distribution of pressure and the air circulation over northern Africa. *London, Q. J. R. Meteor. Soc.*, **43**, 1917, p.113.
Lasserre, M. Les territoires du sud de l'Algérie. Aperçu météorologique, Alger, 1922.
Cox, G. W. Some notes on the circulation of the atmosphere over South Africa. *S. Afric. J. Sci., Cape Town*, **23**, 1926, p.103.

[3] Upper winds at Cairo and Khartoum. *Cairo Physical Dept. Paper* No. **27**, 1930.

[4] London, Admiralty. Chart showing the distribution of observations of upper winds and upper air temperatures over the oceans. London, 1931.

§ 4—THE ANNUAL AVERAGE PRESSURE AT MEAN SEA LEVEL

Fig. 1 shows the mean annual distribution of pressure reduced to mean sea level and mean of 24 hours. Isobars are shown for every millibar, but are broken where the ground exceeds 1000 metres in elevation, as indicated by the thin contour line, the area within which is stippled. This contour is repeated on the monthly maps at mean sea level, but not on those at higher levels.

The maps show the following principal features. Pressure is everywhere relatively high over the oceans and relatively low over the land, the isobars following more or less closely the shape of the continent. The highest pressures are found off the north-west coast, which comes under the influence of the Azores anticyclone and the trade-wind belt throughout the year, and off Durban, which is in the region of the anticyclone of the South Indian Ocean. Across the widest part of the continent, in latitude 5° to 15° N., extends a well marked trough of low pressure, the lowest values, below 1008 mb., being found over the Upper Nile and western Abyssinia. An offshoot of this low-pressure trough extends southwards across the upper Congo valley and then south-westwards towards south-west Africa. West and east of the latter trough pressure rises rapidly towards the South Atlantic and Indian Ocean anticyclones.

The chart shows clearly the " planetary " effect, namely two sub-tropical belts of high pressure separated by an equatorial trough, but this is modified by the continental effect which in low latitudes gives lower pressure over the interior than over the oceans, and the belt of low pressure does not extend completely across the continent.

§ 5—THE ANNUAL AVERAGE PRESSURE AT 1000 DYNAMIC METRES

The distribution of pressure at 1000 dynamic metres (Fig. 2) is on the whole similar to that at mean sea level. The Azores anticyclone is of lesser intensity, and under the influence of the cold Canaries Current the barometric gradient flattens out near the coast, though a definite trough of low pressure is only developed north of 30° N. Most of central Africa is occupied by a large irregular area of low pressure from which a trough extends westwards in latitude 5° to 10° N. The greatest changes are to be found south of the equator. The trough of low pressure over south-west Africa has disappeared, and is replaced by a wedge of high pressure extending north-westwards from the anticyclone near Durban. From this wedge there is a steep gradient to a well marked trough of low pressure over the Benguela Current. The barometric reductions in this region assumed that the low surface temperature extends to a height of 1000 dynamic metres. Upper-air observations are scarce over the Benguela Current, but the following extract from *Les Ailes*, February 19, 1931, describing an Italian flight round Africa, affords some justification for the assumption : " Between Swakopmund and Mossamedes . . . the temperature is very peculiar. . . Near the ground the atmosphere is damp and almost chilly and remains cold up to about a height of 800 metres. Between 800 and 2000 metres the heat is intense." The reality of this low-pressure trough is also shown by the wind observations at Kuibis (26° 44′ S., 16° 54′ E., height 1308 metres). Here the gradient shown by the isobars at mean sea level is for winds from SE., but the actual winds are from NW. throughout the year, in accordance with the isobars at 1000 dynamic metres.

§ 6—PRESSURE AND WINDS IN JANUARY

The distribution of pressure at mean sea level is shown in Fig 3. The highest values (above 1021mb.) are found in southern Algeria, whence a belt of high pressure extends eastwards to Cairo. South of this belt pressure decreases rapidly towards the central low-pressure area, which takes the form of a crescent extending from 5° N. in West Africa through the middle Congo valley to south-west Africa. The area of southward gradient in north Africa is the region of the Harmattan, which meets the south-westerly winds of the Guinea Coast along the west African trough (see Fig. 5).

The lowest pressure is found in the interior of south-west Africa between about 18° and 25° S., but as this region is mostly above 1000 metres elevation, the sea-level low-pressure area has no real existence. There is however a real steep gradient from the south Atlantic anticyclone across the coastal lowlands, which gives rise to steady southerly winds forming part of the system of the S E. trades. Fig. 4 shows the pressure distribution at a height of 1000 dynamic metres. The distribution is on the whole similar to that at mean sea level, the most important changes being the almost complete disappearance of the intense low-pressure area over south-west Africa and the development of a low-pressure trough over the Benguela current. North of the equator the high-pressure belt has broadened and extended considerably further south, while the west African trough lies directly over the Guinea Coast instead of some distance inland.

Fig. 5 shows the stream lines of the air near the surface of the ground. It was constructed in the first place from the resultant winds given in Table II and those given in the list of sources mentioned in § 3. The stream lines were completed by reference to the isobars in Figs. 3 and 4, using the isobars for sea level where the land is below 1000 metres in elevation and those at 1000 dynamic metres where the land is above that elevation. A few broken lines have been inserted to show the probable course of the upper winds where such information appeared to be of interest; these were based on Fig. 4. The dotted lines show the " fronts " between the most clearly marked streams of air.

Five main streams may be distinguished (these are indicated by small letters which will be used throughout the remaining part of this discussion) :

a, b. The combined Atlantic NE. trade and Harmattan blows from north-east over the entire northern part of the continent west of 15° E., and penetrates to within a short distance of the Guinea Coast. This air stream is very steady and stable, only disturbed from time to time in the north by the passage of depressions along the Mediterranean.

c. The Egyptian air stream enters the Nile valley as a northerly wind. Its westerly part turns towards the south-west and approaches to within a short distance of the Kamerun coast, but its eastern part, continuing as a wind from NNE., crosses the middle Congo valley and north-western Rhodesia to northern Bechuanaland, where it meets air streams **d** and **f**, after traversing the axis of Africa for a distance of 3,500 miles.

d. The Atlantic SE. trade and SW. monsoon blow parallel with the west coast of Africa over the whole stretch from 30° S. to about 5° S. On the eastern or coastal side however there is a steady indraught towards the heated land as a south-westerly sea breeze. North of 5° S. the main current turns towards the north-east as the SW. rain-bearing wind of the Guinea Coast. These south-westerly winds however penetrate only a short distance inland before meeting the opposing winds of the Harmattan and Egyptian streams.

e. The Arabian NE. trade blows from the Arabian Sea towards the Horn of Africa. The history of this air stream is somewhat complicated. Part of it turns north-westward, crosses the high ground of British Somaliland and passing over an ENE. surface wind in the Gulf of Aden, enters south-western Arabia. Another branch rises over the high ground of Abyssinia, while a third traverses the Lake Plateau and Tanganyika Territory, where it meets an eastern offshoot of the Egyptian stream.

f. The SE. trade of the Indian Ocean crosses the coast of Portuguese East Africa and Zululand as an easterly wind and enters Bechuanaland, where it meets the southernmost offshoot of the Atlantic S.E. trade **d.**

§ 7—THE WINDS IN RELATION TO THE JANUARY RAINFALL

The Harmattan and the Egyptian streams (**b** and **c**) blow from colder to warmer latitudes and are therefore dry winds; the whole of Africa between 5° and 30° N. is practically rainless (see Fig. 6). The SW. winds from the Atlantic bring a limited rainfall to the coast from Cape Palmas to the mouth of the Congo, but south of the latter point the onshore winds blow from the cold surface of the Benguela Arabian Current over land heated by the summer sun, and the coast here is practically rainless. On the eastern side, the northern branch of the Arabian NE. trade, having blown for but a short distance over the sea, is dry when it reaches Somaliland, and this region also has little rainfall. The southern branch of the Arabian NE. trade however blows for a long distance parallel with the land before striking the coast between latitudes 6° and 16° S., and hence the coastal rainfall increases rapidly south of Mombasa. The SE. trade of the Indian Ocean has also travelled for a long distance over a warm sea before it strikes the coast, and the rainy area therefore extends southward along the eastern coast beyond 30° S.

In the central part of Africa between 5° and 15° S. there is a great convergence of air from three main currents, and inspection of Fig. 6 shows that this is the rainiest part of the whole area.

§ 8—PRESSURE AND WINDS IN APRIL

With the northward march of the sun towards the equator, the features of the pressure distribution characteristic of winter and summer hemispheres rapidly disappear. In April (Fig. 7) both northern and southern Africa show anticyclonic areas in about latitude 30°. The area of lowest pressure is however found not on the equator but in the upper Nile valley between 10° and 15° N., a reversal of the conditions in January. From this centre a trough of low pressure extends westward across the Sahara with its axis in about 10° to 15° N., while another trough extends towards the south-south-west. In north-west Africa there is a rapid rise of pressure towards the Azores anticyclone.

Fig. 8 shows the isobars at 1000 dynamic metres. The most remarkable features are the great weakening of the Azores anticyclone, the well marked trough of low pressure parallel with and only a short distance north of the equator, with an outlier over the Red Sea, and the equally well marked trough of low pressure extending northwards over the Benguela Current. The anticyclone over south-eastern Africa remains with its intensity but little impaired.

The air streams are shown in Fig. 9.

a. The Atlantic NE. trade maintains its position with very little change from January,

b. Further east however the Harmattan penetrates a much shorter distance towards the south, its front extending from the coast at Sierra Leone north-eastwards to latitude 15° N. and eastwards in this latitude across almost the whole width of the continent,

c. The Egyptian stream has suffered the greatest curtailment, penetrating only to about 16° N. instead of to 20° S. as in January,

d. The Atlantic SE. trade blows from SSE. as far as 10° S., where it commences to turn towards the north-east, reaching the coast as a SW. wind between about 9° S. and 9° N. In French Congo and West Africa it penetrates a considerable distance inland as the SW. monsoon, meeting the Harmattan along the front mentioned above.

e. The Arabian NE. trade turns towards the west over Italian Somaliland and northern Abyssinia, where it meets the deflected SE. trade of the Indian Ocean.

f. The SE. trade of the Indian Ocean strikes the east coast of Africa over the whole stretch from the equator to 20° S. Its northern part turns northward and north-eastward to the Nile valley and Abyssinia, finally meeting the Egyptian stream and the Arabian NE. trade in the low pressure centre over the upper Nile valley. The southern part turns towards the north-west and meets the deflected SE. trade from the Atlantic along a front which traverses Angola and the Belgian Congo.

g. In April we meet a new stream of air which may be termed south-east African air. This originates in the anticyclone over south-east Africa and travels westward south of **f.** Its southern branch reaches the coast and after travelling for a time parallel with the Atlantic SE. trade, re-curves over the coastal plain, where it meets the northern branch of **g** which has traversed Bechuanaland and north-western Rhodesia.

§ 9—THE WINDS IN RELATION TO THE APRIL RAINFALL

Fig. 10 shows the distribution of rainfall during April. The northern part of the continent is still dry, the zone of appreciable rainfall extending only to an average latitude of about 10° N. This is remarkable, as the front between Harmattan and the SW. monsoon is found in about 15° N. The explanation would seem to be that the real circulation in West Africa is by no means so simple as that shown in Fig. 9. Away from the neighbourhood of the coast the rainfall is of the instability type, and falls mainly in association with the well known West African " tornadoes." These phenomena occur in the monsoon belt, but are accompanied by a descent of the north-easterly wind which overlies the monsoon to the level of the ground. It appears probable that this descending air must ultimately, by the pressure of the monsoon air, be forced back again towards the north-east, while the monsoon air which rises to the Harmattan level during a tornado is similarly forced back again towards the south-west. Hence the moist monsoon current as it passes towards the north-east gains a greater and greater admixture of dry Harmattan air, and so continually decreases in humidity and in its rain-producing capacity. The drying effect of the high ground in the southern part of West Africa would contribute to this effect, but would seem to be insufficient by itself to account for the very scanty rainfall of the Sahara during the monsoon.

The heavy rainfall of the Guinea coast and French Equatorial Africa may be attributed to the onshore winds which have blown over a long stretch of ocean, but further east the effect of the convergence of air comes into play. In eastern Africa the most remarkable feature is the way in which the isohyets of 2 inches in the north and 1 inch in the south follow the fronts between the Arabian NE. trade (**e**) and the SE. trade of the Indian Ocean (**f**) and between the latter and the south-east African air (**g**). The NE. trade and the south-east African air are dry because of their short passages over the sea, while the SE. trade is moist and gives a heavy rainfall because of its much longer passage. The moderate rainfall of Natal comes when this system of stream-lines is disturbed and an intensification and eastward extension of the SE. trade cause gales from the sea.

§ 10—PRESSURE AND WINDS IN JULY

In July, the warmest month in the northern hemisphere, the trough of low pressure reaches its most northerly position (Fig. 11). Pressure is lowest over south-west Asia, but a long tongue of low pressure extends westwards across the Sahara in latitude 20° N., turning south-westwards near the Atlantic coast. Pressure is relatively low as far south as the equator (except for a local anticyclone in Abyssinia), but in South Africa it rises rapidly to a well marked anticyclone over the south-east.

At a height of 1000 dynamic metres the pressure distribution (Fig. 12) shows several interesting modifications. The low pressure over south-west Asia persists, with a steep rise southwards over the Indian Ocean, but the trough across the Sahara has been replaced by a shallow depression in 10° N., 20°–30° E. The anticyclone still persists in south-east Africa, but as in April a trough of low pressure appears along the Atlantic coast, over the cold Benguela Current.

The winds near the surface are shown in Fig. 13. The NE. trade (**a**) blows along the Atlantic coast as far as latitude 12° N., thus outflanking the Harmattan (**b**), which extends only to 20° N. The Egyptian Current (**c**) reaches the same latitude in the west, but in the east continues towards the south-east along the Red Sea, finally turning north-eastwards towards the low pressure over south-west Asia.

About half the map is occupied by the Atlantic SE. trade and SW. monsoon (**d**). We may distinguish two branches, the SE. trade proper and the continuation of **f** which joins it near the coast. The former continues as a south-easterly wind to the neighbourhood of the equator, where it turns towards the north-east and meets **b** in about 20° N. The second branch after blowing parallel with the coast for some distance, turns inland again between 10° S. and the equator, continuing across the Congo valley towards Abyssinia, where it turns under the influence of the Abyssinian high pressure towards the south-east and finally south before meeting the most northerly branch of **f.**

The Arabian NE. trade (**e**) does not exist during July, being replaced by the SW. monsoon of the Arabian Sea, which is a branch of **f.** The latter originates in the SE. trade of the Indian Ocean, which divides into three main branches. The most northerly turns to the north-east near the equator and after traversing Italian Somaliland parallel with the coast, becomes the SW. monsoon as described above. Between the equator and 10° S. the second branch blows straight onshore, turns to the east across the high ground of east Africa, and finally meets **d** in the Congo valley. The southernmost branch crosses the coast between 20° and 25° S. and traverses the high ground of Bechuanaland and north-west Rhodesia as an easterly wind. In south-west Africa it turns towards the south under the influence of the low pressure at 1000 dynamic metres above the Benguela Current, recurving sharply near the coast and joining **d.** The north-easterly winds descending the high ground towards the coastal zone are very hot and dry ; they occasionally reach the actual coast as the northerly winds which occur at intervals from May to August. It appears that the V-shaped inflection in the trajectories is a quasi-stationary phenomenon, swinging a short distance seaward or landward with the variations of the general pressure distribution.

South of the southernmost branch of **f** is a current of dry south-east African air (**g**) which turns westward and finally southward towards Cape Town.

§ 11—THE WINDS IN RELATION TO THE JULY RAINFALL

Fig. 14 shows the distribution of rainfall during July. Amounts exceeding one inch are almost entirely limited to a narrow belt between the equator and 17° N., while South Africa is practically rainless. The heaviest rain falls in Liberia and the Ivory Coast, the coast of Nigeria and the Cameroons, and in Abyssinia.

The heavy rainfall of the Guinea Coast of West Africa is readily explicable as the result of the SW. monsoon striking the shore almost at right angles. The local area of small rainfall on the coast in longitude 0° presents more difficulty. The winds as drawn from the resultants and pressure distribution show a curious divergence at this point, the stream lines turning to the left in the west and to the right in the east as if they were avoiding an obstacle. W. Köppen explains this area of low rainfall as due to a local patch of upwelling cold water which observations show to exist, though the cause is obscure. It seems probable that a local pool of cold air forms over this cold water, which acts as such a barrier and deflects the air streams to either side. Above this cold air, at a height of 1000 dynamic metres, we should expect a local area of low pressure which would cause the air streams to converge on its eastern side, and this may be the explanation of the local area of heavy rainfall further inland.

In the southern Sahara the rainfall is associated mainly with " tornadoes," which at this season are almost unknown on the coast and have their greatest frequency further north than in April. The probable reason why the rainfall decreases steadily northwards and almost dies out before the monsoon air reaches the " front " at its meeting with the Harmattan, has been set out in § 9. The NE. trade, the Harmattan and the Egyptian Current are dry because their courses are from colder to warmer latitudes, and it is striking to note how the belt of rainfall is cut off in the east exactly at the point where the eastern branch of the Egyptian Current breaks through along the shores of the Red Sea.

The heavy rainfall of Abyssinia appears to be due partly to the SW. monsoon rising over the high ground, and partly to a concentration of air. The SW. monsoon is deflected round a high-pressure area over Abyssinia (which still exists, though weak, at a height of 1000 dynamic metres) and it forms a northerly wind which rises over the most northerly branch of the SE. trade of the Indian Ocean.

The distribution of rainfall along the east coast of Africa south of the Red Sea appears very curious when it is remarked that the whole coast receives air from the Indian Ocean, while only the coast of Kenya has an appreciable rainfall. The absence of rain over Italian Somaliland is obviously due to the way in which the winds are deflected parallel with the coast. In Kenya the winds blow directly onshore and the immediate coastal belt has a rainfall of more than two inches, but towards the interior the air streams diverge and the rainfall is small. Further south the winds also blow directly onshore but produce little rainfall ; this is probably due mainly to two factors, the rain shadow of the high ground of Madagascar, the east coast of which receives more than 10 inches, and the winter anticyclone over the interior, which causes stable conditions and diverging air streams.

§ 12—PRESSURE AND WINDS IN OCTOBER

The distribution of pressure at sea level in October on the whole resembles that in April, the most noticeable difference being that the trough of low pressure extends from north to south along the axis of the continent instead of from west to east. There is however an offshoot from this trough extending westwards in 15° N. The isobars in fact follow the shape of the coast-line very closely, but there are two centres of lowest pressure, one a little north of the equator and the other in about 10° S. At 1000 dynamic metres these two centres have combined into one, and in addition a trough of low pressure has developed in about 5° N. The usual trough of low pressure is found above the cold Benguela Current.

The chart of air movements presents a curious appearance, three main currents meeting at a common point in the centre of Africa. Looking into details, we find that the Atlantic NE. trade (**a**) outflanks the Harmattan as in July. The Harmattan (**b**) has advanced southwards to 15° N. in the west and 5° N. in the east ; the Egyptian Current on the other hand has extended further south in the west but shows little change in the east. The Atlantic SE. trade and the SW. monsoon call for no special comment except in the south, where the southerly trade turns inland and after rising over the high ground is deflected to form a NW. wind, which blows strongly at Kuibis.

The Arabian NE. trade (**e**) is not represented, the whole of East Africa from Cape Guardafui to 30° S. being occupied by **f**, the SE. trade of the Indian Ocean. Three main branches may be recognised ; the northernmost approaches the coast in 5° S., but turns sharply to the north-east and blows almost parallel with the coast of Italian Somaliland. When it has worked a short distance inland however, it reaches the high ground, where the isobars at 1000 dynamic metres again deflect it towards the north-west. The middle branch of **f** strikes the coast between 3° and 7° S. and continues inland as an easterly wind until it meets either **d** or the southernmost branch of **f.** The latter, between 10° and 30° S., enters the land as an easterly wind, divergent in the north, but in the centre of the continent it turns northwards parallel with **d** and finally eastwards to meet the southern part of the middle branch.

§ 13—THE WINDS IN RELATION TO THE OCTOBER RAINFALL

Fig. 17 shows the distribution of rainfall during October. On the Guinea Coast the distribution is similar to that during July and the remarks in § 11 no doubt apply in this month also. Further north, and west of 10° E., the isohyet of one inch approximately coincides with the front between **a** and **b** on the one hand and **d** on the other ; the isohyet turns southwards near the Atlantic coast in the same way as this front. Further east, where the greatest convergence of air occurs, some rain falls in **b** and **c**, but the heaviest rain comes in the region of concentration where **b**, **c**, **d** and **f** all meet. A minor point of interest is that the southern boundary of the rainless area in Egypt (isohyet of 0·04 in.) occurs just where a stream-line turns inland after traversing the northern half of the Red Sea.

The region of heavy rainfall in the Cameroons extends eastwards in a crescent-shaped area which has its greatest southern prolongation along the " front " between **d** and **f**. The coast of Kenya has a moderate rainfall where the middle branch of **f** blows directly onshore ; further north where the northernmost branch turns towards the north-east the coast is almost rainless, and further south where there is considerable divergence the rainfall is again scanty. Another area of moderate rainfall occurs in the south where the winds blow onshore without divergence.

§ 14—GENERAL CONCLUSIONS

The results of this study of the atmospheric circulation over a tropical continent differ in several respects from the schematic ideas set out in many text-books. The existence of a belt of low pressure extending completely across the continent near the equator and following the sun in its annual march north and south, cannot be completely substantiated. The interaction of the various currents described appears to be extremely complicated ; the pictures we have given, although the best that could be obtained from the limited data available, are probably inaccurate in many respects. In particular, the almost complete absence of upper-air data proved a great handicap. Nevertheless the way in which the convergence, divergence or onshore direction of the stream-lines fits in with the distribution of rainfall, although the trajectories were drawn independently of considerations of rainfall, appears to justify the hope that the main outlines are correct.

For the region of north-east Africa and southern Arabia the stream-lines may be compared with those at 0·5 and 1 km. given by A. Wagner.[5] The agreement is good on the whole, but with some minor points of difference.

If we compare the chart for January (Fig. 5) with those for the NE. monsoon of India (Wagner's Figs. 2 and 3), we find that the latter show the northerly current from the Mediterranean dividing near the head of the Red Sea. One branch turns south and south-west towards central Africa ; this is our stream **c**. The other branch crosses Arabia and the Persian Gulf towards the south-east, where it meets the NE. monsoon along a front across north-west India and the northern Arabian Sea. South-west Arabia is left blank, but from Fig 5, it is evident that this front must turn east and then north-east across southern Arabia, where it forms the dividing line between our air-streams **c** and **e**.

The SW. monsoon (Fig. 13 and Wagner's Figs. 5 and 6) presents greater difficulties. Wagner limits his northerly Egyptian current in 20° N., and south of this latitude he shows stream-lines crossing the Red Sea from west to east. This distribution appears to be impossible, however, for winds from NNW. blow the whole length of the Red Sea, both at sea level and at 1 km. The boundary between **c** and the combined streams **d** and **f**, after traversing the southern half of the Red Sea, turns towards the east-north-east along the Gulf of Aden, where it evidently joins on to Wagner's front over north-west India. In the latter respect therefore the maps show good agreement.

[5] Zur Aerologie des indischen Monsuns. *Beitr. Geoph., Leipzig*, **30**, 1931, pp.196–238.

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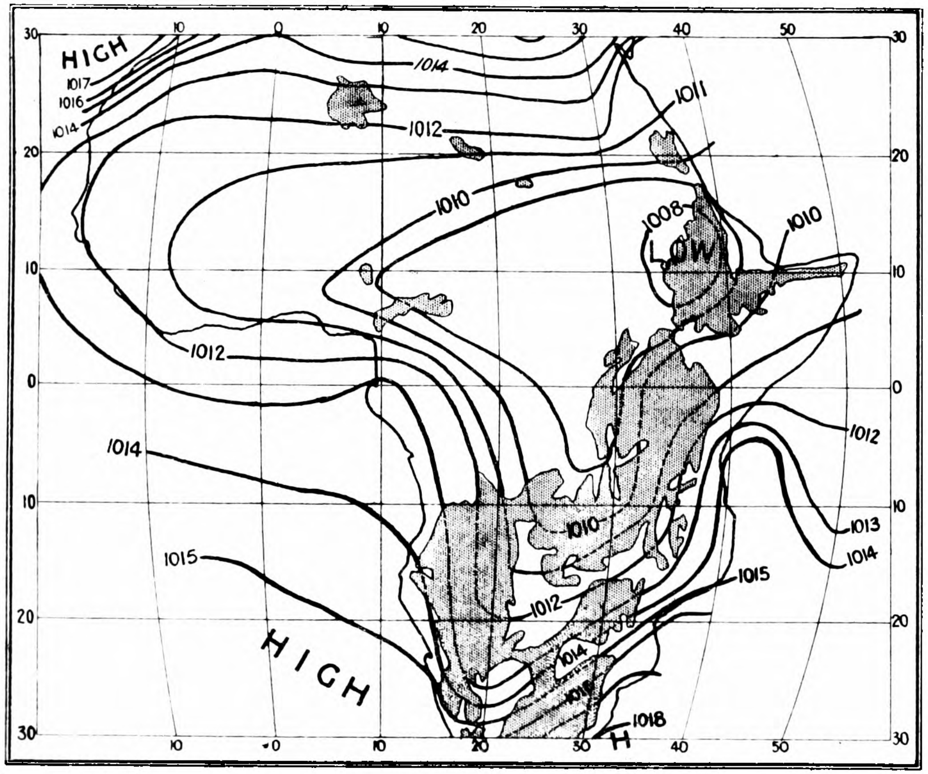

Fig. 1. Pressure (mb) at mean sea level; Year.
[Contour at 1,000 metres is indicated.]

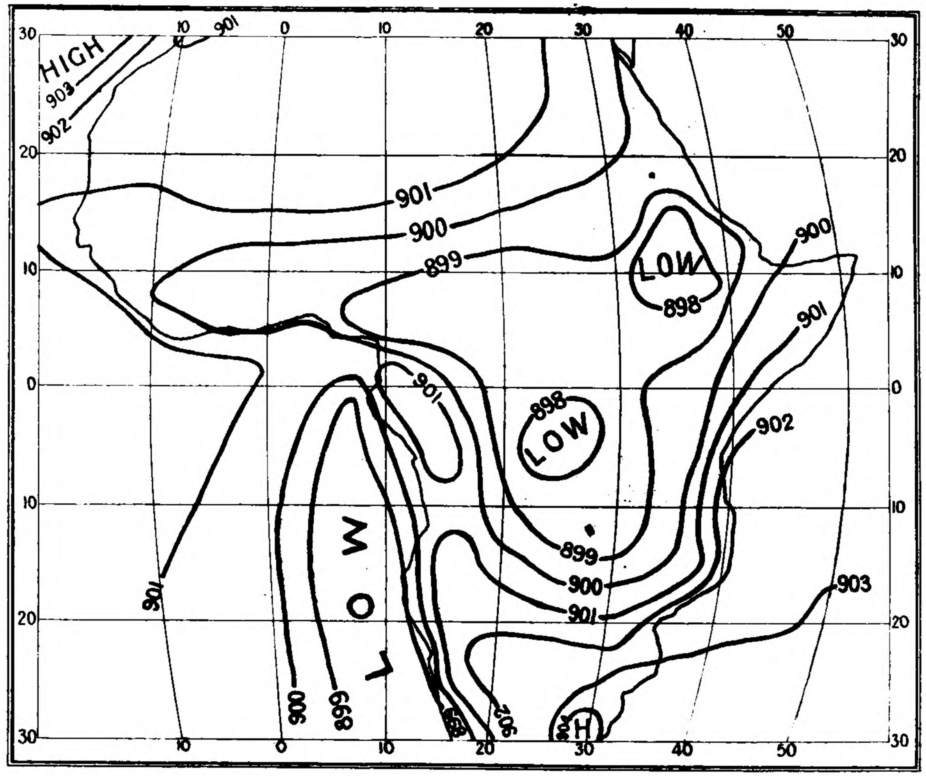

Fig. 2. Pressure (mb) at 1,000 dynamic metres; Year.

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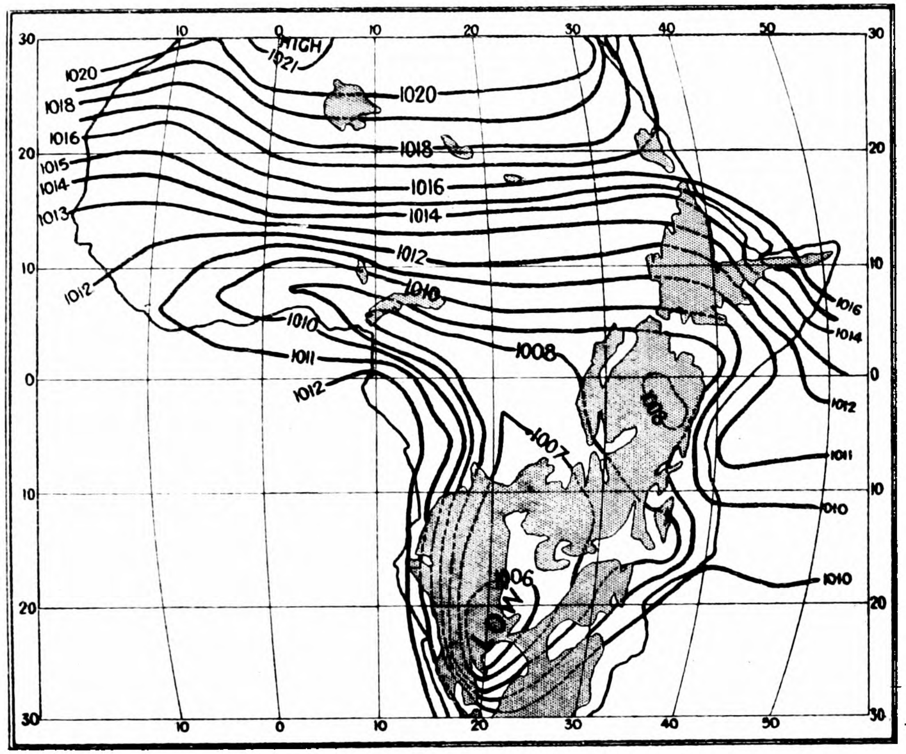

Fig. 3. Pressure (mb) at mean sea level; January.
[Contour at 1,000 metres is indicated]

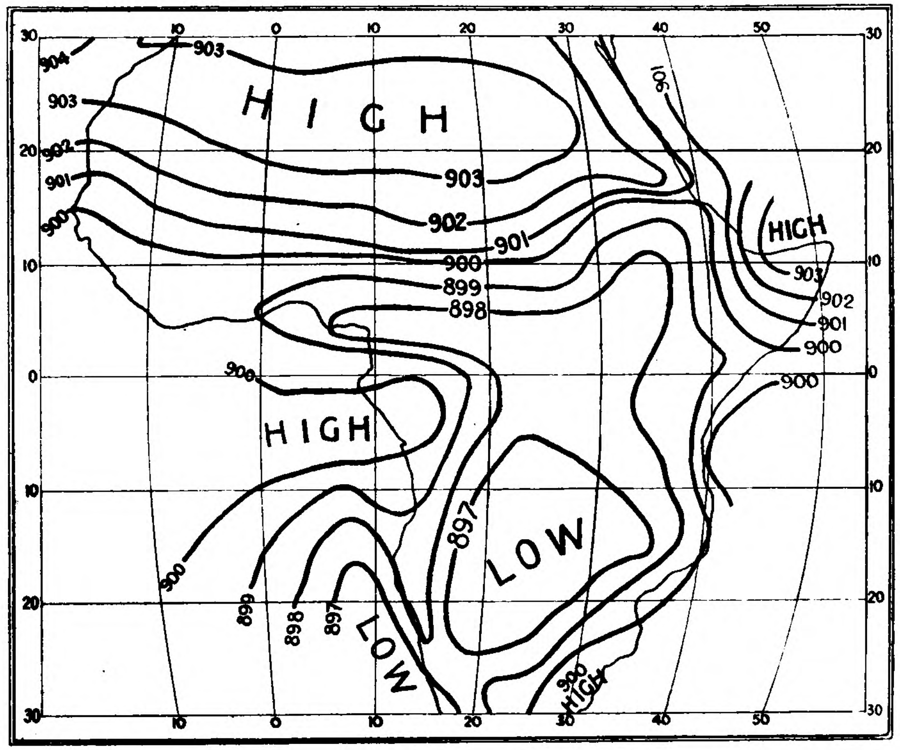

Fig. 4. Pressure (mb) at 1,000 dynamic metres; January.

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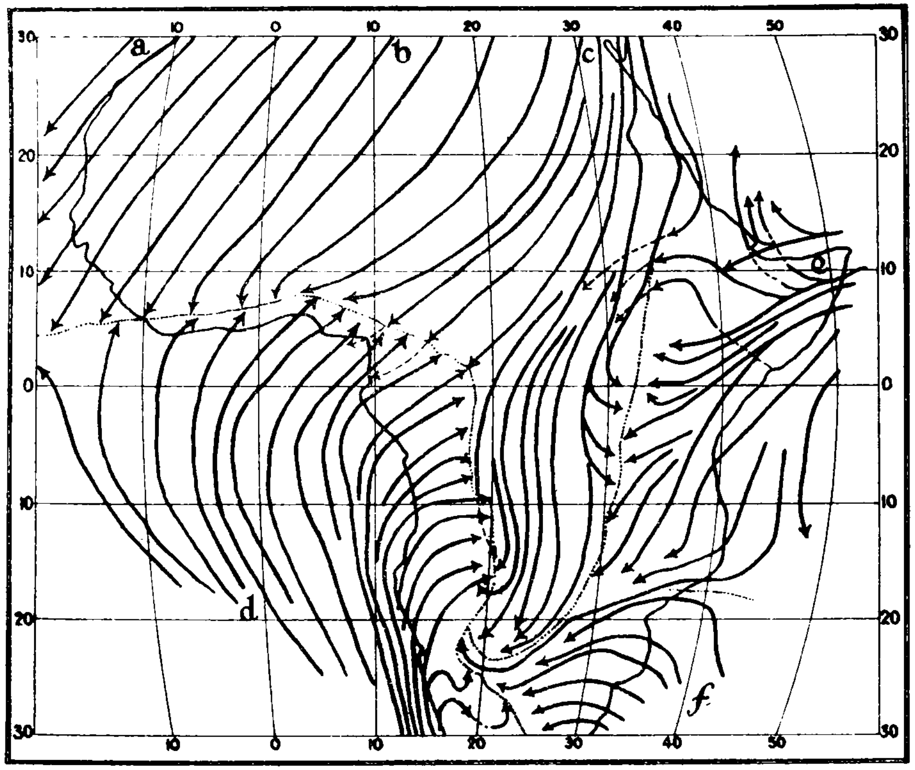

Fig. 5. Air movements January.

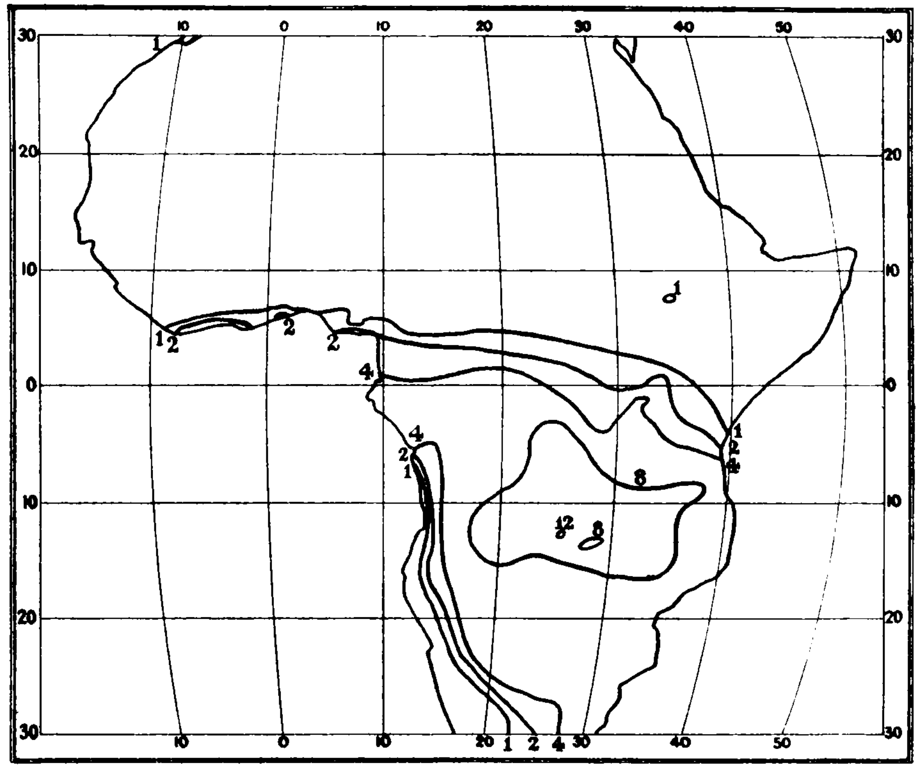

Fig. 6. Rainfall in inches; January.

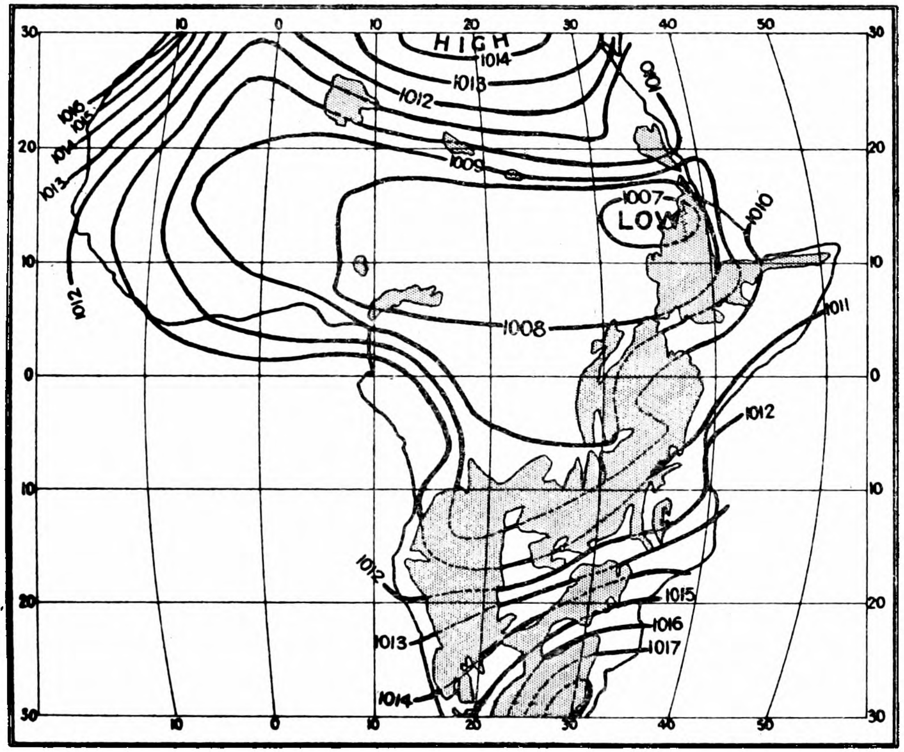

Fig. 7. Pressure (mb) at mean sea level; April.
[Contour at 1,000 metres is indicated]

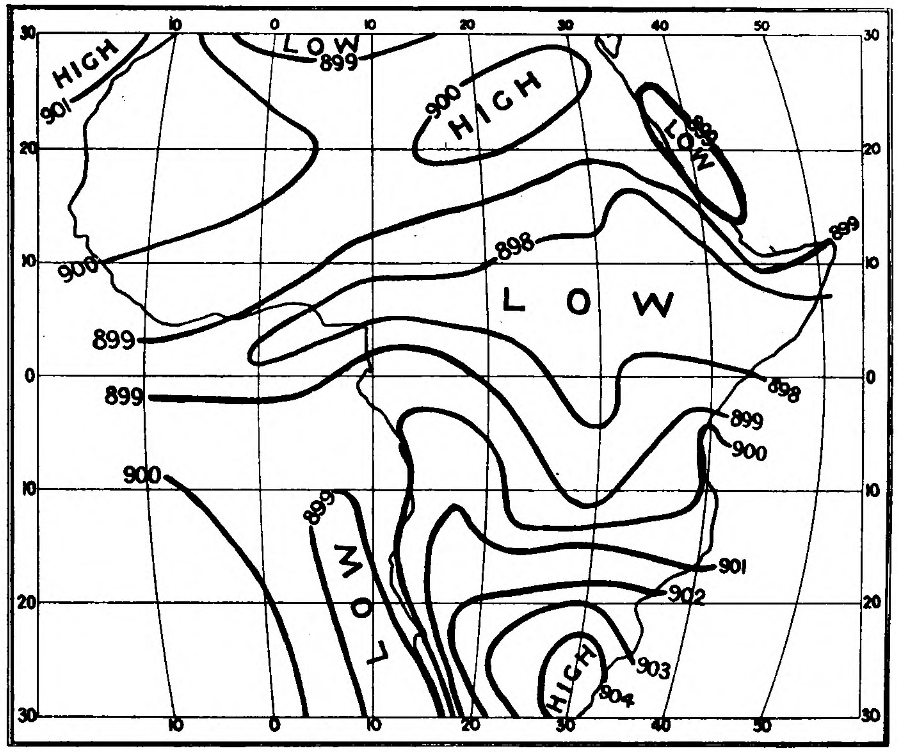

Fig. 8. Pressure (mb) at 1,000 dynamic metres; April.

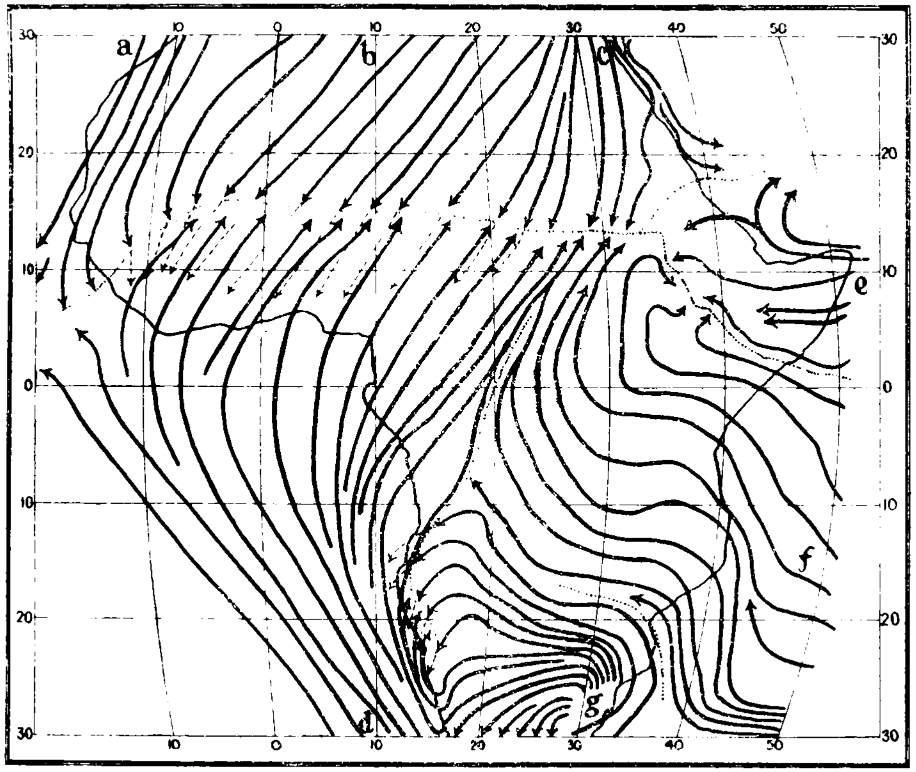

Fig. 9. Air movements; April.

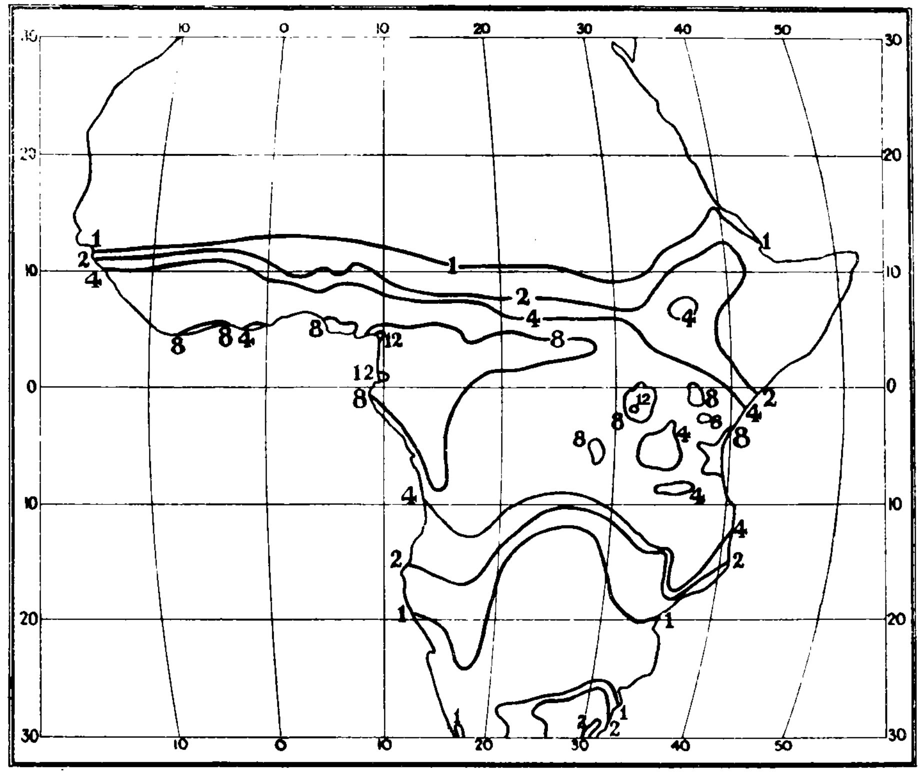

Fig. 10. Rainfall in inches; April.

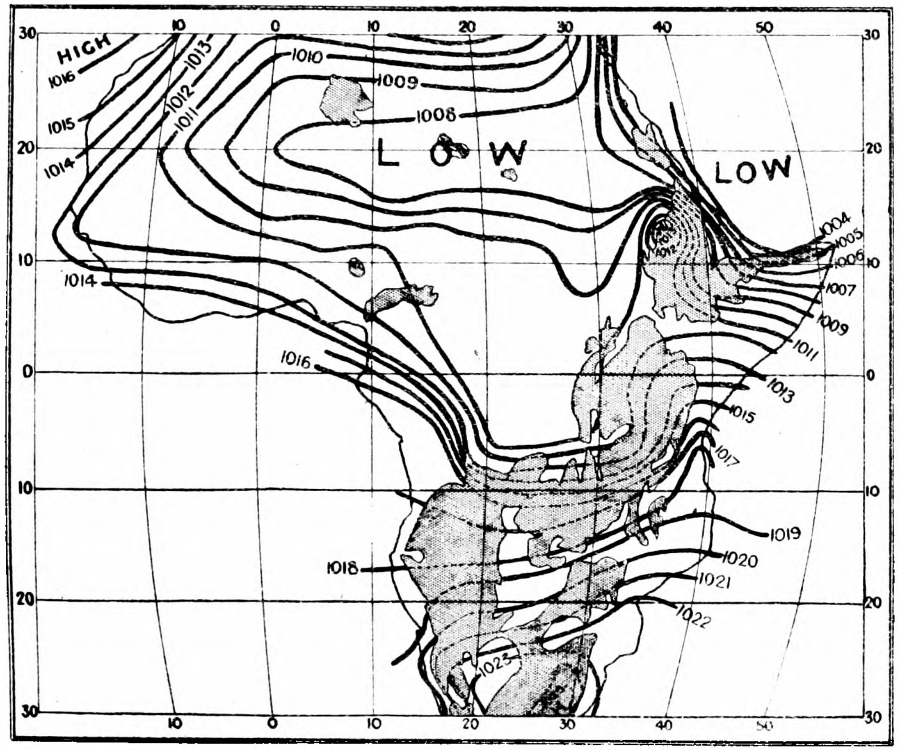

Fig. 11. Pressure (mb) at mean sea level; July.
[Contour at 1,000 metres is indicated]

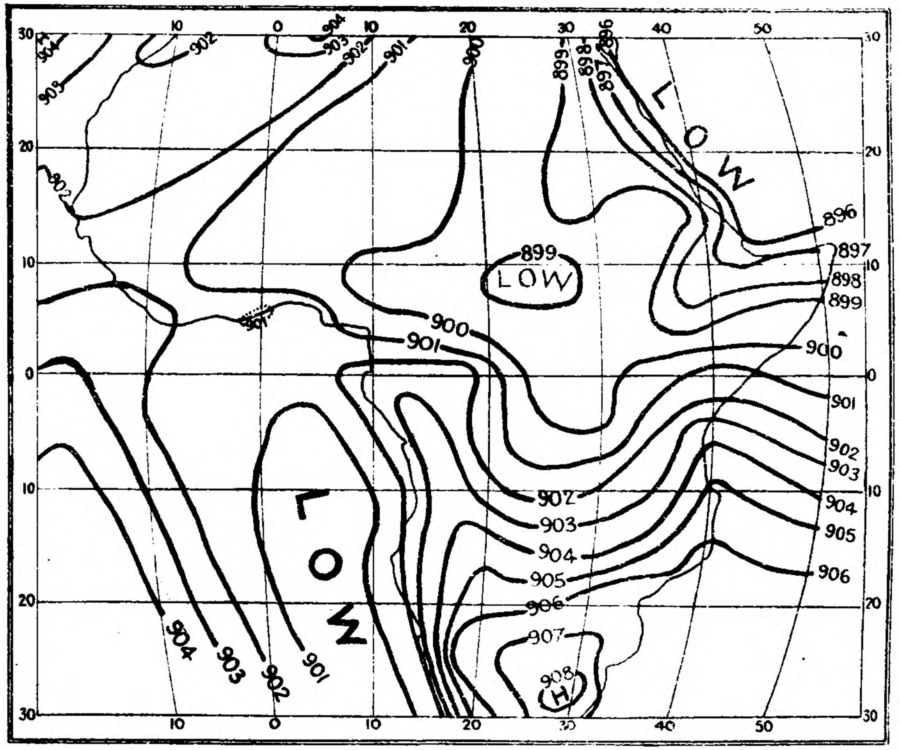

Fig. 12. Pressure (mb) at 1,000 dynamic metres; July.

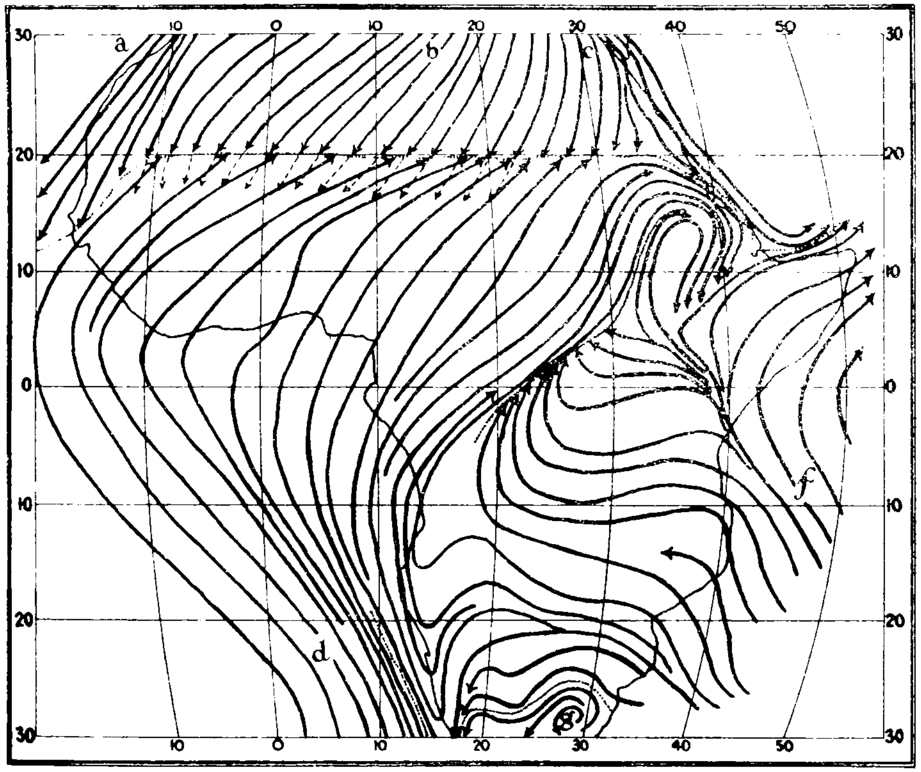

Fig. 13. Air movements; July.

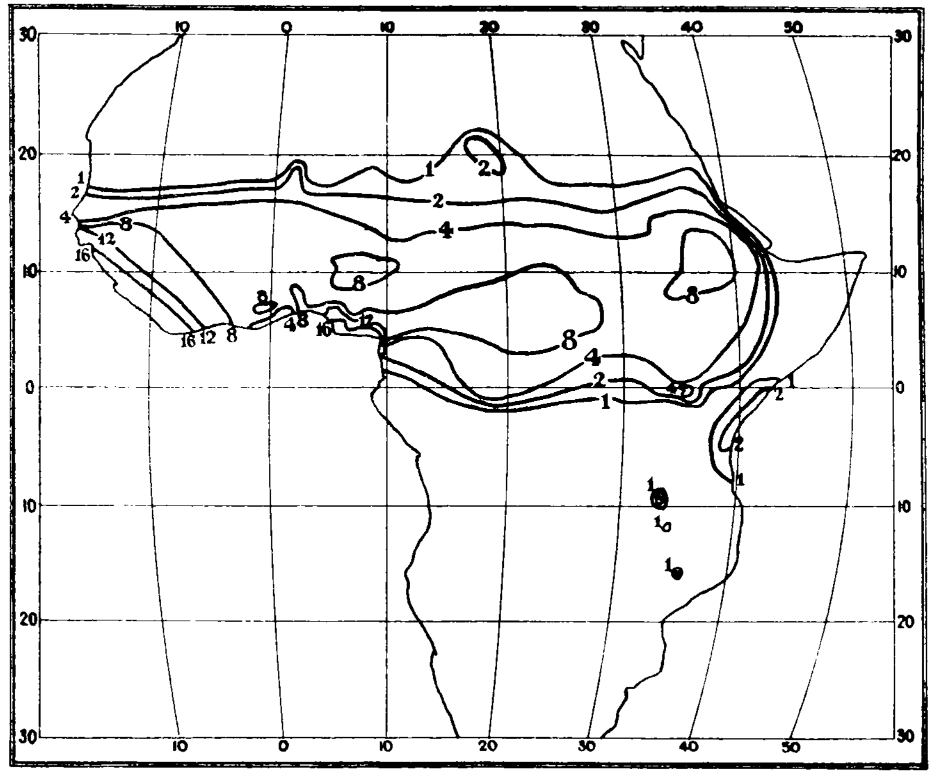

Fig. 14. Rainfall in inches; July.

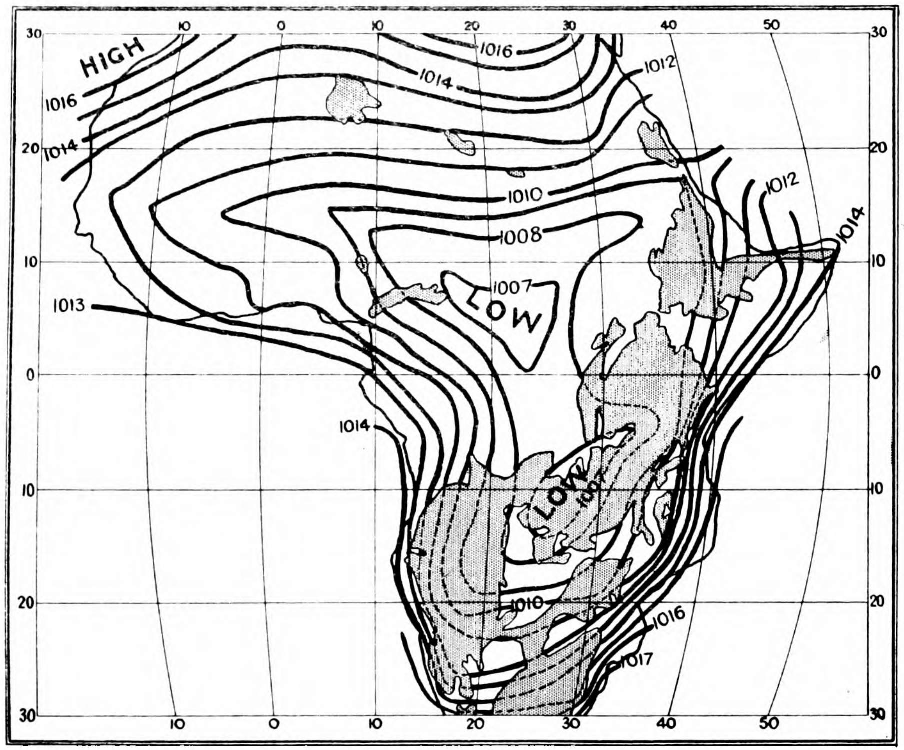

Fig.15. Pressure (mb.) at mean sea level; October.
[Contour at 1,000 metres is indicated]

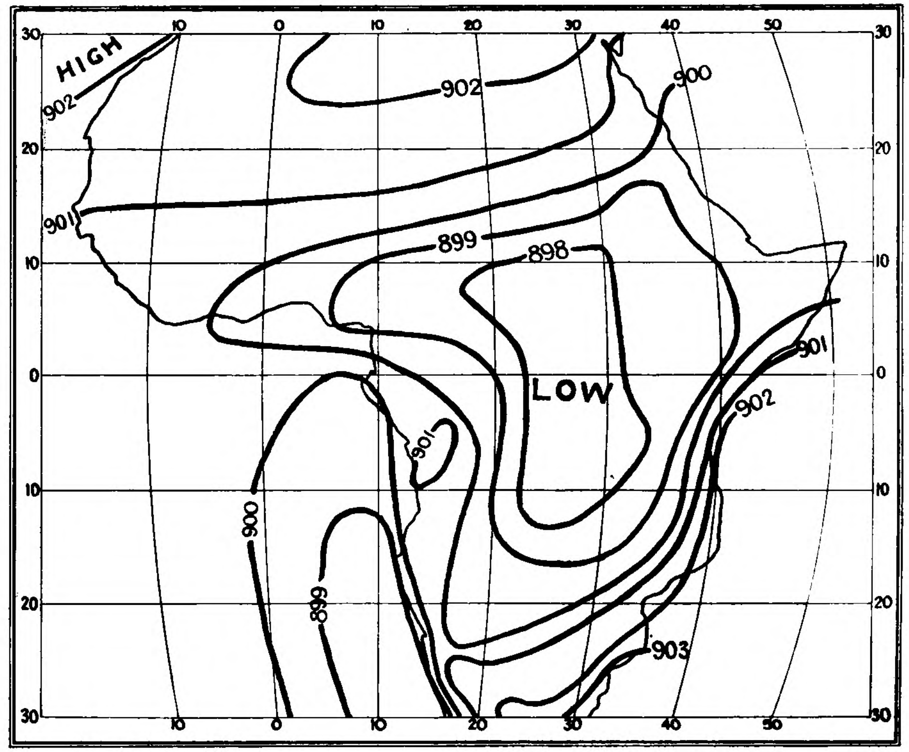

Fig. 16. Pressure (mb.) at 1,000 dynamic metres; October.

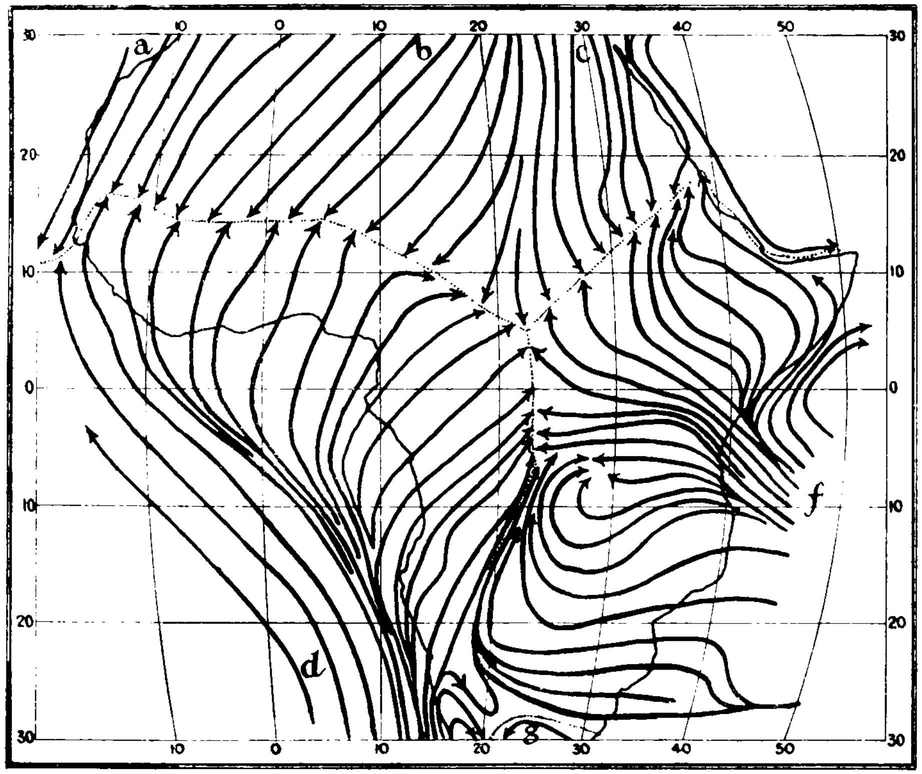

Fig. 17. Air movements; October.

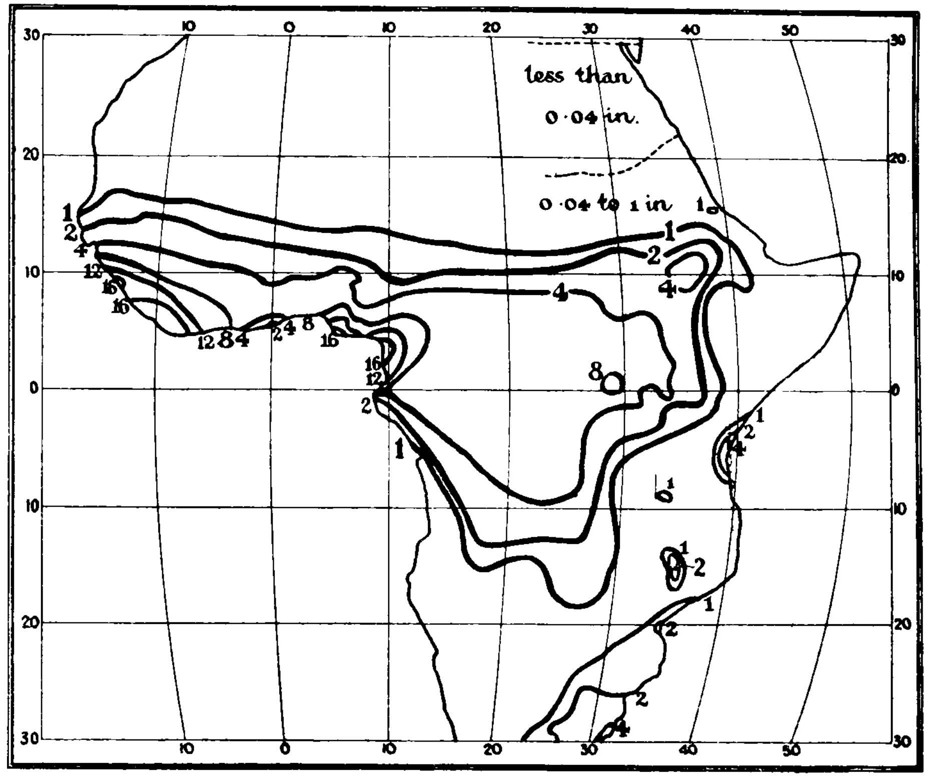

Fig. 18. Rainfall in inches; October.