Abstract of Paper on the Winds of Ben Nevis. By R. T. OMOND and ANGUS RANKIN.*

NOTING the direction of the wind is part of the regular routine of observations at the Observatory on the summit of Ben Nevis. Owing to the frequency of frozen fogs in winter, anemometers are practically useless, but the record is made complete enough for many purposes by the hourly observations; at each hour of the day and night the wind, at the time of making the observation, is noted, and the number of entries of each wind direction in the day, month, or year must very nearly represent the relative frequency of such winds for that time. Table I. is a summary giving the number of times each wind is observed in each month of the year on an average of six years (1884-89) expressed in percentages; thus in January, out of the 744 hours of the month, there are 120 hours or 16·1 per cent. of N. wind. For the year the most frequent wind is N., next come S.W., S.E., and S., all about equal, and the least frequent is E. N. is the point of greatest frequency in all months except May, when S.E. takes its place; in May 1889 there were only 15 hours in the whole month with N., N.W., or N.E. winds, and during three-fourths of that month the air was moving from the S. or S.E. This was, of course, an exceptional month, but in the six years there are only two (1887-88) in which N. was the most frequent wind in May. The exact determination of northerly winds is not very easy on Ben Nevis, owing to the shape of the hill: the great cliff, 2000 feet high, that forms its northern face, breaks these winds up, and makes them squally and uncertain; some may be entered as N. that should be really N.E. or N.W. If we group the percentages of N., N.E., and N.W., and S., S.E., and S.W. together, we get 36·0 for the former, and 39·4 for the latter, thus throwing the preponderance of frequency to the southward, but only by a small percentage. In either case, taking the observations as they stand or as grouped, the relative frequency is totally different from what it is at sea-level. For comparison, Table II. has been drawn up giving the percentage frequency of each wind for all Scotland, from observations at 55 stations for the same six years (1884-89). At sea-level the most frequent wind is W.; and S.W., W., and N.W. include nearly half of the total observations—more than half if we exclude calms. This latter order of winds is in strict harmony with the distribution of barometric pressure over the British Isles, according to BUYS BALLOT's law, by which the winds blow counter-clockwise round areas of low pressure, such an area lying to the north of the British Islands; but the Ben Nevis winds do not fit in with such a distribution of pressure at all, and we may conclude that isobars drawn at the level of Ben Nevis (4400 feet) would lie in quite different directions from those at sea-level. In other words, the distribution of average barometric pressure which extends over the North Atlantic and North-Western Europe,

* See *Trans. Roy. Soc. Edin.*, vol. xxxvi. p. 537.

and dominates the surface winds over that area, does not in this country extend to a vertical height of one mile.

Individual observations show similar differences between the Ben Nevis and sea-level winds. Thus, if a cyclonic storm of small area is lying to the north-eastward, the sea-level winds are W. or N.W., but the Ben Nevis wind may be N.E., blowing straight out from the centre of the low-pressure area. In larger storms, the Ben Nevis winds are practically the same as at sea-level, indicating that in the latter case the disturbance extends to a greater height as well as covers a larger area. But it is remarkable that, with a cyclone covering perhaps Scotland, the North Sea, and Southern Norway, and having the usual circulation of wind round it, the wind at such a low elevation as Ben Nevis should be utterly different. This outflowing wind seldom or never occurs when the centre of the storm is to the S. or W., but only when it lies to the N. or E., and is most marked when an anti-cyclone or high-pressure area is on the other side; the wind appears to be a feeding current carrying the ascending air of the cyclone over to supply the descent in the anti-cyclone.

The complete change in average wind direction with height is, as far as can be gathered from comparison with other mountain stations, a peculiarity of cyclonic regions. The percentage frequency of the different winds on the Säntis (8094 feet), and the Puy de Dôme (4813 feet), as given by Dr BUCHAN in the Challenger Report on "Atmospheric Circulation," are as follows, Ben Nevis being added for comparison:—

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	Calm.
Säntis, . . .	2·7	3·8	4·9	4·1	8·5	22·5	27·7	9·1	16·7
Puy de Dôme, . .	8·2	11·5	7·9	7·4	9·6	15·6	27·7	12·1	...
Ben Nevis, . . .	18·8	8·9	7·6	13·1	13·0	13·3	11·5	8·3	5·5

The low-level winds near the Säntis and Puy de Dôme are on the average of the year westerly, the maximum frequency tending towards S.W. in winter, and N.W. in summer; but at the hill stations W. is the maximum point all the year. Here we have mountain stations whose winds agree in direction with those blowing below; but Säntis in Switzerland, and Puy de Dôme in France, both lie in anti-cyclonic or high-pressure regions, and are not comparable with a high-level station like Ben Nevis, standing on the side of a great barometric depression, and close to the track of the cyclones that sweep our north-western coasts. In connection with this, it should be noted that May, the month in which the north or contra-isobaric winds are at a minimum on Ben Nevis, is the month in which the depression in the North Atlantic is most broken up and dispersed and the high-pressure area which lies off the N.W. of Africa extends towards and partly includes the British Islands.

Although the Ben Nevis winds differ so much from those at sea-level, the variations in the relative frequency of each wind from month to month follow the same course, showing an excess of easterly winds in spring, and of westerly in early winter, both of which departures from the mean are more marked on Ben Nevis than at sea-level. The average percentage increase of N.E., E., and S.E. winds for the months March, April, May is 34 at Ben Nevis, and 31 at sea-level; while the average increase for S.W., W., and N.W. in November, December, January is 16 for the former, and 13 for the latter.

During the harvest months of August and September there is a diminution of 33 per cent. in the N.E., E., and S.E. winds at Ben Nevis, but of only 16 per cent. at sea-level; while the increase in the S., S.W., and W. winds amounts to 16 per cent. at the former, and only 8 per cent. at the latter. Thus at this season, not merely is there an increase of the warmer south-westerly winds, and a diminution of the cold easterly currents, but both of these changes are more pronounced in the higher regions of the atmosphere, a matter of great importance in the prevention of descending masses of cold, dry air, which, accumulating in flat or hollow ground, are so liable to cause "radiation frosts." October presents a complete contrast. The S., S.W., and W. are 8 per cent. below the annual mean at sea-level, and 15 per cent. below on Ben Nevis; and the N., N.E., and E. winds are 13 per cent. above the yearly average at sea-level, and 15 per cent. above on Ben Nevis; showing an increase in the colder currents, slightly greater at high levels, and a diminution in the warmer currents, markedly greater in the upper atmosphere.

In order to see how far the rainfall of Scotland is influenced by the winds, a preliminary examination has been made of the fall in each month on the east and west coasts. The annual fall on the west coast is greater than on the east, and its distribution throughout the year is different. At all purely western stations the maximum rainfall is in the depth of winter, November to January, and the minimum in April or May. At many eastern stations, however, especially in the southern half of Scotland, the greatest rainfall is in July or August, the minimum being like the west in April or May; but there is also on the east coast a secondary maximum in winter. November is a wet month on both coasts.

Comparing the months with the wind tables, we see that the heaviest rainfall on the west coast occurs during the winter maximum of westerly winds, and the least during the spring maximum of easterly winds, and that the summer secondary maximum of westerly and southerly winds in July and August does not affect the west coast, but does largely increase the east coast rainfall. The winds of November have this peculiarity: S.W. is in excess both on Ben Nevis and at sea-level, but E. and N. are slightly below their mean at sea-level, and are above it on Ben Nevis, pointing to the fact that some of the cyclones which cause the heavy rainfall of November have not extended upwards to the height of Ben Nevis, but have there caused reversed or outflowing winds. The month with perhaps the greatest difference between the east and west coast rainfall is December. The winds of December show a marked increase

of S.W. and W. at sea-level, but of N.W. and N. on Ben Nevis, and a diminution of N.E., E., and S.E. at sea-level, and of E. and S.E. on Ben Nevis, indicating that the cyclonic storms of this month were of sufficient depth to include Ben Nevis, and give winds there only differing slightly from those at sea-level. The December rainfall of Ben Nevis for these six years is about 70 per cent. above the twelfth part of the annual average. It would appear that the cyclonic winds of December, mostly W. and S.W., are largely drained of their moisture in passing over the hills of western Scotland, although the region of precipitation in them extends to a height so far exceeding the highest of these mountains as to enormously increase the rainfall there.

From what has been stated above, it will be evident that no hill station, yet in operation, can be regarded as being in the true upper currents of the atmosphere, and that we are still dependent for our knowledge of their motions on observations of the cirrus clouds. A very careful series of observations on these clouds has been made at Blue Hill Observatory, Massachusetts, by Mr CLAYTON. In the year 1887 over 1500 observations were made, giving the following percentages of frequency in the directions of motion:—S.W., 17; W., 40; N.W., 26; all other directions, 17. In other words, for two-thirds of the time the clouds were moving from the W. or N.W., and for half of the remainder from the S.W., leaving only about one-sixth of the total observations for the other five points. These upper currents have the same character as, and are an exaggeration of, the surface winds of Massachusetts, where N. and N.W. are the points of greatest frequency, and the relationship of the two is akin to that between the winds of Säntis or Puy de Dôme, and their low-level winds as given above. But Massachusetts lies in a belt of high pressure, and is far removed from the North Atlantic depression which influences the relation between the Ben Nevis and sea-level winds in Scotland. The highest station from which data are available is Pikes Peak in Colorado, 14,134 feet, and the percentages of wind directions as given in the Challenger Report, page 165, are as follows:—N., 10; N.E., 9; E., 1; S.E., 2; S., 5; S.W., 32; W., 20; N.W., 18; calm, 3. Here we have a marked predominance of S.W. and W. winds, but nothing like the excess from one direction of the cirrus cloud motion indicated by the Blue Hill observations; it would seem that even at this great height the observers are not wholly in the upper currents, though the percentage of westerly winds is in excess of that at any low-level station in that part of North America. The measurements of the heights of clouds taken at Upsala confirm this (see *Nature*, vol. xxxvi. p. 321). They show three layers of clouds—Lower, 2000 to 6000 feet, in or near which most hill stations are; Middle, 12,000 to 15,000, in which Pikes Peak is; and upper, 20,000 to 27,000, which are the true upper current clouds.

Any attempt to elucidate the behaviour of the atmospheric currents in cyclonic storms must be based on a careful study of individual cases, and not on general means, such as are dealt with in this paper. For this we have neither had time nor opportunity as yet, but the following points should be borne in mind when studying the development and behaviour of cyclones.

1. The height of a cyclone is so small compared with its area, that any attempt to represent a vertical section of it diagrammatically is useless and misleading.

2. From the laws of fluid motion it is probable that the upper end of a rotating mass of air, with or without an ascending motion in it, behaves in a very different manner in the free atmosphere from its lower end, which is bounded by the surface of the earth. It is unsafe to lay off isobars for the level of Ben Nevis from the winds observed there according to BALLOT's law; they may blow directly from high to low pressure, or according to some other yet unknown law.

3. The small diurnal variation in wind direction on Ben Nevis will enable us to study the changes of wind connected with variations of pressure, etc., independent of the time of day of their occurrence.

An examination of individual months that are higher or lower than their average in temperature shows that, in the warmest months, southerly winds are in excess on Ben Nevis and also at sea-level; while north-easterly are in defect on the summit, and northerly below. In the months below their average temperature, easterly winds are in excess on the summit, and northerly at sea-level; and the points of greatest defect are south on Ben Nevis, and south-east at sea-level. Thus in both the excess and defect the directions are on the summit several points to the right, looking out from the centre of the compass, of those at sea-level,—eight in the case of the excess, and four in the defect. It must be remembered we are dealing with average results: for in some of our exceptionally warm weather, the conditions on the summit are purely and entirely characteristic of high-level Observatories during anti-cyclones.

The temperature of the different winds has been discussed,* and the warmest point on the Ben Nevis windrose oscillates through 90 degrees from S.W. in winter to S. and S.E. in summer, and all these points are in a warm month in excess of what they are in an average month. These points, again, are in a cold month in defect of what they are in an average month, while the points of the northern half of the compass are in excess. If we take the sea-level wind excess as an index to the distribution of pressure at sea-level, we have in the Ben Nevis warm months an excess of pressure somewhere to the east or south-east, and low pressure to the west or south-west, superimposed on the normal excess in the south, and defect in the north-west or north. With this distribution of pressure, then, we see that the excess winds above and below are from about the same point of the compass. Similarly, in the cold months, the sea-level wind excess indicates an excess of pressure to the west or north-west, and a defect to the east. Here we see that the Ben Nevis excess blows straight out from the indicated centre of diminished pressure. Low temperatures on Ben Nevis are thus connected with winds that indicate a different distribution of pressure there from what holds at sea-level.

There is no marked diurnal variation in the direction of the wind on Ben Nevis, though the mean wind-velocity shows a distinct daily period. The latter, as at all true

* See "Thermal Windrose at the Ben Nevis Observatory," by A. Rankin, *Proc. Roy. Soc. Edin.*, vol. xiv. p. 416.

TABLE I.—*Hours of Each Wind. Ben Nevis Observatory. 1884–89. Percentages.*

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	Calm or Var.
January, . . .	16.1	9.0	5.8	12.9	14.0	15.9	13.8	10.5	2.0
February, . . .	18.5	11.8	9.7	12.8	12.3	15.0	10.0	7.7	2.2
March, . . .	18.6	14.1	10.2	14.6	10.9	11.7	9.2	7.5	3.2
April, . . .	18.5	12.1	11.8	14.3	13.0	9.0	8.5	6.7	6.1
May, . . .	10.6	12.0	9.5	18.1	15.5	11.8	9.8	6.5	6.2
June, . . .	15.6	7.9	8.3	12.5	12.4	13.7	12.4	8.2	9.0
July, . . .	17.5	4.6	7.1	14.9	13.7	11.8	12.2	9.2	9.0
August, . . .	20.3	5.1	4.6	10.5	16.3	13.3	13.6	7.9	8.4
September, . . .	18.5	4.6	4.6	12.0	15.7	14.3	14.2	8.5	7.6
October, . . .	25.3	9.1	8.2	12.1	9.8	12.6	9.7	7.3	5.9
November, . . .	20.7	7.8	9.2	13.9	10.3	15.4	11.6	8.6	2.5
December, . . .	25.5	9.1	4.0	8.5	11.2	15.2	12.4	11.3	2.8
Year, . . .	18.8	8.9	7.6	13.1	13.0	13.3	11.5	8.3	5.5

TABLE II.—*Percentage Winds. All Scotland. 1884–89. From Registrar General's Returns published in Journal of Scott. Metr. Soc.*

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	Calm or Var.
January, . . .	7.0	5.4	9.1	7.5	9.1	22.1	23.7	9.7	6.4
February, . . .	9.4	7.7	12.3	7.7	9.4	18.8	18.8	10.0	5.9
March, . . .	10.2	8.6	14.5	9.7	9.7	15.1	16.1	10.7	5.4
April, . . .	11.1	13.3	18.4	9.4	8.9	11.7	14.4	8.9	3.9
May, . . .	7.5	9.1	15.6	10.7	10.2	14.5	16.2	10.2	6.0
June, . . .	6.7	9.4	13.9	8.3	9.4	13.3	21.2	11.1	6.7
July, . . .	7.0	7.5	12.4	7.5	10.2	15.6	22.1	10.7	7.0
August, . . .	7.5	7.0	9.7	5.9	11.3	18.8	21.0	10.7	8.1
September, . . .	8.3	6.7	10.5	6.7	8.9	18.3	21.7	8.9	10.0
October, . . .	10.7	9.7	11.3	5.9	7.5	15.6	21.0	11.3	7.0
November, . . .	7.8	7.2	11.7	7.2	9.4	18.9	21.1	10.0	6.7
December, . . .	9.7	4.3	5.4	5.4	9.1	21.0	24.7	11.8	8.6
Year, . . .	8.6	8.0	12.0	7.7	9.4	17.0	20.2	10.3	6.8

hill stations, rises to a maximum in the very early morning, and falls to its minimum in the afternoon, the reverse of what occurs at sea-level. But the direction of the wind shows no appreciable changes, even in fine summer weather, when the power of the sun is greatest, and such changes might be looked for, except that there is a very slight excess of W. at night and of E. in the forenoon; and that from 1 to 9 A.M. N. is in excess, from 10 A.M. to 6 P.M. S., and for the rest of the day both these directions are rather below the mean of the whole day.

This result is substantially the same as that arrived at by a more elaborate examination of the summer winds of Ben Nevis for two years, communicated to this Society in 1886 (see *Proc. Roy. Soc. Edin.*, vol. xiii. p. 839). We see no reason to alter the explanation of this very slight diurnal variation given in that paper, viz., that it is entirely due to radiation on the N. and S. sides of the hill, and is not connected with any general system of land and sea breezes. It is rather remarkable that on Ben Nevis there should be practically no diurnal variation in the direction of the wind, situated as it is near the Western Sea, and with the elevated plateau of the Moor of Rannoch, and the great mass of the highest hills of Scotland to the E. of it. At any sea-level station in the neighbourhood, doubtless a diurnal change of marked character would have appeared in a similar set of observations.