VI. *The Vertical Temperature Distribution in the Atmosphere over England, and some Remarks on the General and Local Circulation.*

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During the past four years a considerable number of small free balloons carrying self-recording instruments have been sent up in the British Isles, and sufficient observations have now accumulated to give some idea of the conditions which prevail over England, to a height of about 10 miles, in summer and winter, in cyclonic and anticyclonic weather.

Material Available.

The method of obtaining observations is fully described in a publication of the Meteorological Office, M.O. 202. It will suffice here to state that a small self-recording instrument, weighing 1 oz. (35 gr.), is attached by about 30 ft. (9 metres) of strong thread to a small rubber balloon. The balloon is 1 ft. diameter when unstretched. It is filled with hydrogen until it is expanded to about 1 m. diameter, securely tied up, and then let go. The balloons generally rise until they burst, and carry the instrument on the average to a height of 10 miles (16 km). A label offering a reward of 5*s*. is attached to the instrument, and the reward is claimed and the instrument returned in two cases out of three.

The trace when recovered consists of a pressure-temperature diagram, from which the temperature at any height may be obtained within about 1° C. It is comparatively seldom that a balloon fails to reach 10 km. height, or that the record is undecipherable; and more than 95 per cent. of the instruments recovered are able to yield a more or less satisfactory record. The heights reached have been very uniform, and mostly lie between 14 and 18 km., but in order that there may be no doubt as to the effect of extrapolation the tables are not carried beyond 14 km.

In all about 400 balloons have been sent up, and rather over 250 records have been obtained, but in forming the averages given in the following tables all these have not been used. The ascents of the first six months of the series are excluded, partly that the period dealt with may be an exact number of years, viz., the years 1908, 1909, and 1910, and partly because owing to want of experience the earlier results cannot be as reliable as the later. Thirty-two ascents are thus cut out. Of the remainder, nine either failed to reach 10 km. or had a defective trace. But the 200 odd ascents

that are left are not all available for the following reason. There are two sets of twenty relating to the same day, which were sent up at Manchester (at hourly intervals) for the purpose of investigating the daily temperature variation, and it is obvious that if all these were used in forming an average value, that value would be vitiated if any unusual conditions prevailed on the days in question. On other days, too, notably on the date of the supposed passage of the earth through the tail of HALLEY'S comet, the individual ascents are crowded too closely together to render them fit for the purpose. In cases where more than two ascents have occurred within eight hours the mean of such ascents has been formed and that mean taken as equivalent to an individual ascent.

The ascents have been made chiefly at Manchester, in Oxfordshire, and in Sussex, but there are 14 from Scotland and 6 from Ireland. All meteorologists are indebted to the liberality of Prof. SCHUSTER and to the Manchester University for the 145 balloons sent up there, of which 105 have been found. They are also indebted to Mr. C. J. P. CAVE who, notwithstanding the obstacle of his geographical situation at Petersfield, near to the Sussex coast-line, has made 42 successful ascents out of a total of 70. Pyrton Hill, 16 miles S.E. of Oxford, is the official station of the Meteorological Office. From it, and from Crinan, N.B., 125 balloons have been sent up and 81 found. For the others we have to thank the Joint Committee of the Royal Meteorological Society and the British Association.

The observations are fairly well distributed over the three years. The ascents have been made (mostly about the time of sunset) on days previously appointed by the International Aeronautical Commission, and thus it happens that three ascents are often available for the same day, one from Manchester, one from Pyrton Hill, and one from Ditcham Park, Petersfield. There is generally close agreement between the results from Ditcham Park and Pyrton Hill, since the stations are only 40 miles apart, hence the observations cannot be accounted independent, but in forming the averages the two observations have the merit of helping to cancel out any chance instrumental errors.

It cannot be contended that 200 observations distributed more or less by chance into 36 weeks spread over a period of three years will suffice to give good average values for the temperature of the upper air, but it seems desirable that the figures should be worked up and the best results that they afford obtained. It is also of interest to see what agreement there is with the tables similarly obtained on the Continent.

Annual Temperature Variation.

To obtain the annual temperature variation the observations have been sorted into months, and the mean temperature for each month at each exact kilometre of height formed. The crude result is given in Table I., but it is obvious that the values may be smoothed with advantage. Also, anyone working up these figures cannot fail to

notice that the temperature of the upper air over England is largely dependent upon the height of the barometer, and that above 10 km. the temperature is far more dependent upon the barometer than it is upon the season. If the number of observations were great enough in each month, variations due to the barometric height

TABLE I.—Mean Monthly Temperature at each even Kilometre.

Height.	A.	Grd.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	B.
	mm.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.
January . . .	763	75	72	69	64	58	52	46	40	33	26	22	18	17	16	16	15
February . .	760	78	75	70	65	59	52	46	38	31	25	20	17	16	—	—	14
March . . .	760	77	71	67	62	55	50	44	37	30	25	20	16	17	17	—	22
April	753	81	73	69	63	56	49	42	36	30	24	22	21	21	21	21	21
May	758	85	82	77	72	66	58	52	44	36	28	21	16	16	17	18	20
June	757	87	79	74	69	64	57	50	43	35	28	24	23	25	25	25	26
July	768	88	83	80	74	68	62	57	50	42	35	28	23	20	19	20	18
August . . .	762	88	83	78	74	69	63	56	49	42	35	26	21	21	22	22	23
September . .	765	89	87	80	76	70	65	58	52	45	39	33	27	22	17	17	16
October . . .	765	89	84	78	74	68	62	55	48	41	34	26	21	17	14	13	14
November . .	754	80	75	72	67	62	55	47	40	34	30	27	25	22	20	20	20
December . .	753	76	71	67	60	53	46	38	31	25	22	19	18	17	17	17	16

A.—Mean height of the barometer in mm.

B.—Mean of the temperatures at the highest point.

The temperatures are in absolute measure with the first 2 omitted.

would cancel out, but the column giving the mean of the barometer readings at the times of the observations shows that they do not do so. The first step therefore is to correct the monthly means for the height of the barometer. This has been done by means of Table VII., the formation of which will be subsequently explained.

The variation in the monthly barometric mean is small in England, and the values for the summer and winter are practically identical, hence the values in the table are chance variations. The values given in Table VII. have been plotted for each height, and from the curves so found corrections have been applied for each height in each month so as to reduce the values to a standard value of 760 mm. at ground level.

The corrected values are shown in Table II., and are considerably smoother than those of Table I., although it is obvious that some of them, notably those for May and December, cannot be accepted as correct.

The number of observations for each month, except for February and September, is over 10, but the 13 observations in May are concentrated on two dates, May 5th to 7th, 1909, and May 18th to 20th, 1910, and it chanced that very unusual but like conditions prevailed at both these periods. A similar remark holds for December, for which there are 16 observations, but 14 of them refer to the first week of the month in 1909. The temperatures shown in September are also discordant above 6 km., but this is not surprising owing to the paucity of observations.

Obviously the figures may be smoothed with advantage, and I consider that the best way is to form the first term of a Fourier series and use the values that it gives. The figures would doubtless give an appreciable coefficient to the second, and perhaps

TABLE II.—Mean Monthly Temperatures Corrected for Barometric Height.

Height.	Grd.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14 km.
	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C	° C.	° C.	° C.	° C.	° C.
January	75	71	68	63	57	51	45	39	32	25	20	17	17	17	17
February	78	75	70	65	59	52	46	38	31	25	20	17	16	—	—
March	77	71	67	62	55	50	44	37	30	25	20	16	17	20	—
April	81	72	68	61	55	48	41	34	28	23	22	23	23	22	22
May	85	82	77	72	66	58	52	43	36	28	21	17	17	17	18
June	87	79	73	69	63	57	49	42	34	28	24	22	24	25	25
July	88	82	79	73	67	61	55	48	40	33	26	22	20	21	23
August	88	83	78	74	69	63	56	49	42	35	26	21	22	24	24
September	89	86	79	75	68	63	57	50	44	38	31	26	23	20	20
October	89	83	77	73	66	60	54	46	40	33	25	20	18	17	16
November	80	75	73	68	63	56	48	42	36	31	27	23	20	19	19
December	76	71	68	61	54	47	40	33	27	23	19	16	15	15	16

to higher terms, but, in my opinion, the observations are too few to allow us to attach any importance to such coefficients. The annual variation is a certainty, but the six months' variation seems to me very probably due to pure chance. Taking a sufficient number of terms of a Fourier series we, of course, approximate to the actual figures given by the observations, but we do not thereby obtain a smooth curve.

The temperatures thus obtained are shown in Table III.

TABLE III.—Mean Monthly Temperatures at each Height. Smoothed.

Height.	Grd.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14 km.
	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.
January	76	71	67	63	57	50	43	37	30	24	20	17	17	16	16
February	76	71	66	62	56	49	43	36	29	23	20	17	18	17	17
March	77	73	67	63	57	50	44	37	30	24	20	17	19	19	19
April	82	76	70	65	59	52	46	39	32	26	22	19	20	21	21
May	85	79	73	68	62	56	49	42	36	29	24	20	21	22	22
June	88	82	76	71	65	59	52	45	38	31	25	21	22	23	23
July	89	83	78	73	67	61	55	47	41	34	26	22	22	23	22
August	89	83	79	74	68	62	55	48	41	33	26	22	21	21	21
September	86	81	78	73	67	61	54	47	41	33	26	21	21	19	19
October	83	79	75	70	64	58	51	45	38	31	24	20	19	18	17
November	80	75	72	67	61	55	49	41	35	28	23	19	18	17	16
December	77	72	69	64	58	52	45	38	32	25	21	18	17	16	15

It is of interest to compare these figures with similar results that have been previously given. On p. 42 of Messrs. GOLD and HARWOOD's report to the British Association, Section A, Winnipeg, 1909, a table is given showing the mean value and

the amplitude of the annual and other terms in the temperature curve at each kilometre up to 15. The figures are based on some 400 ascents made from 10 stations, chiefly on the Continent.

Dr. ARTHUR WAGNER has also given values based on 380 ascents between July, 1902, and June, 1907 ('Die Temperaturverhältnisse in der freien Atmosphäre,' III. Band, Heft 2/3, Leipzig, 1909), and in the 'Meteorologische Zeitschrift' for January, 1911, the translation of a paper in Russian by M. M. RYKATCHEW, jun., appears. In it the results of 143 ascents in Russia, mostly at Pawlowsk, are brought together.

The four values thus obtained are shown side by side in Table IV., and I do not think that anyone can fail to notice the close agreement. With regard to the mean annual temperatures, except at Pawlowsk, the values hardly differ by 1° C. at any

TABLE IV.

Height.	Mean temperature.				Amplitude or half-range.				Date of minimum.	
	B.	G. & H.	W.	R.	B.	G. & H.	W.	R.	B.	G. & H.
	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.		
0	82·6	—	80·9	76·1	6·7	—	9·5	12·3	January 20	—
1	77·0	78·1	77·6	70·9	6·3	8·3	8·1	9·5	,, 27	January 25
2	72·6	72·8	73·1	66·2	6·0	6·5	7·0	8·1	February 15	February 5
3	67·7	67·6	68·0	60·9	5·8	6·1	6·2	8·1	,, 8	,, 8
4	61·7	61·8	62·3	55·0	6·1	6·4	7·0	8·0	,, 13	,, 9
5	55·5	55·6	56·1	49·0	6·4	6·7	7·5	7·5	,, 11	,, 8
6	48·9	48·7	49·7	42·6	6·2	7·3	7·7	7·8	,, 15	,, 9
7	41·8	41·5	42·2	35·9	6·0	7·5	8·0	8·0	,, 13	,, 9
8	35·0	34·1	35·0	29·6	6·3	7·6	8·0	7·6	,, 11	,, 8
9	28·9	27·3	28·6	24·9	5·4	7·0	6·9	6·3	,, 15	,, 9
10	23·1	22·3	23·4	22·4	3·3	5·6	5·6	5·0	,, 10	,, 6
11	19·6	19·0	20·2	21·7	2·4	4·7	4·6	4·2	January 29	January 24
12	19·6	18·3	18·8	22·2	2·7	4·6	4·3	4·6	December 28	,, 11
13	19·5	19·1	18·5	—	3·1	4·1	4·0	—	,, 19	December 26
14	19·8	19·1	18·6	—	3·6	4·0	4·2	—	,, 15	,, 29

B.—Results from 200 ascents in the British Isles, 1908, 1909, and 1910.

G. & H.—Messrs. GOLD and HARWOOD'S results: 400 ascents, mostly on the Continent, to end of 1908.

W.—Dr. WAGNER'S results, on the Continent entirely; 1902 to 1907, 380 ascents.

R.—M. RYKATCHEW'S results; 90 ascents at Pawlowsk.

height, and the lower temperature at Pawlowsk is due to its higher latitude, and this, in accordance with a general rule, is reversed above.

The amplitude is least in England and greatest in Russia, but an exact comparison cannot be made because in columns W. and R. half the range between the two extreme months is given and not the amplitude of the curve.

The phase angles are not available for columns W. and R., but it is obvious from

the monthly values that the dates of the minimum would agree closely with those in columns B., G. & H., if they were available.

It must be borne in mind that these are independent investigations, excepting that the figures in columns G. & H., and W., are mostly dependent on the same material. The observations in England were nearly all made at or after sunset, so that solar radiation is excluded; they were also made with an entirely different type of instrument, and refer to a different period. The observations on the Continent were made in the morning; about 8 or 9 a.m. would, perhaps, be a fair average. (With regard to the greater range on the Continent, see p. 261, line 5.)

The following facts appear from the tables. The temperature decreases steadily up to a height of about 10 or 11 km. (9 or 10 km. at Pawlowsk), and remains almost stationary above that height. The annual range decreases from the surface up to 2 or 3 km.; it then continues nearly constant, with perhaps a small increase at 7 or 8 km., up to about 11 km., at which point it is abruptly reduced to less than half its former value. In the strata above 1 or 2 km. the maximum and minimum values are delayed for about a month, but above the point at which the vertical temperature gradient ceases they come back and occur at the summer and winter solstices.

This point is higher in summer than in winter; it is higher in England and the central part of the Continent than at Pawlowsk (59° 41′ N., 30° 29′ E.). Up to it the gradient of temperature is much the same in all places and at all seasons, excepting in so far as the larger annual range of temperature in the East produces a modification near the surface. Above it the annual range is nearly the same, and small in all four results.

In showing the monthly values decimals of a degree have not been given, though they have been used in the work. The observations are not numerous enough to give

TABLE V.—Approximate Gradient in Degrees Centigrade per Kilometre.

Height.	0·5.	1·5.	2·5.	3·5.	4·5.	5·5.	6·5.	7·5.	8·5.	9·5.	10·5.	11·5.	12·5.	13·5.	Mean 0–9 km.
January	5	4	4	6	7	7	6	7	6	4	3	0	1	0	5·8
February	5	5	4	6	7	6	7	7	6	3	3	−1	1	0	5·9
March	4	6	4	6	7	6	7	7	6	4	3	−2	0	0	5·9
April	6	6	5	6	7	6	7	7	6	4	3	−1	−1	0	6·2
May	6	6	5	6	6	7	7	6	7	5	4	−1	−1	0	6·2
June	6	6	5	6	6	7	7	7	7	6	4	−1	−1	0	6·3
July	6	5	5	6	6	6	8	6	7	8	4	0	−1	1	6·1
August	6	4	5	6	6	7	7	7	8	7	4	1	0	0	6·2
September	5	3	5	6	6	7	7	6	8	7	5	1	1	0	5·9
October	4	5	5	6	6	7	6	7	7	7	4	1	1	1	5·9
November	5	3	5	6	6	6	8	6	7	5	4	1	1	1	5·8
December	5	3	5	6	6	7	7	6	7	4	3	1	1	1	5·8
Year	5·3	4·8	4·8	6·0	6·3	6·6	7·0	6·6	6·8	5·3	3·5	−0·1	0·2	0·3	6·1

a mean accurate to 0°·1 C., and I do not care by giving decimals to pretend to a degree of accuracy that does not exist. The temperatures are given in absolute measure, and the first 2 is omitted to save space.

Table V. shows the temperature gradient. The values might probably be smoothed with advantage, but they have been taken from Table III. The uniformity throughout the year between 3 and 8 km. is very striking.

The Daily Temperature Variation and the Effect of the Time of Observation on the Mean Values.

The information available about the daily temperature variation is at present of a somewhat meagre character when we pass the height that can easily be reached by kites.

On June 2nd and 3rd, 1909, starting at 7 p.m. on the 2nd, 25 balloons were sent up at Manchester at hourly intervals, and 21 were recovered. The experiment was very successful, for all but two reached 16 km. and eight reached 21 km. A similar series of ascents was made on March 18th and 19th, 1910, when 28 were sent up and 18 recovered.

The results are discussed in the 'Journal of the Royal Meteorological Society' (April, 1910, vol. xxxvi., No. 154; and January, 1911, vol. xxxvii., No. 157).

Neither series shows anything in the higher strata resembling the ordinary daily change of temperature at the surface, neither is a sudden change at sunrise shown, such as would occur if the solar radiation had any serious effect on the instruments. On June 3rd the temperature began to rise three hours before sunrise, and a minimum occurred at noon.

At a meeting of the International Aeronautical Commission, held at Monaco in April, 1909, it was decided that 7 a.m. Greenwich time should be the time for sending up balloons on the appointed days. Previously, nearly all the ascents made in England had been made at or after sunset. The instruments used on the Continent carry a clock, and thus the rate at which they are ascending or descending is known. It is also known that for correct registration the velocity of the air current past the thermograph must reach a certain value, and when the rate of ascent is shown by the trace not to have reached this value the record is rejected. But in England we use no clock, our instruments weigh about one-tenth of those used on the Continent, and hence the rate of ascent is unknown, and we cannot say if the thermograph was sufficiently ventilated, and are thus compelled to depend on our unaided judgment as to whether a doubtful trace should be accepted or rejected.

Since the meeting at Monaco, balloons have been sent up at Pyrton Hill on most of the appointed days at 7 a.m., but a fair number of additional balloons have also been sent up at sunset, either the same evening or the evening before. This renders a comparison possible in ten cases of the temperature at sunset and at 8 a.m., 8 a.m. and not 7 a.m., because the ascent takes two hours. The values are given in detail

in Table VI., the ascent at sunset is taken as the standard and the temperature of the other expressed relatively to it.

In winter at 8 a.m. the sun has hardly risen, and in any case its rays have passed through so large a mass of air that little heating power can remain. In summer at that time the balloon and meteorograph are exposed to full radiation. The balloon at sunset is timed so that it may reach its maximum height when the sun is on its horizon.

TABLE VI.—Difference of Temperature at Sunset and 8 a.m.

Height.	Grd.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.
January . .	0·0	0·0	0·0	−1·0	+1·0	—	—	—	—	—	—	—	—	—	—
February .	−8·0	−2·0	0·0	−3·0	−2·5	−4·0	−4·5	−3·0	−2·5	−3·0	−1·5	+5·0	+10·0	—	—
March . .	−5·5	−1·0	+1·0	−1·0	+0·5	−0·5	−0·5	+1·5	+2·0	+1·0	+2·5	+1·0	—	—	—
October . .	−6·5	−4·5	−1·0	−2·0	−0·5	0·0	−0·5	−2·0	−1·0	−0·5	−0·5	0·0	0·0	0·0	0·0
November .	−4·0	+1·0	−2·0	−3·5	−3·5	−3·0	−3·5	−1·0	0·0	−3·0	0·0	+1·0	− 1·5	0·0	0·0
Means . .	−4·8	−1·3	0·0	−2·1	−1·0	−1·9	−2·2	−1·1	−0·6	−1·4	+0·1	+1·7	—	—	—
April. . .	−4·0	+0·5	−1·0	+0·5	+2·5	+3·0	+1·5	0·0	−1·0	+3·0	+5·5	+2·5	+ 2·0	+3·5	+3·0
May . . .	+2·0	−3·0	0·0	0·0	−0·5	+3·0	+4·0	+3·5	+4·0	+6·0	+6·5	+4·5	+ 4·0	+6·0	+7·0
„ . . .	+4·0	+7·0	+7·0	+7·0	+4·0	+3·5	+3·0	+3·5	+2·0	+4·5	+6·0	+9·0	+ 7·0	+3·0	+5·5
August . .	0·0	+1·0	+3·5	+6·0	+3·5	+4·5	+5·0	+3·5	+3·5	+4·0	+4·0	+4·0	+ 3·5	+6·0	+3·0
„ . .	−2·0	+0·5	+1·0	−1·0	+1·5	+3·5	+3·0	+2·5	+3·5	+3·5	+2·5	−0·5	+ 1·0	+2·5	+3·0
Means . .	0·0	+1·2	+2·1	+2·7	+2·2	+3·5	+3·3	+2·6	+2·4	+4·2	+4·8	+4·1	+ 3·4	+4·2	+4·3

The ten pairs of observations available have been divided into two groups, one for the summer half-year and one for the winter half-year. The preponderance of negative signs in the winter half and of positive in the summer can hardly be accidental, but I hardly know whether to ascribe it chiefly to solar radiation or to a real change in the air.

At Manchester two balloons have been sent up, one at night and one in the day, each with a pair of instruments, one fixed inside the balloon and one hanging from it in the usual position. As might have been expected, the temperature of the inside of the balloon at night did not appreciably differ from that outside, but the inside by day, *i.e.*, 7 a.m. on July 2nd, was much hotter than the outside, 12° C. at 2·5 km., 17° C. at 5 km., 22° C. at 7·5 km., 30° C. at 10 km., and 35° C. at 12 km. The balloon reached 20 km., and the air inside was close to the freezing-point at 16 km. and above. Now the instruments are well protected from solar radiation by bright metal, except when the sun is near the zenith, but the balloon of course shares the horizontal motion of the air, and therefore ascends in what may be described as a dead calm. The instrument follows and is in the wake of dead air which has inevitably been in contact with the heated balloon. A balloon ascent in the daytime is as though a globe of some 6 ft. in diameter and filled with warm water were kept to windward of the thermometer screen.

How much the results are vitiated it is impossible to say, perhaps not greatly, for the record for the fall seldom differs much from that for the rise. But any comparison between the Continental and English results has got to reckon with this point, because nearly all the English observations were made at or after sunset, and all those on the Continent in the daytime. To this cause I am inclined to ascribe the greater annual range shown on the Continent at heights above 2 or 3 km.

It may be remarked, in passing, that the two series of hourly ascents at Manchester have afforded the best possible practical test of the accuracy of the instruments. If we assume that the temperature at any height at any hour, 10 a.m. say, was exactly midway between the temperatures at 9 a.m. and 11 a.m., then, in general, the instruments record the true temperature within about 1° C. If two separate instruments of any kind are sent up, differences of temperature at a definite height may be due to errors in the observed pressure, since the height can only be obtained by means of the pressure. In some cases the instrument carries two thermographs writing on the same sheet, and in this case the differences for a definite height are solely due to the thermographs.

Temperature and Barometric Pressure.

The relation which undoubtedly exists between the barometric pressure and the temperature of the air at various heights has been investigated by arranging the observations in six groups, and taking the means. The pressure at the place and time of starting the balloon, reduced to sea-level, has been taken as the standard. In certain cases the balloons have travelled long distances. One sent up at Ditcham Park went 800 miles to the E.S.E., and another from Pyrton Hill 660 miles. It is obvious in such cases that the pressure at starting can be no guide to the surface pressure at the time and place where the balloon was at its highest point, and therefore all such cases have been excluded, 150 miles (240 km.) being taken as the limit. The remaining ascents, which amount to 124, have been arranged thus:—

Group	I.	Sea-level pressure		under 741 mm. (29·17 in.).
,,	II.	,,	,,	between 741 and 750 mm.
,,	III.	,,	,,	,, 751 ,, 756 ,,
,,	IV.	,,	,,	,, 757 ,, 762 ,,
,,	V.	,,	,,	,, 763 ,, 769 ,,
,,	VI.	,,	,,	over 769 mm. (30·28 in.).

The numbers for each group are 6, 12, 15, 30, 41, 20 respectively, so that, excepting for the group under 741 mm., there are quite enough observations to form a good mean. But a difficulty occurs from the fact that the low pressures are concentrated into the winter months, for extreme values in North-Western Europe only occur in the winter, and no number of observations can cure this. It is therefore absolutely necessary, if we wish to compare the temperature conditions that

prevail in cyclones and anticyclones, to allow for the annual temperature variation, and this has been done by means of Table III. It is true that Table III. itself depends on Table VII., and therefore Table VII. ought not to be indebted in any way to Table III. The corrections might be applied by means of Table I. instead of III., but the method of continued approximation seems the more suitable notwithstanding that it suggests reasoning in a circle. The inter-relation of the two quantities presents a difficulty, but it is not serious except for heights between 8 and 12 km. Each height in each group has been treated separately, and, using the annual temperature variation for each height taken from Table III., the temperature has been reduced to what it presumably would have been had the ascent occurred at the beginning of May or November, the times of mean temperature for the upper air. As previously stated, both high and low barometric heights are common in the winter, and a comparison between such as are available has been made, and the result is identical with that shown in the table.

The results are shown in Tables VII. and VIII., and the difference A–C in Table VII. shows the difference of temperature at each height that is found to prevail at times of very low and of very high barometer. Table VIII. shows the gradients in a convenient form.

TABLE VII.—Temperature at each Height for Various Barometric Readings.

Barometer.	Grd.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
mm.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.
738	79	75	69	63	55	48	40	32	27	26	25	25	25	26	24
744	81	76	70	64	57	50	43	35	28	25	24	23	24	24	23
754	83	79	74	67	61	54	47	39	33	27	21	20	20	21	21
760	82	76	72	67	61	55	49	42	35	28	21	18	19	21	22
766	82	79	75	70	64	57	51	44	37	30	25	20	17	15	15
773	82	79	77	72	67	61	54	47	40	33	26	21	17	15	15
Difference "A–C"	3	4	8	9	12	13	14	15	13	7	1	– 4	– 8	– 11	– 9

TABLE VIII.—Temperature Gradients at Times of Low and High Barometer.

Mean height of barometer.	0·5.	1·5.	2·5.	3·5.	4·5.	5·5.	6·5.	7·5.	8·5.	9·5.	10·5.	11·5.	12·5.	13·5.
mm.														
738	4	6	6	8	7	8	8	5	1	1	0	0	– 1	2
744	5	6	6	7	7	7	8	7	3	1	1	– 1	0	1
754	4	5	7	6	7	7	8	6	6	6	1	0	– 1	0
760	6	4	5	6	6	6	7	7	7	7	3	– 1	– 2	– 1
766	3	4	5	6	7	6	7	7	7	5	5	3	2	0
773	3	2	5	5	6	7	7	7	7	7	5	4	2	0

The very close connection that exists between the temperature of the upper air and the height of the barometer is plainly shown in these tables. One can form an idea of the reliability of the figures by taking the surface temperature, where the relation is fairly well known. The value 83° C. for the mean barometric pressure of 754 mm. is probably too high, and would be reduced if sufficient observations were available. The mean temperature of the South of England is close to 83° C., but Pyrton Hill is at an elevation of 500 ft., so that its mean temperature is about 82° C., so also is that of Manchester. Thus the mean of these 124 observations is close to the value it ought to have. Also at the surface the temperature, taking the year through, is below its average in times of low barometer, for in winter, the statements in text-books notwithstanding, in England the height of the barometer has but little, if any, effect upon the temperature, but in summer cold is nearly always associated with a low barometer. Thus the values at the surface are and should be below the mean in cyclonic weather.

It is probable that if a very large number of observations were available, the roughness shown in the gradients for the first few kilometres with pressures of 754 and 760 mm. would be smoothed out, but taking the table as a whole the values are remarkably smooth.

These tables show how the lower strata are cold in a cyclone and warm in an anticyclone, and how this is reversed above; how at 10 km. the intermediate type of weather has the lowest temperatures, and how the temperature gradient ceases at 8 km. in the cyclone but not till 12 km. in the anticyclone.

All these particulars have been noted in the Continental results, but not in so pronounced a manner. It will be seen in the line "A–C," in Table VII., that in England at a height of 7 km. the difference amounts to 15° C. In Messrs. GOLD and HARWOOD's report the greatest difference occurs rather lower and only reaches 8° C. This is for barometric heights of below 750, and over 770, but the number of observations on which the figures depend is not stated. Dr. WAGNER gives 18° C. at 8 km., but his values for the centre of a cyclone depend on two ascents only. M. RYKATCHEW gives much smaller differences, but the barometric heights are not defined in either case, the tables being simply headed "cyclonic" and "anticyclonic."

About the actual fact there is no doubt; it was stated by M. TEISSERENC DE BORT long since. It would be of interest to know if the distinction is more pronounced in England than on the Continent, but the question is somewhat involved. Cylones of any depth are rare on the Continent, except perhaps at Hamburg and Pawlowsk, so that the opportunities for studying it are not so good there as here.

The Isothermal Region.

It will be noticed in the tables previously given that the decrease of temperature mostly ceases at a height of about 10 or 11 km., but tables showing mean values do not fairly indicate the nature of the phenomenon. In nearly every individual ascent

there is a definite height at which the temperature gradient becomes zero, or is reversed in sign, and with a very few exceptions this definite height lies between 7·5 and 12·5 km. In three cases out of four the lowest temperature met with occurs at this point. No appropriate and convenient name has been as yet assigned to it; following Messrs. GOLD and HARWOOD, its height will be denoted by H_c and the temperature at the same point by T_c. There are, however, some few cases in which H_c is indefinite, the temperature gradient gradually decreasing, but never reaching zero. In such cases H_c is measured to the point (excluding the inversions in the lower strata) where the gradient becomes less than 1° C. per kilometre. The region above this has had various names given to it, viz., the "isothermal region," or more usually the "isothermal," the stratosphere proposed by M. TEISSERENC DE BORT, or the "advective region" by Messrs. GOLD and HARWOOD. The first is the most common, but the region is not isothermal laterally though nearly so, as far as it has been explored, in the vertical direction.

Annual Variation in H_c.

The actual mean value of H_c for each month is given below in kilometres :—

Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
11·8	10·5	10·7	9·8	11·6	10·3	12·1	11·8	14·0	12·7	10·4	9·7

but H_c is so dependent on the height of the barometer that it, far more than the monthly temperature, requires correction.

The necessary data for correction are given subsequently (p. 265), and we get :—

Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
11·3	10·5	10·7	10·8	11·9	10·9	10·9	11·5	13·3	12·0	11·2	10·7

The values for May and September are discordant, but the causes previously stated vitiate the value for May, and a paucity of observations in September make the value 13·3 for that month of little weight. Still the four observations for September are well distributed, and it is noteworthy that whereas Messrs. GOLD and HARWOOD found an especially low value for September, the British Isles show an exceptionally high value. Smoothing May and September by the formula $\frac{a+b+c}{3}$, and then putting into a sine curve with an annual period, we get :—

Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
10·7	10·6	10·5	10·6	10·9	11·2	11·4	11·6	11·6	11·5	11·3	11·0

The second and third terms of the Fourier series are not taken into account, for reasons previously stated. The figures refer to the middle of each month, and the minimum occurs at the beginning of March, the amplitude is 0·55, and the mean 11·1 km.

Messrs. GOLD and HARWOOD give a very similar range and phase, but their mean height is only 10·6 for the whole set and 10·8 for the British Isles. Dr. WAGNER gives a somewhat larger range with a minimum in March and a mean height of 10·5. M. RYKATCHEW gives for Pawlowsk about the same range, but his mean height is only 9·6 km.

The lower height at Pawlowsk may be explained by the higher latitude. The values at Pawlowsk are included in Messrs. GOLD and HARWOOD'S and in Dr. WAGNER'S results and reduce their mean, but on the whole the Continental stations are not as far north as England. It does not seem possible that there can be any large systematic error in the calibration of the instruments, 0·5 of a kilometre is at this height equivalent to 14 mm. of pressure, so that it appears that the mean value of H_c is greater for England than for the Continent, and this confirms Dr. WAGNER'S statement. He says the H_c decreases from south to north, and from the ocean to the Continent.

Dr. SCHMAUSS pointed out the annual variation in 1909. Whatever the explanation of the isothermal region may be, it seems reasonable to expect it to occur always at the same pressure rather than always at the same height. In August the mean temperature of the air, up to the isothermal, is 13° C. above its value in February, and in consequence at 11 km. the same pressure is met with some 0·5 km. higher, but this does not suffice to explain the whole variation.

The Value of H_c for Various Heights of the Barometer.

Height of barometer . . .	738	744	755	760	766	773 mm.
Value of H_c	8·4	9·1	10·3	11·0	12·4	12·3 km.
Number of cases	6	12	15	30	41	20

These figures have been corrected for the annual variation.

It will be seen that, if we exclude the last group, the relation between H_c and the height of the barometer may be taken as practically a linear one. I am inclined to think that, notwithstanding the large number of observations in the 766 mm. group, the value 12·4 km. for this group is accidentally high. In the lower groups the individual values are very consistent. In the 18 ascents made with the barometer below 750 mm. in one only was a value of H_c above 10 km. met with, and the lowest was 7·5. In the higher groups there is great irregularity, so that it may be said with fair certainty that a low value of H_c will be found with a low barometer, but the converse does not hold. Of all the quantities relating to the upper air this value of H_c is the most capricious and uncertain, save during pronounced cyclones. There is evidence that, in the 40 miles between Pyrton Hill and Ditcham Park, it may differ by at least 1 km., and that the same change may occur in the same locality in less than an hour.

If we combine the last two groups we get the rule that a rise of 3 mm. in height of

the barometer will be accompanied on the average by a rise of 0·4 km. in the value of H_c, but whether this rule holds for the upper part of the barometric scale is a matter that must be left for future observations to settle.

Value of T_c.

Closely connected with the value of H_c is the value of T_c, the temperature of the air at the commencement of the isothermal. The values corrected for the annual variation are

H_c . . .	8·4	9·1	10·3	11·0	12·4	12·3 km.
T_c . . .	24°·5	21°·4	18°·4	15°·0	12°·8	13°·0 C.

Plotted on squared paper these are not quite linear, but a straight line can be drawn that lies within less than a degree of the given temperatures everywhere. The ratio is nearly 3°·0 C. to 1 km.

The rule holds for change of latitude, for H_c is large and T_c low near the equator. It holds as shown above for barometric change, but fails for the annual variation, since H_c and T_c both reach their maximum values in the late summer. No daily change in the value of H_c can be detected with certainty, but more observations are required.

Average Height reached and Distance run by the Balloons.

In the following table column A gives the average maximum height, column B gives the difference between the value of T_c and the temperature at the highest point, T_c being the standard, and Column C the distance in miles of the place of fall from the starting place of the balloon.

The corresponding values for the various pressure groups are in the shorter table on the right.

TABLE IX.

	A in km.	B.	C in miles.
January . . .	15·7	0·5	50
February . . .	14·3	1·1	56
March	14·2	5·0	56
April	14·5	2·0	75
May	16·3	6·0	65
June	16·5	5·5	50
July	17·0	1·0	86
August . . .	16·3	7·7	44
September . .	16·6	2·5	62
October . . .	16·7	2·5	62
November . .	17·1	0·0	45
December . .	15·1	1·0	56

mm.	A in km.	B.	C in miles.
738	14·6	−1·0	36
744	15·6	0·6	60
754	16·0	3·0	66
760	16·1	7·0	59
766	16·2	3·5	58
773	15·6	4·0	54

It will be seen from these tables that the average maximum height reached is greater in summer than in winter. This is partly due to the fact that the bursting-point of a balloon depends on the pressure, and in summer a greater height must be reached to attain the same low pressure. This does not account for the whole variation, and the part left must be ascribed to the effect of temperature on india-rubber. It becomes hard if left unused in cold weather. For reaching great heights the quality of the rubber is of supreme importance.

The figures in column B are instructive. Large inversions of temperature are to be met with at the commencement of the isothermal in summer rather than in winter; and at times when the barometer is near its normal value, and not when it is low.

The figures in column C are not what would be expected. The surface wind in England is certainly stronger in winter than in summer, but the distances run are reversed and are rather greater in summer than in winter. The exact time taken for any ascent is not known, but judging from the few cases where the balloon has been seen to fall it may be assumed to be about two hours.

In the pressure group, places with an average barometer are naturally places where there is a barometric gradient, and hence a long run for a balloon is to be expected, but the value 36 miles, the lowest in the table, for the six cases that occurred in or near the centre of a deep cyclone does not favour the idea that cyclones are eddies produced by a strong upper current in the general circulation. So many of the balloons have doubtless fallen in the sea that there must be large systematic errors in the means of the distance run. Balloons often fall within a short distance of their starting place, and it is certain that there is no strong and permanent upper drift from the west.

With reference to the bearing of the place of fall, no definite statement can be made. The prevailing wind in England is from some westerly point, and so in general a balloon falls towards the east; they seldom seem to go due west, but south-west and north-west are quite common directions, and I do not think the frequencies of winds from various points of the compass are very different above and below. On many occasions a strong current from the north and north-west has been met with at great heights when it has been calm up to the cirrus level, and while the track of a balloon will in general follow an isobar, the track cannot be foretold with certainty from the surface distribution of pressure.

Wave Motion on the Lower Boundary of the Isothermal Surface.

In a fair number of the ascents that are made it is found that the values of H_c and of T_c have changed in the short time that the instrument has remained in the isothermal region. The variations are much too large to be ascribed to casual instrumental errors, neither are they due to any systematic lag of the aneroid or of the thermograph, for they will sometimes be shown on one instrument in one

ascent, and then not on the same instrument in its next ascent. Also they are more prevalent at certain periods than at others. Thus, when there are three consecutive so-called international days, it will often happen that every ascent from the three stations in England will show these irregularities, while on some other three days none or very few will be shown.

It would seem as though some irregular or possibly regular series of waves occurred at the boundary, changing H_c rapidly by from 0·5 to 1 km., and T_c by 5° C., or occasionally even more, and I am inclined to think that there is some connection between these disturbances and the small pressure waves of short period that are not infrequently shown on the micro-barograph.

Discussion of the Results.

The tables and figures given in the preceding part of this paper are, I hope, observational facts about which there can be no serious dispute. In addition to the observations in Europe we have a certain amount of information from the tropical and equatorial regions, and from America. It is certain that as the equator is approached the value of H_c rises, and that of T_c falls. The observations are not sufficient to show the connection between H_c, T_c, and the latitude, but as an approximation we may take $H_c = 16$ km. and $T_c = -80°$ C. at the equator.

Any theory that is to explain the general circulation of the atmosphere, the distribution of temperature, and the formation of storms, must agree with the observed facts, but it is extremely difficult to form any theory without being involved at once in a mass of contraditions. Yet the motion and temperature of the atmosphere must be dependent on the well-known principles of mechanics and thermodynamics, and it ought to be possible to get some clue that may lead to a reasonable explanation. The making of observations and then tabulating them is a tedious business unless it leads to something further, but all I can do in discussing these results is to point out difficulties which I do not profess to have solved.

Firstly, with regard to the vertical distribution of temperature.

Mr. GOLD's theory as to the reason of the decrease of temperature up to a certain height, put briefly, is this ('Roy. Soc. Proc.,' A, vol. 82, p. 43, 1908). Any layer of air is dependent for its temperature on the four following sources of heat:—radiation from the sun, radiation from the earth, radiation from the neighbouring layers, and convection from below, this latter including the supply due to condensation. Its temperature will be such that its loss of heat by out radiation will just balance these sources of supply. Above, the isothermal convection ceases and absorption and radiation are equal. The paper should be consulted. The numerical values are of course somewhat doubtful, especially since the amount of aqueous vapour at different heights is uncertain, but the whole theory seems eminently reasonable, and apart from details explains the general fact of the isothermal region. If this theory be correct, then air that is below the mean temperature for its own height and for the season

will be air that has recently risen and conversely, for the air changes its temperature slowly under the influence of radiation, but instantly under the influence of change of pressure. Also, the magnitude of the temperature departure from the mean should be an index of the intensity of the ascending or descending motion.

For convection to occur it would seem necessary that the lower layer should be potentially at least as warm as the air above it, that is to say, that if the lower layer rises it shall, after cooling adiabatically, still be as warm as the air on its fresh level. For unsaturated air the adiabatic gradient amounts to 10° C. per kilometre, and this is the practical limit to the gradients met with in the individual ascents, but for saturated air at ordinary temperatures the value is much less, the exact value being dependent on the temperature. A fair average for the year in the first few kilometres in England is about 6° C. per kilometre, and this is somewhat over the mean gradient up to 3 km. As the height increases so also does the adiabatic gradient, because the colder air contains less moisture to be condensed, and consequently the latent heat set free is less. The observed gradient also increases, but never becomes as great as the adiabatic gradient for saturated air at the temperature that usually prevails at the corresponding height. The lower layers are potentially the colder by about 1° C. per kilometre, even for saturated air, and convective currents should not occur. One would have expected to find the adiabatic gradient up to the point to which convection extends, or at least up to the limit of the clouds, 7 or 8 km.

Probably owing to the general disturbance caused by winds and the convection currents of the lower strata, a certain amount of forced mixing occurs, and since the lower layers are potentially colder than the upper, the mixing will cool the upper strata. Mixing means the existence of vertical currents, and therefore raises the height of the isothermal region, which begins at the point where vertical currents cease. Could we by any means thoroughly mix up the vertical strata, just after the mixing we should have the same potential temperature throughout, that is to say, the surface layers would be very much warmer and the upper layers very much colder than they are now, there would be no isothermal region, but the adiabatic gradient would prevail to the very top.

It seems possible that the strong convection currents that prevail in the equatorial regions may produce this forced mixing up to a considerable height, and thereby raise the height of the isothermal and lower the temperature. Or the explanation subsequently given as to the conditions that prevail in cyclones and anticyclones may hold (see p. 277). The general rule is that the greater the height H_c the lower the value of T_c. This holds for change of latitude and for the change from cyclone to anticyclone, but it fails in the case of the annual variation, where apparently the values of H_c and T_c should follow those produced by change of latitude.

To have met with the lowest natural temperatures ever recorded in the equatorial region is not what one would have expected, but is what has happened. The isothermal region over the equator receives at least as much solar radiation as it

does elsewhere, and, as the earth and lower layers of air are warmer there, it should receive more radiation from below. It is true that the greater amount of water vapour may cut off radiation from the earth, but if so this radiation must warm up the strata that absorb it, and they in turn should radiate upwards.

The question naturally arises whether there is any appreciable interchange of air between the isothermal region and the strata below it. The diffusion over the whole earth of the dust thrown up into the very highest strata by the Krakatoa eruption in 1883 proves that the air at these levels circulates between the equator and the poles, and if, as we have good reason to think, the air above 16 km. is much colder over the equator than over Europe we should expect this circulation. It is certain, too, that the trades and anti-trades above them do not form a closed system confined to the region between 35° S. and 35° N. This may be proved as follows. The sum total of the angular momentum of the earth's atmosphere about the axis of rotation remains approximately constant from year to year, and hence the moment of the couple acting upon the atmosphere is on the average zero. The only forces that form this couple are forces due to friction at the earth's surface, for the mutual reactions of the atmosphere as a whole cannot alter the angular momentum. From the fact that a persistent wind produces a powerful ocean current we know that the frictional force between the atmosphere and the earth must be considerable. Such a force is persistently exerted in the region of the trades over nearly half the earth's surface, and is constantly acting so as to give an easterly directed momentum to the atmosphere. It is balanced, as FERREL pointed out, by the westerly directed component produced by the friction of westerly winds in temperate latitudes. This requires an interchange of angular momentum between the tropics and temperate latitudes, and this can hardly occur in any way save by the interchange of masses of air which must have both a N.–S. and an E.–W. component. Hence at some level across parts of the boundary either N.E. and S.W. or N.W. and S.E. winds must blow.

The Local Circulation.

When it first became possible to obtain correct observations of the temperature up to 5 or 10 km. height, it was supposed that a few years' observations would show the mechanism of a cyclonic storm, and enable us to say to what it was due. This expectation has not been fulfilled.

There were two theories to account for these storms—one, due to FERREL, that a cyclone consisted of a current of warm ascending air at the centre, which current drew in the air from neighbouring districts and, aided by the directive force of the earth's rotation, produced the characteristic whirl; the other, due I think to Dr. HANN, was that they were eddies in the general circulation, just as small water eddies are formed in a swiftly flowing stream. The facts brought to light by registering balloons do not, so far as Europe is concerned, favour either hypothesis. The cyclone is cold, not warm, and the strong upper westerly current in which the

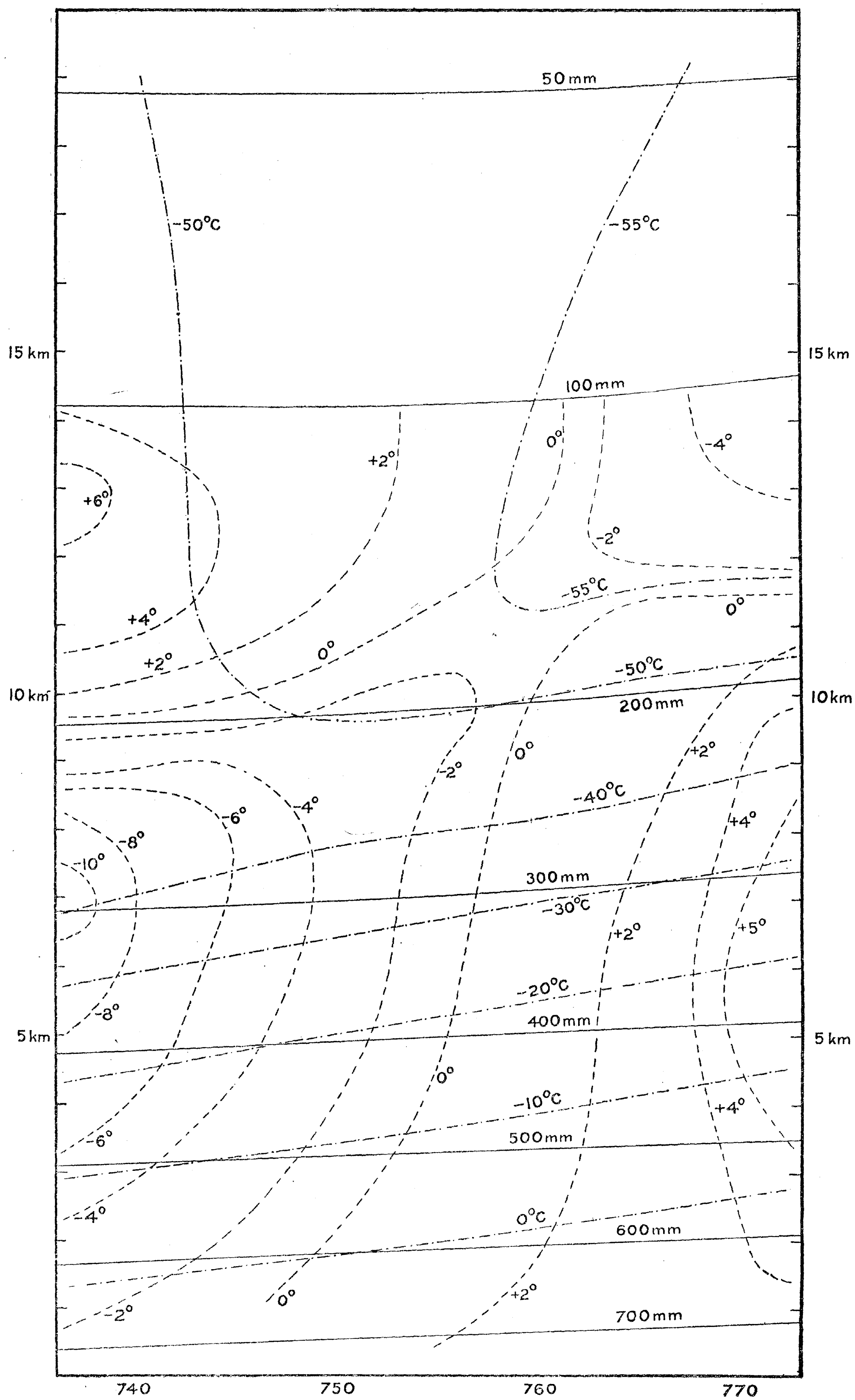
eddies were supposed to be formed is often non-existent, for balloons after rising to a great height frequently fall near to their starting point or to the westward.

It must be borne in mind that the velocity of the air in a vertical direction, save over small areas as in thunderstorms, is very small. It is more conveniently measured in feet than in miles per hour, and the principle of the equation of continuity shows that it cannot exist at all close to the earth's surface.

The information that has been gathered from the English ascents about the distribution of pressure and temperature in cyclones and anticyclones is shown in a graphical form in fig. 1.

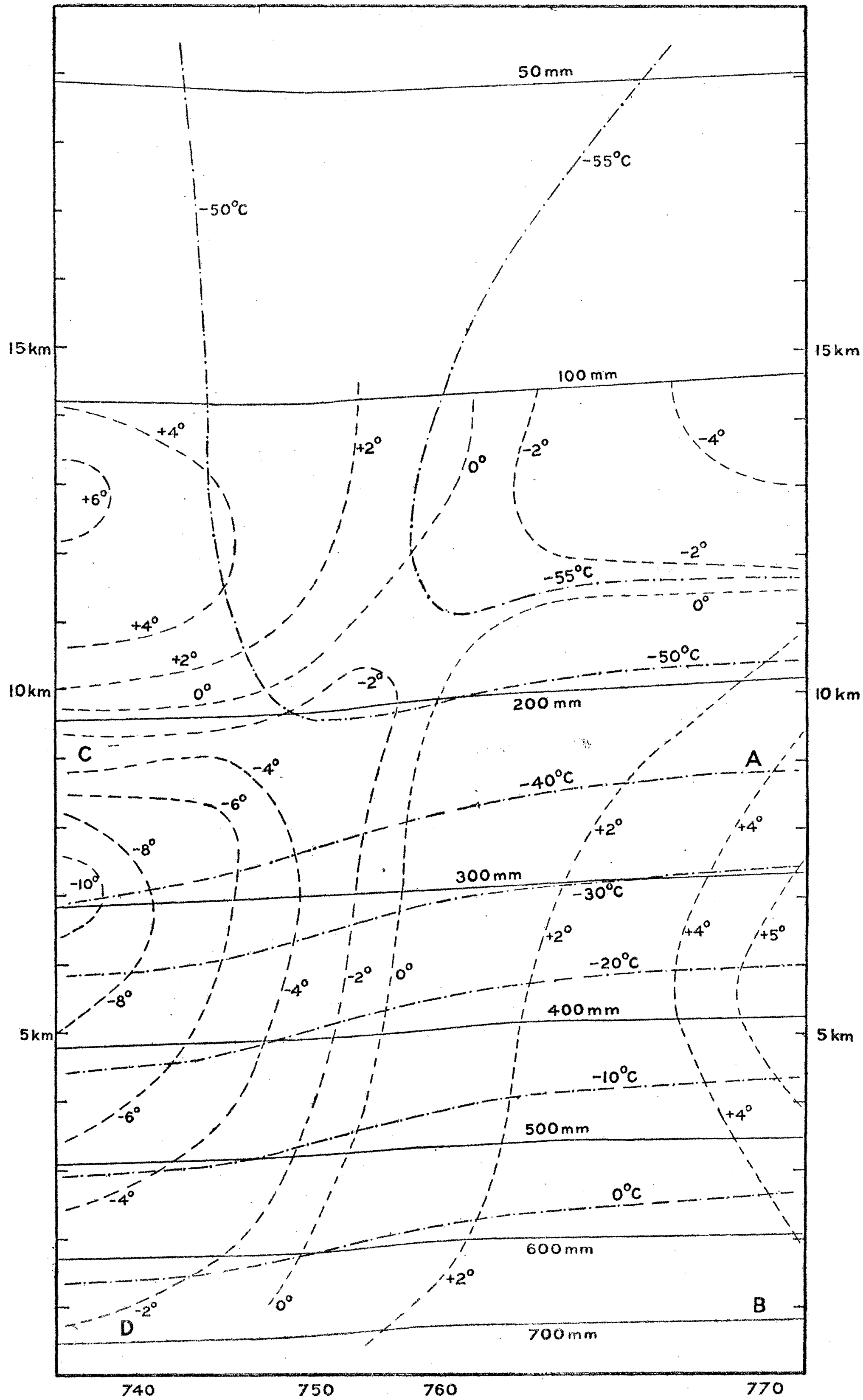
The figure may roughly be taken as a section of the atmosphere stretching from a region of low (29·00 in.) to a region of high (30·50 in.) pressure, but with the following qualifications. As in all such diagrams the vertical scale is out of all proportion to the horizontal, but also the horizontal scale is not the same in different parts. The horizontal distances represent differences of pressure at sea-level, but since the barometric gradient is never uniform, equal distances on the diagram do not represent equal geographical distances. The gradient is always slight in anticyclonic regions, and steepest in the intermediate regions, and hence the right-hand part requires to be opened out. An attempt is made to correct this in fig. 2, where the horizontal distances are meant to represent geographical distances. How to open out the scale on the sides is a matter of judgment, but the amount of enlargement is based on the fact that the mean temperature shown along any even kilometre height should coincide with that given in Tables II. and III. The distance across may be taken roughly as 1000 miles.

Fig. 1 obviously fails in this respect; it is only meant as a representation of the facts disclosed in the tables previously given. In both figures the full lines represent the section of the isobaric surfaces by a vertical plane, and the dotted lines the sections of the isothermal surfaces. The broken lines show the departure of the temperature + or − at any point from the mean value for that height. In drawing the lines irregularities that seem to be due to an insufficient number of observations have been ignored, and the lines are not carried to the ground because the distribution there depends upon the season. If we take a temperature below the mean to indicate that the air there has recently ascended and conversely, the following points appear from the diagram. There is an ascending current in the cyclone starting from close to the ground and reaching up to the isothermal. As the height from the ground increases this current is extended over a larger area and reaches a greater height, so that roughly it forms the frustrum of a cone with its apex downwards. In its outer parts it reaches to about 12 km., and seemingly the air that rises in the centre spreads out still rising obliquely just under the isothermal. Of course, this refers to the conventional cyclone; the actual cyclone is unsymmetrical, but if we could get a series of simultaneous observations in a straight line running from a low pressure to a high-pressure area, say 1000 miles distant, although there would be many local



50mm
-50°C
-55°C
15 km
15 km
100mm
+2°
0°
-4°
+6°
-2°
-55°C
0°
+4°
+2°
0°
-50°C
10 km
200mm
10km
0°
-2°
+2°
-40°C
-4°
-6°
-8°
+4°
-10°
300mm
-30°C
+2°
+5°
-20°C
-8°
400mm
5 km
5 km
0°
-10°C
+4°
-6°
500mm
-4°
0°C
600mm
0°
-2°
+2°
700mm
740
750
760
770

Fig. 1.



50 mm
-55°C
-50°C
15 km
15 km
100 mm
+4°
+2°
0°
-2°
-4°
+6°
-2°
-55°C
0°
+4°
+2°
-50°C
0°
-2°
10 km
10 km
200 mm
C
A
-4°
-40°C
-6°
+2°
+4°
-8°
300 mm
-10°
-30°C
+2°
+4°
+5°
-20°C
-4°
-2°
0°
-8°
400 mm
5 km
5 km
-10°C
-6°
+4°
500 mm
0°C
-4°
600 mm
+2°
0°
-2°
B
D
700 mm
740
750
760
770

Fig. 2

irregularities, and different sectors of the cyclone would probably show systematic variations, yet the distribution of temperature would certainly be in its main features the same as that shown on the diagram.

Using the same data, viz., the indication given by the temperature, we see that the descending current of the anticyclone starts from a height of about 11 km. and also spreads out as it descends; it, too, forms part of a cone, but has the apex upwards. Unlike the upward cyclonic current, its intensity slackens some distance before the end of its course, neither does the current seem to be so pronounced, since the departure only reaches $+5°$ C. against $-10°$ C. for the cyclone (29·00 in.).

The nature of the circulation thus indicated agrees well with what is known from other sources. The ascending current in the lower part of a cyclone can be inferred with certainty from the inward tend of the surface winds; it is also proved by the formation of clouds and rain. That the region of ascending air increases with height may be deduced from the fact that the formation of cirrus is often the first sign of an advancing cyclone, and rain may fall from high clouds some time before the lower cloud sheet and scud are formed. Also high clouds are generally visible after the lower sheet has cleared when the depression is passing away.

The descending current of the anticyclone is proved by the absence of high cloud at the centre of an anticyclone, for no cloud can remain unevaporated in a descending current, also by the great dryness that prevails at such times on mountain summits. But the descending current does not reach the earth at the centre, for Messrs. SHAW and LEMPFERT, in their 'Life-History of Surface Air Currents' (M.O. 174, p. 24), state: "These latter," *i.e.*, the central areas of well-marked anticyclones near the ground, "are for the most part inert and comparatively isolated masses of air, taking little part in the circulation that goes on around them." Also, in England at all events, an anticyclone is in the winter usually associated with a belt of low cloud, just above which, as we know from kite and balloon ascents, there is nearly always a sharp inversion of temperature. The descending current cannot reach the cloud, for if so it would dissipate it at once, and there can be no mixing of air at the boundary, for often just above the cloud the humidity is as low as 20 or 30 per cent.

The question of the difference of temperature in the various segments of cyclones and anticyclones has not been dealt with. In my opinion the number of observations is nothing like sufficient to eliminate chance differences that would inevitably occur. There seems to be no obvious correlation between the direction in which a balloon travels and the temperature conditions, neither can I see that it makes any difference if a cyclone is travelling quickly or slowly. The only point that I have noticed is that there is a tendency for a higher temperature at the first few kilometres in the rainy belt of south and south-easterly wind that lies in front of an advancing disturbance.

It is not safe in meteorology to draw conclusions from a single instance, but the following case may be of interest:—On November 3rd, 1910, at 2.30 p.m., a balloon was sent up at Pyrton Hill. The barometer, reduced to sea level, stood at 735 mm.

and was falling with unusual rapidity. The wind was east, and it was raining heavily. The centre of the depression, which came from W.N.W., passed directly over in the evening. A balloon was sent up in the evening, but not recovered. At 7 a.m. on November 4th a third balloon was sent up, the barometer being at 742 mm. and rising rapidly. The sky was clear save for a little cirrus, and the wind S.W. It had shifted through N.E. and N.W. The two balloons, 2.30 p.m. and 7 a.m., were recovered, and both gave specially clear records, but, excepting that up to 5 km., the afternoon temperatures were a few degrees the higher, the temperatures recorded were practically identical. In this instance, at least above 5 km., the front and back segments of a cyclone were alike. Both balloons reached 16 km. and travelled 60 miles to the eastward, one falling at Chelmsford and the other at Gravesend.

In discussing the mechanics of a cyclone, it is absolutely necessary to consider the question of barometric pressure. It will be seen from the diagram how the low pressure of a cyclone lies under a column of cold and therefore heavy air, and this shows how fallacious it may be to explain high or low pressures by the presence of cold or warm air above them. Also it must be remembered that the atmosphere is perfectly free and unconfined save at its lower boundary. If two large sealed vessels communicate with each other by even a small pipe, it is impossible to maintain any difference of pressure between their gaseous contents unless some force acts tangentially on the gas in the connecting pipe, as, for example, when one vessel is above the other and gravity alters the pressure. Much more so, therefore, with the atmosphere. Suppose a certain pressure at a point A and a lower pressure at a point C, and to exclude gravity let A and C be on the same level. If this difference of pressure is to be maintained a sufficient force must act along every possible line of communication between C and A, that is to say, along every line that can be drawn from A to C without passing through the earth or leaving the upper limit of the atmosphere. Failing this force the pressures at A and C will be equalised in somewhat the same time that it will take for sound to travel along the unopposed line of communication between A and C. At all events, the velocity should be of the same order as that of sound. This statement hardly seems to me to require proof, but if it does the following facts may be quoted. The wave of pressure produced by the eruption of Krakatoa passed round the earth with the velocity of sound. On the equator, where there is no possibility of any opposing force, there are hardly any appreciable differences of pressure, save those due to the semi-diurnal pressure wave which travels with a velocity of about four-thirds of that of sound. The nature of the force that acts between A and C in parts of the earth away from the equator was pointed out by FERREL. If C be the centre of a well-developed cyclone, it is largely supplied by the centrifugal force of the curvilinear winds that blow round C, but in most cases it is due to the tendency of a moving body to turn to the right hand (in the northern hemisphere), which again is due to the earth's rotation. (See a paper by Mr. GOLD, 'Barometric Gradient and Wind Force,' M.O. 190.) Briefly, we may say that a

force acting from C to A is produced by the component of the wind at right-angles to AC, A and C being any points whatever on the same level, although we cannot say what produces this wind. This component is called the gradient wind, if it has the right theoretical velocity. Also it is found that at a height of 500 metres the gradient wind agrees well, on the average, with that observed by means of kites or pilot balloons.

Suggested Cause of the Distribution of Temperature in Cyclone and Anticyclone.

To return to the diagram, fig. 2. Let us take a point C on the left hand at a height of 9 or 10 km., and a point A at the same level on the right, and suppose that a powerful wind is blowing across the line CA, *i.e.*, perpendicularly to the paper. This produces a force acting from C to A, and hence a decrease of pressure at C and an increase at A. The air therefore tries to flow back from A to C. The direct path and neighbouring paths on the same level are blocked by the acting force and a circuitous path has to be followed. Let us take a path ABDC falling vertically from A to 1 km., there running along an isobaric surface to the vertical through C, and then rising to C. The air from A falls towards B and is thereby warmed adiabatically, the air from B goes towards D and is unchanged in temperature excepting near the point B, where the supply has come from above. In the part DC the air is cooled as it ascends, and thus we get the temperature distribution shown in the diagram. It is obvious that this distribution at once raises a force that stops the flow, for the air in DC soon becomes too cold to rise further, and that in AB too warm to sink. The path BD need not be straight, but may follow any track whatever in the isobaric surface, neither need AB and DC be vertical. It will be seen, too, that the amount of circulation is very small. The air falls in AB and rises in DC until its departure from the mean is, say, $\pm 5^\circ$ C. The average gradient is 7° C. per kilometre, and the adiabatic for dry air is 10° C., a displacement therefore of only $1\frac{2}{3}$ km. is required, and this in a track of at least 1000 km. length is inappreciable. Each possible path of this kind will, so to speak, be tried and blocked by the air in its attempt to pass from A to C, and the temperature below A will be raised and that below C lowered. As the temperature in the two vertical legs gradually approximates to its average value, under the slow process of in-and-out radiation, the path will be opened again, but only to be rapidly closed by the same means as before, still in this way a slow circulation can occur.

Exactly similar conclusions apply if we take a path which first rises from A and then falls back to C, but here the low temperatures are found on the right of the diagram and the high on the left. Thus we see that if it be first granted that there is some force acting from any point C to another point A on the same level sufficient to maintain a difference of pressure between A and C, notwithstanding a small but appreciable flow of air across, and further that the line integral of the force for every level path from A to C is the same, but greater than on neighbouring levels, then the

air, in its attempt to get back from A to C, will produce and maintain the distribution of temperature which we know to exist when C lies about 9 km. high in an area of low pressure and A at the same height in an area of high pressure. The force must exist in the neighbouring levels to that of AC, but may decrease rapidly in intensity as that level is left either above or below. Furthermore, A and C are not necessarily points, but may represent areas of large extent and of any form, regular or irregular. The only difficulty is to find the source of the necessary horizontal force. We can think of nothing save wind to supply this, and it could be supplied by a wind of sufficient velocity and of sufficient lateral and vertical extent. If we guess at the curvature, for after all it can only be a guess, we can calculate the required velocity. Near the earth's surface winds of 50 miles per hour, and extending laterally over 400 or 500 miles, produce differences of pressure sufficient to show on a weather chart the isobaric system of a deep cyclonic storm. The slope of the isobaric surfaces at 9 km. is greater, in the ratio of 3 : 2, and hence the winds must be stronger, but the velocities need not exceed 75 miles per hour. But the momentum of such a wind system is very great, and it is hard to see how it can be originated and how destroyed.

The Isothermal Region.

The explanation that has been given of the temperature distribution carries with it an explanation of the fact that the value of H_c is greater over the high-pressure area than over the low. For if we take a line starting from A and rising vertically, then turning and descending vertically to C, the displacement of the air along such a line from A to C will carry with it the displacement of any peculiarity of the temperature gradient. For the same vertical displacement simply alters the temperature of each element by the same amount, but leaves unaltered the difference of temperature between any two elements of the vertical parts. Thus the isothermal region, which begins where the abrupt change of the temperature gradient sets in, is shifted bodily upwards over A and downwards over C, and the invariable phenomenon of a high value for H_c with the anticyclone and the low one with the cyclone is produced. The slow warming by radiation over A does not alter the level, for presumably the neighbouring strata are about equally warmed, but the readjustment required to meet this warming carries the isothermal upward again, and thus a considerable increase of its height may be brought about.*

Velocity of the Wind at Various Levels.

If this theory of the local circulation be correct, it follows that the winds must continue upwards to a considerable height. In fact, it seems inevitable that the

* *May* 30.—Since this was written it has been found that at least for the English ascents there is a very close relationship between the value of H_c and the pressure at 10 km.

winds must continue up to the height at which the isobaric surfaces are level planes, or rather spheroids concentric with the earth. It will be seen from the diagrams that this point lies at a height of about 20 km., and the number and consistency of the observations is sufficient to make this fairly certain. The slope of the isobaric surface reaches the same value that it has at the earth's surface at about 16 km., and if we denote this by 1, it reaches its maximum value 1·5 at about 10 km. Our knowledge of the wind above the level of the highest clouds is very limited. It is true that balloons have been followed by a theodolite up to 16 km. or more. Mr. CAVE, who is an authority on this point, considers that the wind falls off as the isothermal region is reached, but on some occasions a strong wind is found at 15 km.; there are four such instances on record at Pyrton Hill. But the balloons can only be followed to great heights when the air is clear and the lower winds light. If the lower winds are strong, the balloon is too far off to be visible long before it has reached the isothermal region.

On many occasions there is no great wind up to at least 20 km., so that the supposed strong westerly winds, if they exist at all, are intermittent, and different in character to the N.E. and S.E. trade winds.

The fact that from a station in England many quite likely tracks for a balloon end in the sea introduces a large systematic error, so that no just conclusions can be drawn from registering balloons in England as to the prevalence of certain winds. In most cases the track runs parallel, or nearly so, to the surface isobars, so that generally the direction of the upper wind does not greatly differ from that of the lower, and since also very high ascents do not show longer runs than those of average height, it is certain that the wind velocity decreases rather than increases above 10 or 12 km. But there is nothing in the observational results to negative the supposition that strong winds may on some occasions exist at a height of 15 km. A persistent current of this kind in the general circulation would be easily explained, but it is hard to see in the case of intermittent winds whence the energy can come and where it can go. Also cyclones cannot be caused solely by the upper winds, for if so they would have no reason to avoid continental areas, and prefer moist areas, such as the sea or the chain of the Great Lakes of North America, as they undoubtedly do.