The interaction of ice crystals with hailstones in wet growth and its possible role in thunderstorm electrification

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Charge separation during rebounding collisions of ice crystals on hail particles is a probable mechanism of thunderstorm electrification. Modelling of laboratory results successfully predicts the charge structure in thunderclouds under most conditions. An exception is the intense positive ground flashes observed in mid-continental severe storms which contain large hailstones that are generally in wet growth. It is difficult to see how interacting ice crystals may separate from the wet surface of a hailstone without sticking, although some studies have reported charge separation during this process. Our laboratory experiments show that, during ice crystal interactions with a simulated hailstone in wet growth, a small but significant charge transfer occurs during ice crystal interactions. We present evidence to show that the hailstone surface is not uniformly wet and consists of dry zones, particularly at the edges, where ice crystals are most likely to impact, and hypothesize that a small number of ice crystals rebounding off these zones may give rise to the observed charging current. While this may explain wet growth charging in laboratory experiments, we cannot directly extend the findings to natural thunderstorms where hailstones tend to rotate and gyrate as they fall, but they may experience different growth regimes within the cloud.

Key Words: thunderstorm; hail; ice crystal; lightning; rime; graupel

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1. Introduction

In clouds, graupel, or soft hail, is formed by the accretion of supercooled water droplets, a process that is also known as riming. The freezing water transfers latent heat to the graupel and much of this heat is lost to the air by ventilation as it falls through the air. Consequently, graupel pellets are generally warmer than the surrounding environment. In the warmer regions of a cloud where the water content is high, the accretion rate will often be too high for all the latent heat to be lost by ventilation and this will cause the temperature of the hail pellet to rise close to 0 °C when its surface will become wet. Hailstones in wet growth are commonly found in thunderclouds, especially in their lower regions where the air temperature exceeds −10 °C (Pruppacher and Klett, 2010).

It is now generally accepted that one of the dominant mechanisms of thunderstorm electrification is the so-called relative growth rate mechanism, where, when two ice particles impact and separate, the particle with the higher surface diffusional growth rate acquires the positive charge (Baker *et al.*, 1987; Saunders, 2008; Emersic and Saunders, 2010). Laboratory experiments have shown that substantial amounts of charge are separated when graupel pellets interact with vapour-grown ice crystals (Reynolds *et al.*, 1957; Takahashi, 1978; Jayaratne *et al.*, 1983; Keith and Saunders, 1990). The relative growth rate, and therefore the sign of charge acquired, depend on the temperature and cloud water content (Baker *et al.*, 1987). Generally, throughout most of a cloud, graupel acquires a negative charge and the ice crystals an equivalent positive charge. Falling graupel pellets carry the negative charge downwards, while the ice crystals are swept up in the strong updraughts to the top of the cloud, giving rise to a thundercloud dipolar charge structure with the positive above the negative (Simpson and Scrase, 1937). Takahashi (1978) and Jayaratne *et al.* (1983) showed that at a temperature higher than a critical value, the latter labelled the 'charge reversal temperature', the graupel will acquire a positive charge, with the ice crystals carrying away the equivalent negative charge. The charge reversal temperature is dependent on the cloud water content, being colder at higher water contents. Jayaratne *et al.* (1983) used these observations to explain the existence of the lower positive charge centre, giving rise to the commonly observed tripole charge structure in thunderstorms (Krehbiel, 1986; Williams, 1989).

The growth of large hail is assisted by strong updraughts and abundant cloud water (Williams *et al.*, 2005; List, 2014). Many observers have reported a close association between large hail and enhanced positive cloud-to-ground lightning flashes in midlatitude continental thunderstorms in the USA. For example,

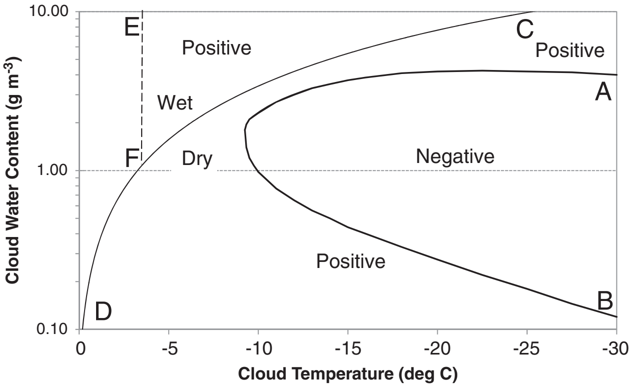

Figure 1. Experimental results of the sign of charge transferred to the graupel by interacting ice crystals on a cloud water content–cloud temperature diagram as observed by Takahashi (1978). See text for explanation of the other features shown.

multiparameter radar observations of a thunderstorm complex by Carey and Rutledge (1998) found that over 74% of cloud-to-ground flashes carried a net positive charge after it became severe, producing large hail. MacGorman and Burgess (1994) studied 15 severe storms in the mid-USA and observed that large hail occurred during periods dominated by positive ground flashes. MacGorman and Nielsen (1991) and Williams *et al.* (1991) proposed that the occurrence of positive ground flashes in severe hailstorms may be due to an enhanced region of significant positive charge carried by large hail in the low levels in thunderstorms. Williams *et al.* (1991) pointed out that at these levels most hailstones of diameter larger than 1 cm would be in the wet growth regime. There is some doubt as to whether an interacting ice crystal would be able to bounce off a wet hail surface, without sticking, in order to allow a separation of charge. Emersic *et al.* (2011) investigated lightning activity in a hail-producing storm and found a sharp reduction in flash rate as hail attained wet growth in a new updraught. Using radar observations, they attributed this 'lightning hole' to an absence or reduction of hydrometeor charging in wet growth.

The present study was carried out to experimentally resolve the question of whether charge is separated during ice crystal–hail interactions under controlled conditions of wet growth. This has been one of the controversial issues over the years, particularly in regards to the observation of strong positive charging in the laboratory studies of Takahashi (1978) under conditions where the hailstone was wet. In his experiment, the charging of an accreting steel rod was measured as it was whirled through a cloud of supercooled droplets and ice crystals at various cloud temperatures and water contents. Figure 1 shows the sign of charge transferred to the graupel on a cloud water content–cloud temperature diagram. The elliptical curve A-B encloses the region where the graupel acquired a negative charge. Williams *et al.* (1991) and Jayaratne (1993) calculated the heat balance of the hailstone used in this study and derived the curve CD which shows the minimum cloud water content required for wet growth as a function of cloud temperature. The graupel surface temperature at every point above the curve CD is 0 °C. We draw attention to the region labelled EFC. Takahashi observed strong positive charging of the order of 20 fC per crystal interaction in this region. No charge transfer was observed with a droplet cloud with no crystals. It is difficult to see how impacting ice crystals could bounce off a wet ice surface without sticking (Saunders *et al.*, 1991). This was later confirmed by Saunders and Brooks (1992) who did not detect any charging under wet growth conditions. However, Williams *et al.* (1991) suggested that crystals can bounce off a hailstone in wet growth, charging it positively.

The collision efficiency (E) of an ice crystal on the target is defined as the probability of a crystal in the geometrical path of the target making contact with it. The separation probability of an ice crystal is the probability that a crystal that interacts with the target will bounce off. Jayaratne *et al.* (1983) defined a quantity termed the 'event probability' (*EP*) which is the product of the collision efficiency and the separation probability. Clearly, for an interaction to separate any charge (a charging event), *EP* must be greater than 0. Takahashi calculated the charge transferred per crystal assuming a separation probability of 1.0 and $E = 0.8$. This is probably a reasonable assumption at the speed of his riming rod (9 m s^{-1}) when the rime surface was dry. However, when the rime surface becomes wet, the separation probability decreases significantly, suggesting that Takahashi's actual charge-per-event values during wet growth were greater than his reported charge-per-crystal-collision values.

2. Experimental methods

The experiments were carried out in a large chest freezer of internal volume 1.4 m^3 in the laboratory. The temperature in the freezer was controlled with a thermostat. A cloud of supercooled droplets was produced by injecting steam through a tube from a boiler placed outside the freezer. In each experiment, the freezer was cooled to a predetermined temperature and the power to the boiler adjusted to produce a stable cloud of supercooled droplets at the required cloud temperature and water content. The cloud was seeded by popping a small plastic packing bubble in a syringe. The rapid expansion and cooling gave rise to ice crystals that grew vigorously at the expense of the droplets to a size of about 50 μm, after which they fell out of the cloud. Crystal size and concentration were determined by collecting them on a formvar-coated glass slide impactor and analysing the replica under a microscope as described in Griggs and Jayaratne (1986). The initial crystal concentration was about 1000 ± 200 cm^{-3}. This was confirmed by placing a slide on the floor of the freezer and allowing all the crystals to fall out of the cloud with no cloud being removed. Concentrations at various stages of the actual experiment were estimated by counting the number of crystals captured by the slide impactor during the preliminary experiments.

Figure 2 shows a schematic diagram of the experimental arrangement. The hailstone was simulated by a stainless steel rod (R) of length 32 mm and diameter 4 mm, fixed horizontally (i.e. non-rotating) in a vertical tube of internal diameter 36 mm. The cloud was drawn through the tube, past the rod, by means of an air pump located outside the freezer. The flow rate was controlled by adjusting the power to the pump and monitored with an air flow meter. The supercooled droplets impacting on the rod formed a layer of rime on its surface. Once the cloud was seeded, the ice crystals interacted with the riming rod simulating ice particle interactions in a thundercloud. The rod was electrically connected through a current-to-voltage converting amplifier (A) to a sensitive electrometer (E) that continuously measured the current due to any charge acquired. The charge acquired flowed through the electrometer to ground with a time constant of 1 s. A small plastic cup (C) prevented a rime bridge forming between the rod and earth that would cause the current to leak to earth bypassing the electrometer. The rod was cleaned of all ice before each experiment. An input current of 100 pA gave an output voltage of 1 V. The minimum detectable voltage was 1 mV which corresponded to a charging current of 0.1 pA.

The temperature of the cloud (Tc) was measured by a bead thermocouple mounted within the freezer. The temperature of the rime or graupel (Tg) was measured by a fine wire K-type thermocouple mounted on the underside of the rod. Another similar thermocouple (Ta) was mounted within the tube just below the rod. Supercooled droplets impacting and freezing on this thermocouple raised its temperature above Tc. The temperature elevation was controlled by the cloud water content, Tc and the air flow rate in the tube. The fine wire thermocouples had a specified accuracy of 0.2 °C under steady conditions and a time response of 0.5 s. This resulted in a maximum overall

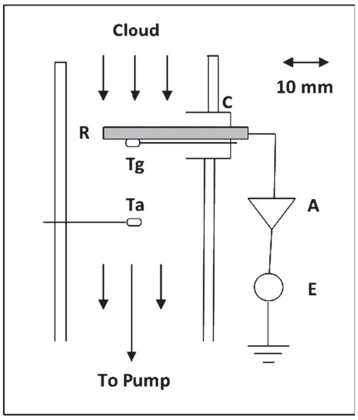

Figure 2. Schematic diagram of the experimental arrangement.

uncertainty of about 0.5 °C in Tg and Ta when these temperatures were varying rapidly but much less than this at all other times. The initial cloud water content was measured by capturing cloud droplets on a high-speed rotating wire of diameter 1 mm, assumed to have a collection efficiency of 1, and weighing the amount of rime collected over a known time. The cloud water content after seeding was estimated from the value of Ta. A series of experiments were conducted to calibrate the cloud water content to Ta at various values of Tc and two flow speeds 12 and 20 m s^{-1}. The ice crystals had a relatively small effect on the value of Ta and this enabled us to estimate the cloud water content in the mixed cloud to an accuracy of about 0.5 g m^{-3}.

At this point, we would like to add a note of caution in extending the conditions simulated in the laboratory to actual thunderstorms. For example, hailstones need to grow to centimetre-size before they fall at speeds exceeding 10 m s^{-1} and at these high fall velocities their physical properties such as density, shape and drag coefficients may well differ significantly from the hailstone that is simulated in these experiments.

3. Results and discussion

The thermostat was set to −15 °C and the freezing compartment was allowed to stand until it reached this steady temperature. This temperature rose by a few degrees as steam was injected into the freezer. The power to the boiler was adjusted until the steam injection rate was just sufficient to provide a stable cloud of supercooled droplets at $Tc = -10$ °C at a total water content of about 3.0 g m^{-3}. The pump was switched on and the power was set to draw the droplet cloud through the tube at a steady speed of 12 m s^{-1}. The graupel temperature, Tg, increased rapidly and the rimed surface on the rod attained wet growth within 30–40 s. The lower curve in Figure 3(a) shows the charging current as a function of Tg. No charging was observed until Tg reached −2 °C when a small positive charging current was observed. This current increased as the rime was visually observed to be wet and then remained steady at about 0.5 pA for about 30 s before the droplets in the cloud were depleted.

Next, the stable cloud of supercooled droplets at $Tc = -10$ °C and cloud water content of 3.0 g was seeded to produce ice crystals. The initial concentration of ice crystals was 1000 ± 50 cm^{-3}. After about 1 min, the ice crystal concentration had fallen to 100 ± 20 cm^{-3} and the cloud water content was down to about 1.0 g m^{-3}. At this point, the pump was switched on, drawing the mixed cloud past the riming target. The charging current at each value of Tg is shown by the upper curve in Figure 3(a). Figure 4(a) shows the charging current to the rod as a function of time from seeding together with the cloud conditions – Tc, Tg and ice crystal concentration. Once again, Tg increased steadily and the surface of the rime on the rod attained wet growth within 30–40 s. In the dry growth regime, the rod charged strongly positively when droplets and crystals coexisted in the cloud. The

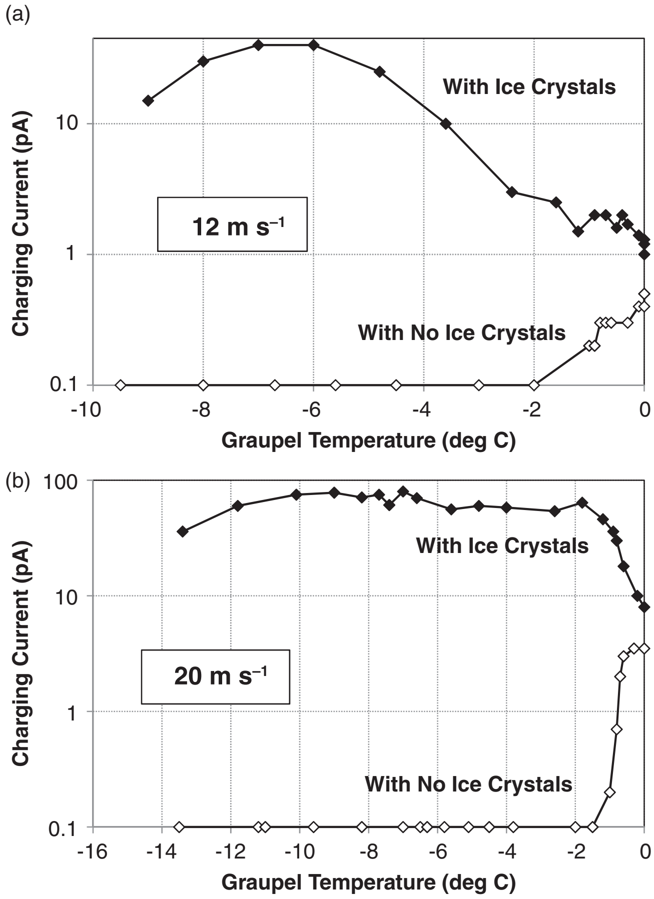

Figure 3. (a,b) Charging current as a function of graupel temperature (Tg) at two different flow speeds, with and without ice crystals in the cloud of supercooled droplets.

charging current was of the order of a few tens of pA as the temperature of the rime increased from −10 to −6 °C. At this stage, with a crystal concentration of 100 cm^{-3}, we estimated the charge per event to be 0.70 fC with the assumption of $E = 1.0$. The sign and magnitude of charge acquired by the hailstone was broadly in agreement with previous laboratory studies under the same conditions (Takahashi, 1978; Jayaratne *et al.*, 1983; Baker *et al.*, 1987; Keith and Saunders, 1990; Saunders *et al.*, 1991). The increase in charging current during the first few seconds is probably due to the increasing flow rate. Thereafter, the charging current decreased with further increase of temperature until wet growth was visually observed. This decrease is probably due to a combination of factors including the decrease of ice crystal concentration, increased sticking of crystals to the rime and a general decrease of the charge per event with increasing temperature as has been reported in previous studies (Takahashi, 1978; Jayaratne *et al.*, 1983; Baker *et al.*, 1987; Saunders, 2008). At this stage, the ice crystal concentration was down to about 10 cm^{-3} and the charging current remained close to about 1.0 pA. The experiment was repeated several times and yielded similar results. If we assume $EP = 1$ at wet growth, the estimated charge per event is 0.2 fC. However, this is not a reasonable assumption. While the collision efficiency does not vary significantly with Tg, we expect the separation probability, and hence the event probability, to decrease at wet growth due to crystals sticking to the wet surface. At this stage, we do not know what fraction of impacting crystals bounce off a wet hail surface. If we assume that 1 in 10 colliding crystals bounce off, the estimated charge per event becomes 2 fC. If only 1 in 100 colliding crystals bounce off, the charge per event increases to 20 fC.

The lower curve in Figure 3(a) shows the charging current when the cloud was not seeded and there were no ice crystals in the cloud. No charging was observed from −10 up to −2 °C when wet growth began. At this stage, there is an interesting observation

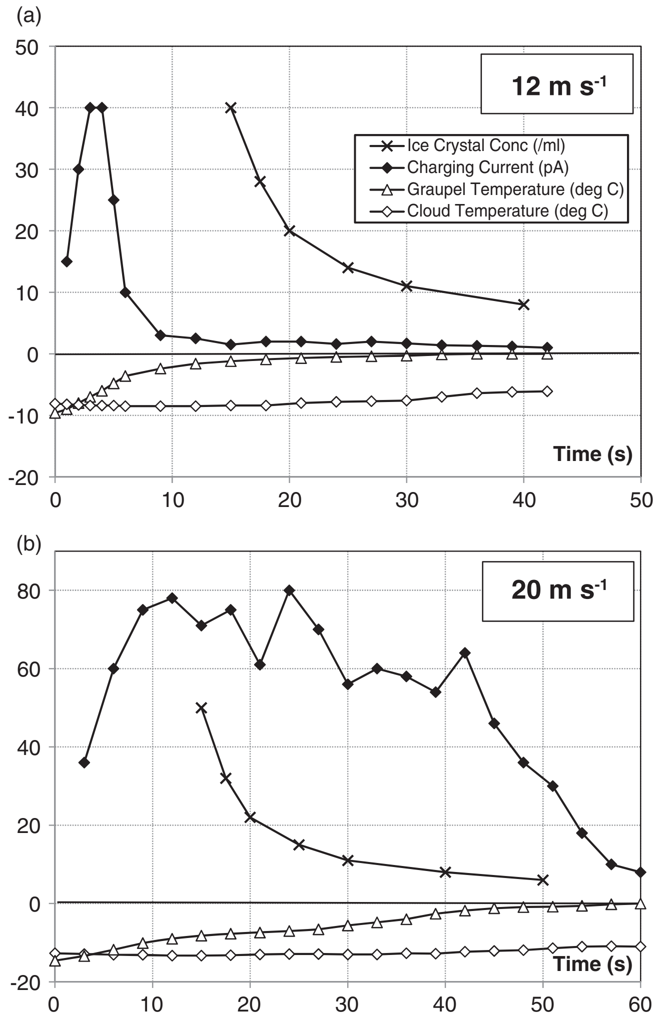

Figure 4. (a,b) Charging current, ice crystal concentration (ml^{-1}), *Tg* and *Tc* as functions of time at the two different flow speeds. For each parameter, the vertical axis units are as indicated in the legend entries.

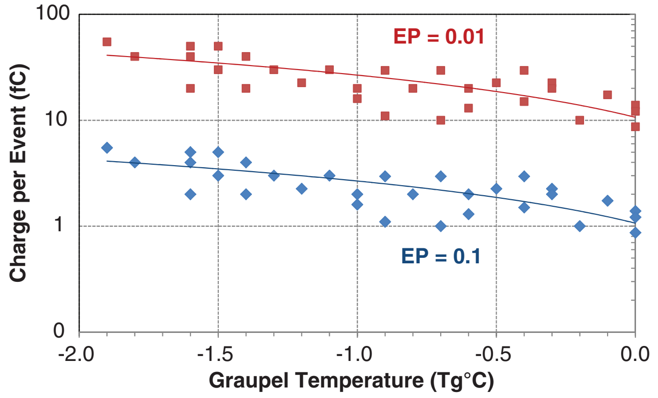

Figure 5. The charge per event near the wet growth regime at a flow rate of $12\ m\ s^{-1}$ calculated for $EP = 0.01$ and $EP = 0.1$.

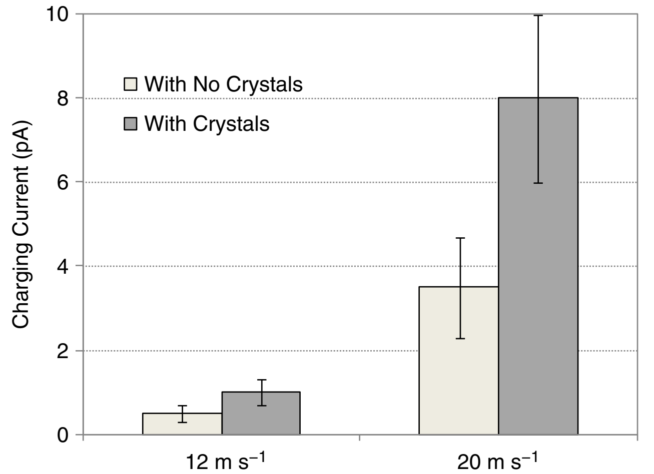

Figure 6. Mean values of the charging current in wet growth with and without ice crystals in the cloud.

of a finite charging current that was clearly not due to ice crystal interactions. We will discuss this phenomenon later. The charge transfer by ice crystals alone can be determined by subtracting the values in the lower curve from those in the upper curve. The charging current without crystals was very much smaller than with crystals, so that the difference in charging due to the different cloud water contents in the two cases was negligible. In Figure 5, we take a closer look at the charging due to ice crystal interactions alone in the graupel temperature range −2 to −0 °C. The graph shows all the results from four different experiments. The charge per event was calculated for two values of the event probability, $EP = 0.1$ and 0.01, all other conditions being the same. The ice crystal concentration and cloud water content were approximately $10\ cm^{-3}$ and $2.0\ g\ m^{-3}$, respectively. One of the difficulties in interpreting this result is the fluctuation in *Tg* due to the rapidly changing conditions. The thermocouple bead has an inherent time lag in attaining thermal equilibrium. Further, it becomes coated with a thin layer of rime so will not register the exact temperature of the surface of the ice. For these reasons, it is not possible to ascertain exactly at what value of *Tg* wet growth is attained. Furthermore, it has been shown that the water skin on a wet hailstone is generally supercooled by up to 2 °C (List *et al.*, 1989). Thus, even when *Tg* registers a temperature lower than 0 °C, the surface may actually be wet. In Figure 5, there is no sharp discontinuity in the two curves as they approach 0 °C, suggesting that the surface may be wet in the entire temperature range shown in this figure. In the dry growth regime, we expect *EP* to be close to 1. However, in wet growth, there is some uncertainty. If 1 in 10 crystals bounce off the wet hailstone, the relevant curve ($EP = 0.1$) indicates a charge per event of about 1 fC in wet growth. If only 1 in 100 crystals bounce off ($EP = 0.01$), the charge per event is 10 fC. Note that these values relate to the ice crystal interactions and exclude the charging current observed in the presence of supercooled droplets alone.

Next, we repeated the experiment at a flow speed of $20\ m\ s^{-1}$. The higher flow rate meant that the rime attained wet growth much faster than at $12\ m\ s^{-1}$, so a lower initial *Tc* was selected. The thermostat was set to −20 °C which resulted in an initial *Tc* of about −15 °C with a cloud water content of $3.0\ g\ m^{-3}$. Once again, with only supercooled droplets present, there was no charging until *Tg* had exceeded −2 °C. At wet growth, a positive charging current of about 3.5 pA was observed as shown by the lower curve in Figure 3(b). The upper curve in Figure 3(b) shows the corresponding result with a mixed cloud. A higher charging current was observed at all temperatures, remaining at 50–90 pA all the way up to −2 °C, beyond which it fell sharply to attain a steady value of about 8 pA during wet growth. Figure 4(b) shows the time variation of the charging current together with the corresponding cloud conditions. Figure 6 summarises the charging current results during wet growth in a graphical form. With a crystal concentration of $10\ cm^{-3}$ and $EP = 0.1$, the charge per event at wet growth was 5 fC. At $EP = 0.01$, it was of the order of 50 fC.

In the dry growth regime, with a crystal concentration of $100\ cm^{-3}$ and $EP = 1.0$, the estimated charge per event was of the order of 0.8 fC. This value is not much higher than the corresponding value at $12\ m\ s^{-1}$ indicating that the charge per event does not increase indefinitely with impact speed. At first, this observation appears to be inconsistent with Keith and Saunders (1990) who found that the charge per event increased with impact velocity to the power 2.5–$25\ m\ s^{-1}$. However, in their experiments, Keith and Saunders maintained the same rime accretion rate by reducing the cloud water content accordingly as the impact velocity was increased. In the present experiments, the rime accretion rate increased with flow speed. Therefore, the experimental conditions were not the same in the two experiments. The present observations with mixed clouds, when ice crystals coexisted with supercooled droplets at a cloud water content of $1-2\,\mathrm{g\,m^{-3}}$, were broadly in agreement with the results of Takahashi (1978) and Jayaratne *et al.* (1983) who also found positive charging under these conditions. As the rime surface temperature reached $0\,^{\circ}\mathrm{C}$, the charging fell by an order of magnitude. This was probably because many of the crystals were sticking to the wet rime, preventing charge transfer. The finite charging current that was observed may indicate that a small fraction of the crystals were still able to rebound off the wet surface. However, this charging current was at least an order of magnitude lower than during dry growth. This observation contradicts Takahashi (1978) who did not find such a large difference in the magnitude of charging between the dry and wet growth regimes. Inspection of the rod under the microscope showed many ice crystals stuck on the surface of the glazed rime.

With a droplet-only cloud, there was no charging in the dry growth regime while a measurable charge separation was observed when the rime attained wet growth. In fact, from Figure 6, we see that a substantial amount of charging observed with a mixed cloud at wet growth, approximately 50% at $12\,\mathrm{m\,s^{-1}}$ and 44% at $20\,\mathrm{m\,s^{-1}}$, was due to the charging that occurred with water droplets alone. We have no conclusive explanation for the observed charging of the hailstone in wet growth with no ice crystals. It is well known that charge is separated due to the Dinger–Gunn effect during the melting of ice (Dinger and Gunn, 1946). Subsequent studies have attributed the charge separation to the bursting of air bubbles during the melting process (Dinger, 1964; MacCready and Proudfit, 1965; Drake, 1968). However, in our experiments, the surface achieves wet growth when the rate of acquisition of latent heat from the accreting water is too high to be lost to the airstream. As such, there was no actual melting, and therefore no bubble bursting, taking place. A more plausible explanation is the electrification due to the evaporation of the meltwater under a temperature gradient (Latham and Stow, 1965). A common observation in all these experiments was that the phenomenon was observed only at or near wet growth and the ice acquired a net positive charge.

The important observation in our experiments was the significantly greater charging current observed during wet growth at both flow speeds when there were crystals in the cloud as against when there were supercooled water droplets alone. This charging current amounted to approximately 50% at $12\,\mathrm{m\,s^{-1}}$ and 56% at $20\,\mathrm{m\,s^{-1}}$, and was in some way related to the interaction of ice crystals on the rime and not due to melting or evaporation. Converting the observed charging current to a charge transfer per crystal required knowledge of the event probability, *EP*, which was uncertain. This amounted to approximately 1 fC at $EP = 0.1$ and 10 fC at $EP = 0.01$ at a flow speed of $12\,\mathrm{m\,s^{-1}}$ and 5 fC at $EP = 0.1$ and 50 fC at $EP = 0.01$ at a flow speed of $20\,\mathrm{m\,s^{-1}}$. These results strongly suggest that a small number of the colliding ice crystals were able to bounce off without sticking to the riming surface. The likelihood of a crystal bouncing off a wet ice surface is very small. However, if the riming surface is not uniformly wet with dry spots on its surface, it is possible that a limited number of crystals might bounce off these areas and transfer the observed charge to the target rod. We have looked at the literature and there is some evidence that this could be happening, as discussed below.

Using remote infrared measurements of rotating and gyrating spheroidal hailstones growing in an icing tunnel, List *et al.* (1989, 1995) showed that their surface temperatures were not isotropic and homogeneous as had always been assumed. The temperature differences were as large as $6\,^{\circ}\mathrm{C}$ for spheres and $4\,^{\circ}\mathrm{C}$ for spheroids. Surface temperatures remained below $0\,^{\circ}\mathrm{C}$ even during wet growth. Wet growth generally occurred in the equatorial region of the hailstone with the dry poles being colder. Lozowski *et al.* (1983) modelled the surface temperature of a riming 'hailstone' in the shape of a non-rotating cylindrical rod with the air flow normal to its axis. They showed that, during dry accretion, the rime formed in a smooth crescent leading to an elliptical profile with the maximum growth rate along the stagnation line of the cylinder directly facing the airflow. Increasing the riming rate, cloud temperature or the accretion time led to an increase in the surface temperature. Wet growth was first attained along the stagnation line facing the air flow. The surface temperature decreased as the angular position increased towards the outside of the hailstone. With further increase in riming rate, the stagnation line became totally wet with runback of liquid water to about 25° beyond which the accretion became dry. Under these conditions, the growth rate was a minimum at the stagnation line with shedding of water from the edges leading to the development of bulges or horns centred at about 20°, giving a V-shape cross-section to the rime. Takahashi (1978) too observed this V-shape structure on his riming probes during heavy riming. Phillips *et al.* (2014) extended the theory of wet growth of hail to inhomogeneities of surface temperature and liquid coverage and showed that both wet and dry parts may coexist on the surface of a hailstone while it is growing by wet growth. The inhomogeneity was attributed to the higher deposition rate of rime at the equator than the poles of the hailstone.

Karev *et al.* (2007) measured the spatial distribution of the surface temperature of a non-rotating icing cylindrical rod simulating a riming hailstone in the laboratory using a remote infrared camera and experimentally confirmed the model predictions of Lozowski *et al.* (1983). They showed that, even with a wet regime near the stagnation line, the outer regions of the cylindrical hailstone remained in dry growth. At an air temperature of $-17\,^{\circ}\mathrm{C}$, a cloud water content of $4.6\,\mathrm{g\,m^{-3}}$ and an air flow speed of $20\,\mathrm{m\,s^{-1}}$, the stagnation line was in wet growth while in the outer region, beyond an angular position of about 30°, the rime remained in dry growth with a surface temperature of around $-10\,^{\circ}\mathrm{C}$. Small droplets impacting on the hailstone in these regions froze immediately after the first contact with the surface, forming white ice feathers.

Figure 7 is a schematic diagram of a non-rotating spherical riming hailstone falling through a cloud. The two block arrows show the direction of air flow relative to the hailstone so that the droplets and crystals impact on its lower surface which will be wet up to an angular position of about 30° and dry thereafter approaching the poles. As the hailstone is fixed, the rime deposit grows downwards. A free-falling, originally spherical, hailstone would rotate about its minor axis, which is the horizontal line in the diagram, and it would be wet all around the equator. While most of the water droplets impact along the equator, the lighter ice crystals are carried along in the air flow around the hailstone and are more likely to make impact at the edges as shown by the broken curve in Figure 7. This is precisely the region of the hailstone that is likely to be dry and where they are least likely to stick to the surface. There is no information about the probability of ice crystals impacting and separating from a wet ice surface. Saunders *et al.* (1991) predicted that, in laboratory experiments where the target hailstone was in wet growth, such as Takahashi (1978), most of the ice crystals would stick on to the hail surface and not be able to separate electric charge. When an ice crystal collides with a wet hail surface, there are two ways in which it can 'stick' to the surface. It could adhere to the water film through surface tension forces much like fluff sticking to a wet surface. This process would not capture all the interacting crystals. List (1990) showed that the water skin on a wet hailstone is generally supercooled to as low as $-5\,^{\circ}\mathrm{C}$ and more. The physical picture is that of an ice sponge from which a fragile dendrite mesh grows into the water skin. When the tip of an ice crystal makes contact with the skin, it is likely to immediately freeze the water at the point of impact and be held fast. However, the freezing rate increases with the degree of supercooling. If the temperature of

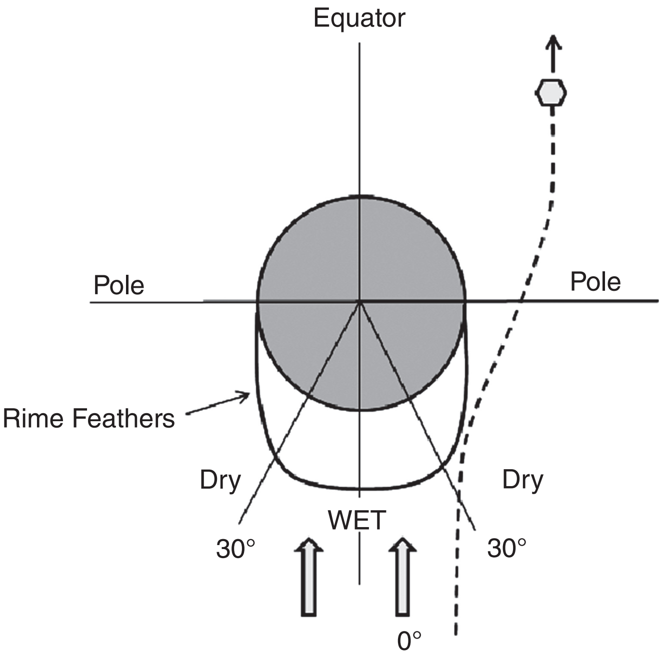

Figure 7. Schematic diagram of the hailstone showing the wet and dry regions. See text for details.

the water skin is close to 0 °C, the freezing rate will not be high enough to capture interacting crystals in this manner. Thus, at present, we are not in a position to predict how efficiently ice crystals would stick to a wet hail surface.

However, due to the inhomogeneous surface temperature distribution, the poles of the target hailstone may remain dry during wet growth. If so, we could expect a significant number of rebounding collisions from this region, thereby allowing charge transfer to take place. In our present experiment, it is reasonable to assume that at least 1 in 100 impacting ice crystals are able to separate. Even a ratio of 1 in 10 does not seem unreasonable if the target ice was not completely wet as has been suggested. There is another factor that needs to be considered. Microscopic observation of the riming rod subject to wet growth in a mixed cloud showed many ice crystals stuck to the surface. When ice crystals impact on such a surface they have an increased chance of rebounding off the captured layer of ice crystals on the hail surface. Furthermore, it is interesting to note that, during wet growth, Karev *et al.* (2007) observed that the dry poles of the hailstone showed the presence of white rime feathers. It has been suggested that a possible charge separation mechanism when ice crystals interact with a graupel particle is the break-up of tiny ice structures on the surface (Avila and Caranti, 1994). In Takahashi's experiment, during wet growth charging of his hailstone, he observed large numbers of rime fragments in his chamber. He attributed the positive charging of his hailstone at high cloud water contents to the fracture of these rime structures on its surface due to ice crystal impacts.

While inhomogeneous distribution of accretion could lead to the coexistence of both wet and dry growth on the surface of a non-rotating hailstone, there is some doubt as to whether it may be extended to natural hailstones in actual clouds that tend to rotate and wobble as they fall. However, the most common shape of large hail is an oblate spheroid with an axial ratio ranging from unity to about one-half with increasing size (Knight and Knight, 1970; List, 1986; Straka *et al.*, 2000). Oblate hailstones fall with the equator oscillating about the vertical plane while rotating around their minor axis, which is near-horizontal and passes through the poles (Knight and Knight, 1970; Kry and List, 1974a, 1974b). Therefore, most of the accretion occurs along the equator while the poles may remain dry at sub-zero temperature. Rasmussen and Heymsfield (1987) and Garcia-Garcia and List (1992) pointed out that water forms a torus around the equator of a falling hailstone during wet growth, while the poles remain dry and icy. There is more evidence for this. For example, Knight and Knight (1973) showed that the section of a spongy hailstone sampled during wet growth exhibited the outer spongy deposit in a wide band around the particle without completely covering its surface.

Furthermore, the internal structure of natural hailstones consists of multiple concentric layers of opaque and clear ice pertaining to uniform dry and wet growth, respectively (Knight and Knight, 1970, 1973; List, 1986). Hailstones are known to recycle several times in the intense updraughts and downdraughts typical of severe storms, before they finally fall out of a cloud (List, 2014). The opaque rime layers are acquired as they pass through relatively low cloud water content regions of the cloud. In the lower regions of the cloud, being adjacent to the high liquid water content regions that produce wet growth, the opaque layers correspond to regions where hail may acquire large charges due to ice crystal interactions in dry growth. This can occur within large regions of thunderstorms, from the freezing layer up to levels where the temperature is as cold as −20 °C, where conditions are suitable for strong positive charging of graupel by the relative growth rate mechanism (Jayaratne *et al.*, 1983; Baker *et al.*, 1987). When the hailstones subsequently acquire a wet skin and fall out of the cloud, they will still retain the positive charge acquired previously. This presents an explanation for the strong positively charged wet hail and intense positive ground flashes observed in severe storms.

4. Conclusions

- During riming of a hailstone at sub-zero temperatures, no charge transfer is observed when there are no ice crystals in the cloud. Once the hailstone attains wet growth, it acquires a small positive charge.
- A positive charge is transferred to the hailstone when there are crystals present in the cloud at all temperatures between 0 °C and at least −14 °C (the limit here).
- The total charging current to the hailstone during wet growth is about an order of magnitude smaller than the current in dry growth.
- We estimate that, during wet growth, approximately one-half of the charging current is due to ice crystal interactions.
- We assessed the possibility of charge transfer by ice crystals impacting and separating from a wet hail surface without sticking by adhesion or being captured by the freezing part of the supercooled water film and conclude that this is possible in a fraction of cases.
- We assess the evidence that suggest that, during wet growth, the edges of a non-rotating hailstone, such as in the present study and in Takahashi (1978), maintain a dry surface, and that interacting ice crystals are able to separate from the hailstone off these dry regions without sticking and so separate charge.
- These laboratory findings are not directly applicable to natural clouds where falling hailstones tend to rotate and gyrate. However, it is known that most large hail is wet and takes on an oblate shape. In free fall, it tends to rotate about the minor axis. Thus, while the equator region is wet, the polar regions of the hailstone may remain dry. This is precisely the part of the hailstone where ice crystals are most likely to interact and bounce off, transferring a positive charge to the hail.
- The internal structure of hailstones often shows alternate opaque and clear ice layers. The opaque ice shows that a hailstone, although wet, had passed through regions of the cloud where it is in dry growth and could have acquired a substantial positive charge due to ice crystal collisions.
- It is tempting to use this possibility to explain how lightning in severe storms with large hail is often dominated by positive ground flashes. However, at present, we do not

have sufficient evidence to support this hypothesis and offer it as a possible explanation.

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