Report on Atmospheric Dust. By JOHN AITKEN, LL.D., F.R.S.

In 1889 the Scottish Meteorological Society decided on making observations on the dust in the atmosphere at their Observatory on Ben Nevis. Having prepared the plans for the apparatus to be used for counting the dust particles, I visited the Observatory on the 1st of August of that year, and, after consulting with Mr OMOND, decided that

FIG. 1.—Dust-Counter.

the tower of the Observatory was the best place for fitting up the instrument. The apparatus was afterwards made by White of Glasgow, and fitted up in the Observatory on 5th June 1890.

Fig. 1 is a photograph of the apparatus taken before it left the low level. *A* is a receiver in which the air is tested in the usual manner by moistening and expanding it,

the small rain-drops that fall on the micrometer in the receiver being counted by means of the lens *S*. *B* is the pump for expanding the air in the receiver. *C* is a filter of cotton-wool for filling the receiver with dustless air, the air being admitted through the stopcock *O*. Water for moistening the air is admitted by the stopcock *D* from the vessel *E* by means of the pipe *E'*. *F* is a lamp for illuminating the micrometer, the light entering the receiver through the glass cover. *G* is a water lens for concentrating the light of the lamp on the micrometer. *H* is a large glass condensing lens which could be used in place of the water lens. The air to be tested was introduced from the outer air by means of the tube *I*, which was connected with the instrument by means of the short india-rubber tube *K*, attached to the tube *L* on the instrument. The tube *I* was of such a length that it could be put through openings on any side of the tower, so as always to point in the direction from which the wind at the time was blowing, so as to get air uncontaminated with local pollution. The air to be tested is admitted to the receiver *A* by the stopcock *O*, which communicates with the receiver and the small chamber *N* by means of a cross passage in the plug of the stopcock. In order that the air in the chamber *N* should be the same as the outer air, a continuous current was kept up through it by means of the aspirator *M*, which was connected with *N* by means of the pipes *P P*, the stopcock *Q* being used for allowing the current to flow when a test was to be made. The different proportions of impure to pure air required for making tests were introduced into the receiver *A* by pumping out, by means of *B*, certain measured quantities of air, its place being taken by the impure air admitted from the chamber *N* through the stopcock *O*; the different proportions of impure to pure air being regulated by means of the bridles *R* and *R'*, one of which, when raised to a horizontal position, checked the length of the stroke of the pump at the required proportion, enabling exactly the same proportion of air to be measured for each of the ten successive tests made during each observation.

DUST PARTICLES AT BEN NEVIS OBSERVATORY.

See "Preliminary Note on the Observations of Dust Particles at Ben Nevis Observatory." By A. RANKIN. *Journal of Scottish Meteorological Society*, vol. ix. p. 125.

Table I. gives the monthly averages and the highest and lowest observations of dust during the first few months that the dust-counter at Ben Nevis Observatory was in use.

TABLE I.—*Number of Dust Particles per cubic centimetre.*

	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
1890.												
Mean, . . .	...	...	1,518	3,582	2,526	700	588	606	...	...	418	...
Maximum, . . .	...	...	12,862	10,750	4,940	3,850	4,000	1,286	...	...	3,150	...
Minimum, . . .	...	...	175	650	250	50	...	67	...	...	12	...
1891.												
Mean, . . .	...	1,515	557	1,018	988	...	...	...	...	...	...	...
Maximum, . . .	...	6,350	7,600	14,400	4,400	...	...	...	...	...	...	...
Minimum, . . .	...	4	0	11	4	...	...	...	...	...	...	...

The means for March, April, and May of 1890 are not comparable with the rest, as the observations in these months were all taken during the daytime and in fine weather. In February 1891 readings were only taken during the last eight days of the month. Taking the average of the remaining months, the mean number of dust particles is 696 per cubic centimetre. The largest number observed was 14,400 per c.c. at 13 hour on 11th April 1891. Hourly readings were taken on the 11th and 12th April 1891, on both of which days the number of particles was great: the values for each hour are given in Table II. This table shows how rapidly the number of dust particles fluctuates.

TABLE II.—*Dust Particles per c.c.*

Hour.	1	2	3	4	5	6	7	8	9	10	11	12
April 11,	1,600	...	1,400	850	1,600	800	450	350	625	712	838	2,250
„ 12,	400	162	300	350	300	275	288	...	288	350	225	325
Hour.	13	14	15	16	17	18	19	20	21	22	23	Mid.
April 11,	14,400	11,200	13,500	9,500	12,000	6,500	4,200	1,750	700	850	950	600
„ 12,	338	1,100	1,200	1,800	2,450	4,400	2,400	1,850	...	1,550	1,850	2,750

Regular observations were made eight times a day for the three months March, April, and May of 1891, the hours of observation being, 1, 4, 7, 10, 13, 16, 19, and 22. A few breaks occurred in the record, but not sufficient to prevent a fairly correct average for each hour being obtained. These averages are given in Table III., with the mean for each month, the mean of the three months at each hour, and the differences of these hourly means from the general mean of the whole period.

TABLE III.—*Dust Particles per c.c.*

Hour.	1	4	7	10	13	16	19	22	Mean.
1891									
March,	421	310	301	656	762	833	701	470	557
April,	809	547	743	505	1218	1912	1190	1221	1018
May,	978	720	666	491	869	1568	1213	1397	988
Mean,	736	526	570	551	950	1438	1035	1029	854
Differences,	-118	-328	-284	-303	+96	+584	+181	+175	...

This table indicates a well-marked diurnal range in the amount of dust, there being a maximum about the warmest part of the day and a minimum in the early morning. This is mainly due, no doubt, to ascending currents of heated air bringing up dust from the lower atmosphere during the middle of the day.

The discussion of the observations taken in later years is not yet completed.

During about a month, generally in July, of the years 1890-91-92-93, simultaneous tests of dust were made at the Ben Nevis Observatory, generally by Mr RANKIN, and by myself at Kingairloch, in order to find the comparative purity of the air at high and low levels. Kingairloch is situated at sea level, at a distance of about 28 miles in a south-westerly direction from Ben Nevis. A situation nearer the Ben would have been preferable, but the great isolation of Kingairloch, and its freedom from local pollution,

gives it a great advantage over most situations nearer the Ben. It was not possible to have the observations taken at the same hours at both stations; but this was of little importance, as, owing to the distance between the two places, even when the wind was in the line connecting them, the passing air would take a time to travel between them, and simultaneous observations would not therefore have given the state of a vertical column of air at high and low levels.

The result of these observations taken at high and low levels, details of which are given in the *Trans. Roy. Soc. Edin.*, vol. xxxvii. parts 1 and 2, show that the air at high level has generally fewer dust particles in it than at low level, but not always so; and further, the observations show that lower readings have been obtained on the Ben than at Kingairloch. On a few occasions no dust has been observed at the high level, whilst the lowest reading obtained at Kingairloch is 16 per c.c. On the other hand, as high readings have been obtained on the Ben as at Kingairloch.

It may be as well to define what is meant by these very low readings on the Ben when it is stated no dust was observed. It simply means that in the air tested no particles were visible. But as the observations are made by counting the number of drops falling on the millimetre squares of the micrometer, and as only a square of nine square millimetres can be observed, that means that, when no dust was observed in the ten tests usually made, there was not one dust particle in the cubic centimetre of air that came under observation during these ten tests; but the observations give little support to the idea that there might not have been one particle in a larger quantity of air.

The observations show that the effect of the direction of the wind is very marked in the amount of dust both at high and low levels. Whenever the wind blew from the N.W. quadrant, the number of particles at both stations was small, and all low numbers were got in air from that quarter. From all other directions the air was less pure, and particularly when it came from the S.E., that is, from the direction in which lie the most populated parts of the country. When the numbers were higher on the Ben than at low level, it was found to be due to the air at the two stations not coming from the same direction. If, for instance, the wind was northerly at low level whilst it was southerly on the Ben, the number of particles was greater at the high than at the low level.

These results have been confirmed by observations made in Switzerland, on the Rigi Kulm. The dust observations taken by me at that high-level station show that the number of particles was always high when the wind blew from the thickly inhabited districts, and low when the air came from the region of the Alps.

The effect of sunshine is to give rise to ascending currents of air, and as this ascending air comes from the lower impure stratum of the atmosphere it brings its dust with it. This is shown by the number of particles increasing on the Ben as the day advances, and again falling after the sun's heat has gone. This effect is also shown in the observations on the Rigi Kulm, the numbers beginning to rise early in the day

if the morning was sunny, but the increase coming later if the morning was cloudy and followed by sunshine, and not appearing at all if the day remained clouded.

The effect of the dust on the transparency of the air was also noted during these observations made at Ben Nevis and Kingairloch, and the general result arrived at is that on all clear days the number of particles was small, and on all thickly hazed days the number was great. Take, for instance, the 16th of July 1892. During the whole of that day the numbers were very low at both stations. At high level the number was 160 per c.c., and at low level 200 per c.c. In the Ben Nevis Observations it is noted: "Ireland seen, only a thin haze." As Ireland is 125 miles distant, the air must have been very clear to give only a thin haze at that distance. The observations made at Kingairloch on that day show the air had its maximum clearness also at low level. Many similar observations might be quoted to show that the air is clear when the number of particles is few, and also to show that it is thick when the number is great, all of which point to the conclusion that dust is the principal cause of the haze in the atmosphere.

The hazing effect of dust is confirmed by the observations on the Rigi Kulm. The air there was never clear unless the number of particles was small. The amount of haze at that station was estimated by the clearness of Hochgerrach, a mountain seventy miles distant from the Rigi. During five visits to the Rigi Kulm, Hochgerrach was visible thirteen times. On eight of these occasions the mountain was only one-half to one-fifth hazed, and the number of particles was from 326 to 850 per c.c. It was seen five times, when the number varied from 950 to 2000 per c.c.; but on these occasions the mountain was little more than visible, and it was never seen when the number of particles was a little over 2000 per c.c.

The hazing effect of dust has been worked out in detail by me from observations made at Kingairloch, Rigi Kulm, and Alford in Aberdeenshire.* In working out the relation between the transparency of the air and the different amounts of dust in it, it was found necessary first to arrange the different observations according to the humidity of the air at the time of observation, as it was found that the humidity had a marked influence on the transparency. It is not supposed that humidity, as humidity, has any effect on the transparency. Water vapour, as such, seems to have no hazing effect, because we know we can have very transparent air with a high humidity if the number of dust particles be small. The effect of the humidity would seem to be to increase the size of the particles, so increasing their hazing effect. Some water seems to be condensed on the particles even in dry air, but less is condensed the dryer the air. The separate observations were accordingly arranged in different tables. In one table were put all the observations taken when the wet bulb depression was from 2° to 4° ; in another, the observations when the depression was from 4° to 7° ; and in a third, all observations when the depression was over 7° . The observations were arranged in the different tables in order, beginning at the top of the column with the observation having the smallest number of particles, and in another column alongside entering the limit of

* See *Proc. Roy. Soc. Edin.*, vol. xvii., 1889-1890, p. 193.

visibility in miles, the limit of visibility being obtained by estimating the amount of haze between the observer and a mountain at a known distance. Suppose the mountain to be 25 miles distant and to be half-hazed, then the limit of visibility will be 50 miles. In illustration of these tables the one showing the Kingairloch observations for 1893 is here reproduced.

TABLE showing the relation between the Number of Dust Particles and the Transparency of the Atmosphere with Wet Bulb Depression of 7° and over.

Date.	Mean Number of Particles.	Limit of Visibility in Miles.	C.
12 July, . .	388	250	97,000
24 June, . .	508	200	101,600
15 July, . .	828	200	165,600
3 " . .	857	150	128,550
5 " . .	1480	100	148,000
6 " . .	1596	80	127,680
11 " . .	1825	100	182,500
30 June, . .	3950	60	237,000
8 July, . .	4100	50	205,000
7 " . .	5100	17	86,700
1 " . .	5175	13	67,275

mean
140,628

When all the observations had been entered in tables similar to the above, it was seen that, while the numbers in the columns of particles gradually increased, the limit of visibility gradually decreased. Further, when the number of particles was multiplied by the limit of visibility, a number was obtained which in a rough way was constant for the different observations in each table, but this number was not the same for the different wet bulb depressions. In the above table there is a column headed C. In this column is entered the number got by multiplying the number of particles into the limit of visibility, and it will be noticed that the value of C is far from constant; but this is only what might be expected, owing to the difficulty of estimating the density of haze, and lack of knowledge regarding very much of the intervening air, which may differ much from that at the place of observation.

Though the different individual observations in the above table give far from the same value for the constant C, yet when we average a number of observations, even though those observations are taken at different places and the haze has to be estimated under different conditions, the agreement is, considering the difficulties, fairly close. This is seen in the following table, in which is arranged the mean values of C from the observations made at different wet bulb depressions at Kingairloch, Alford, and Rigi Kulm.

It will be noticed that the value of C at the three stations is, considering the difficulty of estimating haze, fairly constant in each column for the different humidities, but that the number is not the same for the different humidities, being nearly twice as great in the driest air as it is in the dampest, the explanation of this being that the same number of particles has a much greater hazing effect in damp than in dry air.

Place.	Values of C at Different Wet Bulb Depressions.		
	2° to 4°.	4° to 7°.	7° and over.
Kingairloch, 1893, . . .	77,525	105,923	140,628
„ 1892, . . .	No observations	116,677	174,832
Alford, . . .	75,474	95,153	124,921
Rigi Kulm, . . .	75,176	104,430	124,211
Mean, . . .	76,058	105,545	141,148

To find what is the actual number of particles required to produce a complete haze, that is, render a distant mountain invisible, all that is necessary is to multiply the above constant C by 160,932, that is, by the number of centimetres in a mile. When that is done we get the numbers given in the following table, which shows us the number of particles at the different humidities in a column of air 1 square centimetre section, whatever the length of the column may be, selecting for this table the observations made at Kingairloch in 1893, as they are the most to be relied on and do not differ much from the average.

Wet Bulb Depression.	Number of Particles required to Produce a Complete Haze.
2° to 4°	12,500,000
4° to 7°	17,100,000
7° to 10°	22,600,000

This table shows that, roughly speaking, the transparency of the atmosphere is doubled by decreasing the humidity by one-half, as it only requires half the number of particles to make a complete haze with a wet bulb depression of from 2° to 4° that is required when the depression is 7° to 10°.

With the information we now have of the hazing effect of dust, it is possible roughly to estimate the number of dust particles in the air without a dust-counter. As we have established the numerical relation between the number of dust particles, the haze, and the humidity, so that any two of these being known the third may be calculated, so if we know the wet bulb depression and the limit of visibility we can find the number of dust particles in the air without a dust-counter.

A great many observations have also been made at Falkirk* on the haze in the atmosphere. These observations were made without a dust-counter, with the object of

* *Proc. Roy. Soc. Edin.*, vol. xx. p. 76, Jan. 30, 1893.

seeing how far the pollution due to inhabited districts affected the clearness of the atmosphere. When the haze observations were made, a note was also at the same time taken of the direction of the wind, and of the wet bulb depression. About two hundred observations were used for working out the results. These observations were first arranged in tables for each direction of the wind, and, for the reasons given, these were again separated into other tables at the different wet bulb depressions. The result of this investigation showed that whenever the air came from anywhere from north of west to due north the air was always very clear, and showed the maximum limit of visibility. When the air came from the N.E. quadrant it was much more hazed, and when from all directions with any south in it the air was densely hazed. With the wind in the N.W. quadrant and a wet bulb depression of from 3° to 4° the limit of visibility was about one hundred miles, and with a wet bulb depression of 8° the limit was 200 miles or more, whereas when the wind was southerly the limit of visibility was, with a wet bulb depression of 3° or 4° , only from eleven to fifteen miles, and with a wet bulb depression of 7° or 8° , it was only from fifteen to forty-five miles.

A map of Scotland was also prepared, and on it the different counties were shaded according to the density of the population inhabiting them. Round Falkirk were drawn curves, or isatmid lines, that is, lines of equal clearness, showing the limits of visibility in the different directions when the wet bulb depression was 2° , 3° and 4° , 5° and 6° , and 7° and 8° . An examination of this map shows that there is a close relation between the transparency of the air and the density of the population, due no doubt to the fires, furnaces, etc., which throw their impurities into the atmosphere. From Falkirk as a centre, in all directions between due west and due north, the whole quadrant is but thinly populated, and the isatmid lines over this area open out to a very wide extent, and extend beyond the limits of the Western Isles when the air is dry. In the N.E. quadrant all the lines come much closer to the place of observation, while in all directions to the south the lines approach very close to Falkirk, and the lines approach the closer the deeper the shading on the map in the direction. That is, the denser the population, the more the air is hazed.

Summing up the general results, it is found, first, that with W.N.W. and N. winds the air is six times clearer than with southerly winds when the air is damp, and nine times clearer when it is dry. The air at Falkirk is ten times more hazed when the wind is in the E.S.E., S., and S.W., than it would be if Scotland were a desolate island in mid-ocean. Third, the transparency of the atmosphere increases with the dryness, being 3.7 times clearer when the wet bulb depression is 8° than when it is 2° , a result similar to that obtained from the observations made with the dust-counter.

Passing now to the relative amount of dust in the atmosphere of different parts of the world. As yet but few observations have been made out of Europe, but so far as they go they show that the air of the Western Highlands of Scotland is by far the least dusty of any in the world. Dr Fredlander in 1894-95, while on a tour round the world, made a number of dust observations, but at no part of his journey did he find any air

remarkably free from dust. The following table gives a short abstract of Dr Fredlander's observations :—

	Lowest.	Highest.
Crossing the Atlantic,	2,000	4,000 per c.c.
Near Newfoundland,	420	840 „
Gulf of St Lawrence,	280	350 „
Oak Bay, Victoria,	1,000	1,250 „
Santa Cruz Bay,	700	4,500 „
Pacific Ocean,	245	1,375 „
New Zealand,	875	10,250 „
Australia, King George's Sound, . .	1,000	1,250 „
Indian Ocean,	243	1,375 „
Arabian Sea,	280	1,375 „
Red Sea,	383	490 „
Mediterranean Sea,	875	2,500 „

Dr Fredlander also made a number of tests of the air in Switzerland, generally at considerable elevations, but in most of the observations the number was over 1000 per c.c., except at one or two high elevations. For instance, on the Riffelberg, at an elevation of over 7000 feet, the number was generally over 1000, but on one day the number fell below 900, and on another to 225 per c.c. The lowest numbers observed by him were obtained during an ascent of the Bieshorn. The following table gives the result of his observations :—

Height above Sea Level.	Number of Particles per c.c.
6,700	950
8,200	480
8,400	513
10,665	406
11,000	257
13,200	219
13,600	157

The last number, namely 157 per c.c., is the lowest number, so far as I am aware, yet observed in Switzerland or anywhere out of Scotland.

Professor Melander of Helsingfors has also made a special study of the dust in the atmosphere. His observations were made in 1894-95-96 at Salève, near Geneva, at Biskra in the Sahara, at Torhola in Finland, at Loimola on the borders of Russia, and at Kristianssund and Grip on the west coast of Norway, but at none of these places was the number of particles very low. At Salève the numbers varied from 550 to 7300, at Biskra from 825 to 30,375, at Torhola from 300 to 19,280, at Loimola from 363 to 4128, at Kristianssund from 650 to 55,025, at Grip from 375 to 109,000.

From my own observations taken on the Continent, it appears that the air of the West Highlands is purer than at any of the other stations tested. The following table shows the lowest number of particles I have observed in the air coming to the different stations from what might be called the purifying areas at the different places, that is, from the direction from which all the purest air at the different stations came.

Year.	Mediterranean.	Alps.	Highlands.	Atlantic.
1889,	1600	210	262	205
1890,	725	375	127	16
1891,	785	300	94	34
1892,	650	579	168	38
1893,	698	441	56	67
Mean,	891	381	141	72

In the above table, the Mediterranean air was tested on the shore ; the air from the Alps, on the Rigi Kulm ; in the Highlands, at Alford in Aberdeenshire ; whilst the numbers for the Atlantic are from the Kingairloch observations. So that, though the air of the Alps was tested at an elevation of 6000 feet, yet it was not as free from dust as Atlantic air at low levels. If the Ben Nevis observations had been used, the contrast would have been still greater. A similar result is brought out if, in place of using the lowest dust readings, we use the mean numbers of the particles at the different stations when the wind is blowing from the different purifying areas. These figures are entered in the following table :—

Year.	Mean Number of Dust Particles per c.c. in air coming from							
	Number of Observations.	Mediterranean.	Number of Observations.	Alps.	Number of Observations.	Highlands.	Number of Observations.	Atlantic.
1889,	1	1600	39	698	8	697	8	481
1890,	2	767	21	1030	8	703	65	337
1891,	7	1865	31	575	16	401	74	297
1892,	7	2002	22	1341	21	468	53	366
1893,	11	1363	9	1402	33	605	58	347
Mean,		1611		892		552		338

The above table shows clearly the greater purifying effect of the Atlantic area, which no doubt is due to its great extent, and the amount of condensation and precipitation which takes place over it. The table also shows that the air in its passage across Scotland from the West Coast to Aberdeenshire gets a considerable increase in the amount of its dust, and that the Mediterranean area, with its comparatively small condensation and rainfall, has on an average about five times the amount of dust contained in the Atlantic air. The air from the Alps cannot be compared with the

others, as observations of it were made at a considerable elevation, whilst the others were taken near sea level. It may be as well to note here, that as Dr Fredlander and Professor Melander used the same instrument for counting the dust particles as I did, namely the pocket dust-counter, it is therefore not necessary to make any allowance for instrumental differences.

There are still many questions connected with atmospheric dust waiting an answer, such as its effect on the temperature of the air; how far it absorbs the sun's heat during the day, and radiates its own heat during the night. There are some interesting points connected with radiant heat and dust. It seems somewhat surprising that the large visible dust motes in the air should be able to pass unaffected through the focus of a lens concentrating the sun's heat, where a larger body would be burned up; but the motes take no notice of it, not even seeming to be heated to any extent, as there is no sign of an ascending current of air at the focus, a result one might expect from the freedom with which very small bodies part with their heat to the air. Then again, there are the sources of the supply of the dust particles. Many of these are well known, and perhaps the remains of the meteors dissipated in the atmosphere would keep up a sufficient supply for the formation of clouds; but the dust produced by the action of sunlight on certain gases in the atmosphere has only been studied to a small extent, and a few of the gases indicated which in sunlight give rise to condensation nuclei. Another question is, how high and how far do these particles go? It is hoped that the observers going to the Arctic and Antarctic will be able to make a full series of dust observations in these regions, as any dust observed, when not due to volcanoes, must either be of cosmic origin or have been carried from far away inhabited areas. Dust observations there might help to throw some light on its source, as we would expect the variations in the amount of terrestrial dust would be dependent on the direction of the wind, whilst the cosmic would not.