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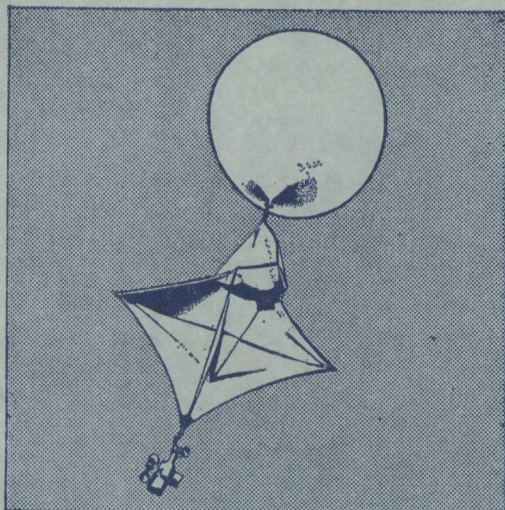
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THE BEHAVIOUR OF THE FIRST SIX ZONAL WAVE NUMBERS AT 50 AND 500 MILLIBARS DURING SOME WINTER MONTHS IN 1958 AND 1959

By G. R. R. BENWELL

Summary.—Results are presented of zonal harmonic analysis applied to the 50 and 500 mb height fields around the three latitude circles 40°N, 50°N and 60°N, during the two winter periods, 1 January 1958 to 28 February 1958 inclusive and 1 December 1958 to 28 February 1959 inclusive. The analysis was carried out on a daily basis since adequate data at 50 mb were available owing to the increased observations made during the International Geophysical Year 1958 and the International Geophysical Co-operation 1959.

The behaviour of wave number one at 50 mb was markedly dissimilar to the behaviour of wave number one at 500 mb; wave number two showed some correlation between the two levels, whilst wave numbers three to six showed closely paralleled behaviour over quite long periods of time at the two levels, even though there were marked differences in the overall behaviour of these wave numbers from one winter period to the next.

Introduction.—The scales of motion present in the atmosphere vary from the large-scale systems recognized by synoptic meteorologists as long waves in the flow pattern to the smallest eddies which can be detected by micro-meteorologists. Harmonic analysis applied to upper air charts permits the examination of the long-wave part of the motion.

The variation of a meteorological parameter, x , around a latitude circle, φ , of the northern hemisphere can be expressed in the harmonic form

$$x = A_0(x) + \sum_{n=1}^{\infty} A_n(x) \cos \left(n\lambda - \psi_n(x) \right)$$

where $A_0(x)$ is the mean value of x around the latitude circle, $A_n(x)$ and $\psi_n(x)$ are the amplitude and phase angle of the n th harmonic and λ is the longitude, increasing eastwards from $\lambda=0$ at the Greenwich meridian. The ridges of the n th harmonic are located at the longitudes

$$\lambda = \frac{\psi_n(x) + 2k\pi}{n} \quad (k = 0, 1, 2, \dots, n-1).$$

The fluctuations of x about its mean value $A_0(x)$ around the latitude circle are regarded as being composed of sinusoidal oscillations the wavelengths of which represent the scales of the motion systems present. Each harmonic gives an integral number of complete wave forms around a latitude circle and this number is referred to as the zonal wave number. The low wave numbers correspond to the large-scale motion systems. The amplitude $A_n(x)$ gives the amplitude of the sinusoidal oscillations representing wave number

n , and the phase angle $\psi_n(x)$ defines the position of the oscillation with respect to the Greenwich meridian. For example if the variation of x was almost entirely represented by wave number four the amplitudes of all the other wave numbers would be effectively zero and there would be four equal maxima and corresponding minima distributed equidistantly around the latitude circle.

It may also be noted that the zonal wave number one is the only wave number which permits flow over the pole, and it can therefore be accepted as giving a measure of the eccentricity of the flow. All the other wave numbers represent flow which is symmetric with respect to the earth's axis. The maximum wave number which can meaningfully be extracted by harmonic analysis is about 15 because of sparse data in some sectors and the inevitable smoothing of the data.

Van Mieghem¹ has dealt very fully with the representation by zonal harmonic analysis of the northern-hemisphere geostrophic wind field, and has appealed for more universal study of the general circulation by means of zonal harmonic analysis.

Teweles² presented some interesting diagrams showing the behaviour of wave numbers one to eight at 50 and 500 mb during January 1958, and mentioned one or two features of the behaviour pattern which required explanation and merited further study.

This paper presents the results of a somewhat similar investigation using data for two winter periods in 1958 and 1959. These winter periods were chosen since there were more complete data at high levels of the atmosphere than were available in earlier years : the increase of data was due to the extra meteorological observations made during the International Geophysical Year (IGY), 1958 and the International Geophysical Co-operation (IGC), 1959. The basic data consisted of the variation of contour height of the 50 and 500 mb surfaces around the three latitude circles 40°N, 50°N and 60°N : the heights were taken at intervals of 10 degrees of longitude and the harmonic analysis was carried out on the Meteorological Office computer, METEOR.

The purpose of the investigation was to determine whether there was any indication of coupling between the stratospheric and tropospheric flow patterns, as represented by the 50 and 500 mb pressure fields respectively. As far as possible it was decided to use data which had already been assembled on tape within the Meteorological Office, even though these data originated from different sources. In some ways this was an advantage since any similar behaviour noted between wave numbers at 50 and 500 mb would be a real effect and would not have arisen from the way in which the analysis at the two levels had been carried out. In the event the data for the five months used in the investigation, January, February and December 1958, and January and February 1959, were obtained from the following sources :

- (i) The 500 mb data for January 1958, February 1958 and December 1958 were largely extracted from data tapes held by the Synoptic Climatology Branch of the Meteorological Office ; these were made from punched cards received from the *Deutscher Wetterdienst*. The gaps in the data at 40°N, over the sector 160°E-180-130°W, and at 50°N, over the sector 180°-160°W, were filled in from the *Sinoptičeskij Bjulleten* issued by the Central'nyj Institut Prognozov, Moscow.

- (ii) The 500 mb data for January 1959 were extracted from the *Daily Series, Synoptic Weather Maps, Part 1, Northern Hemisphere Sea Level and 500 millibar Charts*, published by the U.S. Department of Commerce, Weather Bureau.
- (iii) The 500 mb data for February 1959 were extracted from the *Sinoptičeskij Bjulleten* issued by the Central'nyj Institut Prognozov, Moscow.
- (iv) The 50 mb data for January, February and December 1958 were extracted from *Daily 100-millibar and 50-millibar and three times monthly 30-millibar synoptic weather charts of the IGY period*, published by the U.S. Department of Commerce, Weather Bureau and the 50 mb data for January and February 1959 were extracted from the similar series of the IGC period, published by the same authority.

It was realized that the use of this rather hybrid set of data incurred the risk that some real effects might become blurred or obliterated since Barrett³ had shown that the use of contour charts drawn by different agencies resulted in different values of amplitude and phase angle for the harmonics, because of the subjective nature of the analysis over the areas of the chart where the observations were sparse. This subjectivity was expected to have considerable effects in the higher wave numbers. Attention was therefore confined to the study of the behaviour of the first six wave numbers. The amplitudes of each harmonic are given in units of geopotential metres, and ridge positions have been used to indicate the orientation of each harmonic in preference to the phase angle.

The daily changes in the first six zonal wave numbers.—Figures 1 to 6 show the daily changes in the ridge positions and amplitudes of each of the zonal wave numbers one to six for the two winter periods, 1 January to 28 February 1958 and 1 December 1958 to 28 February 1959. The harmonic analysis was carried out once daily for these periods, but for convenience the daily values have been connected together, by a continuous line as far as the 50 mb surface is concerned and by a broken line for the 500 mb surface. By this means it was hoped to show more clearly the day-to-day variation. No ambiguity arises in the case of amplitude, but some convention has to be adopted if it is desired to show the sequence of ridge positions in this way. The convention used in this paper was to select the ridge position as that which required the smallest longitudinal shift from the previous day's position. If the shift was exactly equivalent to half a wavelength, then the progressive or retrogressive shift was chosen to agree with the shift over the preceding few days. Generally on Figures 2 to 6, only one of the possible 50 mb ridges has been indicated for these wave numbers two to six, but in order to illustrate the movement of the 500 mb wave relative to the 50 mb wave it was necessary to present more than one 500 mb ridge. For convenience on the diagrams the tracks of the various 500 mb ridges which travelled through the 50 mb ridge are marked as a series of broken tracks. Each track lasts for such period as is required for comparison with the 50 mb ridge.

One further comment is required concerning the apparent movement of the ridges, as indicated on these Figures. Most of the large shifts in ridge position occurred when the amplitude of the wave in question was very small. Such shifts therefore should not be given too much prominence and, in some

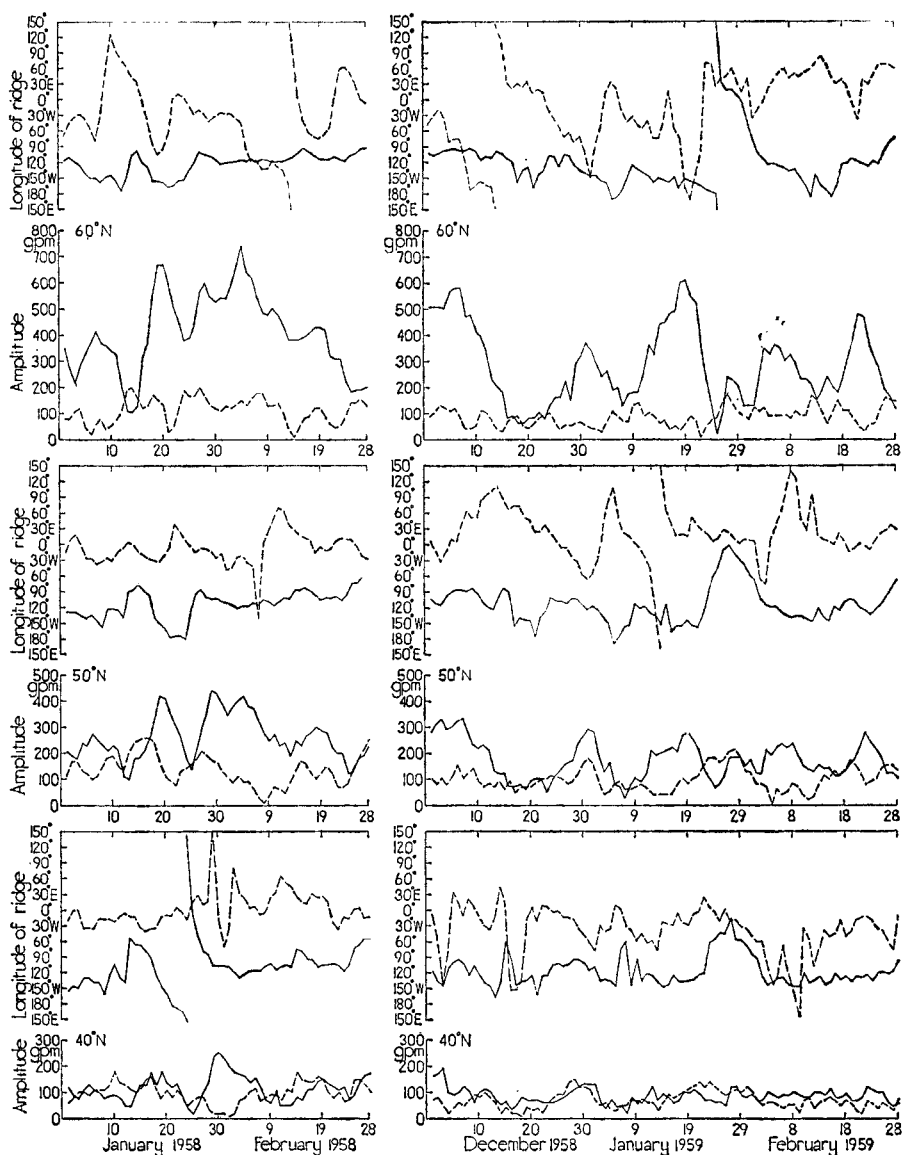


FIGURE 1—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER ONE AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

— 50 millibars
 - - - 500 millibars

ways, it would appear better to confine the study of the behaviour patterns to those periods when the amplitudes are sufficiently large (possibly employing some kind of significance test to determine this). However, as Teweles² has noted, even when the amplitudes of some of the higher wave numbers were low, there often appeared to be a coherent and consistent movement of the wave in question.

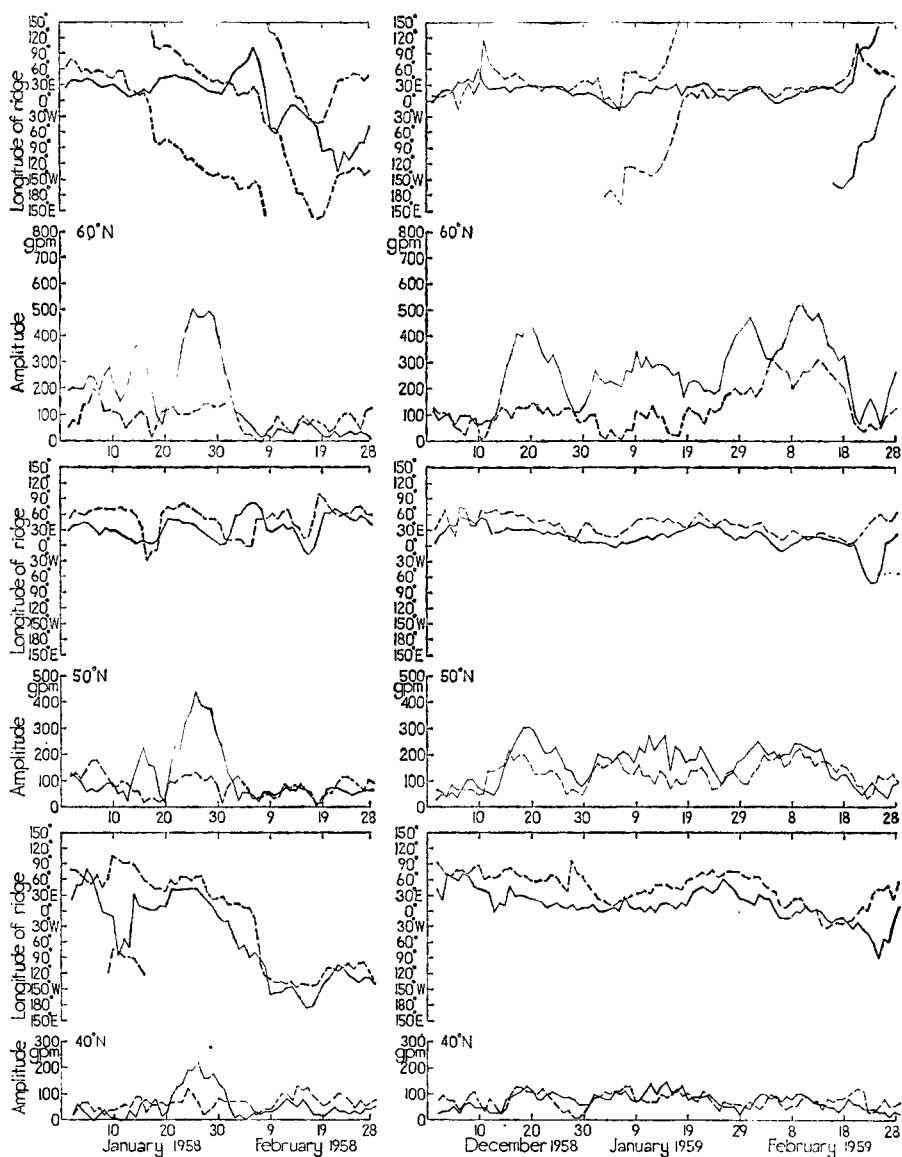


FIGURE 2—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER TWO AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

———— 50 millibars
 - - - 500 millibars

The main features concerning the behaviour of the individual zonal wave numbers can be summarized briefly as follows.

(a) *Zonal wave number one* (Figure 1).—The stratospheric and tropospheric waves are almost always out of phase, with the amplitudes of the stratospheric wave being considerably larger than those of the tropospheric wave on most occasions. The amplitudes of this wave number at both 50 mb and 500 mb

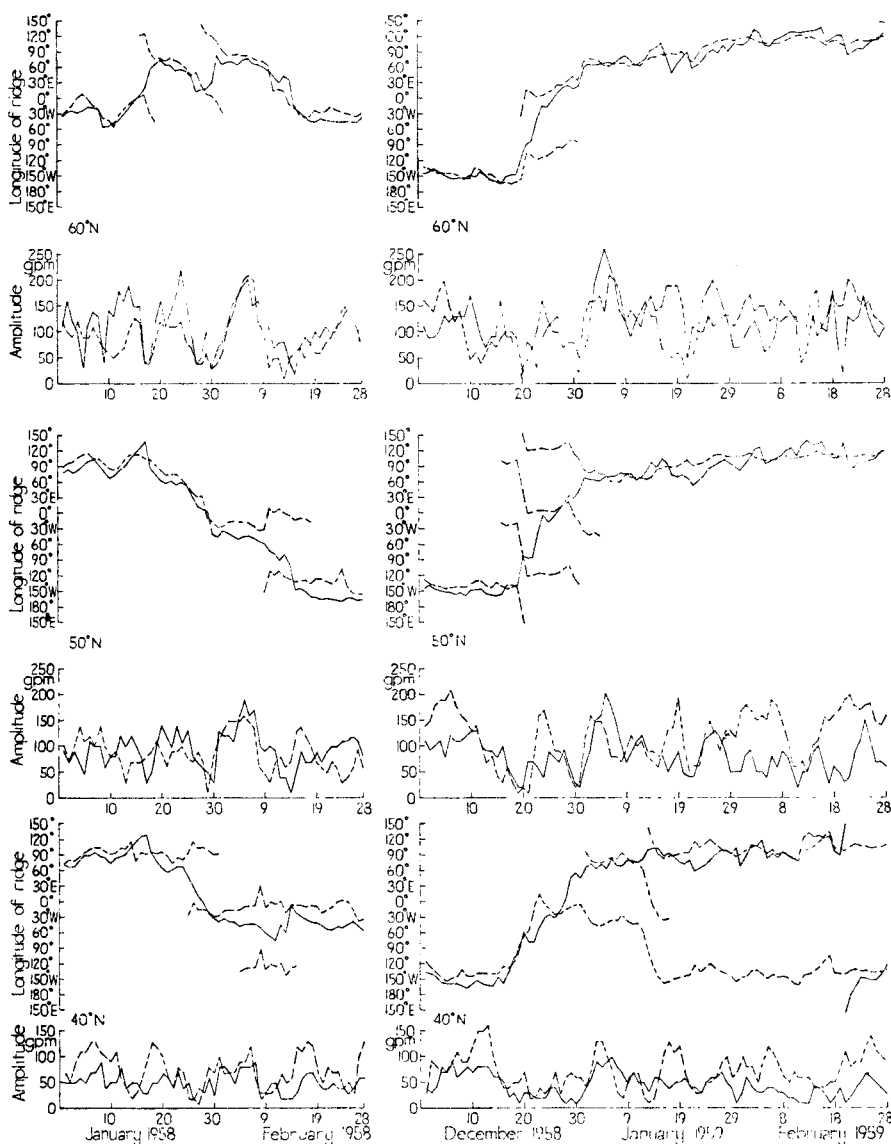


FIGURE 3—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER THREE AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS
 ——— 50 millibars
 - - - 500 millibars

usually decrease with decrease of latitude. The wave at 50 mb is quasi-stationary and pulsatory with the pulsatory behaviour being rather similar at all these latitudes. The 500 mb wave, though also quasi-stationary and pulsatory in character, shows less connected behaviour at the three latitudes and the movement of this wave about its mean position at each latitude appears to be slightly greater than the oscillations of the 50 mb wave.

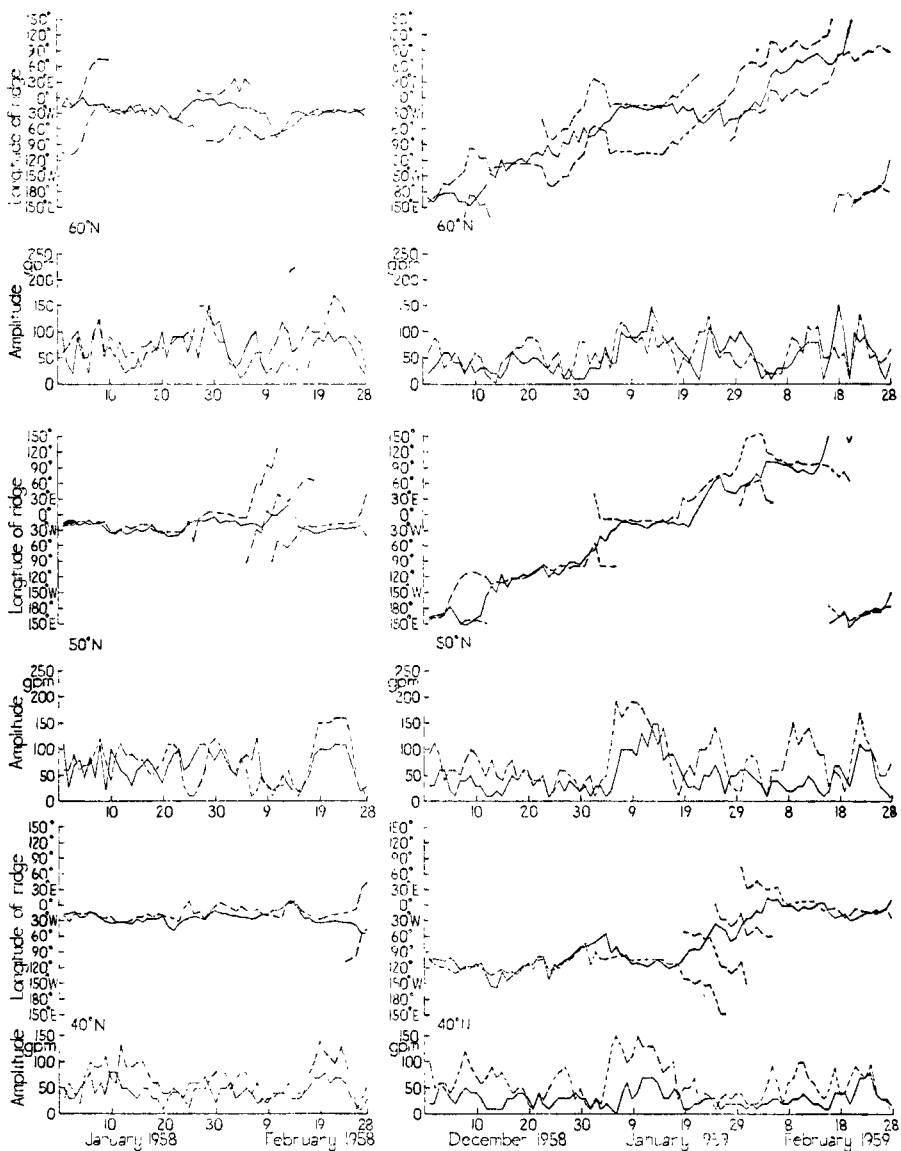


FIGURE 4—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER FOUR AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

— 50 millibars
 - - - 500 millibars

(b) *Zonal wave number two* (Figure 2).—The waves at the two pressure levels behave in a rather similar way, though there is usually a phase difference. For the greater part of the time the waves are pulsatory and quasi-stationary, with the waves during the second period being particularly steady. The changes in amplitude at the two pressure levels are not closely connected but there

are periods when the changes at the two levels are similar. The amplitudes at 50 mb are in general larger than those at 500 mb and show a decrease with decrease of latitude, but the mean values of the amplitudes of this wave at both 50 mb and 500 mb are smaller than those of wave number one.

(c) *Zonal wave number three (Figure 3).*—For long periods the stratospheric and tropospheric waves behave similarly. The amplitudes are of the same order at the two levels and there is not such marked variation of amplitude with latitude as occurs with the first two zonal wave numbers. The marked retrogression of the 50 mb wave, which occurs at all three latitudes for some part of the first winter period has no parallel during the second winter period when, apart from a period of progression in the second half of December 1958, the wave is quasi-stationary. In general the closest connexion between the two pressure levels occurs when the 50 mb wave is quasi-stationary since then the 500 mb wave is also quasi-stationary. When the 50 mb wave is retrogressive in the first period, the 500 mb wave is retrogressive (at 50°N and 60°N) or quasi-stationary (at 40°N and 50°N) ; when the 50 mb wave is progressive, as in the second period, the 500 mb wave is progressive (at 40°N), retrogressive (at 50°N) or quasi-stationary or only slightly progressive (at 60°N).

(d) *Zonal wave number four (Figure 4).*—There is closely paralleled behaviour at 50 mb and 500 mb at each of the three latitudes for quite long periods, though the overall character of the wave behaviour is different in the two winter periods. The 50 mb wave, and also the 500 mb wave for much of the time, are extremely steady in January and February 1958. In the second winter period, however, there are only brief intervals when the 50 mb wave is quasi-stationary and the dominant movement is a progressive one, especially at 50°N and 60°N. The variation of amplitude with latitude is not particularly marked, either at 50 mb or 500 mb, whilst the amplitudes of the tropospheric wave are usually larger than those of the stratospheric wave.

(e) *Zonal wave number five (Figure 5).*—For long periods, especially in the second winter period, the waves at 50 mb and 500 mb move in a similar manner. Over the first period, however, the overall shift of the 500 mb wave at 40°N and 60°N is about 290 and 230 degrees of longitude respectively, whilst the overall shift of the 50 mb wave at these two latitudes is very small. At 50°N the difference between the overall shift of the 500 mb wave and that of the 50 mb wave is not very great. During the second winter period there is closer agreement between the overall shifts of the 500 mb and 50 mb waves ; the shift is almost identical at 40°N and 50°N at the two pressure levels, whilst at 60°N, the 500 mb wave makes a slightly larger progressive shift during the three months than the 50 mb wave. The amplitudes of the 50 mb wave are markedly smaller than those of the 500 mb wave.

(f) *Zonal wave number six (Figure 6).*—The shift in ridge position over periods of the order of a week or so is often about the same at 500 mb and 50 mb. The overall shifts during each of the two periods at the three latitudes show considerable differences however. Whilst the 500 mb wave moves eastward about 150 degrees of longitude at 60°N and between 250 and 300 degrees of longitude at 50°N and 40°N during the first winter period, the 50 mb wave only moves about 90 degrees eastward at 60°N and 40°N and

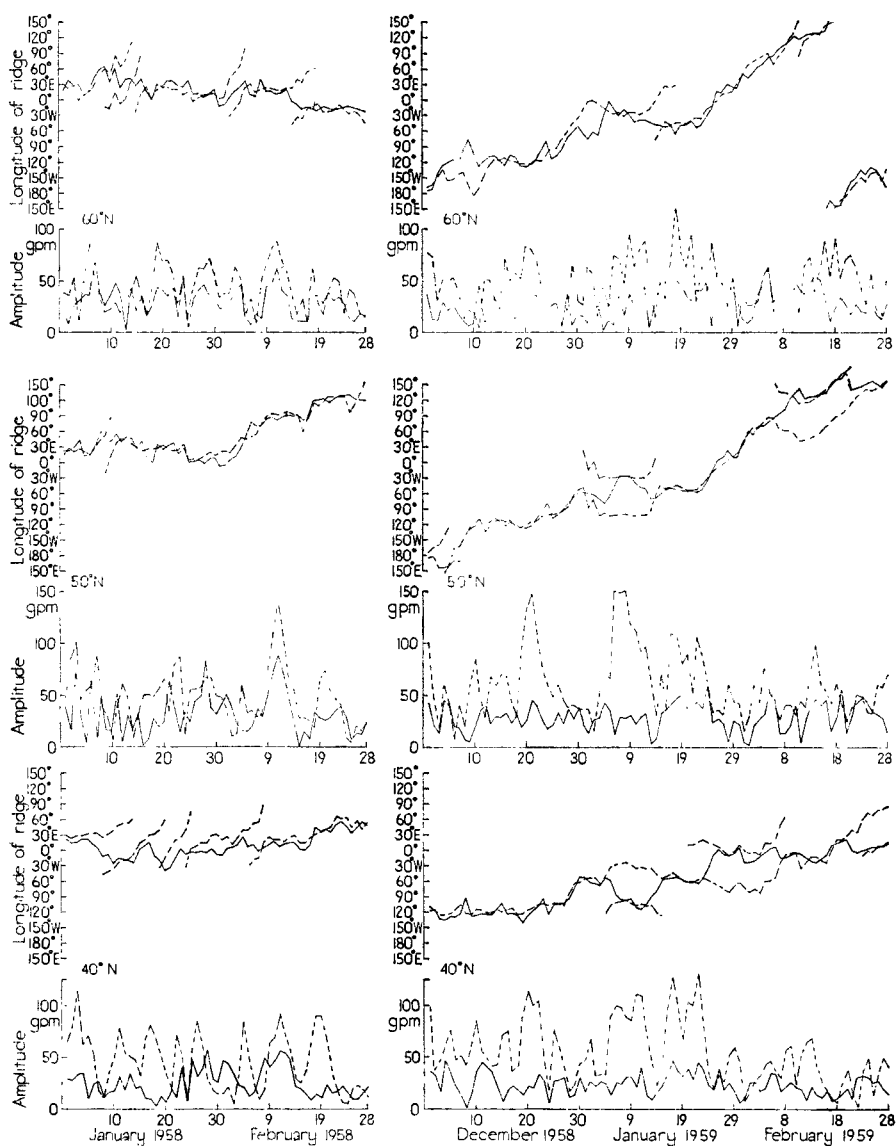


FIGURE 5—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER FIVE AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

———— 50 millibars
 - - - - 500 millibars

about 180 degrees at 50°N. During the second winter period whereas the 500 mb wave moves eastward about 500/550 degrees at all three latitudes, the 50 mb wave moves about 300 degrees eastward at 60°N, about 50 degrees westward at 50°N and 300 to 350 degrees eastward at 40°N. As with zonal wave number five there is a tendency for the long-period movement of the

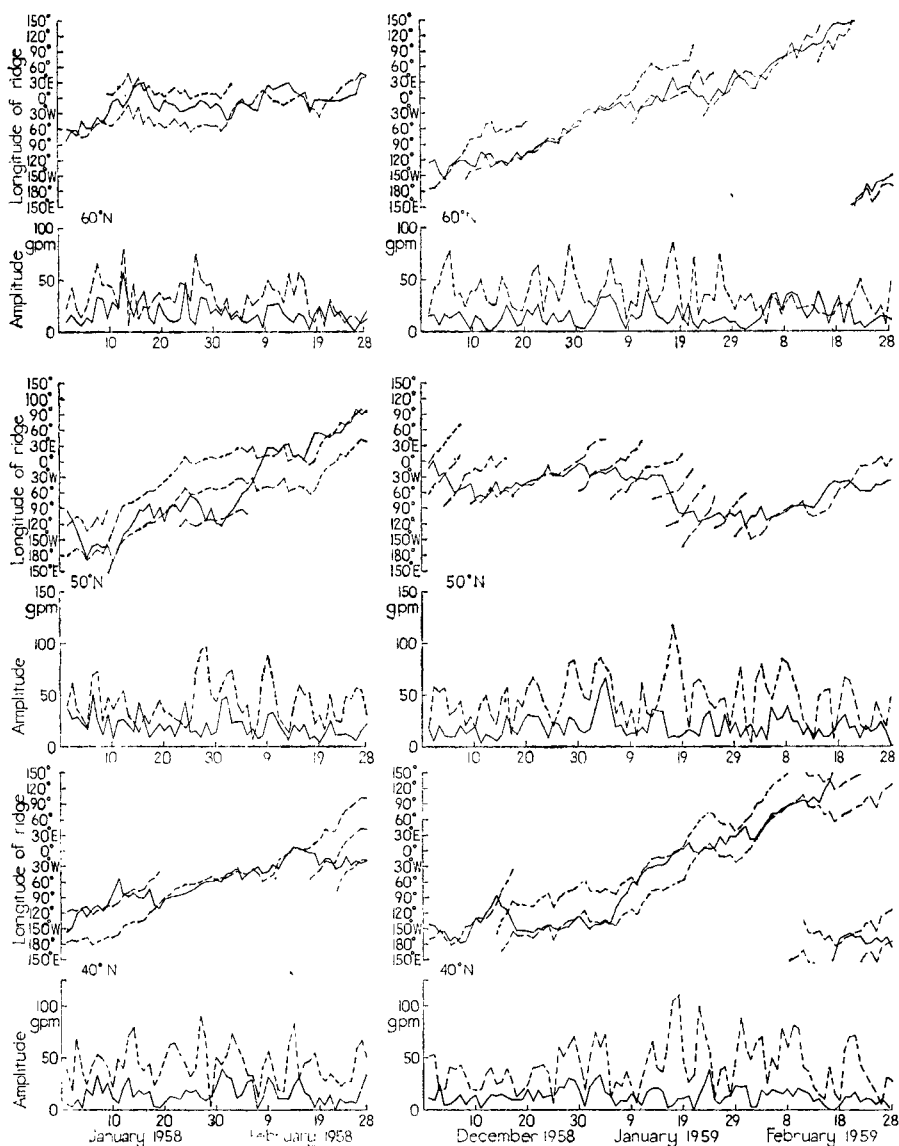


FIGURE 6—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER SIX AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS
 ————— 50 millibars
 - - - - - 500 millibars

stratospheric wave to lag behind that of the eastward moving tropospheric wave and, in fact, the shift of the stratospheric wave may be a retrogressive one. With few exceptions the daily amplitudes of the 50 mb wave are smaller at each of the three latitudes than the amplitudes of the 500 mb wave.

(g) *Zonal wave numbers greater than six.*—No attempt was made to follow diagrammatically the daily behaviour of the zonal wave numbers greater

than six. However Table I, which gives comparative values of the mean daily amplitude at 50 and 500 mb throughout each of the five months at 40°N, 50°N and 60°N, contains information relating to zonal wave numbers seven to ten in addition to the first six wave numbers. This table shows that for the first two wave numbers, the stratospheric waves have considerably larger amplitudes than the tropospheric waves in each month, except for wave number two in February 1958. For wave number three, the amplitudes at the two levels are much the same, but for wave numbers four to ten, the amplitudes of the tropospheric waves are greater than those of the stratospheric waves.

TABLE I—MEAN DAILY AMPLITUDE OF THE FIRST TEN ZONAL WAVE NUMBERS FOR EACH MONTH AT 50 AND 500 MILLIBARS AT SPECIFIED LATITUDES

		Zonal wave number									
		1	2	3	4	5	6	7	8	9	10
		<i>geopotential metres</i>									
January 1958	60°N	397	287	116	78	27	19	14	10	9	9
		(115	119	106	76	43	33	22	17	10	10)
	50°N	259	180	89	46	33	21	17	12	11	10
		(164	103	87	75	54	41	32	25	18	15)
	40°N	115	86	52	47	25	15	10	9	7	6
		(94	69	76	66	50	45	34	28	23	18)
February 1958	60°N	423	54	107	54	27	14	9	6	5	3
		(110	70	99	81	41	25	22	18	15	12)
	50°N	265	61	97	63	33	16	13	7	5	4
		(105	77	90	70	45	42	30	29	21	18)
	40°N	114	44	50	44	26	16	10	7	4	4
		(102	80	72	64	41	43	33	30	20	17)
December 1958	60°N	287	201	95	33	22	12	9	7	6	6
		(72	97	99	51	44	41	25	20	12	11)
	50°N	188	145	79	32	27	16	8	6	6	5
		(97	108	102	60	59	43	26	34	19	15)
	40°N	92	71	44	29	24	13	10	5	6	3
		(66	73	70	59	58	36	24	33	19	15)
January 1959	60°N	292	274	126	74	30	16	13	9	6	6
		(80	94	141	69	55	40	25	23	14	14)
	50°N	159	191	98	65	29	21	13	8	8	5
		(104	123	111	97	72	53	42	27	24	16)
	40°N	80	87	55	30	26	15	10	6	5	3
		(84	84	69	70	68	49	46	37	24	16)
February 1959	60°N	271	313	115	54	33	20	9	8	6	5
		(102	187	133	60	46	26	19	22	11	11)
	50°N	169	146	68	41	30	19	11	8	5	4
		(91	145	145	83	48	44	30	28	18	16)
	40°N	85	60	32	30	20	12	9	8	5	4
		(57	69	78	56	34	43	29	24	17	13)

Note : Rows in brackets refer to 500 mb.

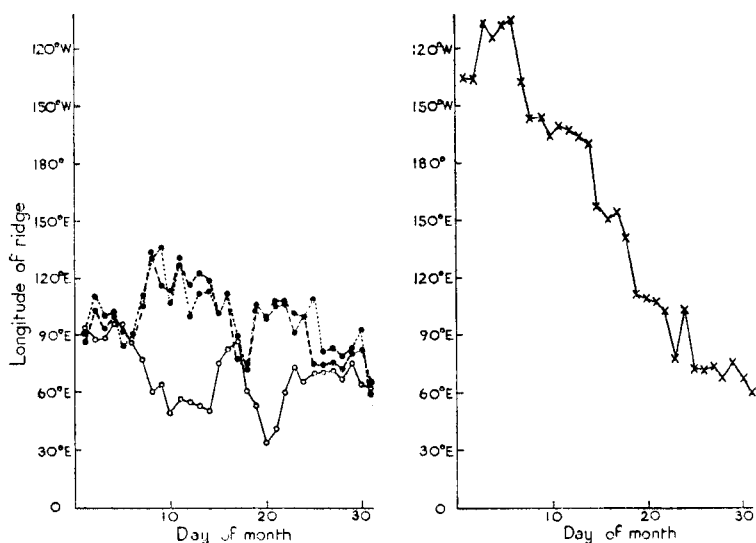
Discussion.—Van Mieghem¹ commenting upon the quasi-stationary behaviour of the ultra-long waves (zonal wave numbers one to three) at 500 mb in the northern hemisphere, concludes tentatively that 'component $n=3$ of the normal circumpolar circulation is mainly of orographic origin, the component $n=2$ is mainly under direct thermal control ; as for the component $n=1$ there is a certain orographic effect without apparently any direct thermal steering'. It is interesting to see how these three wave numbers at 500 mb are positioned during the specific five months of this investigation in relation to their normal position. The normal ridge positions for these waves are given in Table II for the months of January, February and December, taking as normal the period 1949 to 1958.

TABLE II—NORMAL RIDGE POSITIONS OF 500 MILLIBARS ZONAL WAVE NUMBER

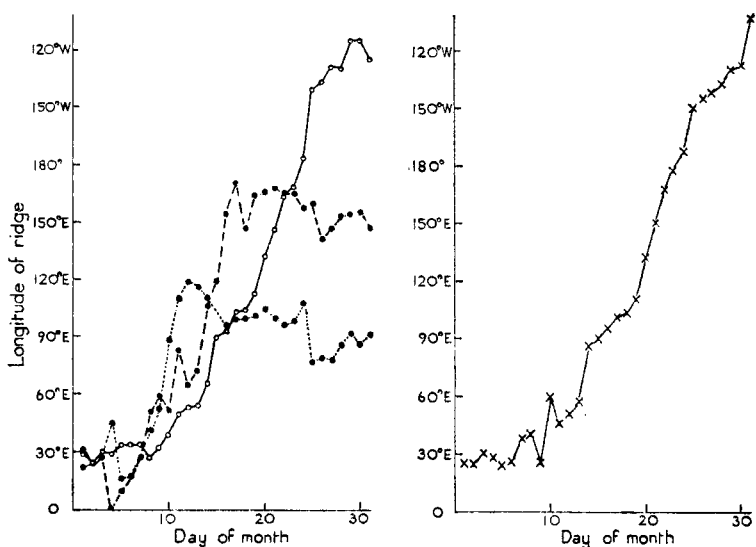
		Wave one	Wave two	Wave three
January	60°N	10°E	26°E, 154°W	26°W, 146°W, 94°E
	50°N	18°E	33°E, 147°W	24°W, 144°W, 96°E
	40°N	46°W	46°E, 134°W	23°W, 143°W, 97°E
February	60°N	22°E	24°E, 156°W	26°W, 146°W, 94°E
	50°N	22°W	38°E, 142°W	23°W, 143°W, 97°E
	40°N	46°W	49°E, 131°W	23°W, 143°W, 97°E
December	60°N	14°E	33°E, 147°W	30°W, 150°W, 90°E
	50°N	7°W	38°E, 142°W	26°W, 146°W, 94°E
	40°N	33°W	45°E, 135°W	27°W, 147°W, 93°E

From a comparison with the details given in Figure 1 and Table II, it will be noted that wave number one at 500 mb varies considerably from its normal position though during January 1958 the wave is quasi-stationary close to its normal position at both 40°N and 50°N. From Figure 2 it will be seen that there are reasonably long periods when wave number two maintains its ridge position close to the normal, more particularly in the second winter period at 50°N. From Figure 3 it is seen that wave number three has ridge positions fairly close to normal when it is quasi-stationary: however, throughout most of February 1959 the ridges are on average about 20 degrees of longitude east of the normal position, whereas in January 1959 the ridges are on average about 20 degrees west of the normal position. These differences may be important.

The daily behaviour of wave numbers one to six during January 1958 was compared with the behaviour of these waves at 45°N and 65°N given by Teweles.² There is fairly close agreement between the results of this investigation and Teweles's results, but the difference in behaviour of wave number five requires further mention as the behaviour of this wave number was the subject of a special comment by Teweles. Figure 7(a) shows the comparison between the behaviour at 40°N, 50°N and 60°N as found in this investigation and that at 45°N as given by Teweles for the 50 mb pressure level and Figure 7(b) shows the comparison for 500 mb. There is not too much difference at 500 mb though wave number five progresses more at 45°N than at 40°N or 50°N. It will be noted in Figure 7(a) that whereas this wave at 50 mb steadily retrogresses throughout the month at 45°N, the behaviour at 40°N and 50°N shows progressive shifts as well as retrogression with the result that there is only a slight overall retrogression during the month. The difference in the two behaviour patterns is largely accounted for by the retrogressive shifts at 45°N which are shown between the 6th and 7th and between the 14th and 15th day of the month when the shift in each case is almost half a wavelength. Teweles² had noted that when the daily movement of a wave is about half a wavelength, the direction becomes arbitrary and, in fact, when the amplitude is small, quite slight differences in the original data, giving a relatively slight change of ridge position, could result in progressive shifts being indicated instead of retrogressive shifts. This comparison suggests that when comparing wave behaviour at two pressure levels attention should be focused on those periods when the amplitudes are sufficiently large and that big progressive or retrogressive shifts which occur when amplitudes are small should be ignored. Despite these comments, however, it does appear that there is a tendency, as noted earlier, for the stratospheric wave numbers five and six to be considerably less progressive than their eastward-moving tropospheric counterparts.



(a) 50 millibars



(b) 500 millibars

FIGURE 7—DAILY CHANGES IN RIDGE POSITION OF ZONAL WAVE NUMBER FIVE DURING JANUARY 1958

o — — — — — 40°N 50°N - - - - - 60°N
x — — — — — 45°N (after Teweles²)

Though this investigation is concerned chiefly with the relative movement of the waves in the troposphere and stratosphere it is as well to keep in mind the character of the periods used in the investigation. The chief comment about the stratospheric behaviour is that whereas in the first period there

was marked stratospheric warming in the latter part of January 1958 (Teweles and Finger⁴), in the second period no stratospheric warmings of any significance affected the 50 mb surface. As far as the troposphere is concerned the first period was one with generally low zonal index with the jet stream displaced far south of its normal position over the American sector of the northern hemisphere (O'Connor⁵). In contrast, during the second winter period the zonal index was higher and the belt of maximum winds was located considerably further north (Green,⁶ Stark,⁷ O'Connor⁸). Despite the completely different character of the two periods examined, the similarity noted earlier in the behaviour of zonal wave numbers four, five and six at the two pressure levels suggests that these stratospheric waves are reduced tropospheric effects. The behaviour of zonal wave number three at 50 mb may also be largely of tropospheric origin.

It would have been interesting to have been able to examine more closely the pulsations of the ultra-long waves in order to determine whether these are periodic. Chu Pao-Chen⁹ put forward the view that the amplitude of the ultra-long waves varies periodically with a period of 10–30 days and, in support of this suggestion, he gave a diagram showing the variation of the amplitude of zonal wave number two at 50°N during January and February 1958. The diagram is very similar to the amplitude graph for the first winter period at 50°N in Figure 2 for 500 mb. Before it is possible to determine whether these long wave pulsations are periodic, however, considerably more results of this present form of analysis are required.

Conclusions.—The results presented in this paper possibly pose more questions than are answered but the following conclusions are tentatively put forward.

The behaviour of zonal wave numbers four, five and six, as shown during the two winter periods examined, suggests that these waves at 50 mb are reduced or damped tropospheric waves. However, the retrogressive shifts which affect the movement of wave numbers five and six in the stratosphere over the middle latitudes whilst the equivalent tropospheric waves progress relatively steadily eastward, cannot be easily explained or dismissed.

Zonal wave number three at 50 mb may also be of tropospheric origin since it behaves similarly to wave number three at 500 mb for most of the time, especially when it is quasi-stationary.

There also appears to be some associated behaviour between zonal wave number two in the stratosphere and its counterpart in the troposphere, but zonal wave number one at 50 mb, far from behaving similarly to wave number one at 500 mb, is at times almost in anti-phase with this tropospheric wave.

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551.552 (672.2)

LOW-LEVEL WIND FLOW AT NAIROBI

By B. RAMSEY

Summary.—The monthly averages of hourly surface wind and the 0000 and 1200 GMT (GMT+3 hours=local time) winds at 800 and 700 millibars at Nairobi Airport (01°19'S, 36°55'E, 5329 feet (1624 metres) above mean sea level — see Figure 1) provide a unique opportunity to present monthly and diurnal changes in the wind régime at a high-level equatorial station on the western fringe of the great Indian Ocean monsoon system. The north-east and south-east monsoons are clearly impressed on the data, but additional

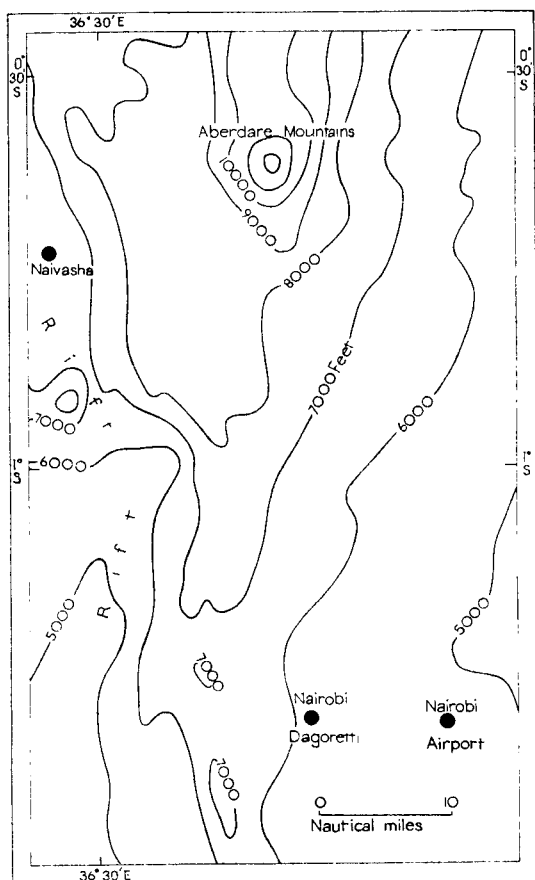


FIGURE 1—SMOOTHED TOPOGRAPHY IN THE NAIROBI AREA

TABLE I—VECTOR MEAN WINDS FOR EACH HOUR AND MONTH AT NAIROBI
AIRPORT (1959-63)

Approximate placing of events on the time scale	Time GMT	January <i>deg kt</i>	February <i>deg kt</i>	March <i>deg kt</i>	April <i>deg kt</i>	May <i>deg kt</i>	June <i>deg kt</i>
Sunrise	0000	007 2.3 (2.9)	346 2.0 (3.1)	012 2.0 (3.3)	048 1.4 (2.9)	127 0.2 (2.7)	258 1.5 (3.6)
	0100	360 1.7 (2.6)	337 1.5 (3.1)	028 2.4 (3.6)	046 1.4 (2.8)	215 0.2 (2.1)	241 1.6 (3.1)
	0200	010 1.5 (2.3)	340 1.5 (3.1)	040 1.7 (3.1)	050 1.4 (2.9)	194 0.4 (2.1)	233 1.6 (2.9)
	0300	355 1.2 (2.1)	342 1.2 (2.9)	040 1.4 (3.0)	058 1.3 (3.0)	209 0.6 (2.0)	220 1.6 (2.9)
	0400	013 0.8 (2.0)	352 0.6 (2.7)	031 1.8 (3.0)	060 1.2 (2.7)	200 1.2 (2.1)	221 1.8 (2.8)
	0500	025 2.2 (3.0)	019 1.0 (2.7)	042 2.5 (3.9)	062 1.7 (3.7)	184 1.7 (2.9)	200 2.0 (3.0)
	0600	045 5.0 (6.0)	036 2.4 (5.3)	048 4.6 (6.2)	072 2.5 (4.5)	170 2.2 (3.8)	178 2.4 (3.7)
Sun zenith	0700	038 8.0 (8.8)	032 7.0 (7.6)	044 6.2 (6.9)	069 3.4 (5.5)	164 2.6 (4.3)	170 3.0 (4.3)
	0800	045 9.5 (10.1)	040 9.0 (9.5)	044 7.8 (8.8)	066 4.2 (6.3)	160 2.9 (4.6)	163 3.0 (5.1)
	0900	046 10.0 (10.6)	043 10.0 (10.4)	044 9.0 (9.7)	069 5.5 (7.3)	151 3.1 (5.1)	156 3.5 (5.2)
	1000	048 9.8 (10.4)	048 10.5 (11.3)	049 10.3 (11.2)	068 6.4 (8.5)	146 3.0 (5.4)	144 3.4 (5.4)
	1100	057 10.2 (10.9)	050 11.0 (12.0)	053 10.6 (11.2)	071 7.0 (8.9)	132 3.9 (6.6)	138 3.9 (5.9)
Maximum temperature	1200	058 10.8 (11.5)	055 11.5 (12.7)	057 10.9 (11.9)	075 7.5 (9.8)	115 3.7 (6.9)	120 4.0 (6.6)
	1300	062 11.0 (11.6)	062 11.6 (12.7)	062 11.2 (12.6)	073 8.4 (10.5)	107 4.9 (8.1)	111 5.1 (7.0)
	1400	063 11.8 (12.3)	063 12.7 (13.5)	064 12.5 (13.3)	074 9.2 (11.2)	102 6.1 (8.5)	105 5.8 (7.7)
Sunset	1500	065 11.9 (12.8)	062 14.0 (14.4)	065 12.7 (13.6)	073 8.9 (10.4)	100 5.9 (8.0)	097 7.0 (7.8)
	1600	062 9.4 (10.0)	057 10.5 (11.1)	061 9.2 (10.2)	074 7.0 (8.1)	096 4.2 (5.9)	095 5.7 (6.5)
	1700	053 7.8 (8.6)	054 8.0 (8.8)	058 7.1 (8.4)	072 5.2 (6.4)	092 2.7 (5.3)	104 4.1 (5.3)
	1800	045 6.5 (7.1)	048 6.3 (7.3)	056 6.4 (7.5)	065 4.1 (5.4)	081 2.1 (4.4)	104 2.0 (4.3)
	1900	035 5.5 (5.9)	043 5.4 (6.3)	048 5.2 (6.2)	055 4.3 (4.9)	052 1.3 (3.9)	077 0.9 (3.4)
	2000	027 4.9 (5.0)	031 4.5 (5.5)	034 4.0 (5.1)	047 2.5 (4.0)	038 1.3 (3.9)	360 0.6 (3.7)
	2100	020 4.0 (4.3)	024 4.2 (4.6)	025 3.6 (5.0)	036 2.0 (4.2)	028 1.1 (3.7)	293 1.4 (4.3)
	2200	020 3.0 (3.6)	013 3.0 (3.9)	019 3.1 (4.6)	038 2.0 (4.1)	031 0.6 (3.8)	272 1.9 (4.5)
	2300	010 2.4 (3.1)	358 2.4 (3.7)	013 2.7 (4.0)	043 2.0 (3.4)	022 0.6 (3.3)	271 1.7 (4.1)

Note: Values in brackets are scalar mean speeds.

effects are present and become more apparent when surface winds are compared with the flow at 800 and 700 mb. In addition, the diurnal variations in anemometer-level wind speeds and screen temperatures show correlations common to all seasons.

Data.—As monthly diurnal temperature curves for the period 1959 to 1963 had already been extracted as an aid to forecasting take-off temperatures at Nairobi Airport, it was decided to undertake a similar analysis of hourly surface winds (vector mean and scalar speed) by the month, for the same period, as an additional forecasting aid. In all, over 42,000 observations were averaged manually. Additionally, from rawin and rawinsonde ascents at 0000 and 1200 GMT, average monthly vector means and scalar speeds were found for the 800 and 700 mb levels. These levels are about 1300 ft (400 m) and 5000 ft (1500 m) respectively above airfield height. The results are presented in Tables I and II.

TABLE 1—*contd*

Approximate placing of events on the time scale	Time GMT	July		August		September		October		November		December	
		deg	kt	deg	kt	deg	kt	deg	kt	deg	kt	deg	kt
Sunrise	0000	228	2.4 (3.8)	234	1.8 (3.7)	360	0.9 (3.7)	043	2.8 (4.5)	039	3.6 (4.8)	029	2.6 (3.1)
	0100	220	2.5 (3.1)	232	2.1 (3.6)	180	0.5 (3.0)	045	3.0 (3.3)	042	3.0 (4.0)	029	2.3 (2.7)
	0200	220	2.6 (3.2)	228	1.9 (3.1)	225	0.6 (2.7)	047	2.3 (2.8)	043	2.8 (3.8)	027	2.0 (2.7)
	0300	217	2.7 (3.3)	207	2.0 (3.3)	208	0.7 (2.4)	050	2.2 (2.8)	043	2.6 (3.5)	029	2.6 (2.8)
	0400	209	2.7 (3.1)	206	1.9 (3.1)	205	1.2 (2.4)	054	2.2 (2.6)	049	2.8 (3.6)	027	1.6 (2.3)
	0500	196	3.0 (3.4)	192	1.4 (3.1)	171	1.4 (2.6)	055	2.6 (3.2)	051	2.9 (4.7)	031	3.1 (3.9)
Sun zenith	0600	173	3.8 (4.7)	166	2.4 (3.5)	150	1.9 (3.3)	065	3.1 (4.0)	050	5.1 (6.2)	036	5.3 (6.5)
	0700	170	3.5 (4.7)	160	2.9 (3.9)	138	2.3 (3.7)	062	3.7 (4.8)	046	5.4 (6.9)	042	2.8 (8.8)
	0800	168	4.4 (5.3)	158	2.9 (4.4)	133	2.5 (4.1)	066	4.7 (5.8)	049	6.4 (8.1)	042	8.9 (10.2)
	0900	158	4.2 (5.1)	144	3.1 (4.9)	124	2.8 (4.5)	069	6.2 (7.2)	049	6.9 (8.7)	045	9.3 (10.7)
	1000	154	4.3 (5.9)	145	3.2 (4.8)	116	3.6 (5.1)	073	6.8 (8.2)	055	8.1 (9.5)	050	9.7 (11.0)
	1100	146	4.4 (6.0)	130	3.5 (5.6)	117	4.2 (6.2)	076	7.4 (8.7)	061	8.4 (9.7)	053	10.1 (11.7)
Maximum temperature	1200	142	4.8 (6.5)	118	4.2 (6.3)	096	5.2 (6.7)	080	7.8 (8.7)	064	8.6 (9.9)	059	10.2 (11.9)
	1300	136	5.4 (7.0)	106	5.0 (6.8)	098	6.2 (7.9)	083	9.3 (10.1)	068	9.6 (11.2)	062	11.0 (12.5)
	1400	122	5.8 (7.0)	097	6.8 (8.3)	094	8.2 (9.3)	081	9.8 (10.7)	070	9.5 (11.2)	062	11.3 (13.2)
	1500	114	6.4 (7.6)	094	7.3 (8.6)	093	9.1 (10.2)	083	10.0 (10.6)	068	9.8 (11.2)	061	10.7 (12.1)
	1600	106	5.6 (6.3)	091	6.1 (7.3)	094	8.0 (8.3)	083	7.8 (8.6)	064	6.6 (8.0)	056	8.2 (9.2)
	1700	114	4.5 (5.4)	093	5.1 (6.2)	095	6.2 (6.8)	081	6.2 (7.2)	053	6.0 (7.0)	048	6.6 (7.3)
Sunset	1800	119	2.9 (4.3)	092	3.4 (4.8)	091	4.4 (5.1)	078	5.8 (6.6)	052	5.6 (6.5)	041	5.8 (6.4)
	1900	143	1.5 (3.7)	074	2.3 (4.2)	078	3.0 (3.9)	068	4.9 (5.6)	044	4.9 (5.6)	035	5.0 (5.4)
	2000	198	1.2 (4.0)	060	0.8 (4.2)	035	1.7 (3.7)	052	3.9 (4.8)	035	4.2 (4.9)	031	4.1 (4.4)
	2100	233	2.6 (4.3)	280	0.5 (4.3)	027	1.8 (4.1)	038	4.4 (5.4)	028	3.8 (4.8)	026	3.7 (4.1)
	2200	237	2.5 (4.1)	256	1.2 (4.6)	344	1.5 (3.9)	041	4.9 (5.6)	030	3.3 (4.5)	027	3.3 (3.7)
	2300	238	2.5 (3.8)	252	1.6 (3.9)	352	1.4 (4.2)	042	4.4 (5.0)	034	3.5 (4.4)	026	2.8 (3.1)

Note: Values in brackets are scalar mean speeds.

To find the depth of the turbulent mixing layer at the time of maximum heating, the mean monthly convective condensation level (CCL) was found by dividing the difference between the average dry-bulb and dew-point temperatures ($^{\circ}\text{C}$) at 1200 GMT by three, to give an approximation to the cloud base.¹ The monthly average rainfall over this period was also found as well as the monthly vector difference between the average component of wind flow from the ground to 700 mb in the early morning and that in the afternoon. The difference in direction between these morning and afternoon winds, together with the rainfall and CCL is shown on Figure 2.

Figure 3 was compiled from the annual hourly scalar wind speeds at the surface and the hourly surface temperatures, together with the curves for the hottest (February), and the coldest (July) months.

TABLE II—COMPARISON OF MORNING AND AFTERNOON VECTOR MEAN WINDS AT NAIROBI FROM GROUND LEVEL TO 700 MB
(1959-63)

	January	February	March	April	May	June	July	August	September	October	November	December
0300 GMT												
Surface	355	342	040	058	209	220	217	207	208	050	043	029
wind	1.2 (2.1)	1.2 (2.9)	1.4 (3.0)	1.3 (3.0)	0.6 (2.0)	1.6 (2.9)	2.7 (3.3)	2.0 (2.3)	0.7 (2.4)	2.2 (2.8)	2.6 (3.5)	2.0 (2.8)
0000 GMT												
800 mb	050	050	052	078	091	117	153	144	097	068	058	048
wind	11.1 (11.6)	14.1 (14.4)	11.9 (14.6)	9.9 (11.3)	4.9 (7.8)	4.2 (7.4)	5.5 (8.2)	4.4 (7.4)	5.5 (7.9)	11.4 (12.0)	11.6 (14.3)	12.4 (13.6)
700 mb	049	044	055	079	083	074	205	241	114	085	073	053
wind	11.5 (13.0)	13.4 (14.2)	14.2 (15.1)	11.6 (13.0)	4.5 (8.6)	2.5 (7.6)	3.9 (8.7)	4.6 (8.4)	2.9 (7.8)	9.5 (11.0)	12.0 (13.4)	11.7 (13.5)
1500 GMT												
Surface	065	062	065	074	102	097	114	094	093	083	068	062
wind	11.9 (12.8)	14.0 (14.4)	12.7 (13.6)	9.2 (11.2)	6.1 (8.5)	7.0 (7.8)	6.4 (7.6)	7.3 (8.6)	9.1 (10.2)	10.0 (10.6)	9.8 (11.2)	11.3 (13.2)
1200 GMT												
800 mb	062	061	064	079	115	125	141	134	111	081	070	063
wind	9.8 (10.9)	12.1 (12.6)	12.3 (12.7)	9.4 (10.5)	5.8 (7.7)	6.5 (7.8)	6.8 (8.6)	6.2 (8.0)	7.9 (8.9)	11.2 (12.2)	11.5 (12.7)	11.5 (12.3)
700 mb	062	057	062	080	088	097	144	158	110	088	076	064
wind	10.3 (11.6)	12.0 (12.4)	13.0 (13.8)	11.2 (12.0)	6.3 (9.2)	5.6 (8.3)	3.8 (8.8)	3.7 (7.0)	7.0 (9.2)	10.9 (11.7)	11.7 (12.6)	11.0 (12.1)
Vector difference												
between morning												
and after-	093	092	097	099	117	102	091	092	101	104	108	102
noon wind (mean												
from surface												
to 700 mb).	4.1	4.4	4.4	2.6	3.0	4.4	3.9	5.3	5.2	3.5	3.2	3.5

Note : Values in brackets are scalar mean speeds.

Local time = GMT + 3 hours.

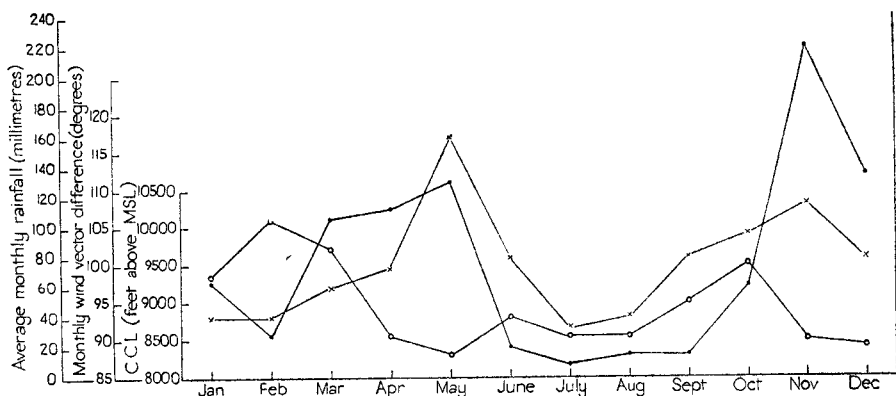


FIGURE 2—AVERAGE MONTHLY RAINFALL AND CCL AND MONTHLY VECTOR DIFFERENCE BETWEEN AVERAGE WIND COMPONENTS FROM SURFACE TO 700 MB IN THE MORNING AND AFTERNOON, 1959-63

—•—•— Average monthly rainfall
 —○—○— Average monthly CCL
 —x—x— Monthly wind vector difference

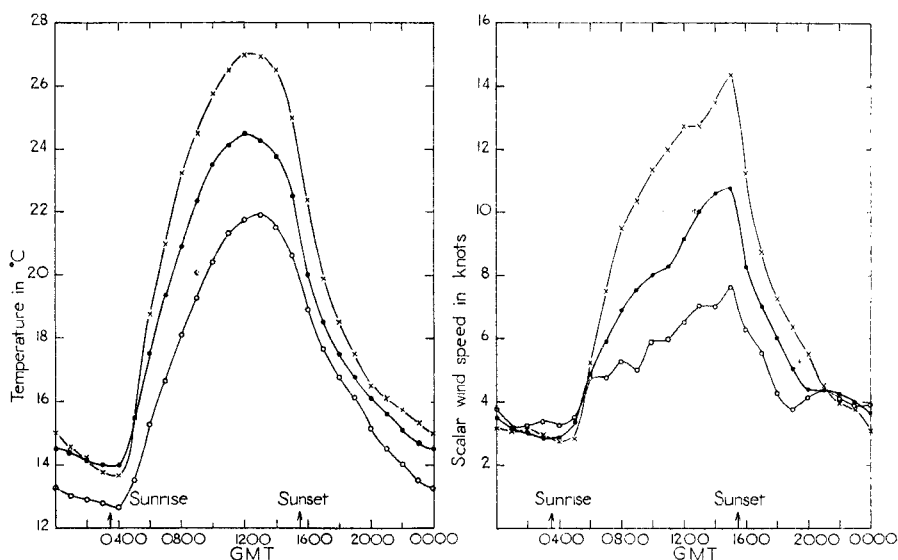


FIGURE 3—HOURLY SCALAR WIND SPEEDS AND SURFACE TEMPERATURES FOR FEBRUARY, JULY AND THE YEAR, 1959-63

x—x—x February —○—○— July
 —•—•— Year

Surface wind.—

North-east monsoon season.—The north-east monsoon begins in October and continues until the end of April. The extreme months, October and April, exhibit rather more zonal flow, as can be seen from Table I and Figure 4, than do the other north-easterly months November to the end of March.

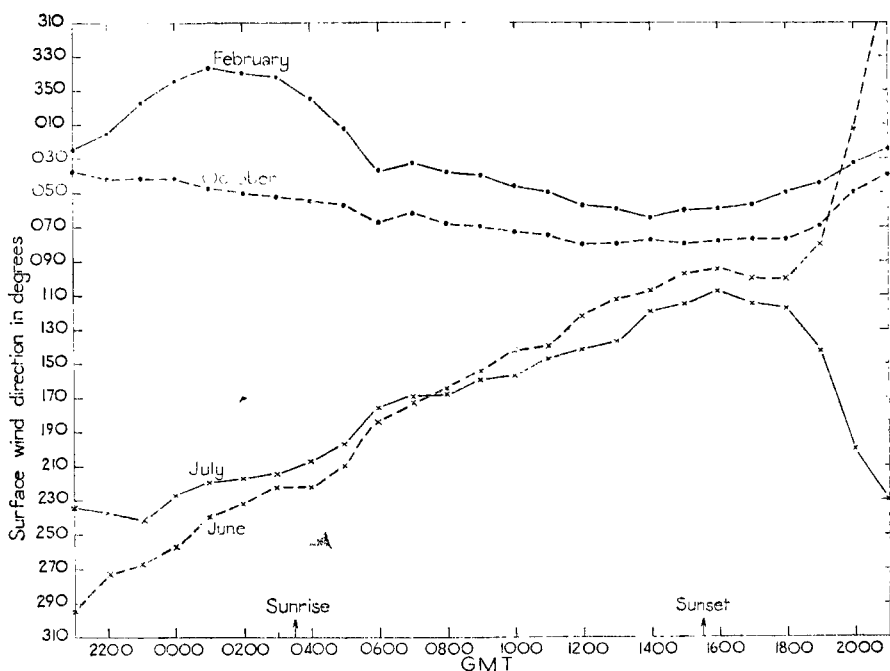


FIGURE 4—DIURNAL VARIATIONS OF SURFACE WIND DIRECTION AT NAIROBI AIRPORT 1959-63

Winds throughout the day at the beginning and end of this monsoon are both more easterly and less strong than in the remainder of the period. The direction of the maximum wind (1500 GMT) from November to the end of March (see Table II) is remarkably consistent. However, in the early part of the day the wind is backed from this direction by a lesser amount in the wetter cloudy months of November and December than in the drier months of January and February. Daily temperature curves reveal more or less the same pattern throughout the year, and the scalar wind speed profile follows these curves faithfully until the period between maximum temperature and sunset (1530 GMT) during which time the winds continue to increase. The greatest increase in wind speed is coincident with the greatest hourly temperature rise from 0500 to 0600 GMT. Similarly, the greatest fall in temperature from 1500 to 1600 GMT (about sunset) coincides with the most rapid fall in wind speeds. As mentioned above, this is not peculiar to the north-east monsoon and applies all the year. It may be noted that the steady progression of the wind direction throughout the forenoon is interrupted on the average each day between about 0600 and 0700 GMT. This is a feature of all north-east monsoon months, although it occurs between 0700 and 0800 GMT in April, and in December there is merely a halt in the gradual veering at this time.

South-east monsoon season.—This monsoon, which lasts from May to the end of September, is marked by a diurnal cycle rather different from that in the north-east season. Only one month, July, the mid-season month,

shows an equal and opposite régime in the backing and increasing surface wind as the day warms up, followed by a veering and decreasing after sunset (Table I). All the other south-easterly months show a rotation through the full 360° with light south-westerly winds in the early morning gradually backing and increasing until sunset and then continuing to back through north round to south-west again by next morning. This variation is shown in Figure 4. However, the vector mean speed is very light compared with the scalar speed during the dark hours, especially in May. The constancy ' q '² of a set of vector winds is defined as $q=100V_R/V_s$ where V_R is the modulus of the vector mean wind and V_s is the scalar mean wind. From Table IV it may be noted that in the annual breakdown of constancy q , the hour of least q in the whole year is 0000 GMT (or 0300 local time) in May.

A feature of the wind speed at this season is the comparative weakness of the flow in the afternoon as compared with the north-east season. However, the south-east monsoon occurs during the local winter and, as may be seen from the July temperature curve, there is a good deal less heating in spite of the loss of only about 3° of sun elevation as compared with January. The season is very much more cloudy, although, as indicated in Figure 2, very dry.

Upper winds at 800 mb.—The 800 mb level is equivalent to a height of 700 ft (200 m) above the release point Dagoretti Corner which is about 10 miles to the west of the Airport (see Figure 1).

North-east monsoon season.—The wind at 800 mb shows a steady annual change at both 0000 and 1200 GMT (Table II). The early morning direction varies as the surface wind from a more easterly point at the beginning and end of the season, to a maximum northerly component in December, almost equalled in January and February. The speed shows a seasonal rise and fall with a maximum in February of 14.1 kt (14.4 kt scalar). By 1200 GMT daily, the 800 mb wind has undergone a rather similar change in direction to the surface wind, a veer towards east and, in general, a decrease.

South-east monsoon season.—There is a southerly component in May to the end of September with, as may be expected, a maximum in the mid-season month of July. This month shows the maximum speed also. By afternoon a rather different picture presents itself. May, June and September show a continuing tendency to veer, whereas in July and August, when the southerly component is greater, the tendency is to show backing at this level. However, a notable difference from the north-east monsoon is the increase in speed at this time, rather than a decrease.

Upper winds at 700 mb.—The 700 mb level is equivalent to 4200 ft (1280 m) above release point.

North-east monsoon season.—At 0000 GMT the north-east monsoon is extended over a longer period than at lower levels (Table II). Northerly components are apparent in all months except July, August and September. Also, apart from October, November and June, the direction is fairly well in phase with the flow at 800 mb. Speeds do not show such a steady progression as those at lower levels and reach a maximum in March (14.2 kt vector mean and 15.1 kt scalar).

Directions, however, do show a steady progression throughout, from well to the east (085° in October), back to north-east (044° in February) and

veering again towards east (083° in May). The steady seasonal progression from northerly to southerly components is interrupted in June when the mean direction at 0000 GMT is 074° . The vector mean speed, however, is very low (2.5 kt) compared with the scalar speed (7.6 kt).

By 1200 GMT, southerly components from May to September, have reduced the north-east season to the same length as at lower levels. All winds from November to the end of April have veered and decreased compared with 0000 GMT as may be expected from the exchange of momentum with lower winds in the turbulent mixing layer. At this time of day the wind flow below 700 mb is extremely uniform in direction, as may be seen from October to the end of April, and December is markedly so.

South-east monsoon season.—At 0000 GMT there is no true south-east monsoon season as such at 700 mb and it may be described as a shorter season with southerly components, July and August showing a good deal of westerly influence, and only September having an easterly as well as a southerly component. The difference between the vector mean and the scalar speeds indicates a large variation about the mean.

By 1200 GMT daily, 700 mb winds have all resumed their easterly components and, as indicated above, a southerly component is apparent at this level from June to the end of September. Again, as opposed to the north-east monsoon season, speeds have increased rather than decreased. Also this applies to May and October at this level ; with a direction of 088° in both months, the season could be called transitional at these times.

Discussion.—

Surface wind.—The overall picture provided by Tables I and II confirms what may be expected from a station on the western fringe of the Indian Ocean monsoon system. There is a well-defined north-east season from October to the end of April, and a southerly or south-easterly season from May to the end of September. However, there are some variations in time and space which are of interest.

Figure 1 shows the line of the contours near Nairobi, and also the position of the Rift Valley and its west-facing escarpment wall. As indicated earlier, the time of maximum wind follows the time of maximum temperature at the Airport by about three hours. Figure 3 shows how the wind speed curve departs from the average temperature curve between the hours of 1200 and 1500 GMT. Several factors may combine to give this late maximum wind speed. Table III shows the average daily maximum temperature for each month at the rawin release point at Dagoretti, 5900 ft above MSL, and at Naivasha,

TABLE III—AVERAGE DAILY MAXIMUM TEMPERATURES FOR EACH MONTH AT DAGORETTI AND NAIVASHA

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
	<i>degrees Celsius</i>												
Dagoretti (5900 ft)	24.6	25.7	25.6	24.2	22.9	22.2	20.9	21.9	23.7	24.8	23.2	23.3	23.6
Naivasha (6234 ft)	27.7	28.3	27.3	25.1	23.8	23.0	22.5	22.9	24.5	25.6	24.7	25.8	25.6
Excess of Naivasha over Dagoretti	3.1	2.6	1.6	0.9	0.9	0.8	1.6	1.0	0.8	0.8	1.5	2.5	2.0

6234 ft above MSL (Figure 1), in the Rift Valley about 50 miles to the north-west. In spite of the excess 300-ft elevation of Naivasha, maximum temperatures throughout the year are higher than at Nairobi. This may help to increase the already established anabatic flow from the land configuration in the Nairobi area, and this may be further augmented by the excess late afternoon heating on the steep west-facing wall of the Rift Valley about 15 miles west of the city. Thus, this late and also greater heating, together with the fact that in the late afternoon the gentle eastward slope at Nairobi is losing its heat, may be the cause of the late maximum of surface wind at the Airport. A rather interesting feature of the anabatic effect on the wind flow over Nairobi is brought out in Table II. The components of the 800 and 700 mb winds at 0000 GMT were combined with the components of the 0300 GMT surface winds and averaged over each month. An average was also obtained for each month for the components of the 800 and 700 mb winds at 1200 GMT along with the 1500 GMT surface winds. The difference between the averaged components for the morning and afternoon times was then taken to represent the vector difference between the mean flow from surface to 700 mb in the morning and that in the afternoon. Over the whole year the vector difference was $100^{\circ} 4$ kt. This may be seen to be almost perpendicular to the average contour line near Nairobi, and the fact that the monthly vector differences were between 091 and 117° indicates a fairly steady component added to the wind flow each day. These monthly directions are shown on Figure 2 and it may be seen that the dry months tend to have a daily component more near to east than the wetter periods, when anabatic effects might be expected to be weaker.

A feature of the daily veering of the surface wind in the north-east monsoon season is the halt in the daily swing each morning between about 0600 and 0800 GMT. This feature is missing from the south-east season although June, August and September have this tendency earlier on, between 0300 and 0400 GMT, about sunrise. Otherwise, the diurnal cycle in the north-east monsoon and July call for little comment, but the rotation of wind directions through the full 360° in May, June, August and September is rather unexpected. Humphreys³ explains a complete daily cycle in the observations from Blue Hill Observatory as the tendency for winds to blow towards the region of maximum heating. At this season, in East Africa, on the macro-scale, the area of maximum heating is far to the north in the summer hemisphere. However, on the meso-scale the situation is rather different. Referring to Figure 1 it may be seen that the contours will allow considerable cold air drainage from the Aberdare Mountains to flow to an area over the flat plains north-north-east of Nairobi Airport. This would create a north-south gradient until the plains were uniformly filled with colder air at the surface, and only then would the weaker katabatic effect of the local gentle slope to the east become effective. That this does not happen in July is probably due to the stronger monsoon flow of mid-season dominating the situation.

Attention is drawn to Table IV which is a summary of constancy q of the surface winds at Nairobi Airport. Hourly values vary widely from a low of 7 at 0000 GMT in May to a maximum of 98 at 2000 GMT in January. These figures fit very well with January as the month of steadiest flow (88) and

TABLE IV—MONTHLY AND ANNUAL CONSTANCY q OF SURFACE WIND AT NAIROBI
AIRPORT 1959-63

Time GMT	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual mean
0000 ...	79	65	60	48	7	42	64	48	24	62	75	84	55
0100 ...	65	48	56	50	9	52	63	58	16	91	75	85	56
0200 ...	65	48	55	48	19	55	81	61	22	82	74	74	57
0300 ...	57	41	47	43	30	55	81	61	29	79	74	71	56
0400 ...	40	22	60	44	57	64	82	61	50	85	77	70	58
0500 ...	73	37	64	46	58	66	87	45	54	81	62	80	62
0600 ...	83	45	68	55	58	65	88	70	58	63	82	82	68
0700 ...	91	91	90	62	60	70	81	76	62	77	78	89	77
0800 ...	94	95	89	67	63	59	74	66	61	81	79	87	76
0900 ...	94	96	93	75	61	67	83	63	62	86	79	87	79
1000 ...	94	93	92	75	56	63	82	66	71	83	85	88	79
1100 ...	94	92	95	79	59	66	68	62	73	85	84	86	79
1200 ...	94	90	92	77	53	70	73	66	78	90	87	86	80
1300 ...	95	91	90	80	60	77	74	73	78	92	86	88	82
1400 ...	96	94	94	82	72	75	77	82	88	92	85	86	85
1500 ...	93	97	94	86	74	89	83	85	89	94	87	88	88*
1600 ...	94	95	90	86	73	88	84	83	96	91	82	89	87
1700 ...	91	91	85	81	51	77	89	82	91	86	90	86	83
1800 ...	91	86	85	76	48	65	83	71	86	88	86	91	80
1900 ...	93	86	88	88	33	27	41	55	77	87	88	93	70
2000 ...	98	82	78	62	33	16	30	19	46	81	86	93	60
2100 ...	94	91	72	48	30	33	60	12	44	82	79	90	61
2200 ...	83	77	68	49	16	42	60	26	38	88	73	90	60
2300 ...	77	65	67	59	19	41	66	41	33	88	80	90	60
Mean ...	88†	76	79	81	46	59	73	60	59	84	80	86	72

* Maximum annual hourly mean.

† Maximum monthly mean.

May as the month of least steady flow (46). The hour of least constant flow throughout the year is 0000 GMT (0300 local time) although there is little difference between that time and sunrise (about 0630 local time or 0330 GMT). The hour of greatest constancy is coincident with the time of maximum wind speed (1500 GMT) just before sunset, again emphasizing the strong effect of the superimposed anabatic flow at all seasons. Seasonally the north-east monsoon is steadier than the south-east, the constancy of January winds being quite remarkable. July stands out among the south-easterly months as the one with highest constancy, which might have been expected from the mid-season month.

Upper winds.—There is little to comment on in the monthly changes at these levels, apart from the peculiar backing of the 700 mb wind in June at 0000 GMT against the seasonal veering.

The diurnal changes in direction show, both at 800 mb and 700 mb the effect of the deepening of the turbulent mixing layer as evidenced by the height of the CCL in the various months (Figure 2). There are fairly significant changes from 0000 to 1200 GMT in each month as the flow between the surface and 700 mb obeys the influence of the upslope wind, although these changes are least in evidence when the season is more transitional than otherwise such as in April and September. The depth of the mixing layer at the time of maximum heating is further evidenced by the organization of the afternoon flow between the surface and 700 mb in most months. The north-east season shows this organization best; apart from November and December, a homogeneous flow exists from 800 to 700 mb in the morning, and from the surface upwards in the afternoon. The south-east monsoon is not so well

organized, probably because this monsoon is shallower than its counterpart, and does not extend to the 700 mb level. In July and August especially, there are considerable differences between the 800 and 700 mb winds at 0000 GMT. However, by 1200 GMT such are the combined effects of the mixing and anabatic influence, that the morning difference has been largely eliminated and the flow regularized to a considerable degree. The early and late months of the south-east season (May and September) which are more transitional, do show a great homogeneity, especially September. Diurnal changes in speed at 800 and 700 mb do not call for much comment in the greater part of the year. In most months, the maximum surface wind scalar speed is greater than that at 800 mb. The exceptions are July, October and November. This may indicate that the anabatic component which is in the direction of the general circulation, is of considerable magnitude.

Conclusion.—The results are what might have been expected in this part of the world with one notable exception. In this latitude just south of the equator it might have been anticipated that instead of a north-east monsoon, there would have been the beginnings of a north-west monsoon, as applies from about 45°E to New Guinea. That there is a north-east monsoon is because of the presence of the large heated land mass to the south and south-west with its resultant large heat low into which the local stream is drawn. The daily superimposition of a local topographic effect on the two monsoons is very clear from all the observations; just how far it extends upward is not known as winds above 700 mb were not investigated. The survey was started originally as applying to surface winds only.

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MAJOR STORMS IN WEST PAKISTAN IN SEPTEMBER IN RELATION TO THE MANGLA DAM PROJECT

By R. FROST

Summary.—As a part of the Mangla Dam project it was planned to divert the River Jhelum in September 1965 and the mean date of the recession of the south-west monsoon was taken as a provisional date for the diversion. Occasionally at the end of the monsoon in September (most often between the 16th and 20th of the month) there are major storms and floods in West Pakistan, and a long-term study which was made of these storms suggested that their frequency, which was low at the turn of the century, reached a maximum in the period 1945–50 and is now declining. The storm pattern appears to be linked with a secular change of sea temperature in the Bay of Bengal where the depressions originate as developments in the Northern Equatorial Trough. The depressions favour a track towards West Pakistan if the 300 mb ridge over East Pakistan extends west of its mean position. Synoptic studies were used to check the suitability of the date for the diversion.

The Mangla Dam Project.—When the Indian subcontinent was partitioned in 1947 the new international frontier between West Pakistan and India cut across the vast irrigation complex of the Indus Basin which had been developed over the past century, and it became necessary, therefore, for some arrangements to be worked out between India and Pakistan for access to and disposal of the waters of the Indus and its tributaries. By the Indus Waters Treaty of 1960 it was agreed that—in return for exclusive use by India of all waters flowing into the three eastern tributaries of the Indus, namely the Sutlej, Ravi and Beas—two major dams would be constructed, one at Mangla on the Jhelum, and the other at Tarbela on the upper reaches of the Indus. These dams, together with a system of canals, would transfer water from the rivers to which Pakistan would have exclusive rights, namely the Indus itself and its two other tributaries, the Jhelum and the Chenab, to the lower parts of the three eastern tributaries the Sutlej, Ravi and Beas (see Figure 1). All the Indus Water Treaty Works have been entrusted for execution to the West Pakistan Water and Power Development Authority by the Government of Pakistan.

A time clause in this treaty made it clear that India's right to the water of the three eastern tributaries would be recognized in 1970 but for three years thereafter Pakistan could demand the continuance of certain flows to her canals on payment of certain royalties. The scale of these however would increase from year to year until 1973 when India's proprietary rights would become all-embracing. It can be seen therefore that it is a matter of urgency for Pakistan for all replacement works and in particular the Mangla dam to be ready by the dates laid down by the Indus Waters Treaty.

On the design side the main consultants for the Mangla scheme are Binnie and Partners of London and the contract for the Mangla Dam which was awarded to a consortium of eight American firms is believed to be the largest-ever civil engineering contract. The estimate of the cost of this dam amounts to £425 million, based on 1963 costs, and the target date for its completion is July 1968.

In 1959 Dr. Tucker of the Meteorological Office assisted Binnie and Partners in carrying out maximum flood studies for the Mangla project and an account of his work is given in *Weather*.¹

The Mangla dam is now under construction and in order to complete the work of carrying the main dam across the final gap in the river Jhelum the contractors planned to carry out the critical diversion of the river immediately following the present south-west monsoon season, approximately one year ahead of schedule. For this to be successful it was necessary that the diversion should take place as early as possible in order that the dam could reach certain specified heights before the floods of the winter and the next summer monsoon. On the other hand as the consequences of a large flood immediately after the river diversion could be very serious the selection of the suitable date for the diversion was a matter of some importance. The provisional date of 10 September was selected for the commencement of the diversion and the Meteorological Office was asked if it could carry out studies of historic storms causing flooding in September and of the recession of the south-west monsoon, in order to assist in the interpretation of meteorological forecasts made on or immediately prior to 10 September. The Meteorological

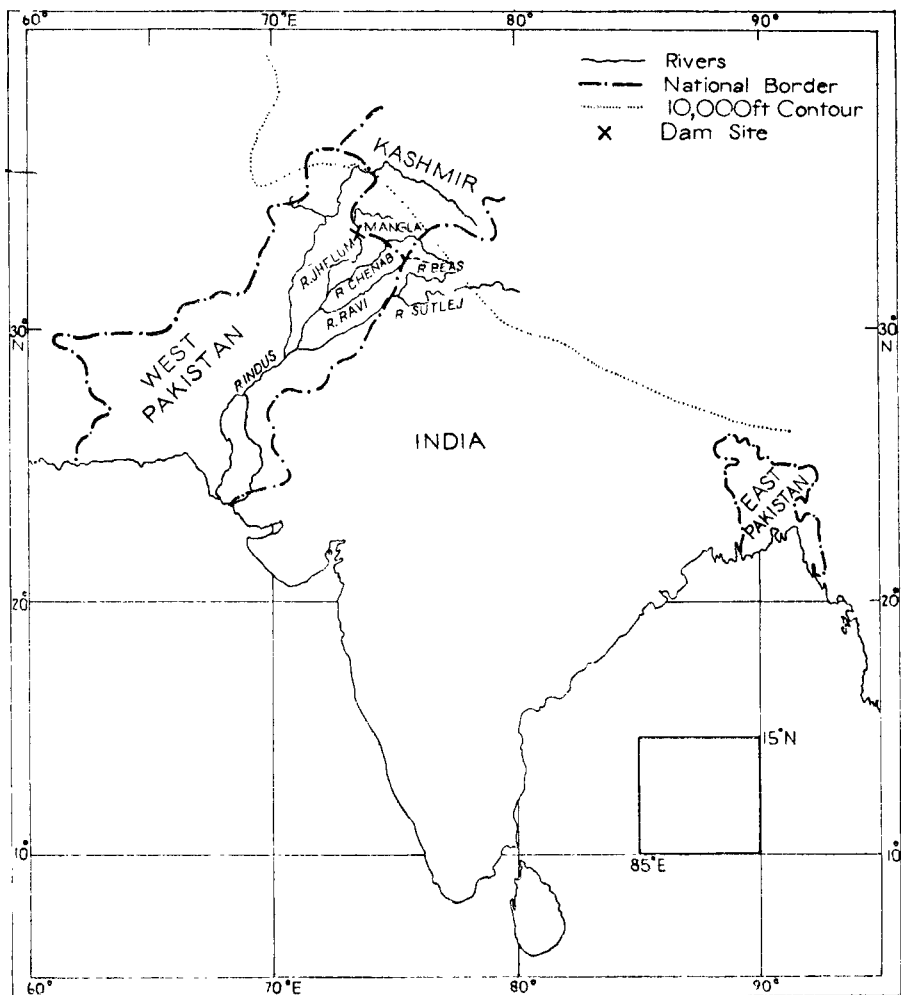


FIGURE 1—INDUS BASIN AND MANGLA DAM

Office was also asked if the writer, who had been closely associated with the present studies, could visit Lahore in early September to act as meteorological consultant on the project.

The mission in Pakistan was marred by the war which broke out between India and Pakistan on 6 September, and the imposition of meteorological security upon all weather reports made life somewhat difficult for the meteorological consultant. Fortunately, as indicated by the long-range weather forecasts based on the present studies and issued prior to 6 September in conjunction with the Pakistan Meteorological Service, no major storms affected West Pakistan during the critical phase of the river diversion and the work was carried out satisfactorily.

The recession of the south-west monsoon.—According to the *Climatological Atlas for Airmen* published (in Poona) by the India Meteorological Department in 1943, the mean date of the recession of the monsoon from that

part of India which is now Pakistan is 10 September and this was the provisional date selected for the diversion of the River Jhelum. Naqvi² however, using a longer series of observations, listed all dates of the recession of the monsoon from 1878 to 1960 and obtained as the average date of the recession 13 September with 31 August and 2 October as the earliest and latest dates respectively. The method of arriving at the dates of recession differed in the two cases. The India Meteorological Department in deriving their dates of recession used only 5-day normals of accumulated rainfall and selected the middle date of the period in which the characteristic fall occurred whereas Naqvi used all climatological data irrespective of rainfall amounts to determine when the monsoon current actually withdrew from West Pakistan.

Although the recession of the monsoon is less spectacular than the onset and has correspondingly received less study the floods which occur in West Pakistan in September at the end of the monsoon are in general more severe than those which occur at any other time.

Historic storms affecting West Pakistan.—From studies made by Naqvi³ and an examination of the September synoptic charts of the Indian sub-continent, it is clear that all major floods in West Pakistan during this month are caused by depressions which form over the north Bay of Bengal in the Northern Equatorial Trough (NET), more commonly known as the Intertropical Front (ITF), and move west-north-west across the Indian sub-continent curving northwards when at a line extending from about 24°N 70°E to 20°N 80°E. These depressions which do not in general reach beyond the 300 mb level have a life of about eight days from the time they form till the time they reach West Pakistan.

Approximately one in seven of all depressions which form over the Bay of Bengal in September and move over India curve northwards in this manner to affect West Pakistan and the main problems are to forecast the development of such depressions and to predict their tracks.

Table I lists the dates of all major storms which have affected West Pakistan in September during the period 1890–1964.

TABLE I—DATES OF MAJOR STORMS IN SEPTEMBER IN WEST PAKISTAN DURING THE PERIOD 1890–1964

Year	September	Year	September
1893	19	1945	14
1902	6	1945	25
1905	19	1947	26
1914	20	1949	19
1928	2	1950	19
1933	19	1954	25
1933	27	1955	25
1937	16	1959	16
1941	12	1961	16

Table II, which is derived from Table I, gives the number of major storms in West Pakistan for each 5-day period in September during the period 1890 to 1964.

TABLE II—NUMBER OF MAJOR STORMS IN EACH PENTAD OF SEPTEMBER DURING THE PERIOD 1890–1964

Pentad	1 – 5	6 – 10	11 – 15	16 – 20	21 – 25	26 – 30
Number of storms	1	1	2	9	3	3

Inspection of Table II suggests that if a major storm affects West Pakistan in September the most likely time for this to occur is between the 16th and 20th of the month.

The somewhat striking peak occurrence in the storm frequency over West Pakistan between the 16th and 20th of the month appears to be associated with the increased convectivity which develops in the NET as it moves southwards from over the land to over the north Bay of Bengal during the first week of September.

TABLE III—NUMBER OF STORMS PER DECADE IN SEPTEMBER

Decade	1890-99	1900-09	1910-19	1920-29	1930-39	1940-49	1950-59	(1960-64)
Number in decade	1	2	1	1	3	5	4	(1)

In Table III the storms listed in Table I are grouped within decades. It can be seen from the table that for the 50 years from 1890 to 1939 there were only 8 major storms in West Pakistan in September whereas in the 20 years from 1940-59 there were 9. There is a suggestion in Table I that the storm activity reached its peak in the period 1945-50 and is now declining. Since these storms all form over the sea it was a logical first step to investigate whether the decadal variation in storm frequency was associated with a secular change in sea temperature in the Bay of Bengal similar to that found by Brown⁴ in the tropical Atlantic between the decades 1910-19 and 1940-49. This is discussed in the following section.

Storm frequency and sea surface temperatures.—It is known that tropical cyclones form only over warm tropical areas and that, with other factors remaining the same, the frequency of formation is greatest during the months when the sea surface temperatures are the highest.

Palmén,⁵ from a consideration of the release of latent heat energy with normal lapse rates in the tropics, found that sea temperatures in excess of 26-27°C were necessary for the type of deep convection which always accompanied tropical cyclones, whilst Fisher,⁶ from an examination of hurricanes in the tropical Atlantic, concluded that temperatures of 28°C were necessary to initiate hurricane formation. Table IV shows the mean sea temperature since 1900 in the five-degree sea square bounded by 10-15°N and 85-90°E. Observations on punched cards were unfortunately not available for the decade 1890-99.

TABLE IV—MEAN SEA SURFACE TEMPERATURES IN SEPTEMBER FOR EACH DECADE DURING THE PERIOD 1900-64

Decade	1900-09	1910-19	1920-29	1930-39	1940-49	1950-59	(1960-64)
Temperature degrees C	28.0	27.9	27.9	28.6	28.7	28.5	(28.0)

It can be seen from Table IV that the change in sea temperature between 1910-19 and 1940-49 is 0.8 degC which is of the same order of magnitude as the change found by Brown.⁴

Comparison of Tables III and IV indicates that the frequency of depressions over West Pakistan in September increases with increase of sea temperature above 28°C in the Bay of Bengal. This suggests that a sea temperature of 28°C is the critical temperature not only for the vigorous tropical cyclones discussed by Fisher but also for the tropical depressions in the Bay of Bengal. (Note.—Few tropical depressions over the Bay of Bengal develop into tropical cyclones in September, probably because the temperature at 200 mb is too

high and the necessary deep convection from the surface to 200 mb cannot take place. The temperature at 200 mb over the north of the Bay of Bengal reaches its maximum in July and does not in general fall below a critical value of -51°C until October).

Tracks of depressions originating over the Bay of Bengal.—

Various studies have been made of the tracks of depressions originating over the Bay of Bengal and the present studies support the conclusion that the flow pattern at 300 mb is the crucial pattern for forecasting the movement of storms over the Indian sub-continent, see for example Chelam.⁷

Figure 2, which is based mainly on data made available by Mr. C. V. Raman of the International Meteorological Centre, Bombay, shows the mean flow pattern at 300 mb in September over India and the adjacent land masses.

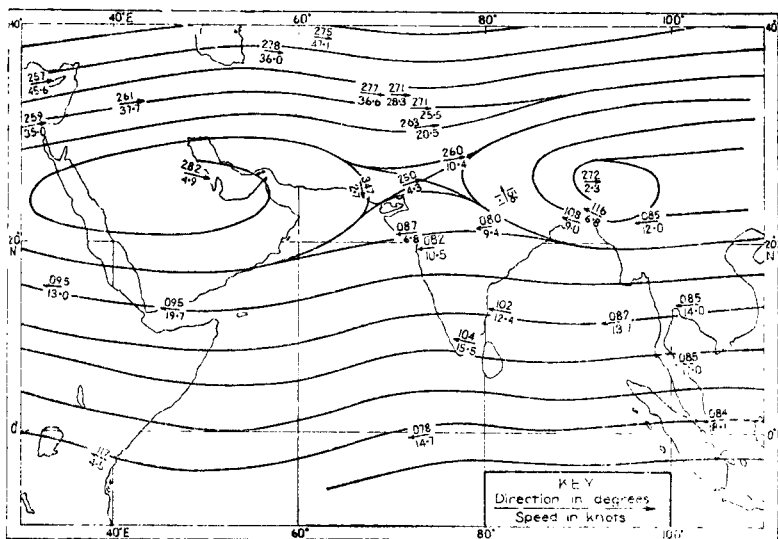


FIGURE 2—STREAMLINES AT 300 MB IN SEPTEMBER

Whether or not a depression from the Bay of Bengal causes severe flooding in West Pakistan depends upon the position of the subtropical ridge cell, which in Figure 2 is centred near East Pakistan. If the cell extends a few degrees to the west of its mean position the depressions move further west across India before curving north to give rise to heavy rains and severe flooding in West Pakistan. Conversely if the cell shifts a few degrees to the east then the curving northwards occurs earlier resulting in dry weather over West Pakistan.

Depressions which develop along the NET may occur singly or in families. If the latter is the case the first in the series appears to be the one most likely to affect West Pakistan. Following the passage of each depression the ridge cell at 300 mb over East Pakistan is displaced a few degrees to the east so that the next depression at the surface passes to the east of its predecessor. The number of depressions in a family is variable but in general appears to be about three.

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Binnie and Partners for permission to publish this paper. The author also wishes to acknowledge with thanks the help and co-operation which he received from Dr. Naqvi, Director of the Pakistan Meteorological Service, whilst in West Pakistan.

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OBITUARY

Mr. L. H. G. Dines, M.A.—Lewin Henry George Dines died on 6 October 1965 at his home in Teddington, less than three weeks before his 82nd birthday. He joined the staff of the Meteorological Office in 1912, and served as Chief Assistant at Eskdalemuir Observatory and Valentia Observatory, and as Superintendent at Valentia from 1920 to 1922. After a year at Benson—the Observatory of those days, not the airfield—he came in 1923 to Kew Observatory where he remained until his retirement in 1947 at the age of 64.

He was the son of W. H. Dines, and his life's work was guided by his father's interests ; at Eskdalemuir he was a contemporary of L. F. Richardson. As a scientist he did not compare with these two great men, but he was for many years their loyal and diligent helper, and would be content to be so remembered. Though his publications include notes on wind structure and on the dynamics of cyclones he was mainly concerned with instrumentation and the exploration of the upper air in the days before the radiosonde. Before he joined the Meteorological Office he spent some time in the locomotive workshops of the Great Western Railway at Swindon and this experience may have contributed something to the strength and durability of even the lightest of his balloon-borne instruments. Perhaps his most ingenious device was that flown in the 1930's to obtain samples of stratospheric air subsequently analysed for water vapour and helium in Professor Paneth's laboratory at Durham. He did not solve the problem of how to exclude extraneous water vapour from the sample, but he may have come nearer to a solution than others working twenty years later. He was in charge of the first radiosonde flights made by the Meteorological Office.

His retirement was devoted to Church administration and the spirited companionship of the four daughters who survive him.

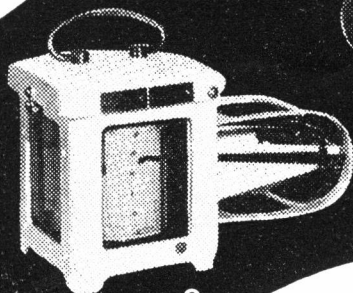
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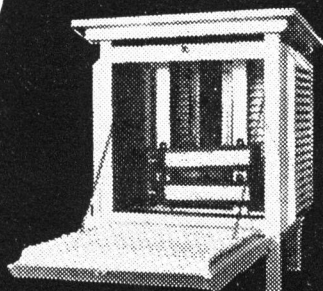
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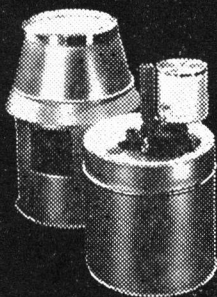
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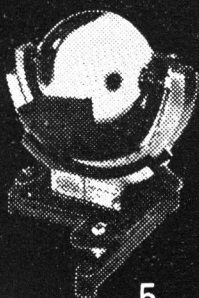
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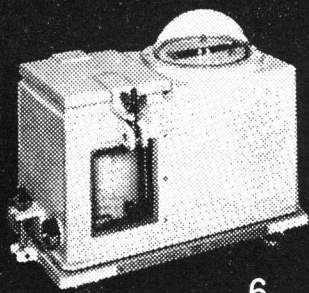
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CONTENTS

	<i>Page</i>
The behaviour of the first six zonal wave numbers at 50 and 500 millibars during some winter months in 1958 and 1959. G. R. R. Benwell	33
Low-level wind flow at Nairobi. B. Ramsey	47
Major storms in West Pakistan in September in relation to the Mangla Dam Project. R. Frost	57
Obituary	63
Corrigendum	63

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