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THE STRUCTURE

OF THE

ATMOSPHERE OVER BENSON (OXON) ON 3RD MARCH, 1920.

BY

E. G. BILHAM, B.Sc.

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CHANGE OF WIND DIRECTION WITH HEIGHT ON 3RD MARCH, 1920.

A registering balloon was sent up at Benson on March 3rd at 4.15 p.m. and kept in view by means of a theodolite for the unusual time of 97 minutes. Its rate of ascent should have been 1k. in 6 minutes (547 feet per minute), giving a height of at least 16k. (52,500 feet). On the return of the instrument it was found that the balloon had not burst and had only reached a maximum height of 12·6k. (41,300 feet), hence the ordinary rule of working up cannot be applied. But the conditions were so unusual that they are worth putting on record. The balloon went away with a WSW. wind of about 5 m/s. (11 m.p.h.), which veered to WNW. at about 3k. (10,000 feet) with decreasing strength. It then came back reaching an altitude of 57° to the North, and when last seen was at an altitude of 22° to WNW. It fell at Islip 15 miles to NNW. There must have been a fairly strong easterly component in the higher strata, which is contrary to the rule that the westerly component increases with height. The height of the stratosphere was met with at 12·5k. (41,000 feet), and the temperature was practically isothermal to 2·5k. (7,500 feet).

(Signed) W. H. DINES.

For the purpose of examining the structure of the atmosphere on this occasion in greater detail it is fortunate that observations of pilot balloons to sufficiently great heights are available from the neighbouring stations of Kew Observatory (Richmond) and Calshot. The results for each 5,000 feet are given in Table I. At both stations the balloon was liberated earlier in the day than at Benson, but as the pressure distribution remained practically the same throughout the day, the difference of time is probably negligible. Both observations show a diminution in the westerly wind at 10,000 feet and the development of an easterly component above. If we disregard the Kew value at 45,000 feet (which seems anomalous), it is clear that the easterly current was predominant up to at least 55,000 feet.

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TABLE I.—PILOT BALLOON OBSERVATIONS. 3RD MARCH, 1920.

Height.	Kew Observatory. 14h. 15m.		Calshot. 12h.	
Feet.	Direction (° from N.)	m.p.h.	Direction (° from N.)	m.p.h.
55,000 ...	100	33	—	
50,000 ...	100	20	—	
45,000 ...	290 (?)	18	—	
40,000 ...	105	9	—	
35,000 ...	40	26	—	
30,000 ...	130	22	85	33
25,000 ...	165	13	100	21
20,000 ...	165	5	80	15
15,000 ...	175	7	130	12
10,000 ...	215	7	275	6
5,000 ...	270	25	265	21
Surface ...	240	8	135	2

It may be remarked in passing that the rule referred to by Mr. Dines that the westerly component increases with height is one to which exceptions are very numerous. An inspection of published upper air data shows that easterly winds at great heights are not unusual. Taking the values published in the Geophysical Journal for the years 1917 and 1918 a height of 33,000 feet (10k.) or above was reached on six occasions, the velocities found at that level being as follows :—

Station.	Date.	Wind at 10k.		
		Direction.	Velocity.	
		°	m.p.h.	m/s.
S. Farnboro' ...	July 6, 1917	270	35	15·5
Benson	Aug. 6, 1917	50	21	9·4
Cahirciveen ...	Dec. 22, 1917	55	54	24·0
Cahirciveen ...	April 26, 1918	315	22	10·0
Cahirciveen ...	April 30, 1918	135	5	2·4
Eskdalemuir ...	Nov. 16, 1918	95	29	13·0

It will be seen that an easterly component was present on four out of the six occasions. In his discussion of pilot balloon ascents reaching the stratosphere* G. M. B. Dobson gives a diagram showing the variation in wind direction with height for all such ascents published by the International Commission for Scientific Aeronautics from 1904 to June, 1912. This diagram shows that at great heights an easterly component is almost, if not quite as prevalent as a westerly, a fact to which attention was directed by Sir Napier Shaw in the discussion of the paper. Only one case is shown, however, in which there was an easterly current above a westerly or south-westerly current of appreciable thickness, so that it would appear that the case now under consideration is correctly described by Mr. Dines as so unusual as to be worth putting on record.

* G. M. B. Dobson "*Winds and Temperature Gradients in the Stratosphere*," Q. J. Roy. Met. Soc. XLVI. Jan., 1920. pp. 54–64.

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The surface conditions at 13h. on March 3rd are shown in Fig. 1, isobars being drawn for steps of 4mb. and isotherms for steps of 5°F. During the two preceding days there had been considerable changes in pressure distribution. At 7h. on the 1st a deep V-shaped depression was approaching the West Coast of Ireland from the Atlantic. The trough moved eastward across the British Isles and was over the North Sea at 13h. on the 2nd. A rapid rise in pressure occurred in its rear, with strong north-westerly and northerly winds. At Valencia at 17h. on the 2nd a pilot balloon observation showed that the northerly current extended as high as 15,000 feet, where its velocity was 60 m.p.h. The rise of pressure was due to a north-easterly extension of the Azores anticyclone which subsequently formed a belt of high pressure along the English Channel. At 1h. on the 3rd the barometer stood as high as 1,040 mb. at Pembroke and Valencia but pressure fell somewhat during the day. Meanwhile a deep depression had developed over Iceland and there was a steep westerly gradient extending from about lat. 52° to 63° N., the surface wind reaching gale force in places. Pilot balloon observations at Sleaford and Pulham during the evening of the 3rd showed that this current was "solid" up to 12,000 feet. Pulham is 100 miles NE. from Kew and was close to the southern edge of the region of parallel isobars lying to north of the anticyclonic region of which Benson and Kew were representative. With the exception of the Benson observations no upper air temperature readings on the day in question are available for British stations. At Puy-de-Dôme (4,800 feet) in Central France the temperature at 18h. was 48°F. (282a.) and at Servance (3,950 feet), 45°F. (280a.).

It was pointed out by F. J. W. Whipple that the easterly wind in the higher strata would be accounted for by warm air between the surface and 10,000 feet over England and cold over the Continent giving a temperature gradient from North to South, and in asking me to investigate the matter Lieut.-Colonel E. Gold suggested that the sources of air supply should be determined by drawing trajectories of the upper winds. The Puy-de-Dôme observations showed, however, that the air at 5,000 feet over Central France was not markedly cold, and it was felt that a more detailed knowledge of the temperature gradients in the neighbourhood of Benson at various heights was desirable. The Kew upper wind data were used as the basis of calculation in preference to the Calshot values partly because of the greater height reached and partly because the conditions over Kew were more likely to approximate to those over Benson. Actually, the upper winds reported by Kew give the balloon a trajectory closely agreeing with Mr. Dines' description. The values at the levels corresponding to the temperature observations were obtained by interpolation from the original data in which values for wind velocity are given at each 1,000 feet of height up to 10,000 feet and for each 5,000 feet above. The full data are given in Table II.

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DISTRIBUTION OF PRESSURE AND TEMPERATURE AT 13h., MARCH 3rd, 1920.

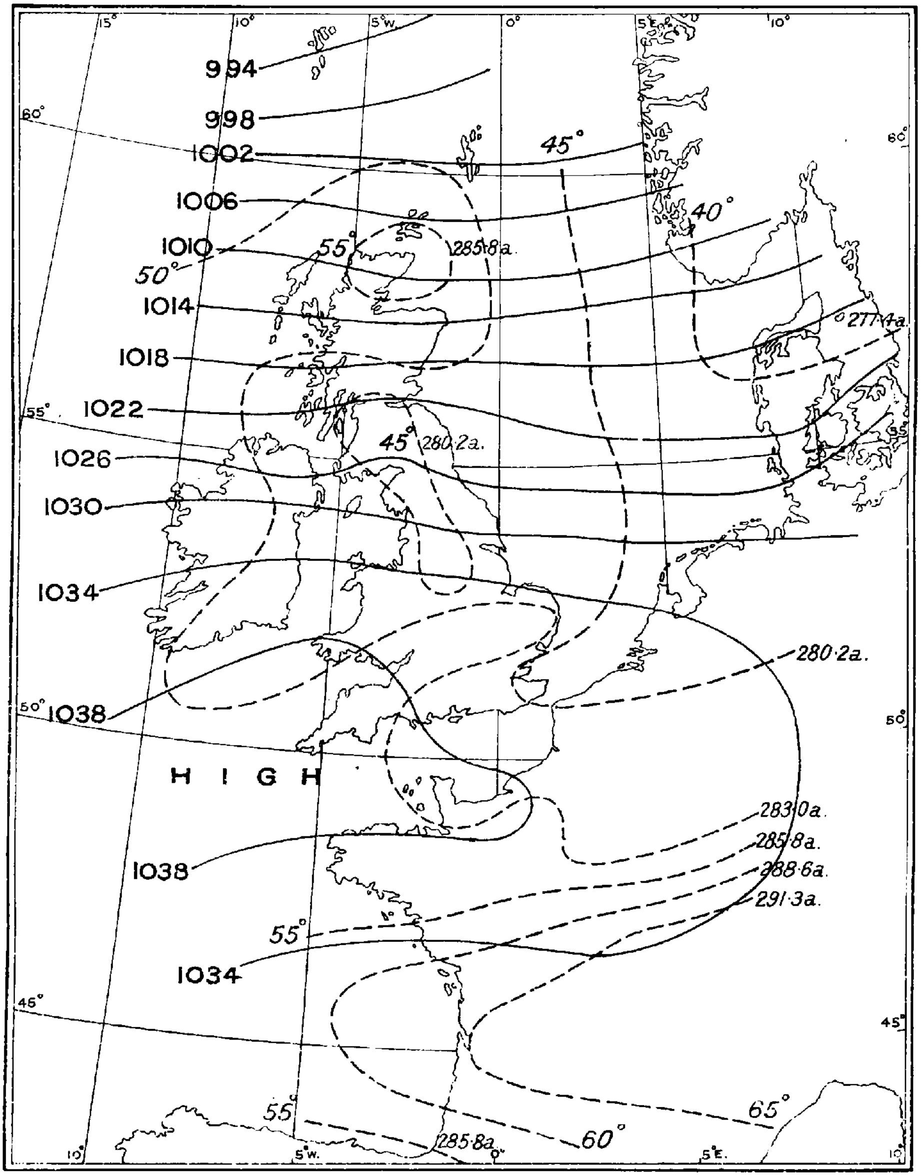


TABLE II.—UPPER AIR PRESSURES AND TEMPERATURES AT BENSON AND UPPER WINDS AT KEW.

Benson 16h. 15m.					Kew Observatory 14h.			
h		*p*	T	*p*/T	V	ϕ	V_{W-E}	V_{S-N}
ft.	k.	mb.	200a+	mean.	m.p.h.	° from N.	m.p.h.	m.p.h.
41,300	12·6	185	9	0·88	—	—	—	—
41,000	12·5	188	9	0·90	—	—	—	—
39,400	12·0	204	13	0·96	9·0	105	—8·7	2·2
36,100	11·0	238	21	1·08	21·0	57	—17·7	—11·4
32,800	10·0	277	28	1·22	25·1	76	—24·4	—1·8
29,500	9·0	320	36	1·36	21·9	130	—16·8	14·1
26,200	8·0	369	43	1·52	16·1	155	—6·7	14·6
23,000	7·0	425	49	1·68	10·0	165	—0·9	9·8
19,700	6·0	487	59 54	1·90	4·9	165	—0·4	4·9
16,400	5·0	556	63	2·12	6·0	172	—0·9	6·0
13,100	4·0	631	68	2·36	6·9	188	0·9	6·9
9,830	3·0	717	75	2·61	6·9	215	4·0	5·6
8,200	2·5	762	77	2·75	—	—	—	—
6,550	2·0	810	78 78	2·92	4·9	310	3·8	—3·1
4,920	1·5	862	79 79	3·09	25·1	270	25·1	0·0
3,280	1·0	917	79 78	3·29	24·0	272	23·0	0·0
1,640	0·5	975	80 75	3·55	15·0	256	14·6	3·6
Sur	face.	1027	80 76	3·70	8·1	240	6·9	4·0

The notation is that of the Computer's Handbook II. § 3.

The mean temperature and pressure gradients for consecutive layers 3,280 feet (1 kilometre) thick, have been calculated by the method given in The Computer's Handbook Sec. II. §.3, and the results are given in Table III. In this table the term

TABLE III.—MEAN GRADIENT OF PRESSURE AND TEMPERATURE IN SUCCESSIVE LAYERS 3,280 FEET (1k) THICK.

Number of Layer.	Height of Top of Layer.		Pressure Gradient.	Distance Apart of Isobars.*		Direction of Slope.	Temperature Gradient.	Distance Apart of Isotherms.		Direction of Slope.
	ft.	k.	mb. per 100 k.	miles.	k.	°from N.	a per 100 k.	miles/°F.	k/a.	°from N.
12	39,400	12	0·27	235	376	340	1·82	19	55	122
11	36,100	11	0·46	136	218	344	1·32	26	76	238
10	32,800	10	0·49	128	205	18	2·04	17	49	298
9	29,500	9	0·48	131	209	51	1·32	26	76	358
8	26,200	8	0·36	173	277	74	0·98	36	102	42
7	23,000	7	0·23	271	434	85	0·75	45	134	82
6	19,700	6	0·20	311	498	84	0·14	242	698	245
5	16,400	5	0·27	233	372	92	0·27	128	370	338
4	13,100	4	0·31	204	327	113	0·48	71	209	25
3	9,830	3	0·21	304	486	166	1·27	27	79	92
2	6,550	2	0·79	79	127	186	2·63	13	38	350
1	3,280	1	0·92	68	109	171	2·38	15	42	194

* Consecutive 1 mb. Isobars.

"direction of slope" means the direction of most rapid increase in the quantity specified. A graphical representation is given in Fig. 2, which has been drawn on similar lines to those in Shaw's "*Manual of Meteorology*" Part IV. p. 87. Within each circle is a plan of consecutive isobars and isotherms for the layer indicated in kilometres by the figures at the side. In each case isobars are represented by full lines and isotherms by pecked lines. The isobars shewn at each level are the one passing through the point of observation and that representing a pressure 1 mb. higher. The arrows are drawn so that higher pressure lies to the right of their direction of flight. The representation of temperature distribution is exactly similar, the space between the isotherms being shaded. The radius of each circle represents 156 miles (250 kilometres).

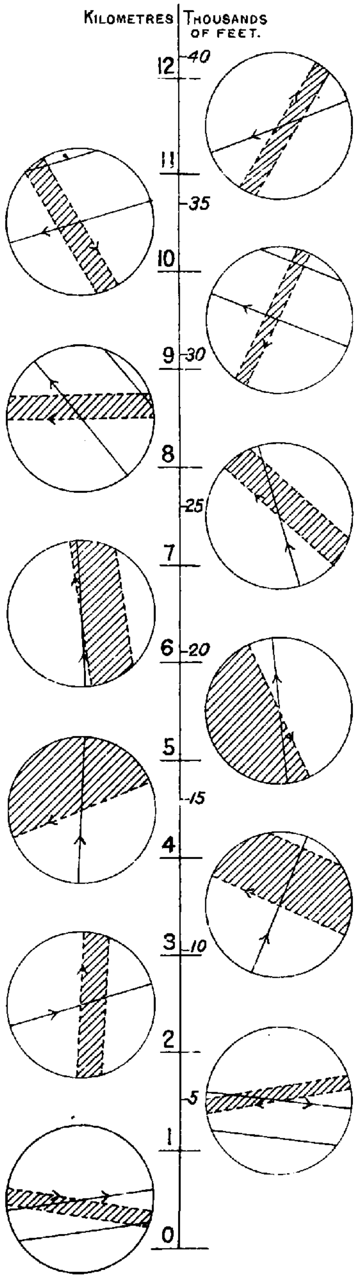
The results show a remarkable degree of complexity, especially in the lower layers. In the first layer we find a steep temperature gradient towards South, in the next layer towards North, in the next towards East, and in the next towards North-East but considerably less steep. Between 10,000 feet and 20,000 feet there is little variation in temperature in the horizontal plane, but a fairly strong gradient towards East reappears in the next layer. Each successive layer then shows a regular backing of the gradient, the total change of direction between 19,700 feet (6k.) and 39,400 feet (12k.) amounting to 320°.

Turning to pressure, we observe that there is practically no gradient between 6,550 feet (2k.) and 23,000 feet (7k.), and that between 23,000 feet (7k.) and 39,400 feet (12k.) the direction of slope backs from 74° to 340°, a total change of 94°.

It is now clear that in order to account for the easterly current we have to explain the existence of a very complex temperature distribution in the upper air. We shall, however, go far towards a complete explanation if we can account for the reversal of the horizontal temperature gradient between the first and second layers. Fig. 1 shows a rather curious distribution of surface temperature. The warmest region is Central France where readings above 65°F. (291·3a.) are found. Another warm area is seen over the North of Scotland and the Orkneys. A well marked cold area extends from Glasgow to Nottingham, so that we find a range of more than 10°F. (5·6a.) in what appears to be a uniform westerly current of air. It may be remarked, however, that the cold area referred to is not found on the 18h. chart, the temperature having risen to 48°F. (281·9a) at Nottingham and 49°F. (282·4a) at Glasgow. From the general distribution of surface temperature it would be difficult to say what temperature gradient in the first layer is to be expected in the neighbourhood of Benson. The average gradient at the surface between Nottingham and Central France is 4·9°F. per 100 miles (1·7a. per 100k.) towards South but local variations are considerable. Estimating the Puy-de-Dôme 14h. temperature as 50°F. (283a.) there was an average gradient towards SSE of 2·3°F. per 100 miles (0·8a. per 100k.) at about 5,000 feet.

Professional Notes No. 21.

HORIZONTAL PRESSURE AND TEMPERATURE GRADIENTS.

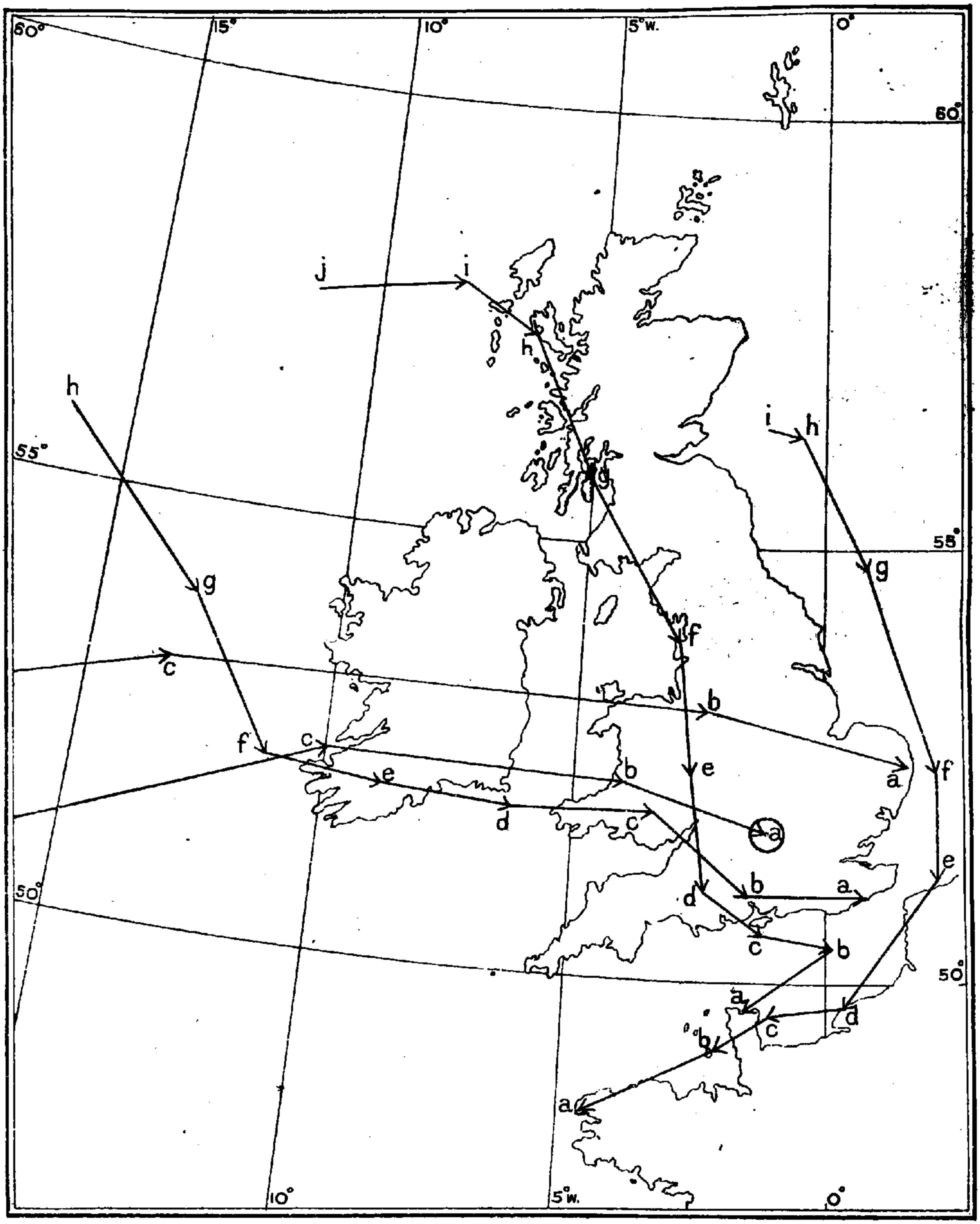


Full lines are isobars drawn for 1 mb. intervals. Pecked lines are isotherms drawn for 1 a intervals. The radius of each circle represents 250 kilometres. Higher pressure or temperature lies to right of the direction of flight of the arrows.

Figure 3a.

Professional Notes No. 21.

TRAJECTORIES OF GRADIENT WIND.



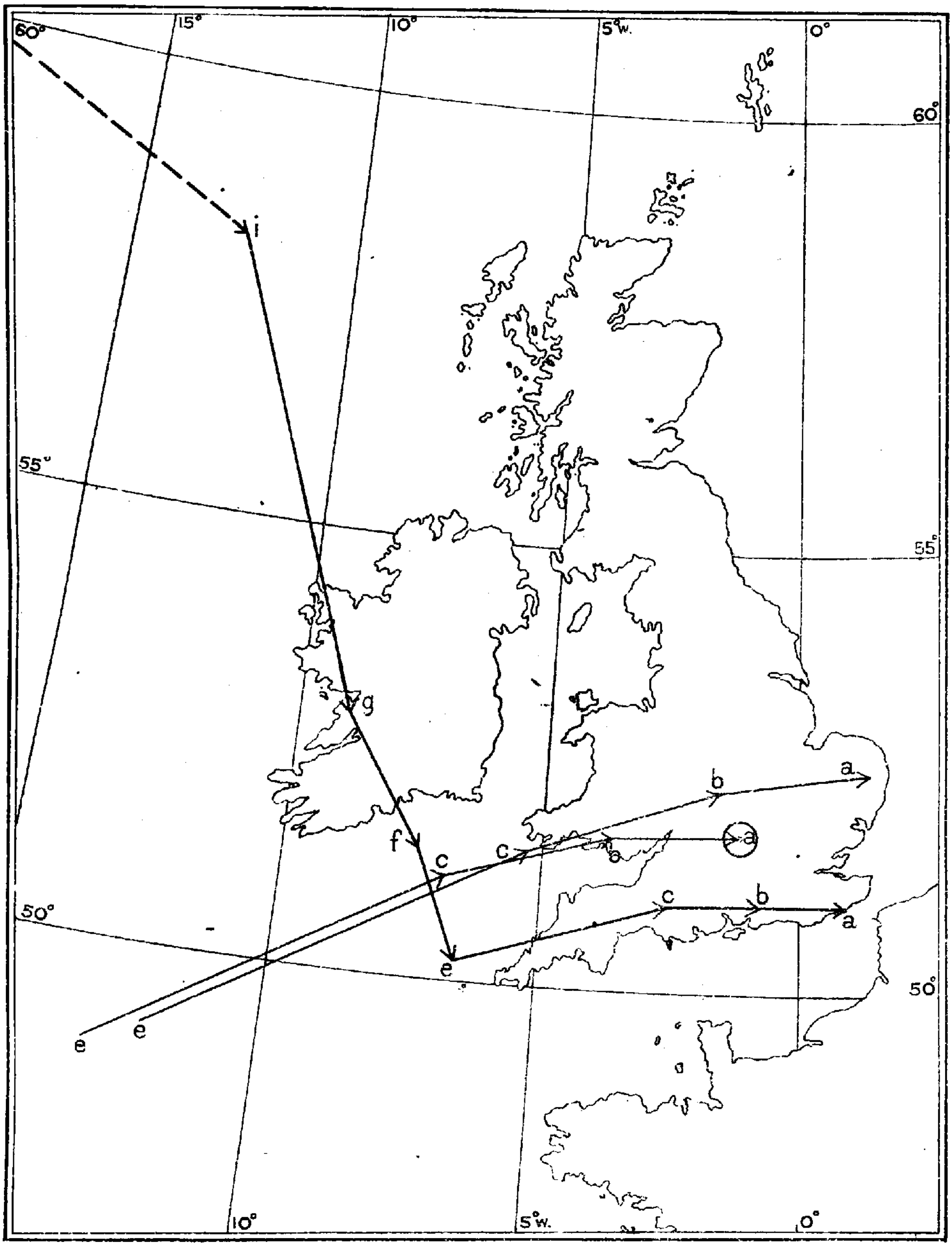
a — March 3rd, 18h. ; b — March 3rd, 13h. ; c — March 3rd, 7h. ; d — March 3rd, 1h. ;
e — March 2nd, 18h. ; f — March 2nd, 13h. ; g — March 2nd, 7h. ; h — March 2nd, 1h. ;
h — March 1st, 18h. ; i — March 1st, 13h. ; j — March 1st, 7h. ; k — March 1st, 1h.

Benson is at the centre of the small circle.

Figure 3b.

Professional Notes No. 21.

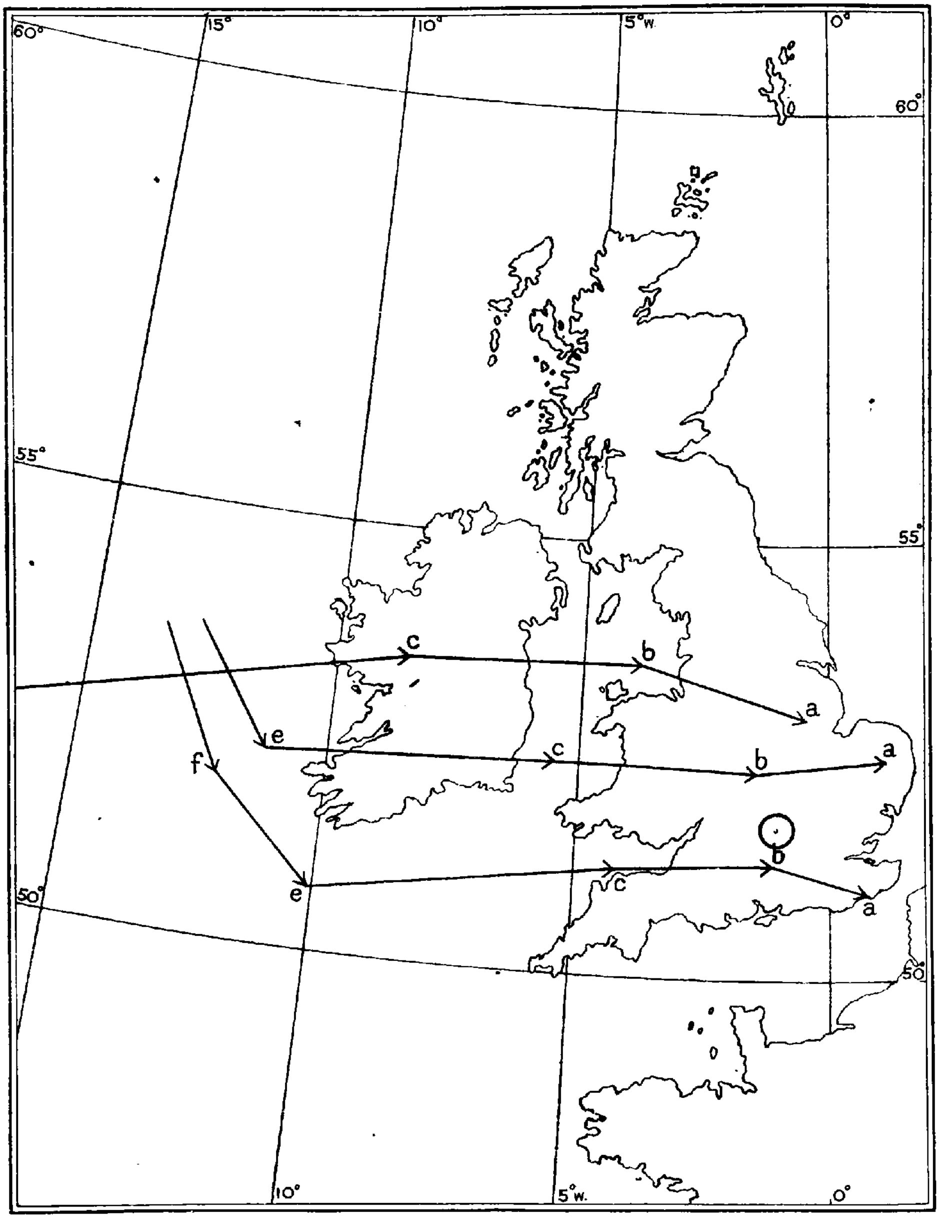
TRAJECTORIES OF WIND AT 2,000 ft.



The significance of the letters is the same as in Fig. 3a.

Professional Notes No. 21.

TRAJECTORIES OF WIND AT 5,000 ft.



The significance of the letters is the same as in Fig. 3*a*.

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An attempt has been made to trace the source of the upper winds by two methods. The first consisted in drawing trajectories of gradient winds, these being computed from the sea-level isobars by the ordinary method, without reference to the pilot balloon observations. Trajectories of air arriving at various selected points at 18h. on March 3rd are shown in Fig. 3a. They suggest that the air lying to northward of Benson had moved rapidly up from the Azores region, while over the Channel and South Coast of England the supply of air was derived from a more northerly region. A trajectory, not shown in Fig 3a., was also drawn for the air reaching Paris. It showed that this air had moved up very slowly from the South.

The use of computed gradient winds is, however, open to some objections especially in anticyclonic conditions where the gradient is slight and often indefinite in direction. Where the upper air conditions are very complex, as in the present case, there is moreover a considerable element of uncertainty as to what particular height the calculated wind system is to be attributed. On the other hand there are serious difficulties to be overcome in attempting to draw trajectories from the actual wind observations, on account of the comparatively small amount of data available. It was, however, felt to be essential to make some attempt to investigate the life history of the currents at 2,000 feet and 5,000 feet, representative of the first two layers. The following method was eventually adopted. For each hour of observation (7h., 13h. and 18h.) on March 1st, 2nd and 3rd, the observed wind at each station was represented on a chart by means of an arrow drawn up to the station whose direction was that of the wind and whose length was equal to the velocity of the wind multiplied by the time elapsed since the previous chart. Thus if a station reported "270° 15 m.p.h." at 18h., an arrow was drawn in a westerly direction 75 miles long on the scale of the chart. The end of the arrow thus represents the point from which air would have to start at 13h. to reach the station at 18h., travelling with the velocity and direction observed at 18h. If we knew the velocity and direction corresponding to its position at 13h. we could continue its trajectory back to 7h. and so on. If no observation were available it was usually possible to make an estimate from neighbouring arrows. Some trajectories sketched in this way are shown in Fig. 3*b* (2,000 feet) and 3*c* (5,000 feet).

It will be observed that the trajectories at 2,000 feet are in reasonable agreement with those drawn from the gradient winds. We observe that immediately to northward of Benson the air had come up rapidly from a west-south-westerly point while to southward the air had moved more slowly from a region to north-west of the British Isles. At 5,000 feet we see a somewhat similar state of affairs, but the line of demarcation between the two currents is much further northward. Calling the more northerly current A and the more southerly B, it would appear that a vertical through Benson lies in B at 2,000 feet and in A at 5,000 feet The interface between the currents therefore appears to be an inclined plane sloping downwards towards South at the rate of 3,000 feet in 100 miles. The angle of slope is 18′ (1 in 193), and it would intersect the surface about 100 miles South of Benson, that is to say, along the ridge of the anticyclonic belt over the English Channel. In spite of its more northerly origin we have to conclude that A is the warmer of the two, at any rate up to 5,000 feet. The observational material is insufficient to carry the investigation to greater heights. The Benson temperature observations indicate, however, that whatever its origin may have been the air above 5,000 feet was unusually warm. The temperature at each point up to 32,800 feet (10k.) was about 20°F. (11a.) above the mean for March and from 3·6°F. to 5·4°F. (2a. to 3a.) above the mean anticyclonic temperature. It seems probable that if the trajectories could have been carried further backward it would be found that the current A was initially derived from an equatorial source.

It is much to be regretted that no upper air observations to sufficiently great heights are available from stations North of Benson in order to confirm the existence of the inclined plane referred to above. The work of V. Bjerknes and J. Bjerknes on the mechanism of cyclones has shown that the surface of separation between the warm (equatorial) and cold (polar) currents takes the form of an inclined plane up which the warm air has to ascend. In spite of the manifest sources of error in the present enquiry we have found a distinct indication of something similar in the case of an anticyclone. The case we have investigated resembles to some extent one quoted by M. A. Giblett (March 11th, 1918) in the discussion of a recent paper by V. Bjerknes.* The value for the angle of slope of the surface bounding the warm current above in that case was 0·8°. V. Bjerknes finds that the average slope of such surface agrees with Margules' theoretical estimate of 1 in 50 to 1 in 100 (1°·1 to 0°·5). We conclude therefore that the slope found on 3rd March, 1920, was considerably below the average value.

* "*The Structure of the Atmosphere when Rain is falling.*" Q. J. Roy. Met. Soc. XLVI., 1920, pp. 119–140.