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Collin, H. L.

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The ground based study
of clouds

H.L. Collin

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Man has long observed the forms and movement of clouds and attempted to account for them. Aristophenes and Lucretius among others have reported contemporary ideas, but a more detailed knowledge of cloud structure was required before much progress could be made towards understanding them.

A certain amount can indeed be learned by visual observations. The ice or water phases can be recognised and the lifetime and development, in particular of cumulus clouds, can be observed. Time lapse photography and theodolite measurements of cloud tops (Scorer and Ludlam, 1953) can be used to determine the updraughts inside them. Radar can be used to follow the development of clouds over a large area. Such studies have shown that cumulonimbus exhibits a cellular structure. These cells have a characteristic life history (Byers and Braham, 1949) and orographic features are often found to influence their initiation. The influence of orography can also be studied by means of a fine network of rain gauges (Bergeron, 1960). Ice and water have different dielectric constants so the same intensity of precipitation gives rise to a much stronger radar echo if it is in liquid form. The melting zone gives an especially strong echo since the just melted drops have not yet reached their terminal velocity and spread out. Thus examination of the radar characteristics of clouds can reveal their gross structure. However, such important factors as temperature and humidity cannot be found and the detailed structure of the precipitation and air movements only with some ambiguity and in limited circumstances. Since the radar echo exhibits a doppler shift if the target is moving a vertical pointing radar can be used to determine the fall speeds of precipitation elements. In a convective storm the terminal velocities of the particles are less than the updraughts, and Atlas (1965) has made use of this to determine the pattern of convection in a storm. Such an investigation requires assumptions to be made about the size distributions of the precipitation particles, but radar can be used to determine these if the updraughts can be neglected as in nimbostratus conditions (Caton, 1966). Since radar gives the size distributions at all heights it becomes possible to study the growth of the particles as they fall through the cloud. Similar studies can be made at the ground if a number of observing stations are situated at various heights, for example on a mountain side (Magono, 1960). While this kind of investigation is limited to only a few levels and these below or only in the lower part of the cloud, it does not suffer from the uncertainties that are attendant on similar radar work and there is also the advantage of being able to determine the local meteorological conditions. Some studies can be made at ground stations that are impossible for radar, for example the size distributions of cloud droplets (Okita, 1962) and studies in the region where ice crystals are melting and their velocities varying (Ohtake, 1965). In principle it is possible to use the variation of drop size to indicate the mechanisms which control their growth and dissipation and some authors have attempted to determine the distributions to be expected in certain circumstances (Kombayasi, 1965 and Kovetz, 1969). A number of workers, both with radar (Mason and Andrews, 1960) and ground level sampling (Blanchard, 1953) have found that rains from different types of cloud system are characterised by different drop size distributions and some (Caton, 1966) have been able to attribute variations to a particular process. Because a number of processes, condensation, melting, coalescence, disintegration and electrical effects (Moore et al, 1964) may all contribute to the final distribution and because of the difficulty of observing the initial development of the particles it is hard to produce a complete picture of the formation of rain.

The development of ice crystals is easier to determine since an examination of the crystal shows the phases it passed through and whether any accretion took place. Indeed the growth of ice under various meteorological conditions is so well understood that Grunow (1960) was able to use the size and form of those reaching the ground to determine the distribution of temperature and humidity in the clouds from which they came.

The ground-based study of the electrical structure of clouds is also subject to limitations. The distribution of charge in cumulus and cumulonimbus can be estimated by the use of a network of instruments to measure the potential gradient patterns produced at the ground (Takenti, 1965). These estimates are not unique however, and it is necessary to make assumptions about the number of charge centres and the volumes they occupy. Furthermore, such measurements can only give an outline of the charge distribution and do not reveal detail or the relative contributions of precipitation and ions. In thunderstorms the changes of potential gradient which accompany lightning can be analysed in a similar way to examine the movements of charge that they occasion (Pierce, 1955), and the rate of recovery afterwards indicates the rate at which the charge is replaced. It is not easy to obtain sufficient evidence to determine what mechanism produces the large charges necessary for lightning, although hints are given by a number of readily observable phenomena such as strong updraughts, heavy rain, and, not invariably, ice which accompany thunderstorms. Measurements from mountain stations can give some additional information about the interior of the lower parts of the clouds (Kuettner, 1950) but thunderclouds are too high for a complete examination to be conducted in this way. This leaves us with only an outline model of the thundercloud which needs many additions from other sources before a complete understanding of its operation is possible.

The electrical structure of the less active nimbostratus clouds is also difficult to explore from the ground. As they are of much greater horizontal extent than cumulus any charges in the upper regions tend to be masked by those below and potential gradient measurements from below cannot give any information about them. Here again mountain stations can assist (Reiter, 1965) although the presence of the ground surface may be a disturbing influence. Both below and within nimbostratus the potential gradients are usually found to be positive in snow and negative in rain and since most such clouds are known to contain ice in their upper layers this pattern is believed to hold generally. The current brought to earth by the charged precipitation is usually opposite in sign to the potential gradient and it has been established that the current is proportional to the product of the rate of precipitation and the potential gradient (Ramsey and Chalmers, 1960). This would appear to fit well with the idea that the potential gradient is set up first and then gives rise to the precipitation charges. An alternative explanation is that the same charge separation process produces both and the precipitation falls leaving the opposite sign of charge on the cloud (Magono and Orikasa, 1961). This would lead to the rate of increase of the potential gradient being related to the precipitation current, but dissipation effects would be expected to lead to a steady state where the potential gradient is related to the earlier current. A possible phase difference would be obscured by the space charge of the precipitation (Chalmers, 1965). The problem is further complicated because the observed relationship is based on measurements made at only one station which cannot follow developments in a single section of the moving cloud structure, but only the average situation. However, Chalmers (1958) has been able to deduce a simple model of the electrical processes from this limited data, but little light can be thrown on the processes themselves which must not only account for the gross features but also the wide spread of charges that are found on similar hydrometeors at the same time and place (Smith, 1955). Reiter (1965) has found evidence that suggests that a charging process accompanies the melting of snow under natural conditions and a mountain station could be used to examine the details of this process. However, it is probable that any charge separation mechanism that takes place in the snow region of the cloud will be too high to be investigated fully with ground-based instruments.

It can be concluded that while ground-based studies show the general features of clouds adequately they cannot provide sufficient information to allow a fully detailed picture of their structure and development to be constructed.

It was with the hope of being able to probe a little way into the interior of clouds that the experimental arrangement at the Durham University Observatory was set up. It comprised field-mills and rain-collectors at the top and foot of a 22m mast and a rate-of-rainfall recorder. The potential gradients, precipitation currents and rate of rainfall were all recorded with a resolution of 1%. The instruments could perhaps have been calibrated to 1% had no difficulties arisen with the determination of exposure factors on the mast and this would have given an overall accuracy of about ±2% which would have corresponded to ±40 Vm^{-1} and ±4 pAm^{-2}. This would have meant that the minimum detectable differences between the top and bottom of the mast would have been 80 Vm^{-1} and 8 pAm^{-2}. Now because the potential gradient at the top of the mast is influenced not only by space charge above it but to a lesser extent by that below an indicated difference of 80 Vm^{-1} corresponds to a real difference of 110 Vm^{-1} or 45 pCm^{-3} throughout the 22m layer of air below the mast top. This compares unfavourably with a filtration device (Bent, 1964) which has a sensitivity of 1 pCm^{-3}.

These figures are not very meaningful in that they bear little relation to the sensitivities actually achieved, but they are perhaps reasonable for what might be done with a more carefully devised arrangement. They are included here because it is felt desirable to indicate the practical limitations of the 22m mast.

A source of space charge that would always occur during precipitation would be that of the charged precipitation itself. This must be accounted for before any observed space charge can be attributed to another source. Unfortunately it is difficult to determine its magnitude without detailed information of the drop size spectrum and the charges carried by drops of various sizes. However, a rough estimate can be made. If a rate of rainfall of 0.01 mm min^{-1} is taken as a typical value and the drop size distribution is assumed to fit the general formula suggested by Best (1950) then the water in the air can be divided into equal parts comprising drops which fall into the ranges of sizes shown below.

Drop diameter (mm)	Mean fall speed ($m\ s^{-1}$)	Time to fall 22m (s)
0.0 - 0.6	1.2	18.3
0.6 - 0.9	2.9	7.6
0.9 - 1.2	4.0	5.5
1.2	5.9	3.7

In each range the contribution of the drops to the space charge below the mast is given by the product of the time taken to fall through the height of the mast and the contribution it makes to the total precipitation current. If the rain's charge is distributed uniformly throughout the water then there will be about nine times as much charge below the mast as reaches the ground in a second. With a rate of rainfall of 0.01 mm min^{-1} and a potential gradient of -500 Vm^{-1} the precipitation current would be expected to be 15 pAm^{-2} which gives a space charge density of 6 pCm^{-3} which is well below the detectable limit although in unusually heavy rains the effect would be noticeable.

The most doubtful assumption which has been made here is that of uniform distribution of charge. Smith's (1955) measurements, which were made when corona discharge was occurring, showed that the smaller drops tended to carry charge which was opposite in sign to the potential gradient whereas the largest drops carried charges of the same sign. Because of the disparity of fall speeds such a charge distribution would set up a larger space charge than suggested above.

Snow falls at a much lower rate than rain, Langleben (1954) found fall speeds of 0.7 to 1.4 m s^{-1} for snow flakes and crystals with equivalent spherical diameters from 0.5 to 2.5 mm. This would more than double the estimate of precipitation space charge density.

Since the Observatory is at an elevation of only 100m it is normally well below the cloud base so that it would not usually be possible to examine processes occurring inside clouds directly. Some inferences about clouds can be formed from measurements made below them (Chalmers, 1958) but the use of the mast would add nothing to ground level measurements. However, if charging processes occur at ground level direct measurements could be made of them. Chalmers (1958) was able to show that relation between the potential gradients and precipitation currents in steady currents could be adequately explained by postulating one charge separation process in a snow cloud and another in or below the cloud which would begin to operate when the precipitation became rain. The evidence of the Observatory experiment would indicate whether this simple picture is a sufficient explanation of the phenomena. If in snow a charging process was found to operate close to the ground it would mean that the cloud model would be more complicated than Chalmers supposed since he showed that in such a case it would still be necessary to have a charging process in the cloud itself. In the case of rain a process close to the ground could be the predominant one when it would be expected to give rise to a negative space charge in the air and positively charged rain in order to account for the precipitation currents and potential gradients usually observed.

A number of ways in which rain could become charged have been suggested and it is necessary to determine the extent to which they can be studied.

Several workers have found that when drops splash a negative charge is left in the air while the drops gain a positive charge of the order of 33 pCg^{-1} (Nolan and Enright, 1922). Since splashing would occur at both rain collectors no variation in precipitation current over the height of the mast would be apparent. With a rate of rainfall of 0.01 mm min^{-1} 0.17 gm^{-2} of water would reach the ground in a second and this would contribute 5.5 pAm^{-2} to the space charge. If this remained close to the ground a measurable space charge would be built up within a few minutes. In practice, turbulence would distribute it throughout the lower layers of the atmosphere. The rapidity and extent of the mixing is hard to estimate since it is dependent on the wind, stability of the air and the obstacles in the vicinity of the Observatory. However, Bent et al (1965), at the same site, made measurements on space charge produced by corona discharge and found that a wind of 3.9 m s^{-1} caused mixing over a height somewhat greater than that of the mast within one minute. If in one minute the space charge was distributed uniformly over twice the height of the mast then for it to be just detectable a total current of 33 pAm^{-2} would be required. To produce this the rate of rainfall would need to be 0.06 mm min^{-1}. This is rather high, but occurred occasionally. With lower wind speeds the onset of the effect would be readily observable and in any case turbulent mixing would allow some accumulation near the ground. In conclusion, if splashing in natural conditions produces as much charge as in the laboratory there will be enough occasions when a measurable space charge density is produced for its expected dependence on windspeed and rate of rainfall to be observed.

Raindrops falling in a potential gradient can capture ions (Wilson, 1929 and Whipple and Chalmers, 1944). With a rate of rainfall of 0.01 mm min^{-1}, potential gradient of -1000 Vm^{-1}, space charge density +500 pCm^{-3} and if all the raindrops are assumed to be initially uncharged and 1 mm in diameter then the difference in precipitation current over 22m is 1 pAm^{-2}. This would be undetectable even with a space charge density that is unlikely to be produced expect by corona discharge. When the production of the space charge ceases it would be easy to determine the rate at which it is dissipated but only under special circumstances would it be possible to be sure that rain is the only cause.

Reiter (1965) measured precipitation currents and potential gradients at several stations at different heights. During steady precipitation he found that, as is usually observed, the current and potential gradient were mirror images of each other with the potential gradient usually negative during rain and usually positive during snow. Also their signs reversed at a level where the temperature was between $0^{\circ}C$ and $1^{\circ}C$ which was where the precipitation melted. It has been suggested that this could be caused by the melting snow shedding water droplets while polarized by the potential gradient (Stow, 1969). The droplets would leave the upper surface of the ice and retain a charge opposite in sign to the potential gradient which would be reduced below the melting zone, by the space charge of the droplets. In order to reverse the sign of the potential gradient a proportion of the droplets would have to fall to below the bottom of the melting zone since if any melting were to take place where the potential gradient had been reversed the direction of the charge separation process would also be reversed tending to cancel itself out. This distribution of space charge would not be necessary to a charging mechanism which was independent of the ambient potential gradient like the one studied by Drake (1968). If the process is controlled by the potential gradient in the region of solid precipitation the potential gradient below it must always have the opposite sign, or at least be smaller, even if the potential gradient in the upper region has the less common negative polarity. In nimbostratus conditions the potential gradient is positive in the case of snow or negative in the case of rain in about 90% of cases (Reiter, 1965). If they occurred independently of each other they would still be opposite to each other in 82%

of cases so if all observed cases showed opposite polarities it would not be possible to be sure that this was not occurring by chance unless there were a large number of cases. To give a risk of only one in fifty of a mistake at least twenty cases would been to be examined. Even with a large number of observations the use of the mast could not give a completely unambiguous result since it would be desirable to have instruments above and below the melting zone as well as inside it in order to take account of changes in potential gradient produced by other causes.

Reiter's results indicate that the melting zone for nimbostratus lies between the 0°C and 1°C isotherms. With the environmental lapse rate usually observed this is a range of about 150 m. If above the melting zone the potential gradient and precipitation current were +500 Vm^{-1} and -50 pAm^{-2} while below it they were -500 Vm^{-1} and +50 pAm^{-2} then the differences over the height of the mast would be 150 Vm^{-1} and 15 pAm^{-2}. Differences of this order would be measurable which would make it possible to examine the distribution with respect to temperature of charging of precipitation and space charge. As suggested earlier this might give some indication of the charging mechanism involved.

Finally, it seems that the mast experiment could have been expected to detect at least some of the charging processes which might be expected to occur near the ground and could have given sufficient information to make it possible to asses their importance.

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