XIII.—*On the Solid and Liquid Particles in Clouds.* BY JOHN AITKEN, Esq.

(Read 6th July 1891).

Towards the end of May of this year I made my third visit to the Rigi Kulm, for the purpose of continuing my observations on the amount of dust in the atmosphere and other meteorological phenomena. It was with a feeling of no little satisfaction that I found myself at that elevated situation during broken weather, and under conditions very different from any previously experienced by me. On this occasion I had come in the hope of finding opportunities for making some observations on the conditions existing in clouds, in addition to the usual dust observations, and had brought with me the small instrument for observing the water particles in a fog, described in a previous communication to this Society. As the weather continued to be variable during the week of my visit, I was fortunate enough to succeed in making a number of interesting observations on the water particles in clouds, and also of comparing the conditions in clouds at this elevated situation with those previously observed in fogs at a low level.

Before giving the results of my observations on the water particles, it may be desirable to make a few remarks on the solid or dust particles. When making the ordinary dust observations this year, it was frequently noticed that, when surrounded by clouds, the number of particles varied greatly at short intervals of time. Even when making, in quick succession, the ten tests from which the average was obtained in the usual way, it was sometimes observed that the ten numbers varied more than usual. I had previously found when working at elevated situations, that the numbers were fairly constant for intervals of an hour, and often for many hours, whereas in clouds they were observed to vary every few minutes.

There are two ways of investigating the cause of this variability in the number of dust particles in the different parts of the same cloud. By the first we may proceed by observing the number of particles, and noting the condition of the clouds at the same time as regards density, &c. This plan, however, requires two observers, one counting the particles, the other observing the other conditions. The other and simpler plan is to select extreme conditions, and to observe the air in a cloud and the clear air immediately outside of it. For my first observations of this kind I had to descend the hill some distance to get the required conditions, the top being covered with a continuous mass of cloud. Near the lower limit of the cloud the difference in the amount of dust in the clear air underneath and in the cloud was quite marked. There were about twice as many particles in the cloud as in the clear air. On this occasion the clouds were clearing away, and there would therefore previously have been a good deal of mixing of the cloudy with the clear air; no very great difference could therefore be expected, though there was quite enough to encourage further investigation.

A much more favourable opportunity of testing the relative proportions of dust particles present in clouds and in clear air occurred on the 25th of the month. The sunrise on that morning had been cloudless, and the air clear; but as the morning advanced the air gradually thickened, and clouds began to form in different directions and at different elevations. These newly formed clouds occasionally passed over the mountain top. It was therefore unnecessary to change the site of making the observations. All that was necessary was to observe the amount of dust while the cloud surrounded the observer, and again when the cloud had passed. Readings were taken in this way, from time to time, between the hours of 9 A.M. and 10.30 A.M.; the numbers so obtained are entered in the following table, each of them being the average generally of ten tests. In the table is also entered the state of the air at the time. Many more tests were made, but as they were taken in more or less clouded air, and the number of particles was intermediate between the extremes given, it has not been thought necessary to enter them in the table. After 10.30 A.M. the clouds closed quite in, and the mountain top was in dense cloud for the rest of the day.

Table showing the Number of Dust Particles in Cloud and in Clear Air on the Rigi on May 25th.

Hour.	Number of Particles per c.c.	State of the Air.
9	1225	Haze
	1625	In cloud
	1025	Clearing
	2450	In cloud
	3250	In dense cloud
	3450	
	1250	Clearing "
	700	Clear
	1850	In cloud
10.30	4200	"

The above figures show that on this occasion there was a vast difference in the number of dust particles in the clouds and in the clear air surrounding them. In this case, as in all clouds hitherto tested, a greater number of dust particles was observed in the cloud than in the clear air surrounding it. It may be as well, however, to note here that these observations were all made in cumulus clouds, and the remark applies only to that form of cloud. It seems probable that other conditions may exist in stratus and other clouds.

When the above observations began at 9 A.M., it seems very probable that the valley air had already begun to ascend, as the upper air had thickened a good deal since early morning, and though no clouds had yet formed, the upper air was rapidly approaching saturation. Another reason for supposing that the lower air had already begun to ascend, is that the number of particles on the previous evening was only about 500 per c.c., and had been about that number for a considerable time. Further, it will be observed from the figures in the table, that a mass of clear air outside the cloud had only

700 particles per c.c. The probability seems to be that on this occasion the upper air had about 500 particles per c.c., while the lower air which was rising and forming the clouds may have had somewhere about ten times that number, the ascent of this impure valley air, and its mixture in different proportions with the purer upper air resulting in the formation of masses of air having degrees of impurity varying between 500 and 5000 particles per c.c., as indicated by the numbers in the table. Neither extreme number was, of course, observed, as the conditions would not continue while the whole ten tests were being taken.

As already stated, the number of particles was always greatest in the clouds. This simply means that the ascending air was both moist and dusty; and when little of the valley air was mixed with the upper air, the amount of dust was not greatly increased, and the humidity was not sufficient to cause condensation. But when the proportion of lower air was large the number of particles was great, and the humidity sufficient to cause condensation.

It may be mentioned here, that on testing the lower air at the surface of the lake on the afternoon of the same day, the number of particles was a little under 3000 per c.c. It would seem as if the accumulated impurity of the previous day, which had been nearly calm, had risen to the mountain top, and a purer air taken its place, as the maximum observed in the clouds was rather higher than that observed at the level of the lake after the air forming the clouds had risen.

That there should generally be more solid particles in cumulus clouds than in the air surrounding them, is a result which might have been expected from the conditions. The clouds which form during the day on hill tops are composed mostly of valley air, which has ascended to the upper regions, expanded, cooled, and condensed part of its vapour. The dust in clouds thus acts as a kind of ear-marking, which enables us to trace to its source the air forming the clouds.

It may be as well to give a word of caution here regarding the observations made of the dust in the clouds and that in the air surrounding them. In all cases there was more dust in the clouds than in the surrounding air. But it by no means follows that this is always the case. It seems quite possible there may be valleys where the air is not polluted, and from which the moist ascending air may be purer than the air at the time at a greater elevation.

And now a few words as to the water particles in clouds. To those who have been in clouds, especially when they are not dense, and who have felt the glow of heat which radiates from every side, and have seen the surfaces of all exposed objects quite dry, it is difficult to realize that the air is saturated with moisture, and full of suspended drops of water, although those who have thought about the subject may have realized that the thickness is really due to suspended water particles. Yet, so far as I am aware, no one has previously seen, far less attempted to count these drops; while now, with the aid of the instrument already referred to, these particles can be seen and counted with ease.

The instrument for observing these water particles consists of a glass micrometer ruled into small squares of 1 mm. or other convenient size. The micrometer is

illuminated by means of a spot-mirror, and viewed through a magnifying lens. The instrument is held in the clouded air with the micrometer horizontal, the observer watching its surface through the lens, when little drops of rain are seen falling in rapid succession on the micrometer and rapidly evaporating. One small square is selected, and the number of drops that fall in a measured time are counted. The number falling will be found to vary greatly from time to time. If any difficulty is experienced in counting the drops owing to their rapid evaporation, it will be found of great assistance to cool the micrometer, either by fixing a piece of wet paper or a little snow to the metal mounting; or if this is inconvenient, then a similar effect, though somewhat short-lived, may be obtained by breathing on the surface of the glass. It was only after observing with this instrument that I realized the true state of matters in certain clouds, and saw that though all exposed surfaces were dry, they were really exposed to a continuous shower of immense numbers of fine drops of rain.

The general result of the observations made in clouds on the Rigi is very similar to that derived from the observation of fogs at low levels. The size of the particles and the number falling are about the same in both cases. Of course both the size and the number vary greatly at both places under different conditions. As already pointed out, the number of dust particles varies greatly at different parts of a cloud, and when we are in the midst of clouds and examine them closely, we find that most of them vary greatly in density or thickness from time to time, or, more correctly, in their different parts. At one time the passing cloud may be so dense that we cannot see beyond 30 yards; in a minute or two the limit may be extended to 100 yards, when it may again close in to its original density. This variability in the density of clouds is probably greatest in clouds formed of the air rising from the valleys, where the mixture of the pure and impure air is necessarily imperfect. Stratus and other forms of cloud probably do not have this want of uniformity. All the clouds observed on this occasion varied greatly from point to point, and it was also observed that the number of water particles falling varied greatly. At times they showered down so quickly that it was impossible to count the number that fell on one square millimetre; but generally it was easy to count the number falling on so small an area, and occasionally they were so few that they only fell at considerable intervals.

It was observed that the more dense the cloud the greater was the number of drops falling, and that as the cloud thinned away the number gradually decreased. The greatest number actually counted was 60 per square m.m. in 30 seconds. If they had been counted for a shorter time a quicker rate would have been obtained, as they did not fall so quickly during the last half of the time as during the first. Very heavy falls seldom lasted more than a few seconds; a rate of 30 drops to the minute was, however, frequently observed. The maximum rate of 60 drops per square m.m. per half minute gives 12,000 drops per square centimetre per minute, or 77,400 drops per square inch per minute. This does seem an enormous rate of fall, yet the particles are so

extremely small, they evaporate so quickly, that never more than two or three are ever visible at a time on one square of the micrometer. As the cloud gradually thins away, the number of drops diminishes and their size at the same time decreases.

The maximum number of water particles actually observed in a cloud is four times as great as the maximum yet observed in a fog. We cannot, however, from this draw any conclusion, as the recorded observations are too few to found upon.

There is an interesting point connected with the conditions existing in some clouds, which I have not yet been able to study as fully as is desirable. The point to which I refer is, What is the state of the air with regard to humidity in a cloud when all exposed surfaces are dry? We have seen, that while the fog-counter showed the air to be full of water particles, showering down at the rate of thousands of drops to the square inch in a minute, yet all exposed surfaces were frequently quite dry. Not only were they dry, but if wetted they soon dried again, showing that the air was absorbing moisture while it was at the same time packed full of water drops. Further, wet and dry bulb thermometers hung in the open may show a difference of a degree or two, proving that evaporation is going on.

What, then, is the explanation of this apparent contradiction? Simply this: radiant heat. The sun's rays, falling on the upper surface of a cloud, are partly absorbed and spent in heating it and evaporating some of the suspended water, but a good deal of the heat penetrates the cloud, and falling on the surface of bodies heats them; while these heated surfaces in turn heat the air in contact with them, and the small cloud particles, when they fall into this hot stratum of air, are either evaporated before reaching the surface of the bodies, or are rapidly evaporated after they touch.

In all cases in which I had an opportunity of testing the humidity of the air in a cloud, it was found to be saturated. Though the wet and dry bulb thermometers may have shown a difference of a degree or more, when not properly protected from radiation, yet they read alike when radiation was completely cut off. That a vast amount of radiant heat may penetrate through clouded air is easily proved by exposing a thermometer with black bulb *in vacuo*. An instrument of this kind exposed while these observations were being made, indicated 40 and 50 degrees above the temperature of the air, and it was always above the temperature of the air when surfaces were dry. Further, when the clouds overhead get thin, a glow of heat can be distinctly felt on the hands and face. It is this radiant heat passing through the clouded air, and absorbed by exposed surfaces, which heats them and keeps them dry, though surrounded by saturated air and exposed to a continuous shower of fine rain.

Although this conclusion has been arrived at by the aid of the fog-counter and the vacuum thermometer, yet the same conclusion was drawn from some observations I made on the summit of Pilatus, which I visited last year, while it was in cloud. The result of the observations made at that time I had incorporated into my dust observations of last year, which are only yet in preparation, but as they properly belong to the present subject I have transferred my remarks to this paper.

During this visit to Pilatus the top of the mountain was entirely surrounded by cloud, and the air was thick with fog particles ; and though one might naturally conclude from this that the air was saturated with moisture, yet wooden seats, walls, and all exposed surfaces, were quite dry. In a previous communication, from observations made on the Rigi, I have stated reasons for supposing that this dryness of exposed surfaces in a cloud does not necessarily prove that the air is not saturated. That is to say, if the air is saturated, it does not necessarily follow that all surfaces will be dripping with the fog particles falling on, or being driven against them. I therefore made on this occasion as many observations of the conditions of the different surrounding objects as possible while attending to the usual dust counting. The following facts were observed : seats, wall tops, wooden posts, nails projecting from the posts, and stones on the ground, were all quite dry. But thermometers hung up rapidly got wet, and the pins driven into the wooden post for hanging the thermometers rapidly got covered with beads of water.

It was of course natural to suspect radiation to be the cause of this difference. It is true the mountain top was surrounded by a dense mass of clouds, and the sun could not be seen, nor even a preponderance of light in one direction more than another to indicate its position ; yet as light penetrated, it seemed possible that a perceptible amount of radiant heat might do so also. A thermometer placed on a wooden seat showed that a considerable amount of heat penetrated the cloud, as it rose to 60° , while one hung up registered only 48° . As has been explained in a previous communication, bodies exposed to radiant heat are heated in proportion to their size, the larger bodies being heated to a higher temperature than the smaller ones. Now the effect of this radiant heat on objects exposed in clouded air is to heat them above the temperature of the air, and if the objects are of any size they are considerably heated, and become surrounded by a layer of hot air, and the water particles are either evaporated in this hot layer before they touch the surface, or they are evaporated after they have come in contact with it. This is the reason why the seats, walls, posts, &c., were dry, though surrounded by saturated cloudy air. These large bodies received so much heat by radiation that they were able to evaporate the water particles falling on them, but small bodies, such as thermometers, not being heated to the same degree, on account of the passing air taking away more heat from them, they did not keep themselves surrounded with a layer of hot air, and the cloud particles fell on and wet them. It is true that nails, which were smaller than the thermometer, were quite dry. But they were driven into wooden posts which were hot, and from this supply the nails drew enough heat to keep them dry. The pins for hanging the thermometers did not do this, though driven into the wood, on account of their small cross section compared with their length not being sufficient to conduct the necessary amount of heat. These few observations of different objects exposed in a cloud, showed that the air was saturated, though most of the exposed surfaces were quite dry, and that if it had not been for the radiant heat everything would have been dripping wet. This conclusion, written out last year from observations made on Pilatus without

special instruments, agrees with the result of our last observations made on the Rigi.

While on the Rigi this year I tried to find whether the density of cloudy condensation depends on the number of dust particles present, or on the number of water particles. The question was, however, much more difficult of solution than I expected, owing to the great rapidity with which the constituent parts of the passing clouds changed. To have answered the question satisfactorily in the case of the clouds tested, three observers would have been required, one observer noting the density of the cloud, one counting the dust particles, and the third observing the water particles,—all three making their observations at the same moment. I had, however, to depend on my observations alone, and so far as they go they point to the conclusion that the density of a cloud depends principally on the number of water particles. Wherever the water particles fell at the rate of about 100 drops per square mm. per minute, the limit of visibility in the cloud was about 30 yards, and as the limit of visibility increased the rate of fall decreased.

There were too few opportunities of testing the effect of the number of particles of dust on the density of the air in a cloud, as on most occasions the numbers were far too variable to offer satisfactory results. But on comparing the density of a fog and a cloud when the same number of drops fell, it would appear that the number of dust particles has a much smaller effect than the number of water particles. For instance, in a fog last winter, as stated in a previous paper, drops were observed to fall at the rate of 30 per minute per square mm., and the limit of visibility at the time was about 100 yards. Now this is not very far from the limit of visibility observed on the Rigi when the rate of fall was the same. But on the Rigi there were only a few thousand dust particles per c.c., while in the fog there were about 50,000. It would thus appear that in cloudy condensation the thickness depends chiefly on the number of water particles, and only in a secondary way on the number of dust particles. The observations are, however, as yet too few to warrant a definite conclusion.

Although in all the cases of foggy or cloudy condensation investigated by me the air was saturated, though it may have appeared to be dry, I do not, however, wish it to be understood that there is no such thing as a dry fog, only that in my experience I have not observed one.

We see from the observations made with the fog-counter, that whenever a cloud is formed, it at once begins to rain, and the drops shower down in immense numbers, though small in size. These drops fall into the air under the cloud, where they evaporate if the air is dry, and the distance they fall will depend on their size and the dryness of the air underneath. So that on a summer day, with white clouds passing overhead, it is really raining, but the drops being very small, they evaporate in the air under the cloud long before they reach the earth. It seems probable, therefore, that much of the melting of clouds is produced in this way, the particles falling from the saturated air in which they were formed and dissolving in the drier air underneath.