PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Meteorological Observations Obtained by the Use of Kites off the West Coast of Scotland, 1902

W. N. Shaw and W. H. Dines

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III. *Meteorological Observations obtained by the Use of Kites off the West Coast of Scotland*, 1902.

By W. N. Shaw, *Sc.D., F.R.S., and* W. H. Dines, *B.A.*

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[Plate 12.]

The investigation, of which the results are given in the following pages, was undertaken by a Committee of the Royal Meteorological Society appointed in the spring of 1901, with the co-operation of a Committee appointed by the British Association at Glasgow. Towards the cost of the experiments £75 was contributed by the Government Grant Committee of the Royal Society, £75 by the British Association, and £25 anonymously by a Fellow of the Royal Meteorological Society. The remainder of the cost, amounting to £106, was defrayed by that Society.

The Meteorological Council lent the instruments required for a base station at Crinan, and defrayed the cost of maintaining the station. The Council have afforded further assistance to the investigation by undertaking the tabulation of the curves and the preparation of the necessary diagrams. This work has been carried out in the Observatory branch of the Meteorological Office.

The experimental arrangements were designed and carried out by Mr. Dines, with the assistance of his two sons.

For many years past observations on the temperature and humidity of the upper air lying over the United States and the Continent of Europe have been obtained by means of kites, but although this method of investigation was originally started by Dr. Watson, of Glasgow, in 1749, Mr. Archibald seems to have been the only person to make much use of kites for meteorological purposes in England. It was felt by many interested in meteorology that, as the British Isles lie close to the usual track of the cyclonic disturbances which reach Europe from the Atlantic, information as to the conditions prevailing in the upper air over their surface, and more particularly over their Western Coasts, is of especial importance.

In the spring of 1901 a Committee was appointed by the Royal Meteorological Society to consider what could be done, and in the same year, at their Glasgow meeting, the British Association appointed a Committee to co-operate in the matter. These Committees, working together, decided to obtain the necessary apparatus, and to make observations during the three summer months of 1902 at some convenient place on the West Coast of Scotland. It was decided that, if possible, a steam vessel should be employed, since this would enable observations to be made in comparatively calm weather when otherwise no ascent could be made.

Locality of Observations.

The observations were made partly from a small island in Crinan Bay, Argyllshire, but chiefly from the deck of a steam tug in the Sounds of Jura and Scarba, or on the open sea lying to the South of Mull. The position is indicated by circles with Crinan Harbour as centre, drawn in the charts included in fig. 5, p. 135. Could anyone have ascended with the kites, he would on every occasion have had a clear view, apart from mist or clouds, of the Atlantic Ocean lying to the westward, and since the winds, with a few exceptions, were from some westerly point, the results obtained may be taken as approximating to the conditions prevailing over the open sea.

Apparatus and Methods.

Details of the apparatus used and the methods employed for raising the kites are published in the 'Quarterly Journal of the Royal Meteorological Society,' vol. 29, p. 65, 1903. It will be sufficient to state here that flying a single kite from a small steam tug is a very simple and easy process under all ordinary conditions of weather. With a vessel steaming 12 knots, a kite, with recording instruments attached, could be sent up at any time that the wind did not exceed force 8 on the Beaufort scale. The tug used at Crinan could not steam more than 7 knots, and a kite could not be started unless there were sufficient wind to make a ripple on the surface of the water. Unfortunately the summer of 1902 was not a favourable one for kite work in that particular locality, as there were a large number of very calm days. On these days, with the assistance of the tug, there was always a chance of raising a kite to at least 1000 feet, but it was not always possible to get sufficient lifting power to raise the instruments. On the other hand, there were a few days on which the wind equalled or exceeded force 7, a moderate gale; on these days a kite could be, and in fact was, sent up, but as the Committee were unable, for want of funds, to provide a spare set of recording instruments, it did not seem advisable to risk the loss of the single set by sending them up in very strong winds.

Between June 19 and August 26, 71 ascents were made with an average height of 4200 feet (1280 metres). In 40 of these, with an average height of 5900 feet (1798 metres), records from self-recording instruments were obtained. Those on July 4 and 7 were from land, the others from the tug. The great advantage of a steam vessel for this purpose is shown by the fact that whereas during the three weeks when ascents were made from the land, it was only found possible to get a kite up on ten occasions and the instruments on two occasions, during the seven weeks when the tug was used 61 ascents were obtained; a height of at least 1350 feet was reached on every day on which it was available, and the instruments were raised 38 times. A far greater average height would have been obtained had there been a spare set of recording instruments; as there was only one set, and as the risk of losing the instruments is greatly increased by using additional kites, not more than two kites were used for any ascent until the last week.

The average angular elevation given by the kites with a short length of line was 62° 30′. The greatest heights attained were 5500 feet (1676 metres) with one kite, 9200 feet (2804 metres) with two, 12,400 feet (3790 metres) with three, and about 15,000 feet (4500 metres) with four. In the last case the instruments were lost through the breaking away of the top kite on August 26, and the precise elevation is unknown.

Recording Instruments.

The recording instruments were of the well-known form made by Messrs. RICHARD FRÈRES, of Paris, in which a single drum is used for three pens, recording in aniline ink, on ruled paper, the height in metres, the temperature in degrees centigrade, and the humidity in percentages of saturation. As regards the sensitiveness of graduation of the instruments, it may be remarked that the rulings on the sheet were such that a sufficiently fine trace would give a reading of the height to 10 metres, of temperature, with somewhat less certainty, to ·1 °C., and of humidity, with still less certainty, to ·1 per cent.

No special calibration of the instruments was made. Temperature comparisons with ordinary thermometers were made from time to time at ordinary temperatures, and for the range of observation, which was not large, the differences were found to be within the probable errors of reading and exposure. The temperatures are accordingly taken from the curves without correction. No claim is made to any high degree of accuracy in the measurement, but differences of temperature are probably recorded with sufficient accuracy for this stage of the inquiry.

In view of the uncertainties attaching to the estimation of heights by an aneroid barometer, independent measures of the height of the kites were made for the purpose of correcting the instrumental readings. With a kite ascent from land, this is not very easy, since a kite is seldom stationary, and it is difficult to identify the time on the chart exactly with the time of an observation. It is different when using a vessel, for by altering the speed or direction of the vessel, the angular elevation of the kite can, as a rule, be varied at pleasure within wide limits, and by this means a decided crest or hollow, that is easily identified on the trace, is obtained. The angular elevation corresponding to the top of the crest or the bottom of the hollow is observed by a sextant, and this, together with the known length of wire out and a small correction for sag,* gives the height with fair accuracy.

* 'Monograph on the Mechanics and Equilibrium of Kites,' by C. F. MARVIN, U.S. Weather Bureau, Washington, 1897, p. 69.

The heights, as read on the trace, corresponded with the computed heights within about 5 per cent. until July 23, when the instrument fell into the sea. Upon its recovery it continued to give satisfactory curves, but direct observations of height showed that the scale-value had become altered, and from that date a correction of 15 per cent. was applied to the readings of height on account of the change of scale-value, the percentage being determined from observations of height in the manner described. With these corrections the determination of heights reached an accuracy of about 5 per cent.

The estimate of the humidity depends on the extension or contraction of a bundle of hairs. Very accurate results are certainly not obtainable in this way when the hygrometer is used over the sea, and it is doubtful whether they are in any case. In rough weather the spray flew over the tug, the hairs were at times wetted with salt water; then also during rain, and when the kite was in a cloud, they were actually covered with drops of water. The charts frequently show the condition of over-saturation, and all that could be done was to set the pen frequently by the screw provided for the purpose, so that in saturated air it should indicate a humidity of 100.

In spite of these disadvantages, the hygrometer retained its sensitiveness during the ascents, but it was felt that no great degree of accuracy could be attributed to the readings, and on that account, in dealing with the results, only four stages of humidity have been used, viz.:—Very dry (V.D.), under 60 per cent.; dry (D.), from 60 per cent. to 80 per cent.; moist (M.), from 80 per cent. to 95 per cent.; and saturated (S.), above 95 per cent.

Another question that requires consideration is the relation between the temperature and humidity of the instrument and the temperature and humidity of the air which surrounds it. The current of air which supports the kite, whether due to wind or the motion of the vessel carrying the apparatus, must in any case be considerable, and under ordinary conditions the whole instrument may be supposed to take up rapidly the temperature of the air current within narrow limits of accuracy, but in the moist atmosphere which is generally to be found not far from the surface of the coasts of the British Isles a special difficulty arises. The temperature of the air, and, in consequence, that of the instrument, decreases as greater heights are reached, and increases during the descent. In descending, the instrument is therefore exposed to successive layers of air warmer than itself, at the same time the humidity not infrequently increases during the descent, and some condensation of water from the moist air may result if the change of height is rapid. Such condensation would be slight, and perhaps with sufficiently slow descent its effect might be neglected. In the actual experiments a good deal of water was certainly found occasionally in the wire during the winding in. Sometimes a constant drip took place from a piece of cotton waste placed on the wire to prevent the water reaching the reel of wire. This was attributed to drops of water collected by the wire from clouds and not to condensation. Water would be collected in a similar manner by the exposed parts of the instrument, including the hairs of the hygrometer, but the thermometer was protected from rain and, to a certain extent, from drifting particles of water by its case. If the thermometer became wet, it would for a time give a wet bulb instead of a dry bulb temperature; but, under the conditions of deposition of the moisture, the difference would not be large. It would, in effect, show the temperature in descent less than that in ascent. The readings obtained do not give any clear indication of any such effect.

A further uncertainty as to temperature readings arises from the variation in actual temperature of the atmosphere from point to point in the same horizontal layer. The primary object of the temperature observations may be said to be the determination of the vertical distribution of temperature; but an inquiry of not less interest, though of greater difficulty, would be the examination of the details of horizontal distribution of temperature. Two striking instances of horizontal variation of temperature may be mentioned. First, the temperature recorded on Ben Nevis is generally several degrees below that at the same level over the sea at Crinan, 60 miles away, and, secondly, the cloud level indicated by the disappearance of the kite was always much higher than the cloud layer on the hills of the near land, sometimes, as on July 16, by as much as a thousand metres. This matter will be referred to later on. But besides these instances, it may be mentioned that a characteristic type of weather in the neighbourhood was indicated by detached cumulus clouds forming first over the land, but sometimes drifting over the sea. These well-marked detached cumulus clouds were a very common feature, and they certainly indicate a want of horizontal uniformity of condition as regards moisture, probably as regards temperature also. Probably contiguous portions of a horizontal layer are moving, one upward and the other downward, with considerable difference of temperature. The descending column may perhaps be traced in the ruffling of the surface, which is characteristic of "catspaw" weather. On several occasions, notably on August 8 and August 20, convection currents, which would correspond with this state of the atmosphere, produced a noticeable effect on the kites, the angles of which varied from time to time in a very irregular manner. The apparatus employed is not sufficiently refined for the records to identify these differences without very special observations; they have accordingly been disregarded in the discussion of the observations.

Tabulation of the Traces.

The meteorograph was raised 40 times between July 4 and August 25; single ascents were obtained on 23 days, two ascents were made on eight days, on one of which, July 26, a third ascent was made. The clock stopped at the commencement of the ascent on August 21 and before the conclusion of the ascent on August 18. In the other ascents more or less satisfactory records of temperature were obtained, less satisfactory records of humidity.

The traces recorded on the drum give the variations of height, temperature, and humidity with time. As a specimen, a reproduction of the original trace is given for August 11 (fig. 1).

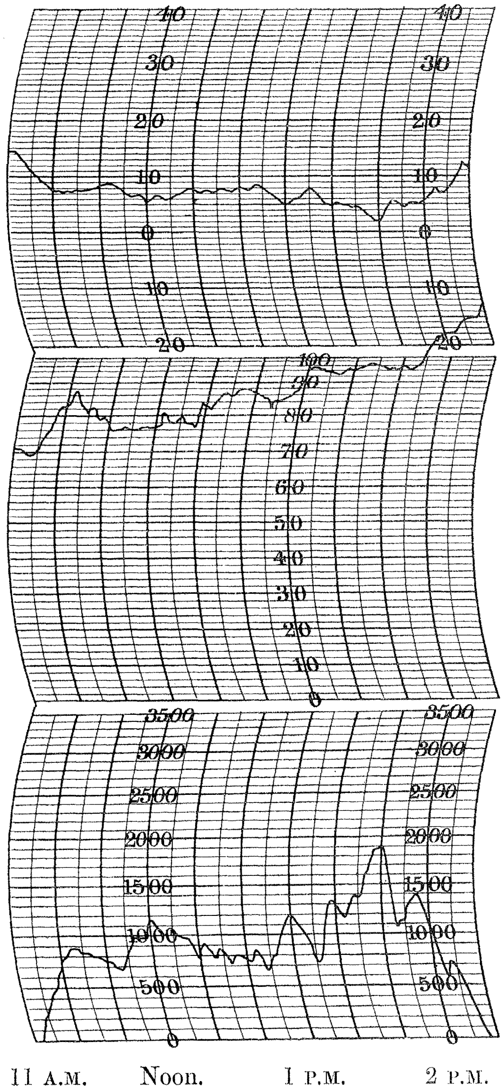

Fig. 1. Facsimile of records of the ascent of August 11.

Notes of the ascent. August 11. Scarba Sound and sea south of Mull.

11.3 A.M., 250 feet of wire out, 60° angle of kite wire, 30 lbs. pull, wind W.N.W.
11.27 ,, 6000 ,, ,, best angle 37°, 20 ,, ,, N.W.
11.40 ,, Second kite.
12.1 P.M., 11,450 feet of wire out, 23° 55′ angle of kite wire, 40 lbs. pull.
Third kite.
1.20 ,, 18,000 feet of wire out. First kite in clouds; commenced winding in; got 2000 feet extra height by winding in.
2.15 ,, All in.

First kite generally below and to right of second, ditto second with regard to third. Wind above N.W. and evidently light. Shower in W. at 2 P.M.

To ascertain the variations of temperature and humidity with height, it is necessary to obtain simultaneous readings of all three elements from the curves. This presents some little difficulty. The time scale of the paper is 2 centims. for 50 minutes, or a millimetre for $2\frac{1}{2}$ minutes. Simultaneous readings could be easily obtained if the pens were always so adjusted that the lengths of the levers for the several records were always equal, but the displacement of a pen by half a millimetre implies a difference of more than a minute in time, and the winding in was occasionally sufficiently rapid to give a variation of height of upwards of 100 metres per minute (see fig. 1). From an examination of the curves it appeared that the setting of the temperature pen as compared with the height pen might show a time difference of from a minute fast on the one side to six minutes slow on the other. During the ascents, if the wind is strong, the levers are subject to considerable mechanical vibration, and the setting of the pen, which is simply slid on to the lever and held by small clips, is not sufficiently secure. In any future ascents it will be desirable to pay special attention to this part of the apparatus, with a view to securing really synchronous readings without difficulty. In the present discussion an error of 50 metres of height must be regarded as not improbable, on account of the uncertainty of the correspondence of the time scales.

One might expect to obtain a series of truly synchronous readings from the curves as they stand by taking readings at salient points, such as are given by projections from the height curve with corresponding projections on the temperature or humidity curve. Such a series of salient points is very conspicuous in the curves for August 11 (fig. 1), but to proceed in this way first assumes that the instruments register the maxima or minima of the separate elements simultaneously, though such an assumption is not necessarily justified, and, secondly, it prevents the use of a continuous curve to smooth the effects of isolated peculiarities which may arise from the peculiar circumstances of the moment, or even from the instruments themselves.

The process adopted with the traces under discussion was to tabulate each curve according to its own time scale for each two minutes of time, and subsequently to determine by a careful examination of the original traces the proper equation of time between them.

Curves of variation of temperature and height were plotted for each ascent. The curve thus obtained for the ascent of August 11 (represented in fig. 1) is given in fig. 2, p. 130. The adjustment of the time scales was subjected to careful scrutiny, and to obtain a final curve of variation of temperature with height the observations were re-plotted, after the scrutiny, and a mean curve taken between the curves of ascent and descent; with a little practice it is easy to recognise in the plotted curves the eccentricities due to want of synchronism, and in the correspondence finally adopted the observations are synchronous within a minute. The smoothed curve probably gives the relation between temperature and height well within that limit. More accurate equivalence of the scales could be obtained by closer tabulation as

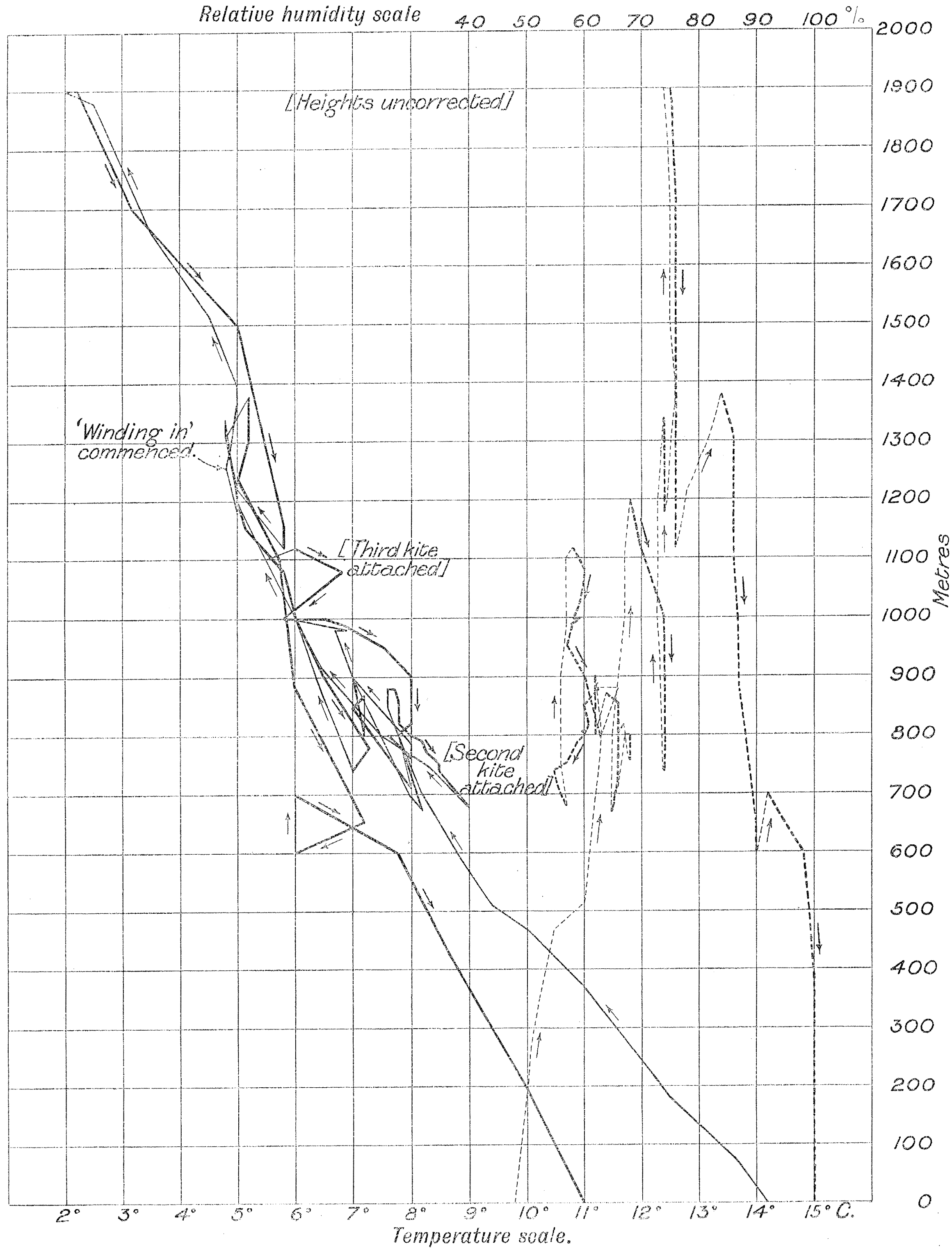

Fig. 2. Temperature and humidity gradients on August 11. Obtained from the tabulation of the curves of fig. 1.

Full lines show the relation between temperature and height.
Dotted ,, ,, ,, humidity and height.
Arrows show whether the kite was rising or sinking.

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regards time, but such a proceeding would entail an amount of labour quite out of proportion to the increased accuracy, having regard to the character of the traces obtained. It has been already mentioned that the mechanical vibration of the levers was considerable in high winds, and this gave rise to a thickening of the lines of the traces, sometimes to almost undecipherable smudges. The stability of the aneroid lever is considerably greater than that of the others, so that the height trace is generally sharp and distinct, while the others are relatively blurred, so much so in some cases that the reading cannot be relied upon to within a division of the paper scale or a degree of temperature. The difficulty that may arise from this cause is illustrated by the record for August 23, the highest obtained, which is reproduced in fig. 3.

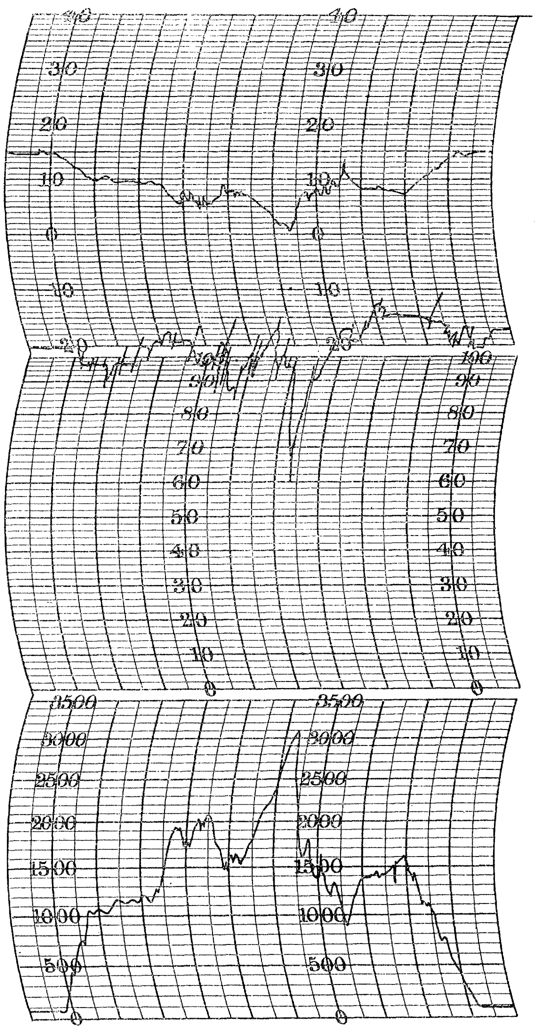

Fig. 3. Facsimile of record of August 23.

As a degree of temperature C. could in no case correspond to less than a hundred metres of height, the system of tabulation and adjustment of time scales may be regarded as sufficiently accurate in comparison with the other uncertainties of the experiments. But the method of recording is a matter which requires very careful attention with a view to increased accuracy. The results as they are here presented must be regarded as giving the general relation between height and temperature; any local variations, due to differences in parts of the same horizontal layer at short intervals, have been smoothed out by the process of reduction. Such variations form a separate subject of study, which requires apparatus specially adapted for this purpose.

It has been pointed out already that the humidity traces are subject to special disadvantages, so that as a rule only rough approximation can be regarded as secured. On two occasions, however, very interesting traces were obtained, namely, on July 31 and August 12, when the air became dry at some distance above the surface (see diagram, fig. 4). July 7 also gave an interesting record of humidity (see Plate 12). In a number of cases the humidity trace was either lost or undecipherable, owing to the relative instability of the pen lever.

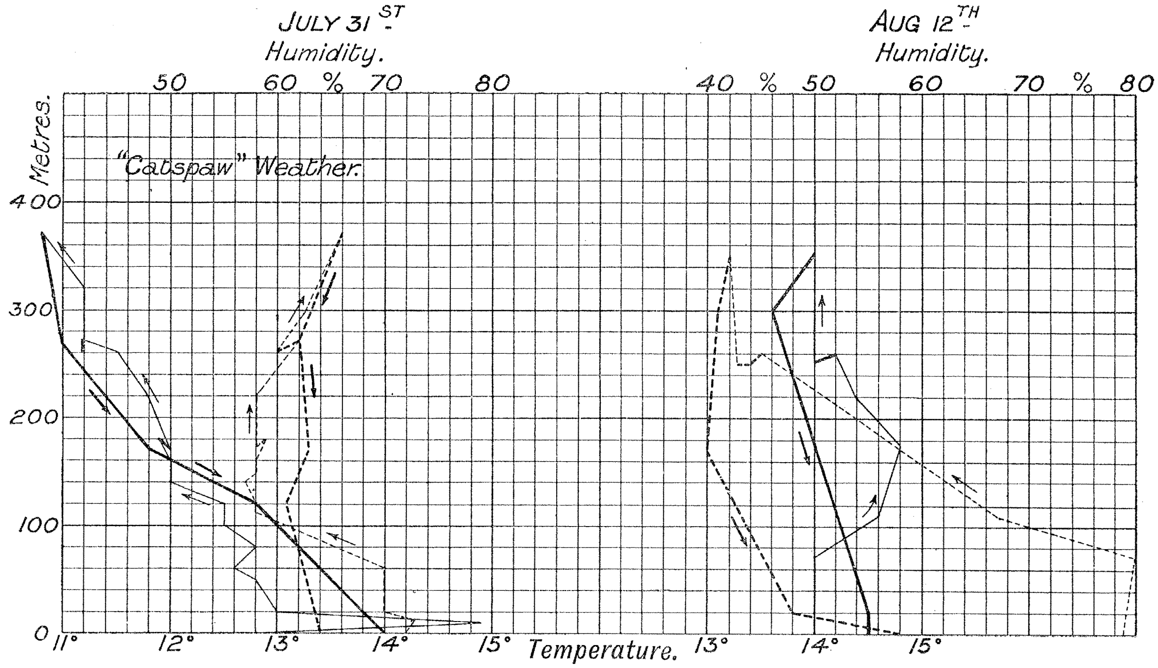

Fig. 4. Exceptional variations of temperature and humidity with height.

Full lines represent the relation between temperature and height.
Dotted „ „ „ humidity and height.
Arrows indicate whether the kite was rising or sinking.

NOTE.—No importance is attached to the large variations of temperature at the commencement of the ascent of July 31, which may have been due to accidental causes.

Results of the Observations.

The final results obtained for temperature are plotted on a diagram (Plate 12), and where ascents were obtained on consecutive days the heights of corresponding temperatures are joined by full lines. As a guide to the eye, dotted lines have been added to connect lines of corresponding temperature. The state of the air as regards humidity at the different levels is represented by the letters V.D., D., M., and S. respectively with the meanings already given. When the letters have not been inserted, the humidity trace has failed.

During the course of the ascents notes were made of the disappearance of the kite in clouds and of its reappearance. From these observations the heights of the cloud layers were determined. The position of the first visible cloud layer thus indicated is shown on the diagram, and varies between 450 metres on July 8 and 2000 metres August 25; two cloud layers were identified in this way on August 1.

The determination of the heights of clouds by this method is not altogether free from uncertainty when detached clouds are drifting across the sky. The kite may become invisible, although it is not itself in cloud, because a cloud drifts under it.

The distinction between the two cases is not so easily drawn in practice as might be supposed.

The direction of the wind was observed at the surface, and is represented by arrows at the base of the diagram. The direction of the wind in the upper air was estimated by the direction of the kite wire, and is indicated by arrows at the top of the isotherms for the different days. In making the estimate the motion of the vessel was allowed for, but the estimates do not claim minute accuracy. On every occasion on which a difference of direction is shown in the upper current the wind had veered aloft.

The weather on the days of the ascents is indicated by letters of the Beaufort scale at the foot of the diagram.

Temperature Gradients.

From the diagram a table (Table A) of results for temperature variation with height for each 500 metres on each day of ascent has been compiled. In each case the figures represent the *fall* of temperature for the range of height specified. The differences of temperature are given to the nearest half degree only. Some of the numbers for the last step of height have been obtained by extrapolation for a short distance of height when the diagram did not actually reach the upper limit. Such numbers are enclosed in square brackets.

For the purpose of a comparison, which will be referred to later on, the differences of temperature between the sea level at or near Crinan and the top of Ben Nevis have been added.

In order to complete the comparison of the variations of temperature gradients with the meteorological conditions at the time of observation, reference may be made to the barometric curves for Fort William and Ben Nevis, which are plotted above the diagram from the hourly observations forwarded to the Meteorological Office, and to the charts of the paths of depressions in the monthly summaries of the "Weekly Weather Report" for July and August. The latter are reproduced in fig. 5. The position of the sea area at which the series of observations were made is indicated by a small circle on the maps. As a matter of fact, the barometric variations were comparatively inconspicuous during the period of observations, and the weather presented a succession of nearly calm days of a somewhat uninteresting character.

Barometric observations were also made at Crinan, and they have been utilised in the comparison, but the variations follow so closely the variations at Fort William for which a continuous curve is available that it has not been thought necessary to represent the Crinan observations on the diagram.

The conditions under which the kite ascents were made during the period of the experiments tended to confine the higher ascents to days upon which the weather has a particular feature, namely, a moderately strong wind in the upper strata.

TABLE A.—Diminution of Temperature for each 500 Metres of Height in Degrees Centigrade.

July.	4.	7.	8.	9.	11.	12.	15.	16.	17.	18.	21.	23.	24.	26.	28.	29.	30.	31.	Average.
metres 0–500	2	4	2	2·5 3	?	?	4 3	2	2·5 3·5	3·5	4 2·5	3	4	2·5 2	2·5	3·5 3	3	3	3·0
500–1000	—	1	—	3	—	—	3 2·5	2·5	3 3	3·5	2	—	3	4 2·5	3	3 3	2·5	—	2·8
1000–1500	—	0	—	2	—	—	3	1·5	—	[3]	—	—	[3]	2	—	2	3	—	2·2
1500–2000	—	—	—	—	—	—	[2]	—	—	—	—	—	—	—	—	—	2	—	2·0
2000–2500	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	—	2·0
Temperature at sea surface above that at Ben Nevis (1342 metres)	—	5	6	6 8	—	—	9·5 9	7·5	9	11	—	—	—	—	—	—	11	—	8·2
August.	**1.**	**2.**	**6.**	**8.**	**9.**	**11.**	**12.**	**19.**	**20.**	**22.**	**23.**	**25.**							**Average.**
metres 0–500	3	3 2	3	3	3	4	1	3	2	2·5	1·5	3	—	—	—	—	—	—	2·6
500–1000	4	2 3	3	3	3	2·5	—	3	2·5	—	2·5	2·5	—	—	—	—	—	—	2·8
1000–1500	3	2 [2]	—	2·5	2·5	2	—	—	2	—	2	3	—	—	—	—	—	—	2·3
1500–2000	[2]	2	—	2	2	2	—	—	2	—	2·5	4 (1500–2500)	—	—	—	—	—	—	2·1
2000–2500	—	[2]	—	—	—	—	—	—	2	—	2		—	—	—	—	—	—	2·0
2500–3000	—	—	—	—	—	—	—	—	2	—	2	—	—	—	—	—	—	—	2·0
3000–3500	—	—	—	—	—	—	—	—	2	—	1·5	—	—	—	—	—	—	—	1·7
Temperature at sea surface above that at Ben Nevis (1342 metres)	12	9 9	—	11	10·5	12·5	—	—	9	9	9	13	—	—	—	—	—	—	10·5

When the winds became very strong, for the reasons already given, only one kite was used and the height was limited in consequence, and if the winds were only light a great length of wire could not be supported.

The Fort William barometer curve shows that the pressure was as low as 29·5 inches on three occasions only during the two months, and exceeded 30 inches

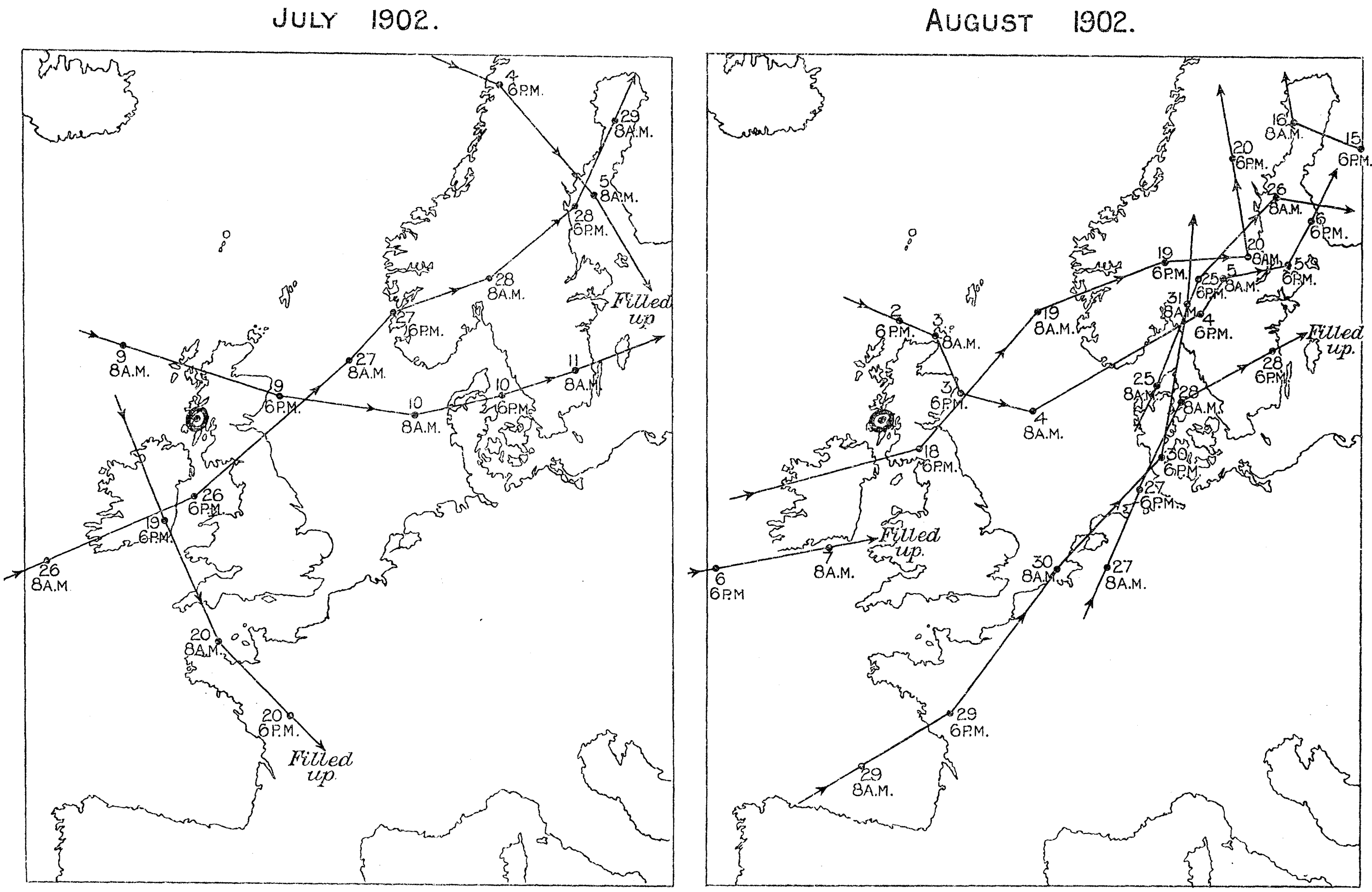

Fig. 5. Movements of depressions.

on eight occasions. There were five well-marked minima, viz., on July 9–10, July 26–27, August 2, August 18, with a secondary minimum on the 20th, and August 22–24; otherwise the variations were inconspicuous.

Turning now to the table of temperature gradients, it will be seen that in July the average fall of temperature for the first 500 metres, computed from 22 ascents, is 3°; for 500–1000 metres (16 ascents) 2°·8; for 1000–1500 metres (9 ascents) 2°·2; 1500–2000 metres (2 ascents) 2°·0; and for 2000–2500 metres from a single ascent 2°·0. In August the corresponding figures are 2°·6 (13 ascents), 2°·8 (11 ascents), 2°·3 (9 ascents), 2°·1 (7 ascents), 2°·0 (3 ascents). In that month also higher stages were reached, 2500–3000 metres on two occasions, with a fall of temperature of 2°·0,

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and 3000–3500 metres on the same two occasions with a fall of 1°·7. There is considerable irregularity in the gradients for the first 500 metres. These irregularities may, perhaps, be accounted for partly by uncertainties attaching to the temperatures at the start and finish of the ascent when the instruments have to be handled by the observer. The range of gradient was between 4° C. and 1° C. for the 500 metres. The first case of gradient 4° (*i.e.*, ·8° for 100 metres) is on July 6, when an anti-cyclone was beginning to give way to an approaching depression, and the gradient, although very high near the surface, disappeared altogether at 1000 metres, where an inversion of gradient was disclosed with very dry atmosphere above a layer of clouds. Another occasion of similarly steep gradient under very similar barometric circumstances was on 24th July, but there was apparently no inversion of gradient. The depression in this case passed to the south of Crinan (see fig. 5) and gave north-easterly winds, while on the 9th it passed to the northward and gave westerly winds. The other occasion on which a steep gradient was observed in the lowest region presented no specific characteristics; it may, however, be noticed that the temperature gradient up to 500 metres may be a good deal affected by the land in the neighbourhood which here and there reaches a height of some 1500 feet.

The very slight gradient of 1° C. for 500 metres on August 12 was connected with an inversion of temperature gradient not far from the surface.

For the step between 500 and 1000 metres the fall of temperature reached 4° C. on two occasions, July 26 and August 1. Both occasions corresponded with the initial stages of advancing depressions. The former passed south of Crinan, the latter north. It seems that a general characteristic of the passage of a depression is that the isothermal lines on the diagram open out and a steep gradient becomes transformed into a slight one. As examples of this may be cited the transition between the 7th July and 9th July, which is better represented in the diagram than in the table; between morning and afternoon of the 26th; between the 1st August and the 2nd; between the 19th August and 20th, and between the 22nd and 23rd.

Taking such corresponding heights for these dates as are available, there is an average diminution of gradient of as much as 50 per cent., and the indication would seem to be that the columns of air in depressions are columns of relatively warm air. There are not enough observations at sufficient heights to confirm this suggestion. It is noticeable that in the depression the gradient does not reach that of the adiabatic gradient of saturated air in the higher regions. It will be noticed, on reference to the maps, that in every case the centres of the depressions were at some distance from the place of observation; they passed it on all sides.

In both months the temperature gradient fell off in the higher regions, and amounted to 2° for the steps of 500 metres beyond 1500 metres.

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Comparison with Previous Results.

In order to compare the general results obtained from the experiments with more or less corresponding results obtained elsewhere, the following table has been compiled from data quoted in HANN's 'Meteorologie,' and the references in the first column are to the pages of that work.*

TABLE B.—Table of Average Temperature Gradients, in Degrees Centigrade, for 100 Metres, for Vertical Columns of Different Heights.

Height of column in metres	500.	1000.	1500.	2000.	2500.	3000.	3500.	4000.
Berlin balloon ascents (p. 157)	—	·50	—	·50	—	·51	—	·52
Kite ascents, U.S. Weather Bureau (p. 124)	1·10	·80	·71	·68	—	—	—	—
Average gradient for mountains (p. 128)	·56° C.	per 100	metres ap	proximat	ely equal	to 1° F. fo	r 300 feet	of height.
Average gradient for Ben Nevis – Fort William, July and August (p. 131) .	—	—	[1340] metre. ·70	—	—	—	—	—
Adiabatic gradient for saturated air (p. 756). Initial temperature, 12° C.	·52	·54	—	·53	—	·62	—	·70
Average results for Crinan experiments, July and August, 1902	·56	·56	·52	·50	·48	·46	·43	—

The average results of the Crinan experiments, for the whole series of ascents, are given in the last line of the table. Up to 2000 metres they agree closely with the adiabatic gradient in saturated air for the initial temperature of 12° C., exceeding that gradient somewhat for the lower strata, for which the results agree with the average temperature gradient of ·56° C. for 100 metres (or 1° F. for 300 feet), which is derived from observations at high level stations, and which is in general use in this

* The results of the Crinan experiments must be regarded as being more or less preliminary, and in the present paper we have thought it desirable to deal only with the general features of the results.

country for the reduction of average temperatures at a network of stations to a common level. They are much below the results of the kite ascents at 17 stations in the United States, obtained by the Weather Bureau, but they agree very closely with the results of the Berlin balloon ascents. With regard to these last, however, a higher figure should be taken for the lowest stage of 500 metres for day ascents in the summer.

All these differences may probably be satisfactorily accounted for by the circumstances of the Crinan ascents, which were over the sea on the edge of the Atlantic, where the daily range of temperature is almost negligible. At greater heights the Crinan results are substantially lower than the Berlin results and the adiabatic gradient, but the number of high ascents is very small, and, as already stated, they refer to a particular type of summer weather which is probably different from those of the balloon ascents.

The average gradient for Ben Nevis—Fort William for the corresponding months, ·70°, is considerably higher than the Crinan gradient for the same height. The actual differences between the temperature at the sea level at Crinan and the top of Ben Nevis, on the days when the Ben Nevis temperature was reached by the kites, as shown in Table A, vary between 13° on August 25 and 5° on July 7, the average being 9·3°. The height in the free atmosphere, at which the Ben Nevis temperatures were reached by the instrument, is shown by the cross marks on the Diagram (Plate 12).

The differences of temperature between the summit of Ben Nevis and the free air at the same level over the sea near Crinan, as determined by the kite experiments, are shown in the following table (Table C). The same table gives also the wind direction and force, and the wet and dry bulb readings for the mountain and for Fort William.

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TABLE C.

Date.	Fort William. Dry bulb.	Fort William. Wet bulb.	Ben Nevis. Dry bulb.	Ben Nevis. Wet bulb.	Wind. Direction.	Wind. Force.	Weather.	Temperature differences. Ben Nevis – Free air at same height.
	° C.	° C.	° C.	° C.				° C.
July 7, 12.25 P.M.	14·7	12·7	4·4	4·4	Var.	0–1	d.m.	– 3·3
,, 9, 12.5 ,,	12·9	12·6	6·1	6·1	W.	0–1	d.m.	– 1·6
,, 15, 11.30 A.M.	13·7	13·1	5·7	5·7	W.	1–2	m.	– 0·3
,, 15, 5.40 P.M.	15·8	12·8	4·3	4·3	W.	1–2	m.	– 1·8
,, 16, 12.10 ,,	13·2	12·4	4·8	4·8	S.W.	2	r.m.	– 1·8
,, 18, 12.10 ,,	13·2	10·0	1·7	1·7	N.	0–1	f.	– 2·7
,, 24, 6.0 ,,	12·9	8.3	– 0·7	– 0·9	N. & W.	0–1	f.	– 1·7
,, 26, 10.45 A.M.	10·2	9·4	3·1	3·1	E.	2–6	r.m.	– 1·4
,, 26, 8.5 P.M.	10·6	9·2	2·0	2·0	N., N.E.	1–3	m.	– 4·7
,, 28, 7.0 ,,	11·9	11·0	3·1	3·1	S.S.W.	0–2	r.m.	– 1·9
,, 29, 12.30 ,,	13·1	10·6	1·8	1·8	Var.	0–2	m.	– 2·0
,, 29, 7.40 ,,	12·1	8·9	0·6	0·6	Var.	2–3	m.	– 2·8
,, 30, 11.10 A.M.	12·7	9·0	1·0	1·0	Var.	0–1	r.s.m.	– 2·2
Aug. 1, 7.0 P.M.	11·1	10·5	2·3	2·3	S.	1–3	r.m.	– 1·6
,, 2, 12.10 ,,	12·4	12·1	3·9	3·9	S.W. & S.	1–2	d.m.	– 1·1
,, 2, 5.0 ,,	13·3	12·7	3·5	3·5	N.W. & W.	1	r.m.	– 2·0
,, 6, 1.40 ,,	15·7	10·9	1·9	1·9	E.S.E.	3	m.	– 5·3
,, 8, 5.10 ,,	13·9	10·2	2·4	2·2	N.E.	1–2	f.	– 2·8
,, 9, 5.0 ,,	13·3	11·2	3·1	3·1	N., Var.	1	r.m.	– 1·9
,, 11, 12.5 ,,	11·9	10·1	1·5	1·5	N.N.E.	1	r.s.m.	– 3·4
,, 11, 2.0 ,,	12·8	10·2	1·3	1·3	Calm	0	r.m.	– 3·6
,, 12, 10.30 A.M.	13·0	9·9	4·4	2·9	N.	2	f. to N. & E.	– 0·7
,, 19, 3.30 P.M.	15·0	11·2	2·4	2·2	Var.	0–1	f.	– 2·8
,, 20, 11.0 A.M.	13·5	11·5	2·8	2·8	Var.	0	r.m.	– 3·3
,, 20, 1.0 P.M.	12·3	10·5	2·3	2·3	E.	1	m.	– 3·8
,, 23, 11.40 A.M.	14·4	13·8	5·6	5·6	S.W.	0–2	m.	– 3·3
,, 23, 1.30 P.M.	14·8	14·0	5·7	5·7	W. & S.W.	1–2	m.	– 3·1
,, 25, 3·40 ,,	16·5	13·1	3·4	3·4	N. & N.N.W.	1–2	f.	– 5·5
							Mean . .	– 2·6 °C.

Although it could hardly have been expected that actual agreement would have been found, the differences are striking, and it is desirable to consider whether it is possible to suggest a reasonable explanation without attributing them to instrumental errors. As the ascents were in the daytime, any effect of the daily range of temperature on the mountain would probably give a result in the opposite direction.

The following considerations would tend to account for such a gradient:—With westerly winds the actual air particles that pass through the thermometer screen on the mountain are probably those which a short time previously have been close to the sea surface, for the stream lines must more or less follow the form of the bounding surface. The temperature on the mountain is therefore not likely to differ much from the temperature at the surface of the sea diminished by the adiabatic decrease due to the altitude; or to put it in another way, the potential temperatures on the mountain and at the sea surface are not likely to be very different. At the place where the kites were flown, the stream lines, apart from convection currents, are probably horizontal, since the disturbance produced by the mountains cannot extend very far to windward. The temperature gradient has been shown to be generally less than the adiabatic gradient in undisturbed air. In any fluid that expands with heat the potentially coldest layers will be at the bottom. The opposite condition can only be transient, otherwise it would involve the continuance of a state of unstable equilibrium. Admitting therefore that these two suppositions are correct, namely, that the temperature gradient over the Atlantic is generally less than the adiabatic one, and that the air rises from the sea level up the slopes of the mountain and in its ascent follows the adiabatic law of cooling, the temperature on the mountain must be less than that in the free air over the sea at the same level.

The adiabatic fall of temperature for the height of Ben Nevis would be 13°·5 C. for dry air, and 7° for saturated air, with an initial temperature of 12° C. The observed differences between the temperatures of the Ben and at sea level near Crinan are between these limits, except on July 7. The peculiar conditions of the atmosphere on that occasion are well illustrated by the diagram, Plate 12. The differences may therefore be accounted for by circumstances which tend to produce an adiabatic gradient in the air, as it is found near the sea level. For example, on the 25th August, the day of the greatest difference, the wind was due west, and though the weather was showery, the cloud level is set at 2000 metres over the sea, and the surface temperature, 16° C., is the highest recorded during the experiments. The mass of the mountain itself, therefore, was probably relatively cold, and the drift of surface air over the land might give a temperature difference even exceeding that of the adiabatic gradient for dry air, but the difference of 11° on July 18, when there was a northerly wind, *i.e.*, blowing from the mountains towards Crinan, with cloud over the sea at 750 metres, cannot be explained in a similar way. No other single suggestion is more fortunate. But the fact that the Ben Nevis—Fort William average gradient in July and August, though it agrees with the kite gradient of the United States Weather Bureau, exceeds the Berlin balloon gradient and the average mountain gradient, points to an explanation depending on some differences of effect of a high level station in that position as compared with a layer of free air at the same height.

It will be noticed, on comparing the readings of temperature at Fort William (Table C) with the initial temperature of the kite ascents (Plate 12), that there is no corresponding difference between the sea-level temperatures at the two positions.

There is another fact which supports the idea that the Ben Nevis temperatures are below those of the free air at the same altitude. The level at which the kites entered the clouds was invariably higher than the level at which the clouds lay upon the mountains. The Paps of Jura, some 2500 feet (760 metres) high, were often covered with clouds at times when the kites did not reach the cloud level under 4000 feet (1220 metres), and the same rule held for lower altitudes. If, then, the lower cloud surface over a limited district be considered as approximately coinciding with an isothermal surface, and this does not seem improbable, it follows that mountain temperatures are lower than those of the free air; at least this was the case at Crinan last summer, for the clouds were undoubtedly lower when in contact with the mountains than they were when formed over the surface of the neighbouring sea.

Thus the existence of such cloud layers on the mountain slopes at a level considerably lower than the clouds over the adjacent sea may be taken as an indication of the effect suggested, although it must be allowed that it might also be attributed to evaporation from the lower mountain surface.

Further and more minute investigation alone can really decide what the explanation of the difference is.

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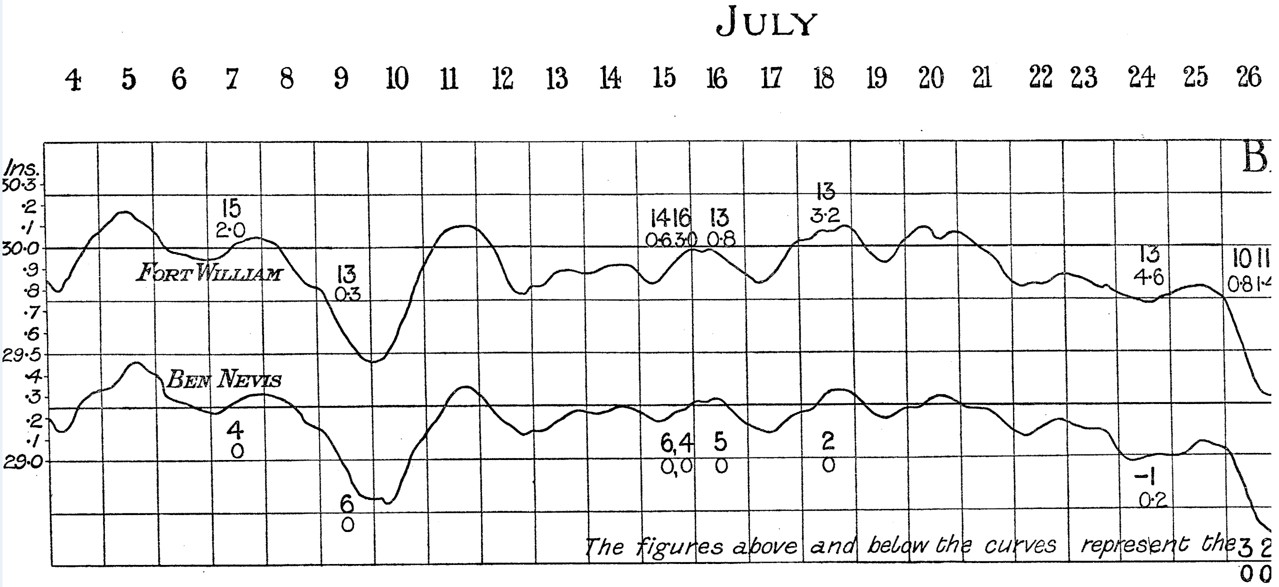
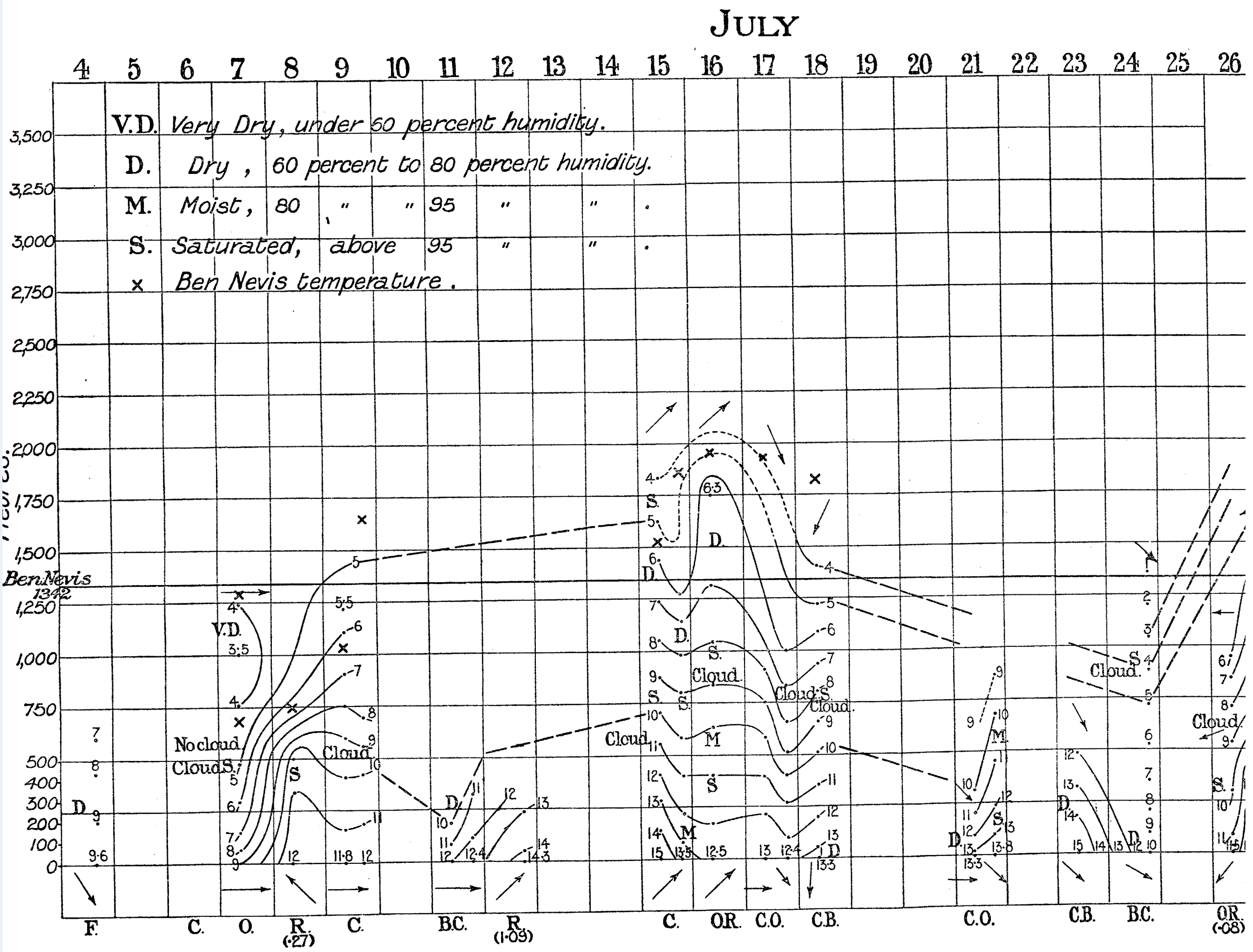
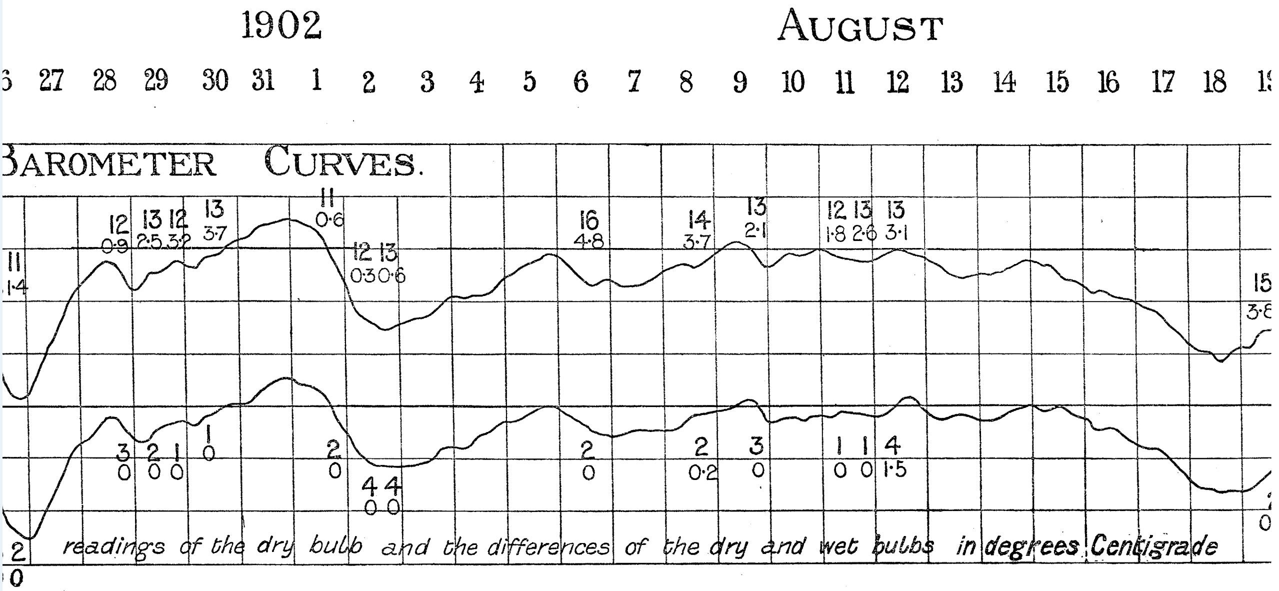
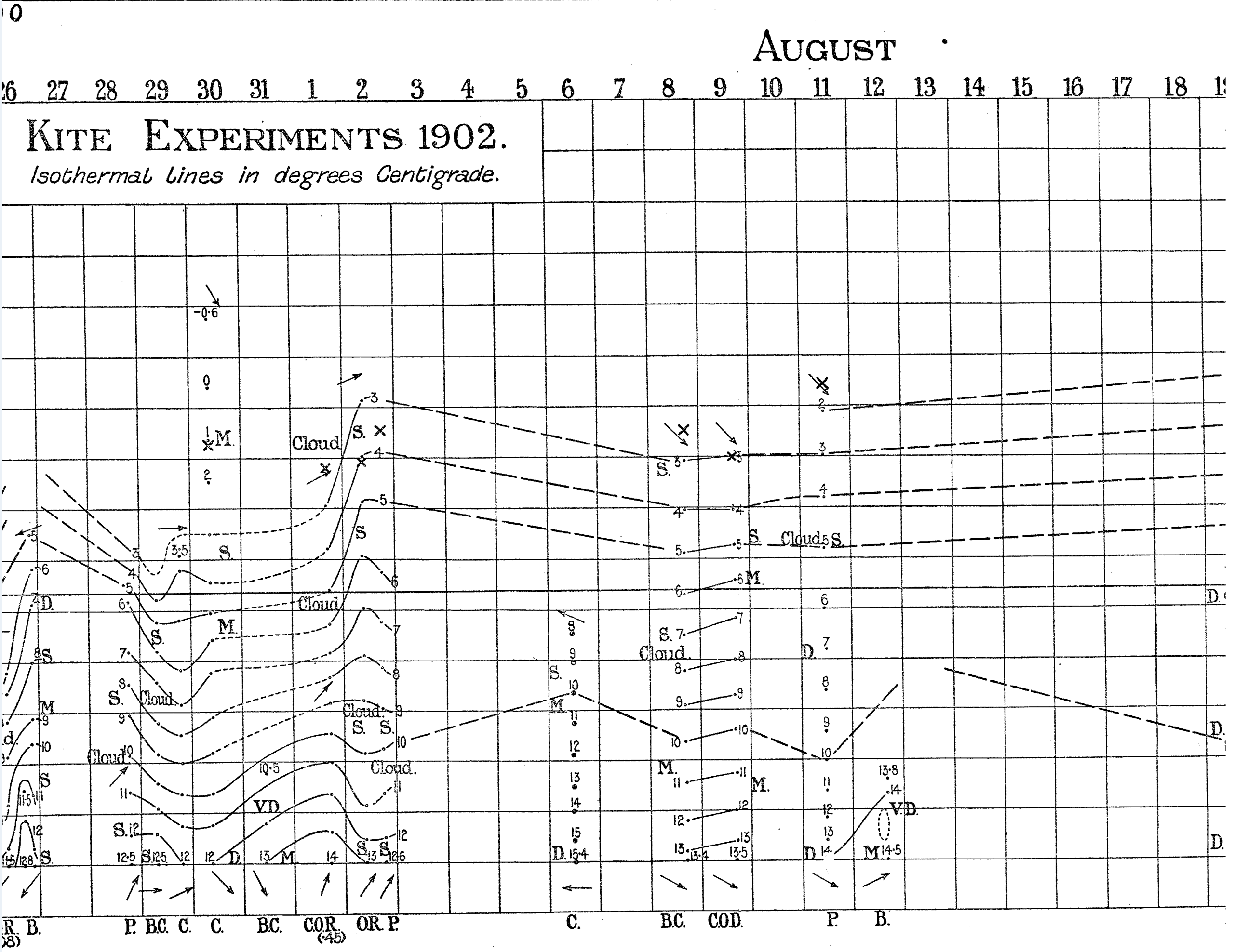
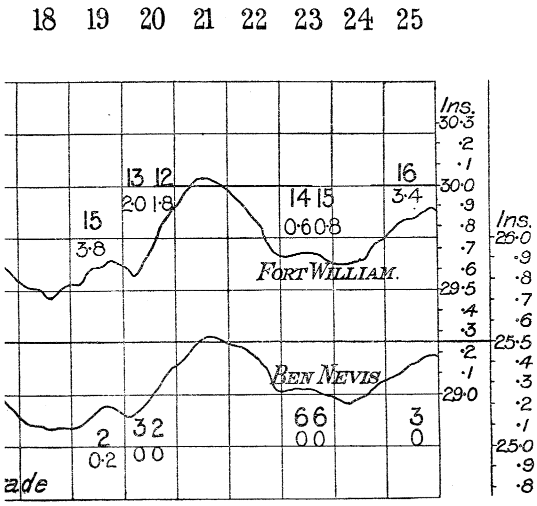

JULY
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Ins.
30·0
29·5
29·0
FORT WILLIAM
BEN NEVIS
B
The figures above and below the curves represent the

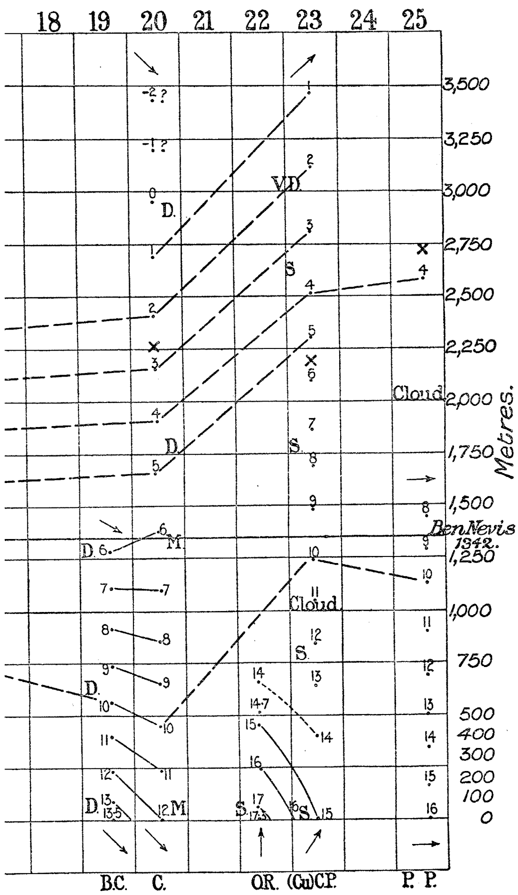

JULY
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
V.D. Very Dry, under 60 percent humidity.
D. Dry , 60 percent to 80 percent humidity.
M. Moist, 80 " " 95 " " .
S. Saturated, above 95 " " .
× Ben Nevis temperature .
3,500
3,250
3,000
2,750
2,500
2,250
2,000
1,750
1,500
1,250
1,000
750
500
400
300
200
100
0
Ben Nevis
1342
No cloud
Cloud
Cloud
Cloud
Cloud
Cloud
Cloud
F. C. O. R. (·27) C. B.C. R. (1·09) C. O.R. C.O. C.B. C.O. C.B. B.C. O.R. (·08)

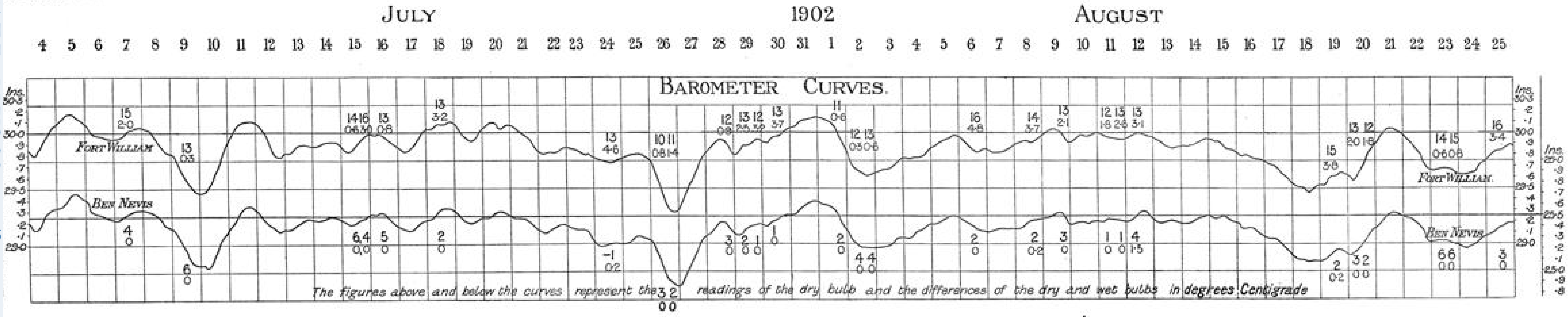


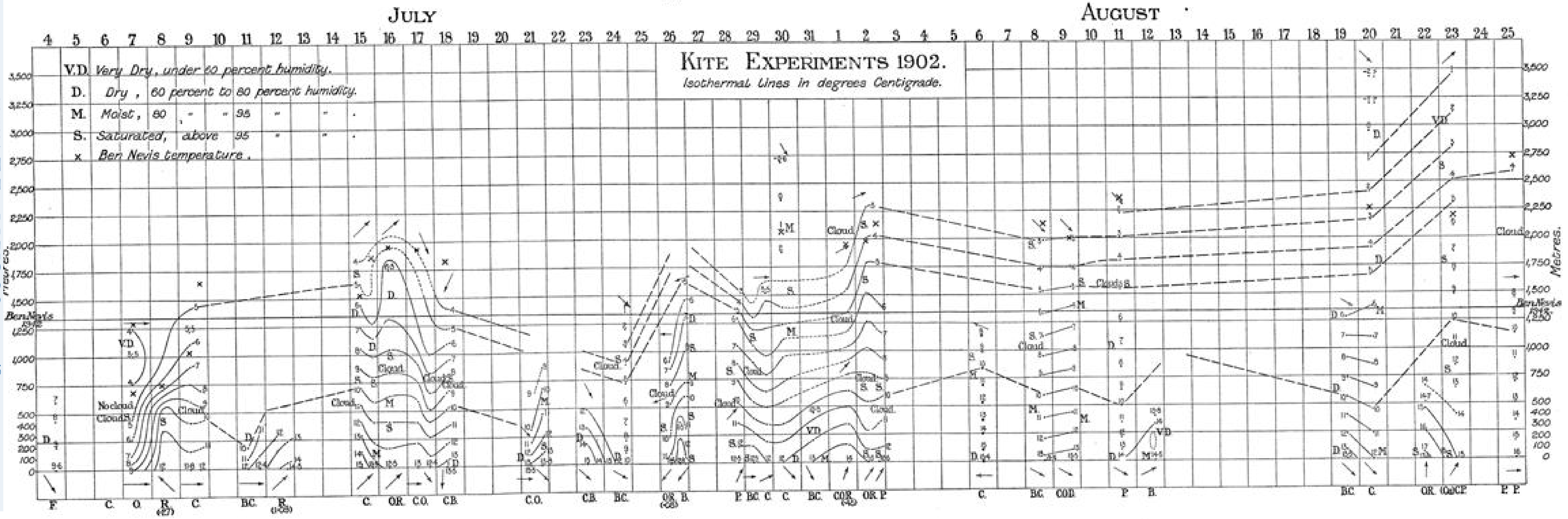


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES


18 19 20 21 22 23 24 25
Ins.
FORT WILLIAM.
BEN NEVIS
ade


18 19 20 21 22 23 24 25
3,500
3,250
3,000
2,750
2,500
2,250
2,000
1,750
1,500
1,250
1,000
750
500
400
300
200
100
0
Metres.
Ben Nevis 1342.
Cloud
Cloud
B.C. C. O.R. (Cu)C.P. P. P.


JULY
1902
AUGUST
BAROMETER CURVES.
FORT WILLIAM
BEN NEVIS
Ins.
The figures above and below the curves represent the readings of the dry bulb and the differences of the dry and wet bulbs in degrees Centigrade


JULY
AUGUST
KITE EXPERIMENTS 1902.
Isothermal Lines in degrees Centigrade.
V.D. Very Dry, under 60 percent humidity.
D. Dry, 60 percent to 80 percent humidity.
M. Moist, 80 " " 95 " " "
S. Saturated, above 95 " " "
× Ben Nevis temperature.
Metres.
Ben Nevis