
Published article:

Saunders, CPR and Brooks, IM (1992) *The Effects of High Liquid Water Content on Thunderstorm Charging.* Journal of Geophysical Research, 97 (D13). 14671 - 14676. ISSN 0148-0227

http://dx.doi.org/10.1029/92JD01186

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. D13, PAGES 14,671–14,676, SEPTEMBER 20, 1992

The Effects of High Liquid Water Content on Thunderstorm Charging

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Charge transfer to a riming graupel target during interactions with ice crystals has been investigated in the laboratory. When liquid water contents sufficiently high to cause wet growth are achieved, the charge transfer falls to values which are insignificant to thunderstorm electrification. The implications of this null result to a recent analysis of thunderstorm-charging processes by Williams et al. (1991) are discussed.

INTRODUCTION

There is a large body of evidence from laboratory studies to suggest that the interaction of ice crystals with low-density graupel pellets, in the presence of supercooled water droplets, is one of the principal thunderstorm-charging processes. While the mechanism of charge transfer is unclear, studies undertaken over the last 30 years or so have led to a detailed knowledge of the sign and magnitude of the charge separated under a wide range of conditions [*Reynolds et al.*, 1957; *Marshall et al.*, 1978; *Takahashi*, 1978; *Jayaratne et al.*, 1983; *Baker et al.*, 1987; *Keith and Saunders*, 1989, 1990, and *Saunders et al.*, 1991]. However, there does not appear to have been a detailed examination of the charge transfer, if any, under conditions of wet growth when the rate of accretion of supercooled water drops by the graupel pellet is high enough for the latent heat released as they freeze to maintain a surface layer of liquid water on the pellet. *Saunders et al.* [1991] assumed that under such conditions, impacting ice crystals would stick to the pellet rather than bounce off, and so there would be no charge separation, while Williams et al. [1991] suggest that crystals do bounce off graupel in wet growth charging it positively. Williams et al. have reinterpreted the results of *Takahashi* [1978] in the light of this suggestion. The current work was undertaken to resolve the question of whether or not charge is separated by ice crystal/graupel interactions under conditions of wet growth.

THE EXPERIMENTS

The experiments were carried out in a large cloud chamber, situated in a cold room as described by *Keith and Saunders* [1990]. The cloud was formed by the entry of water vapor from a boiler situated below the cloud chamber, the water droplets rapidly supercooling to the ambient temperature. *Jayaratne et al.* [1983] showed that any impurities in the droplets formed by this technique are at a low enough concentration to have no effect on the charge transfer. The cloud was mixed by means of a fan in order to reduce inhomogeneities. Ice crystals were seeded by briefly inserting a fine brass rod, cooled to liquid nitrogen temperatures, into the cloud. Mixing was stopped just before seeding to avoid charging the crystals by collisions with the fan.

The graupel pellet was simulated by a 5-mm-diameter metal rod mounted within one arm of a pair of tubes, as shown in Figure 1. A sensitive charge amplifier, with a time constant of 1 s and an output of 1 mV equivalent to 10^{-13} amps, was connected to the riming rod. The second arm of the tube supported an identical rod with a thermocouple mounted close to its surface to measure the rime temperature during the course of the experiment. In order to keep the temperatures of the two rods as close as possible the second rod was provided with a similar coaxial cable to the charge measuring rod to give it the same thermal path out of the chamber. The airspeeds in the two arms of the tube were equal to within ± 0.2 m s^{-1}. Peltier elements were mounted on both rods in order to allow them to be heated in order to force wet growth; this was necessary at lower airspeeds because at liquid water contents high enough to obtain wet growth without heating the rods, the ambient temperature in the chamber became too high to grow ice crystals effectively. The liquid water content of the cloud before seeding was estimated by FSSP measurements to be in the range 2.5 to 3.5 g m^{-3}, with droplets up to 30 μm diameter present, the modal diameter being around 8 μm. The vapor supply was maintained throughout the experiment and the crystals grew to 100 μm. Following initial experiments showing no charge during wet growth, the crystal concentration was increased to 10^3 cm^{-3} in order to increase the charge transfer sensitivity.

In each experiment, the cloud was allowed to become established and was then seeded at time t = 0. The airflow, and hence riming, was started after 1 to 2 min, once the ice crystals had grown. The conditions necessary to obtain wet growth were determined and then the charging current was noted under various surface conditions.

The experiments were carried out at airspeeds between about 4 m s^{-1} and 11 m s^{-1} (speeds below 4 m s^{-1} proved too low to obtain wet growth at temperatures low enough to get reasonable growth of the ice crystals).

RESULTS

Figure 2 shows typical characteristics for the charging current to the riming rod under various conditions. The horizontal axis shows the time elapsed since the cloud was seeded, in minutes. The arrows indicate the start and end of the period during which the ice crystals and supercooled water droplets were drawn past the riming rod. The cloud temperature at the level of the riming rods was between -10°C and -11°C and that near the top of the chamber was about -7°C to -8.5°C. The power to the boiler was kept constant in all cases except that noted below, and the ice crystals remained in the cloud for approximately 2.5 min.

Figure 2*a* shows a typical positive charging current to the target caused by ice crystals removing negative charge under conditions of dry growth, at an airspeed of 4 m s^{-1}, which is a familiar result

Paper number 92JD01186.
0148-0227/92/92JD-01186$05.00

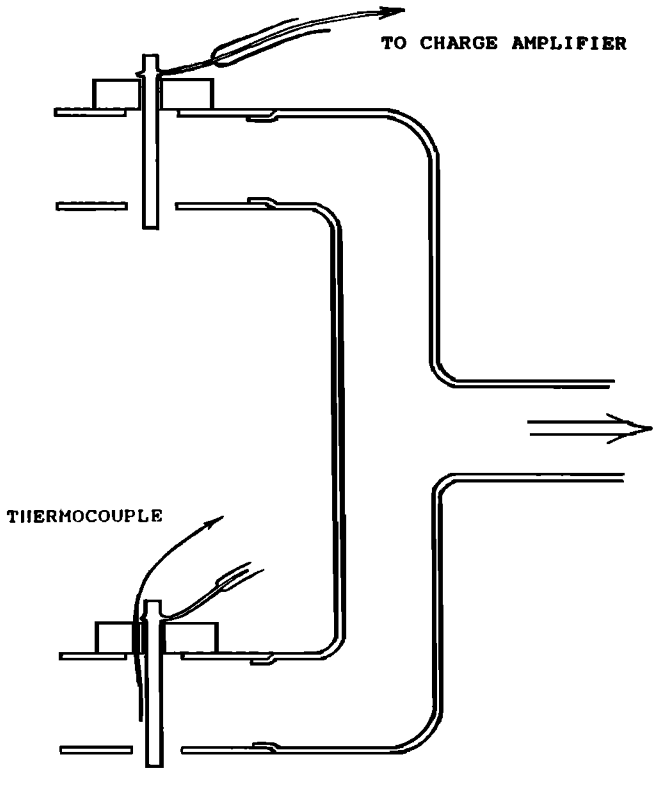

Fig. 1. The double tube supporting the riming targets.

from many previous studies; the current falls to zero when the crystals are exhausted. Figure 2*b* shows a current to the target before the onset of wet growth with the same cloud conditions and airspeed as in Figure 2*a* but with the rod heated by the peltier element. At about 1.6 min after seeding, the current falls to zero; from photographic evidence and temperature measurements, this occurs when wet growth is established. The low charging current in Figure 2*c* was also obtained at 4 m s^{-1} but with a slightly higher liquid water content and with increased heating which led to a rapid onset of wet growth. Figure 2*d* shows the current peak before the onset of wet growth at a velocity of 11.3 m s^{-1} with an unheated rod. Figures 2*e* to 2*h* show similar cases with a heated rod. All four runs in this latter set were carried out under identical conditions, but the riming was started at successively later times: 1, 1.25, 1.5, and 2 min after seeding the cloud. In each successive case the magnitude of the peak current was reduced and the duration of a significant current became shorter. A similar reduction in the duration of the current peak was also found with increasing airspeed.

The temperature of the rime as measured by the thermocouple on the second rod was found to rise to 0°C for wet growth. The measured temperature tended to fluctuate rapidly by up to 1°C due to the random arrival of droplets, and since the thermocouple rapidly became embedded in the rime ice, it is difficult to gain any detailed idea of the surface temperature variations.

Figures 3 to 7 show typical photographs of the rime buildup under various conditions. There is a very marked difference in the appearance of the ice for dry and wet growth. Dry-growth rime, Figure 3, is white, opaque, and has a structure revealing the accretion of individual drops, which can appear feathery where the air velocity past the target was low. The wet growth rime (Figures 4 and 5) is clear and solid, with a smooth surface. In Figure 4 the boiler power was increased to achieve wet growth, while in Figure 5 it was achieved with the aid of the peltier element. Figure 5 shows that water has run to the bottom of the rod before freezing. Figures 6 and 7 show cases where the growth appears to be part way between wet or dry. In such cases the rime appears translucent rather than white but maintains the visible structure of the dry growth, and the charging current tends to behave as for dry growth.

DISCUSSION

The results show that for a riming target under conditions of wet growth the charge separated during interactions with incident ice crystals is reduced by an order of magnitude or more compared with dry growth. In all but one of the wet-growth cases there is an initial positive current to the target, which drops rapidly to a negligible or zero level. This current is due to interactions taking place before wet growth has been established, since it will take a finite time for enough heat to be released from the freezing drops to warm the surface to above 0°C. It was usually possible in these cases to see a white dry growth layer at the surface of the rod, beneath the transparent wet growth ice. Further evidence for this explanation comes from the series of runs made with increasing intervals between the seeding of the cloud and the start of riming (Figures 2*e* to 2*h*). When the time interval is increased, the duration of the current peak decreases as the wet growth is established faster. This is because there is more time available for the liquid water in the cloud to have reestablished its initial value following its depletion due to the rapid initial growth of the ice crystals from the vapor. The onset of wet growth also occurred earlier at higher air velocities due to the increased rate of deposition of water on the riming rod. Figure 2*c* shows a wet-growth case where there is no initial positive current. In this case, the liquid water content of the cloud was slightly higher than usual and the effective heating of the rod somewhat greater because the peltier element was positioned closer to the region of the rod being rimed. Thus the liquid surface layer was established rapidly when riming commenced, which prevented the usual charge transfer in dry growth. From a knowledge of the ice crystal concentration the charge separated per crystal collision during wet growth of the rimer can be calculated. The maximum charging current shown in Figure 2*c* leads to an average charge separation per crystal collision of the order of 10^{-3} fC which is insignificant to thunderstorm electrification by several orders of magnitude.

Significance to Thunderstorm Charging Studies

Takahashi [1978] carried out charge transfer measurements when ice crystals collided with a 3-mm-diameter riming target at 9 m s^{-1} over a range of temperatures and liquid water contents. Figure 8 summarizes his findings: the target charges negatively in the shaded area and it charges positively everywhere else. *Williams et al.* [1991] have used the analysis of the heat balance of a riming cylinder, [*Macklin and Payne*, 1967] to determine the surface condition of the riming target, and the lines in Figure 8 delineate three charging zones which they interpret as follows: (1) wet growth at high liquid water contents associated with positive charging; (2) zone of rime surface evaporation (sublimation) at intermediate liquid water contents associated with negative charging; and (3) low liquid water content zone of positive charging due to rime target growth by vapor deposition. Note that the ordinate in Figure 8 is "effective liquid water

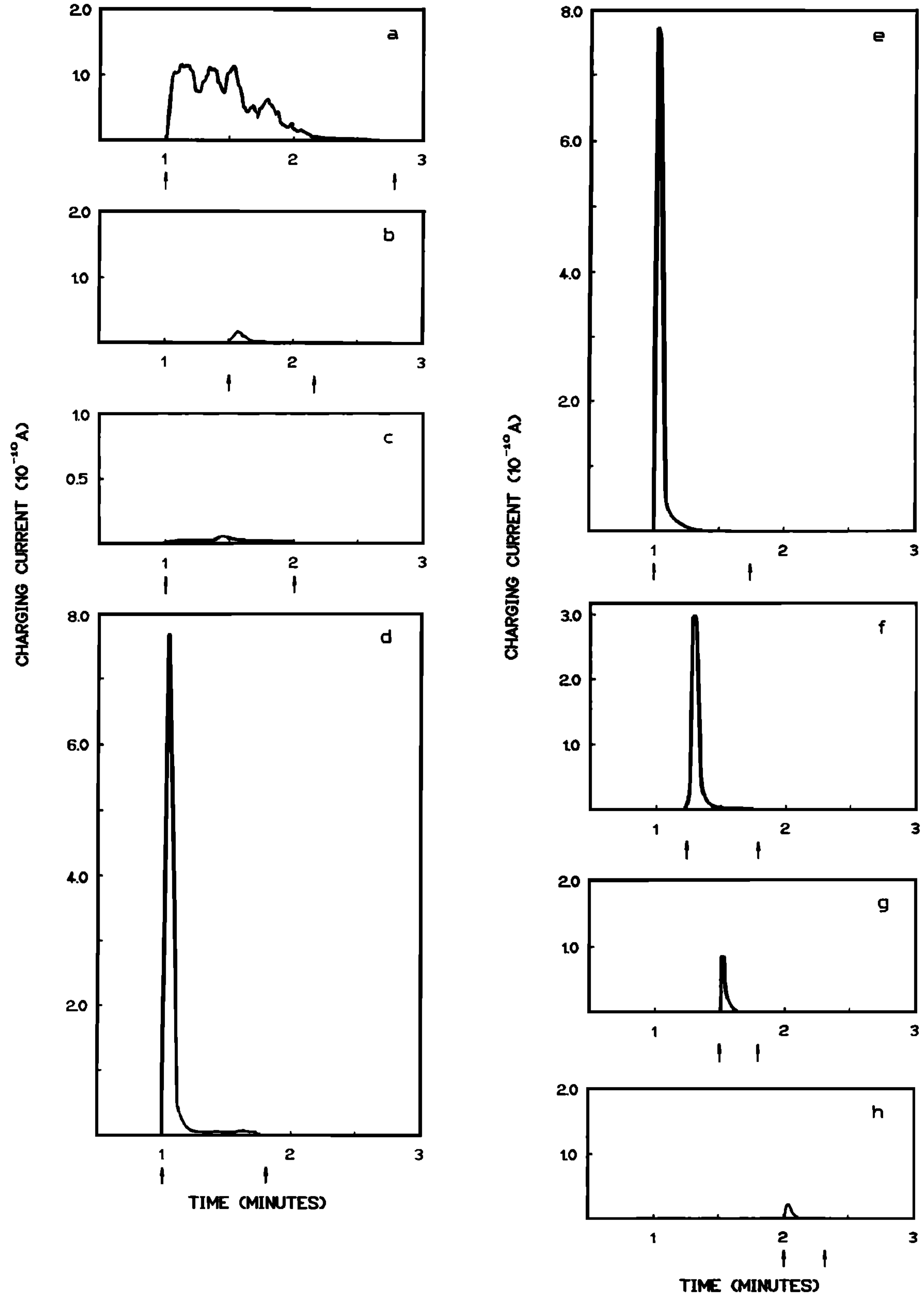

Fig. 2. Current to a riming target against time since cloud seeding. The arrows indicate the start and stop times of cloud flow past the target. (*a*) Dry growth at 4 m s^{-1}; (*b*) to (*h*) initial dry growth followed by wet growth); (*b*) and (*c*) 4 m s^{-1}; (*d*) 11 m s^{-1}; (*e*) and (*h*) 11 m s^{-1}, with riming starting at successively later times after seeding.

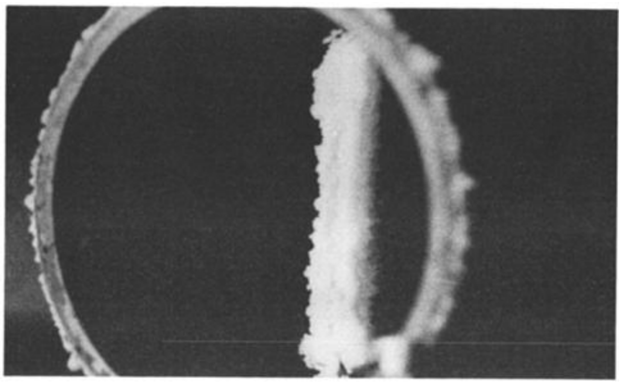

Fig. 3. Rime ice under dry growth.

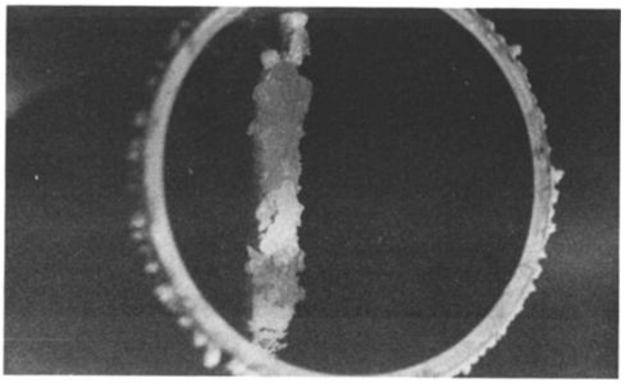

Fig. 6. Mixed growth.

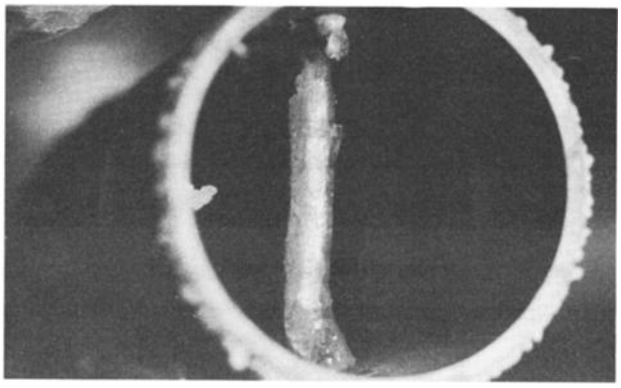

Fig. 4. Rime ice under wet growth.

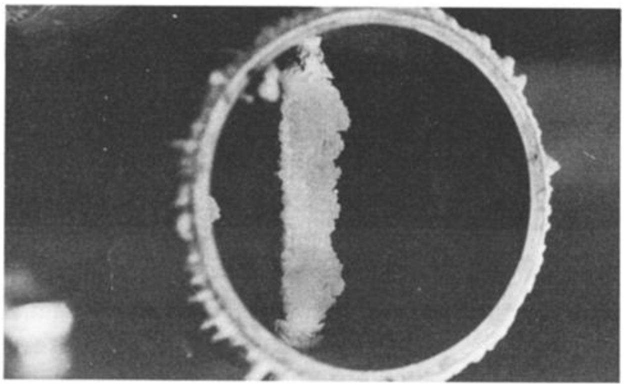

Fig. 7. Mixed growth.

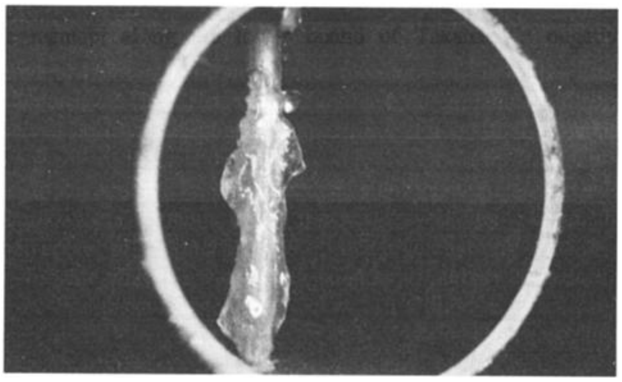

Fig. 5. Rime ice under wet growth.

content," EW, as determined from the *Macklin and Payne* [1967] heat balance equation. *Takahashi* [1978] presented his negative charging zone as a function of cloud water content and so we have used his stated droplet collision efficiency of 80% to redraw the negative charging zone appropriately for effective liquid water content values.

Several points can be made with reference to Figure 8. First, *Williams et al.* [1991] state that they have no explanation for the observed positive charging at temperatures above -10°C. Second, the present work has shown that there is no significant charging in wet growth and yet Takahashi obtains significant charging results at liquid water contents above the wet-growth line. Third, the upper bound of *Takahashi's* [1978] negative charging zone does not coincide with the wet-growth boundary line between zones 1 and 2. Fourth, at temperatures below -15°C there is charge sign disagreement along the lower bound of Takahashi's negative charging data. In Figure 8 the effective liquid water scale is logarithmic, and so these third and fourth points are of major significance.

Saunders et al. [1991] presented charge transfer results obtained over a wide range of conditions relevant to thunderstorms. Their data were parameterized so that the charging of graupel pellets by ice crystals may be determined for appropriate values of ice crystal size, crystal/graupel relative velocity, temperature, and liquid water content. It is therefore possible to use the parameterization to calculate charge transfer values for the experimental conditions used by other workers. Comparison with *Takahashi's* [1978] data gave fair agreement in the negative charging zone when *Saunders et al.* [1991] assumed that Takahashi's cloud water content was overestimated. The present work appears to confirm this suggestion, particularly in view of the fact that Takahashi does not use the term "wet growth" in his paper. Takahashi refers to the work of *Hosler et al.* [1957], in connection with a liquidlike layer on the ice surface rather than a water layer due to the surface experiencing wet-growth conditions. Furthermore, by comparison with the rime photographs obtained in this study, Takahashi's photograph of rime clearly shows dry growth. It is possible that Takahashi did not have wet-growth conditions in his experiments. On the assumption that Takahashi overestimated his liquid water content values, then his negative charging zone in Figure 8 should move down the diagram leading to even larger disagreement with the charging zone hypothesis of *Williams et al.* [1991].

The experimental crystal/graupel charging data obtained by *Jayaratne et al.* [1983], *Keith and Saunders* [1990], and *Saunders et al.* [1991], which included observations of charge sign reversal controlled by temperature and water content, were obtained under dry surface conditions. This is confirmed by the appearance of the

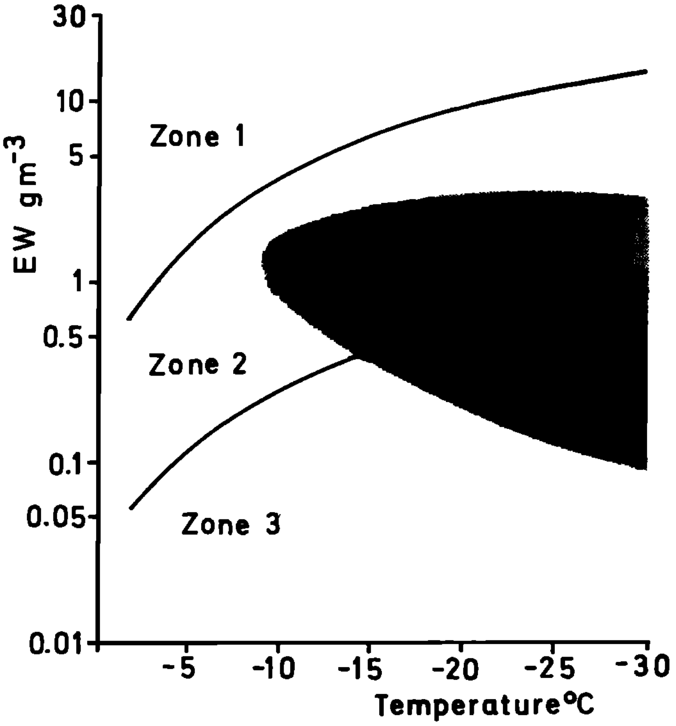

Fig. 8. The influence of effective liquid water content and temperature on graupel charging. Shaded portion, negative charging according to *Takahashi* [1978]. Zone 1, wet growth; zone 2, rimer evaporation; zone 3, dry growth; from *Macklin and Payne* [1967] and *Williams et. al.*, [1991].

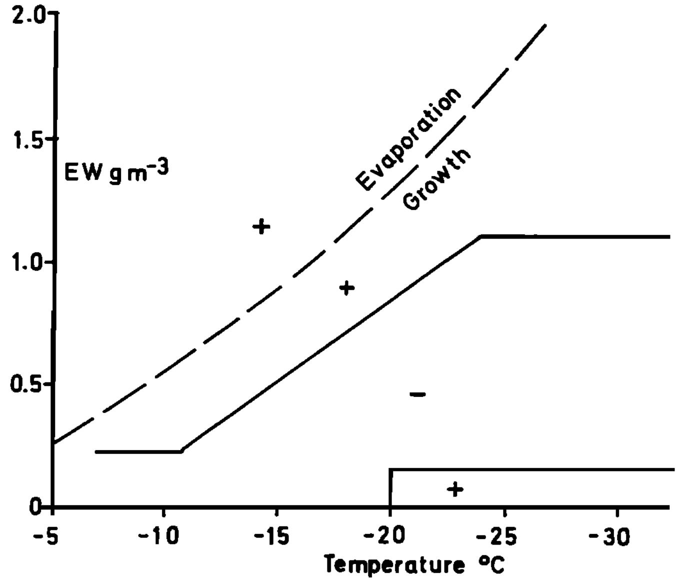

Fig. 9. The influence of effective liquid water content and temperature on graupel charging. Charge sign regimes according to *Saunders et. al.*, [1991]. Evaporation/growth line from *Macklin and Payne* [1967].

rime ice in all their experiments which never showed evidence of wet growth and also by calculations of the heating of their riming target using the equation for a riming cylinder of *Macklin and Payne* [1967]. The equation involves a heat transfer coefficient which is the ratio of the heat released to a cylindrical rod by riming to the heat lost to the environment. For smooth cylinders the numerical factor in the heat transfer coefficient, χ, takes a value of 0.28 which is applicable to a riming cylinder under wet-growth conditions. The maximum effective liquid water content used in those experiments was around 1.3 g m^{-3} with a riming target of 5-mm diameter and typical target speed of 3 m s^{-1}. The Macklin and Payne equation applied to this situation shows that EW needs to be above 2.2 g m^{-3} to obtain wet growth on a target riming at - 5°C; wet growth at 9 m s^{-1} requires 1.4 g m^{-3}; at lower temperatures the required values of EW for wet growth are even higher.

Williams et al. [1991] argue that in their zone 2 the riming target is heated sufficiently by the accreting rime for the surface vapor pressure to be above ambient leading to its evaporation (sublimation) resulting in negative charging. In zone 3 they surmise that the positive charging occurs because the rimer is growing by vapor diffusion. They liken these charging processes to the positive/negative charging of growing/evaporating ice targets during ice crystal interactions in the absence of riming, which are well documented [*Buser and Aufdermauer*, 1977; *Marshall et al.*, 1978; *Gaskell and Illingworth*, 1980; *Jayaratne et al.*, 1983; *Caranti et al.*, 1991]. However, the view of Williams et al. is not consistent with the results obtained under riming conditions. Figure 9 summarizes the graupel charging results of *Saunders et al.* [1991] obtained when ice crystals rebound from a riming target. Of interest here is the continuous, diagonal line representing the transition from negative to positive charging of graupel which occurs with an increase in the effective liquid water content at any particular temperature. On both sides of this line, the experimental conditions lead to the growth by deposition of the graupel target, as confirmed by the heat balance equation of *Macklin and Payne* [1967]. The dashed curve represents the calculated values of effective liquid water content required for transition to conditions of surface evaporation (sublimation). In these calculations, χ = 0.28 for a smooth cylinder was considered inappropriate to the rough, riming cylindrical target used here and so subsidiary experiments were performed to obtain a more suitable value for a dry rimer surface. Measured riming rates on the cylindrical target gave values of the cloud effective liquid water content, while the corresponding rime surface temperature elevation was monitored; substitution into the Macklin and Payne equation showed that χ = 0.48 is commensurate with our experimental conditions. The dashed curve in Figure 9 applies to a 5-mm-diameter riming cylinder, as used in the experiments, at a speed of 3 m s^{-1} which is appropriate to the fall speed at altitude of millimeter-sized lump graupel [*Heymsfield and Kajikawa*, 1987], a size shown by *Gaskell et al.* [1978] to carry substantial charge in thunderstorms.

It is clear from Figure 9 that the laboratory observations show charge sign transitions within the growth regime and so surface evaporation or wet growth cannot account for the observations of charge sign reversal. Furthermore, positive rimer charging has been observed for values of EW above the evaporation/growth line in Figure 9 by *Saunders et al.* [1991], which shows that for riming surfaces the transition from growth to evaporation does not affect the sign of the charge transfer. This observation points to the importance of detailed analysis of heat and vapor fluxes on the riming surface. The *Macklin and Payne* [1967] equation deals with the average conditions on the rimer rather than the local conditions around a droplet freezing on the surface. Even when the surface is, on average, evaporating, there will be surface growth at certain distances around freezing droplets. Interactions of ice crystals with growing regions leads to positive rimer charging which could dominate any negative charging due to collisions with evaporating areas. (In the Manchester experiments, positive charge transfers in riming and growth conditions are 2 orders of magnitude larger than negative charge transfers in conditions of surface evaporation possibly due to the growth rate being higher than the evaporation rate.) This analysis is strengthened by the recent results of *Caranti et al.* [1991], who studied individual particle interactions with an ice target and found charge transfers of both signs. They surmise that the particles are striking areas with differing surface properties.

The graupel-charging process, as detailed by *Saunders et al.* [1991], relies on competition between two charging mechanisms. Possibly at low temperatures a rime contact potential [*Caranti et al.* [1985], leads to negative rime charging, while at higher temperatures rime surface growth, in the presence of liquid water droplets, leads to a temperature gradient along surface structures (Caranti et al. [1991]), which causes ice crystal interactions to charge the surface positive. The transition between the charge sign regimes is dependent on liquid water content and temperature in the manner described by *Saunders et al.* [1991].

Acknowledgment. This work was supported by the Natural Environment Research Council, United Kingdom.

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(Received February 5, 1992;
revised April 28, 1992;
accepted May 13, 1992.)