Atmos. Chem. Phys., 10, 1661–1669, 2010
www.atmos-chem-phys.net/10/1661/2010/

Atmospheric Chemistry and Physics

Measurements of electric charge separated during the formation of rime by the accretion of supercooled droplets

R. A. Lighezzolo, R. G. Pereyra, and E. E. Avila

FaMAF, Universidad Nacional de Córdoba, IFEG-CONICET, Córdoba, Argentina

Received: 3 September 2009 – Published in Atmos. Chem. Phys. Discuss.: 3 November 2009
Revised: 21 January 2010 – Accepted: 5 February 2010 – Published: 15 February 2010

Abstract. In these experiments, the electric charge carried by single particles ejected from the surface of a graupel particle growing by riming was measured. Simulated graupel pellets were grown by accretion of supercooled water drops, at temperatures ranging from −2 to −10 °C in a wind tunnel at air velocities between 5 and 10 m s^{-1}, with the goal of studying the charging of graupel pellets under conditions of secondary ice crystal production (Hallett-Mossop mechanism). The graupel, and induction rings upstream and downstream of the graupel, were connected to electrometers and analyzing circuits of sufficient sensitivity and speed to measure, correlate and display individual charging events. The results suggest that fewer than 1% of the ejected particles carry a measurable electric charge (>2 fC). Further, it was observed that the graupel pellets acquire a positive charge and the average charge of a single splinter ejected is −14 fC. This mechanism of ejection of charged particles seems adequate to account for a positive charge of around 1 pC that individual precipitation particles of *mm*-size could acquire in the lower part of the cloud, which in turn could contribute to the lower positive charge region of thunderstorms.

1 Introduction

Hallett and Mossop (1974) and Mossop and Hallett (1974) observed that ice splinters were ejected during the formation of rime by the accretion of supercooled droplets on a cylinder of diameter 2.4 mm at 3 m s^{-1}, providing that the air temperature is between −3 and −8 °C. In addition, Mossop (1976) showed that the ice splinters are produced only when rime grows in a supercooled cloud containing water droplets with a spectrum that extends beyond 24 µm diameter and Mossop (1978) found a requirement for the presence of both droplets larger than 24 µm and smaller than 13 µm diameter.

The ejection of the splinters is thought to be produced when the supercooled droplets freeze on impact with the accreted rime. Chourlarton et al. (1978, 1980) proposed that under suitable conditions, the freezing droplets form a shell of ice which can shatter under the high stresses involved caused by the effects of expansion upon freezing. The ice surface may break up into fragments, or a spicule of material may be formed through which liquid is ejected that rapidly freezes. Dong and Hallett (1989) proposed another mechanism; they suggested that the thermal gradients experienced by an accreted droplet can result in thermal shock and shattering of ice during freezing. The possible reason for the high temperature cut-off at −3 °C is that at high temperatures, the freezing time is long so the droplet has time to spread on the rimer before freezing and it does not produce a shell so does not fragment. Dong and Hallett (1989) point out that the spreading is particularly effective at temperatures above −3 °C because the liquid like layer on the ice surface is thicker at higher temperatures. While for the low temperature cut-off at −8 °C, Griggs and Choularton (1983) say that at temperatures below −9 °C several ice dendrites cross the liquid droplet from the substrate side to the outside which initiates freezing at several points on the outer surface of the droplet so that the freezing front moves inwards, making the shell very strong, so it does not fragment; Dong and Hallett (1989) suggest smaller and more concentrated air bubbles will be formed at lower temperatures because the solubility of air in water increases at lower temperatures (more air to come out on freezing). The air makes the ice more plastic and so less likely to fracture and Mason (1996) points out that on freezing, the droplet expands (by the same amount

---

Correspondence to: E. E. Avila
(avila@famaf.unc.edu.ar)

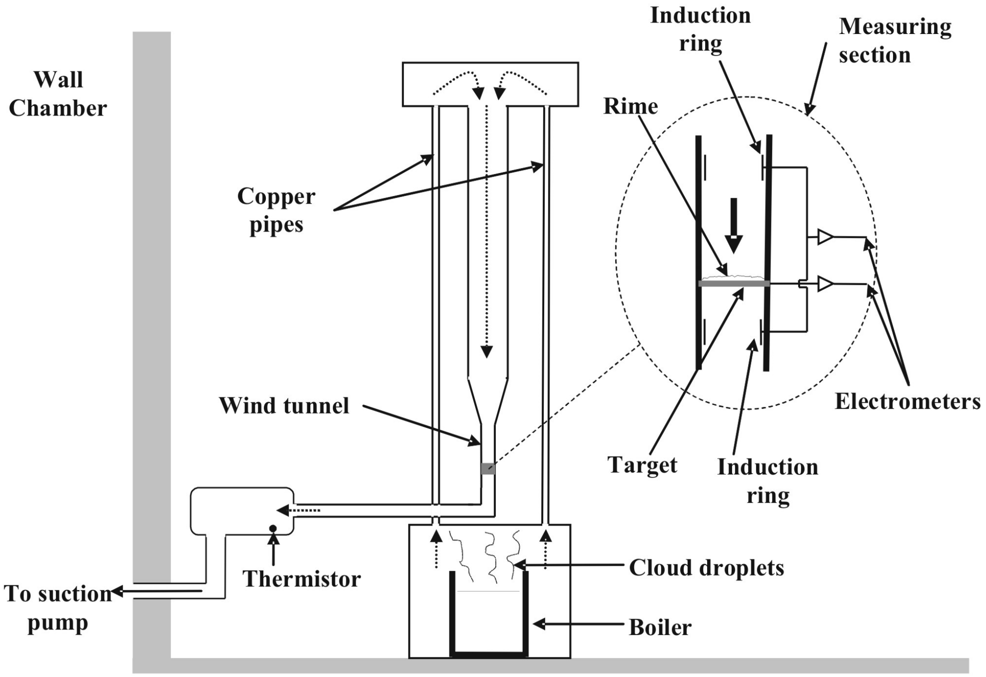

Fig. 1. General layout of the cloud chamber and the associated equipment used in this study.

at all temperatures). He suggests that at low temperatures the shell thickness is greater than the radial expansion so the shell is not ruptured. At temperatures above −8 °C the shell thickness is less than the radial expansion so the expansion causes the shell to rupture.

Regardless of which mechanism is correct, the net effect is to produce a large number of small ice particles that could grow very rapidly by the diffusion of local water vapour and form ice crystals that can in turn accrete smaller droplets thus continuing the multiplication process. Evidence that the Hallett-Mossop (H-M) mechanism is an important source of ice particles in clouds has been reported in field measurements by Hallett et al. (1978) in Florida cumuli and Harris-Hobbs and Cooper (1987) in cumuli in Montana, Florida and California.

Despite the evident importance of the H-M mechanism for secondary ice crystal production in clouds, there is only one work in the literature Hallett and Saunders (1979) that describes studies of the possibility that the ejected ice fragments were electrically charged and that they can contribute to thunderstorm electrification. Hallett and Saunders (1979) determined in an indirect way the electric charge of the ejected fragments by measuring the charging current to a riming rod moving through a cloud of supercooled water droplets under conditions of secondary ice crystal production. The measurements were performed at −4 °C with air velocities between 1 and 3.5 $\mathrm{m\,s^{-1}}$. Saunders (2008) concluded that the magnitude of the charges on the fragments was too small to be able to account for the observed electrification rates in thunderstorms. Hallett and Saunders (1979) observed that in the presence of liquid cloud, the ice crystals grew rapidly and when these larger crystals collided with a riming ice surface, then substantial charges were separated. The results of this study led to subsequent research of graupel charging during ice crystal collisions.

In this study we extend the laboratory experiments performed by Hallett and Saunders (1979) and provide direct measurements of the electric charge carried by single particles ejected from the surface of a simulated graupel growing by riming. The experimental evidence shows that the graupel pellets acquire a positive charge and the average charge of single splinter ejected is -14×10^{-15}C. Further, it was observed that fewer than 1% of the ejected particles carry a measurable electric charge. The results obtained are used to evaluate the contribution that the ejection of charged particles can make to cloud electrification, in particular to the lower positive charge region.

2 Experimental

The experiments were carried out by using an open circuit wind tunnel which was assembled in a cold room of height 2.5 m and floor area $2\times2\ \mathrm{m}^2$. Figure 1 shows the general layout of the apparatus. The experimental devices used in this work are similar to those used by Avila and Pereyra (2000), Pereyra et al. (2000, 2008), Pereyra and Avila (2002), and Bürgesser et al. (2006).

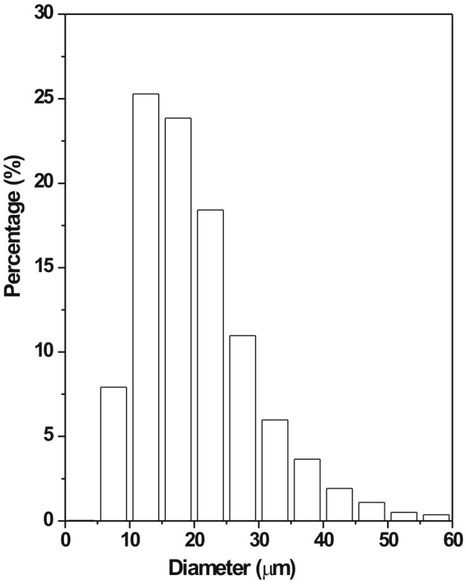

Fig. 2. Cloud droplet size distribution used in the experiments. The mean diameter is 21 µm.

Riming occurs on a fixed brass cylinder of radius 2 mm (target), which is placed in the measuring tube perpendicular to the airflow. The measuring tube is a cylindrical tube of section 33 mm diameter connected to an air pump which controls the velocity of the droplets past the target.

The water droplets used to rime the target were generated by water vapour condensation from a boiler located inside the cold room; the boiler output fed a small cubic cloud chamber of 0.5 m side, whose lower vents allow the mixing of the cloud droplets with cold air. The cloud chamber is connected to the measuring tube through a vertical precooling tower ∼2 m high allowing the cloud of droplets to reach ambient temperature before entering the working section. Figure 2 shows the histogram of the droplet size distribution used in the measurements; the spectrum extends to 60 µm with a mean diameter (dm) 21 µm. The cloud droplet spectra were obtained by taking cloud samples with a glass strip of 4 mm width covered with a thin film of 5% formvar solution. Several cloud samples were taken at the position of the target for different temperatures. It can be observed that 30% of the droplets had diameter larger than 24 µm.

The effective liquid water content (EW) is defined as the portion of the liquid water content (LWC) captured by the target on account of its collision efficiency, then EW depends on the droplet and collector size and their relative velocity. The effective liquid water content was experimentally determined by weighing the deposit of rime collected on the rod target (Δm) during a given time period (Δt) and then using the equation:

$$EW = \frac{\Delta m}{\Delta t\ V\ A} \tag{1}$$

where A is the cross-sectional area of the target, exposed to an air flux of velocity V. The mass of the rime was determined by using a balance with an error of 0.1%.

The air temperature was measured by using a calibrated thermistor placed in the wind tunnel downstream of the target. It was continuously monitored throughout the runs. The rime temperature was raised above the ambient temperature by the release of the latent heat of fusion, this temperature was calculated from EW using the Macklin and Payne (Macklin and Payne , 1967) equation, which considers the balance between the rate at which heat is released by the freezing droplets and is exchanged with the environment by forced convection and sublimation. The effects of the surface roughness on the heat balance equation were considered by using the corrections given by Avila et al. (1999) and Castellano et al. (1999). The speed of the airflow past the target was controlled by adjusting the power to an air pump and was determined by using a Pitot-tube type anemometer with an error of $\pm 0.5\,\mathrm{m\,s^{-1}}$. The air speed was measured in auxiliary experiments and the anemometer probe was inserted into the measuring section about 5 cm below the target.

The electronic system for measuring and evaluating single events of charged particles ejected from the rimer was similar to that used by Avila et al. (2003) and consisted of electrometers connected to the target and induction rings placed upstream and downstream of the target, as shown in Fig. 1. The electrometers are sensitive charge amplifiers capable of detecting electric charges larger than 2 fC (2×10^{-15}C, which gives an output signal of 100 mV) and sufficiently fast to measure, correlate and display individual charging events. Examples of waveforms caused by an event of charge separation by ejection can be seen in Fig. 2 of Avila et al. (2003). The downstream ring was used to identify charged particles originating at the graupel; thus, a genuine event should show equal charges of opposite sign on the two interacting particles, both charges were measured and correlated. The experiment was designed to exclude spurious charging events from analysis; in fact, charged particles entering the apparatus could be excluded from analysis by the signal from the upstream induction ring.

In order to diminish the number of spurious events (typically between 5 and 20 events per run), the measuring section was completely cleaned at the beginning of each run and the cloud chamber and the precooling tower (Fig. 1) were defrosted after 3–4 runs. We did not observe any systematic difference between the first and last experiments.

3 Results and discussions

According to Hallett and Mossop (1974) and Mossop and Hallett (1974) and subsequent work in this area, splinter production takes place at cloud temperatures between −3 °C and −8 °C; for this reason, the range of temperature chosen for the present investigation spans −2 °C to −10 °C to

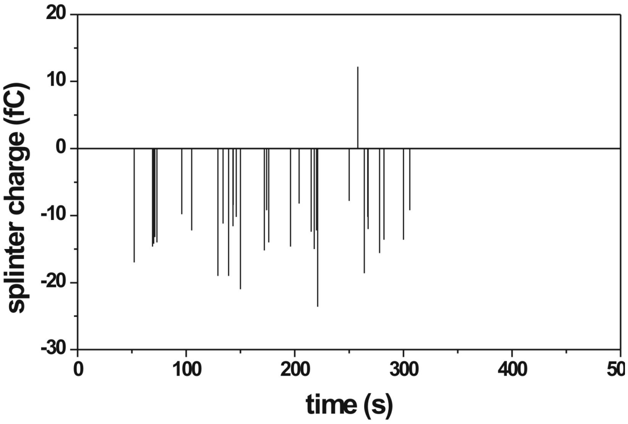

Fig. 3. Production of charged fragments during riming for a cloud temperature of $(-7.6\pm0.2)°C$, $EW=(0,61\pm0.09)\ g\ m^{-3}$ and velocity 6.8 m s^{-1}. Each bar represents the charge of one individual event.

ensure complete coverage of the range of temperature where the Hallett-Mossop mechanism is active. The liquid water content was also varied in a range which is characteristic of the conditions existing within real clouds.

Saunders and Hosseini (2001) conducted laboratory experiments in which simulated graupel pellets were moved on a rotating frame through a cloud of supercooled droplets to become covered in rime ice. Ejected ice fragments were counted after they grew to visible sizes in the cloud. They studied the effect of rimer velocity on the splinter production in the range 1.5–12 m s^{-1}, and found that the maximum secondary ice particle ejection occurs at 6 m s^{-1}. The current experiments were performed at four different velocities around 6 m s^{-1} (5.3, 6.8, 8 and 9.4 m s^{-1}) in order to get the most favorable production of splinters.

Each one of the current experiments lasted 500 s and was started with the target clean of ice. The riming process occurred during the first 300 s and then the cloud droplet supply was cut off while the airflow remained for up to 200 s (non-riming condition). Typically, the charged particles ejected from the target appeared after the first minute of starting the riming process and significant charge separation was observed only under riming conditions. Figure 3 shows the production of charged particles from the graupel as a function of time for a cloud temperature of (-7.6 ± 0.2) °C, $EW = (0.61\pm0.09)$ g m^{-3} and velocity 6.8 m s^{-1}. Each bar represents the charge on an ejected crystal, which was mainly negative, as can be seen from the figure. Some charged particles were ejected few seconds ($<$20 s) after vapor supply was cut off (Fig. 3).

One of the most remarkable results of this study is the low number of charged particles per mg of rime accreted found ($\sim$0.5 particles per mg rime) in comparison to the splinter production by the H-M mechanism as determined by several authors. For instance, the number of splinters produced per mg of rime accreted measured by Saunders and Hosseini (2001) is at least two orders of magnitude larger than the number of charged splinters measured in this work. The most important difference between the present study and the earlier reports is that in the current study the accretion of supercooled droplets was produced on a fixed target, instead of a rotating one as used in previous work. However, there is no reason to assume that this difference in the measurement technique could be the cause of the difference between the results. Likely, most of the ejected particles by the H-M mechanism are too small to carry a detectable electric charge; only a few of them have suitable size to carry a charge on the order of 1 fC. Indeed, Bader et al. (1974) found evidence that sub-micron particles of ice are produced when water droplets freeze on riming, these splinters can be as small as 0.2 µm diameter and they also observed that appreciable numbers of small splinters are produced. It is important to remark that they used a low impact velocity and the water droplets were appreciably larger than those normally encountered in clouds. The maximum charge that a liquid drop of 0.2 µm diameter may hold before disruption is around 0.5 fC as given by the Rayleigh Limit (Rayleigh , 1882); this magnitude of charge cannot be detected by the amplifier used in this study. Therefore, the results seem to indicate that only a small percentage of splinters produced by the H-M mechanism ($\sim$1%) are ejected with electric charge of magnitude above 1 fC.

Table 1 lists the values of the variables used in each run: ambient temperature (T_a), rime temperature (T_r), effective liquid water content (EW), velocity (V), number of charged particles produced in the run (N), total charge (Q) acquired by the graupel per minute and the percentage (%) of the ejected particles with negative charge. By considering all the experiments reported in Table 1, it was observed that the 93% of the ejected charged particles were negatively charged.

The results from Table 1 show that for $T_a > -6$ °C the production of charged particles was substantially lower than that obtained for $T_a < -6$ °C. Secondary ice crystal production by the Hallett- Mossop mechanism has been observed at $T_a > -6$ °C by many authors, which confirms that these particles could be uncharged or with undetectable electric charge.

The ice particle production from freezing droplets is governed by the way in which they are accreted and also by the environmental conditions. As can be seen from Table 1, the number of charged particles produced per run was highly variable, indicating that the ejection of charged particles depends on microscopic processes that cannot be completely described by environmental variables such as T_a, EW and V. From the rime temperatures listed in Table 1, it is possible to discern, using the Macklin and Payne (1967) heat balance equation, that the graupel was in the dry growth regime in all experiments.

The results of all the experiments are illustrated in Fig. 4, where the charging rate of the graupel (Q) is plotted as a function of cloud temperature and the rate of rime accretion,

Table 1. Values of the variables in each run: ambient temperature (T_a), rime temperature (T_r), effective liquid water content (EW), velocity (V), number of charged particles produced in the run (N), total charge (Q) acquired by the graupel per minute and the percentage (%) of the ejected particles with negative charge.

T_a (°C)	T_r (°C)	EW (g m^{-3})	V (m s^{-1})	N	Q (fC min^{-1})	% (−)
−2.0±0.1	−1,2	0.59±0.07	8.0±0.5	0	0	
−2.1±0.2	−1,3	0.60±0.08	6.8±0.5	0	0	
−2.2±0.3	−1,7	0.33±0.04	8.0±0.5	0	0	
−2.4±0.2	−1,8	0.36±0.04	9.4±0.5	0	0	
−3.4±0.5	−2,1	1.03±0.1	6.8±0.5	0	0	
−3.7±0.5	−2,9	0.59±0.1	6.8±0.5	1	26	100
−3.8±0.5	−2,9	0.61±0.1	6.8±0.5	0	0	
−4.0±0.2	−3,5	0.29±0.1	6.8±0.5	0	0	
−4.3±0.3	−2,6	1.3±0.2	6.8±0.5	0	0	
−4.3±0.4	−2,4	1.3±0.2	9.4±0.5	0	0	
−4.4±0.8	−3,2	0.75±0.09	9.4±0.5	1	7	100
−4.6±0.3	−3,5	0.9±0.2	5.3±0.5	0	0	
−4.8±0.8	−3,8	0.63±0.09	8.0±0.5	3	11	100
−4.8±0.9	−4,1	0.43±0.07	5.3±0.5	0	0	
−5.0±0.3	−4,1	0.57±0.08	6.8±0.5	1	7	100
−5.0±0.4	−4,2	0.42±0.05	9.4±0.5	0	0	
−5.1±0.2	−4,6	0.23±0.03	8.0±0.5	0	0	
−5.2±0.8	−4,8	0.17±0.02	6.8±0.5	0	0	
−5.3±0.1	−4,9	0.18±0.03	5.3±0.5	0	0	
−6.0±0.7	−4,5	1.08±0.1	6.8±0.5	6	21	100
−6.2±0.5	−4,9	0.81±0.1	6.8±0.5	7	56	86
−6.2±0.5	−4,9	0.87±0.1	6.8±0.5	4	13	100
−6.3±0.4	−5,2	0.69±0.1	6.8±0.5	20	71	100
−6.7±0.5	−5,7	0.57±0.1	6.8±0.5	5	25	100
−6.9±0.4	−6,2	0.35±0.1	6.8±0.5	5	6	80
−6.9±0.6	−5,1	1.2±0.2	8.0±0.5	1	4	100
−7.1±0.5	−5,6	1.0±0.1	6.8±0.5	1	3	100
−7.1±0.5	−5,8	0.9±0.1	5.3±0.5	0	0	
−7.1±1.2	−5,7	0.8±0.1	9.4±0.5	2	11	100
−7.5±0.3	−6,3	0.7±0.1	8.0±0.5	5	27	100
−7.6±0.2	−6,5	0.61±0.09	6.8±0.5	32	102	97
−7.8±0.2	−6,9	0.55±0.09	5.3±0.5	1	5	100
−7.8±0.5	−6,9	0.40±0.05	8.0±0.5	17	58	100
−7.9±0.3	−7.0	0.41±0.05	9.4±0.5	8	28	88
−8.1±0.1	−7,4	0.28±0.04	6.8±0.5	11	30	100
−8.2±0.1	−7,6	0.23±0.04	5.3±0.5	5	9	80
−8.3±0.4	−6,4	1.3±0.1	6.8±0.5	20	38	70
−8.5±0.4	−7,3	0.7±0.1	6.8±0.5	11	97	91
−8.9±0.3	−8,3	0.24±0.1	6.8±0.5	6	32	84
−9.0±0.9	−7,1	1.2±0.2	8.0±0.5	6	10	67
−9.4±0.4	−7,9	0.9±0.1	6.8±0.5	19	57	85
−9.4±0.9	−8,2	0.62±0.07	9.4±0.5	17	59	88
−9.6±0.3	−8.0	1.1±0.2	5.3±0.5	10	31	100
−9.6±1.4	−8,0	0.9±0.1	8.0±0.5	15	96	100
−9.7±0.2	−8,5	0.64±0.09	6.8±0.5	39	123	95
−9.9±0.2	−9,1	0.40±0.06	5.3±0.5	10	34	100

RAR = $EW \times V$, which represents the mass of rime accreted on the graupel per unit time and unit surface area (Eq. 1). The error bars indicate the range of values which have been averaged in deriving the plotted points. Figure 4a shows, once again, that the charging rate of the graupel was very low at $T_a > -6$ °C; while for temperatures -6 °C $< T_a < -10$ °C the charging rate increases as the temperature decreases. Figure 4b seems to indicate that the range

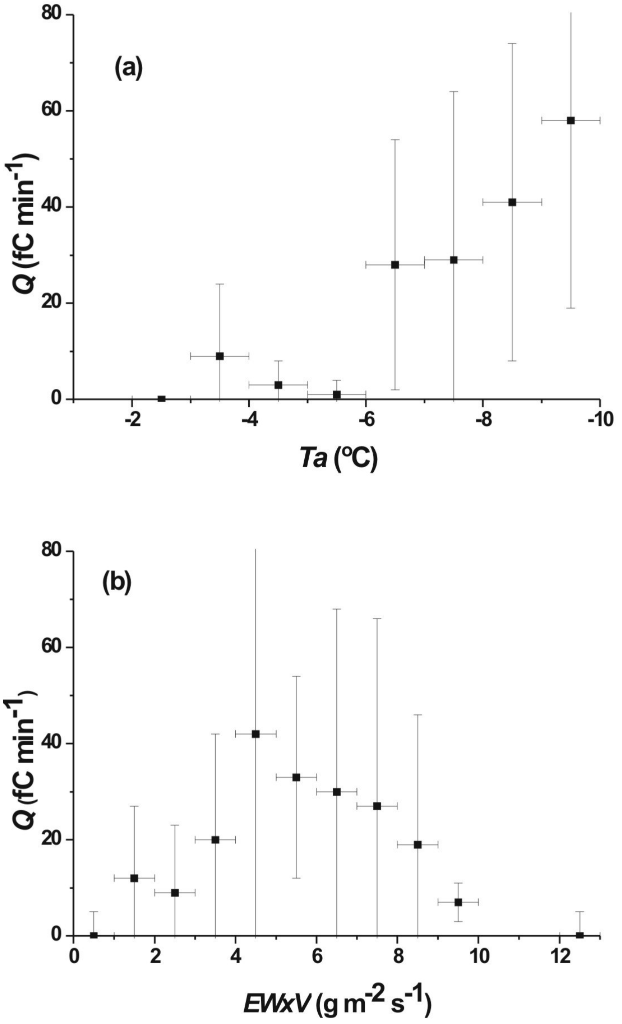

Fig. 4. Plots of the charging rate of the graupel (Q) as a function of cloud temperature and the rate of rime accretion.

$4\,\mathrm{g\,m^{-2}\,s^{-1}} < \mathrm{RAR} < 8\,\mathrm{g\,m^{-2}\,s^{-1}}$ is the most suitable for the production of charged particles during the riming process.

Figure 5 displays the trend of the total charge acquired by the graupel (Q_t) during each run as a function of the number of charged particles produced in the corresponding run (N). Although an important dispersion of the data is shown in the graph, a linear trend is observed between the total charge and the number of ejected particles. If the total charge is directly proportional to the number of particles ejected, then

$$Q_t = q\ N \tag{2}$$

where q represents the average charge separated per event, which can be calculated from the slope of the fitted line in Fig. 5, giving a value of 14 fC. Since all the experimental data were used in this graph, the result suggests that q is roughly independent of T, EW and V. Therefore, the variations of Q with T_a and RAR observed in Fig. 4 are not consequences of the variations in q but the variations in N and the increase in charge in Fig. 4a is simply indicative of an increase in the number of charged particles ejected at lower temperatures and does not imply that multiplication itself increases at lower temperatures. Foster and Hallett (1982) reported a wider range of temperatures for multiplication, between −3 and −11 °C.

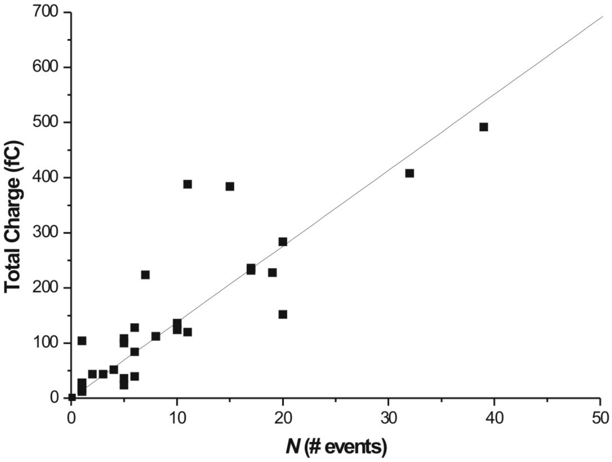

Fig. 5. Plot of the total charge acquired by the graupel (Q_t) as a function of the number of charged particles produced (N). The solid line represents the linear fit of the data.

There are few previous studies which have reported measurements of charge separation for ejection of particles from the surface of graupel growing by accretion of supercooled water droplets. Hallett and Saunders (1979) measured charge separation under conditions of secondary ice crystal production. Although they concluded that this mechanism is unsuitable to explain the observed electrification rates in thunderstorms, they estimated an approximate charge per ice particle ejected of 50 fC. Although, the magnitude of the charge is larger than the average charge per charged splinter obtained in the current work (14 fC), both are of the same order of magnitude. Likely, this charge has been overestimated in their study given that their estimates include various assumptions and inherent uncertainties, including the number of splinters produced by the charging rod and the ice crystal/graupel collisions produced by the secondary ice particles ejected from the experimental device used in the measurements. The advantage of the current work is that the charge of each single ejected particle was measured, thus the number and the charges of the splinters can be accurately determined.

The physical mechanism of multiplication was largely discussed by Chourlarton et al. (1978), Dong and Hallett (1989) and Saunders and Hosseini (2001). The physical mechanism responsible for the electric charge carried by the particles ejected from the graupel growing by riming is still a matter of discussion. Likely, the temperature gradient maintained between a freezing droplet (∼0 °C) and the graupel surface ($\sim T_r$) generates a net electric charge on the freezing droplet due to the different mobilities of H^+ and OH^- in ice (thermoelectric effect – Latham and Mason (1961)) with the colder ice surface becoming positively charged and the warmer freezing droplet negatively charged. Thus, it is possible that charge separation occurs when the freezing droplets fragment and a portion of droplet is ejected from the surface.

Values of the freezing and subsequent cooling times of the water droplets on an ice surface were calculated for various values of the ambient temperature and droplet radius by Macklin and Payne (1967). They estimated that the freezing times of water layers of 20 µm thickness is between 10 and 50 ms for temperatures above −10 °C. On the other hand, theory and experiment show that about 10 ms are required for the process of proton migration by temperature gradients (Latham and Stow , 1967). Both times are of the same order of magnitude; therefore, this mechanism, in principle, could be viable to account for the observed charge separation during the ejection process. However, more accurate estimations of these times are required in order to validate the mechanism.

It is important to note that maybe an important number of fragments ejected from the graupel growing by riming could carry electric charge with magnitude under the detection level. However, it is not possible to quantify this production so far.

Many authors (See review by Saunders (1994)) have observed that, in general, droplets alone colliding with a rimed target do not separate charge. The main difference between the present and previous studies of the H-M process with droplets larger than 24 µm and smaller than 13 µm, is that the electric current acquired by the rimed target was measured; in the present study the charge carried by individual particles ejected from the rimer has been measured. The results indicate that the electric current cannot be detected because there are only sporadic charged particles ejected from the target.

4 Effects on cloud electrification

In order to evaluate the contribution that the ejection of charged particles can make to cloud electrification, we have estimated that the rimed surface of the artificial graupel capable of ejecting charged particle is approximately 132 mm^2. By taking a charging rate of 50 $\mathrm{fC\,min}^{-1}$, then, this mechanism is able to produce approximately a charging rate of 0.4 $\mathrm{fC\,min}^{-1}\,\mathrm{mm}^{-2}$ of graupel surface. Thus, soft hail of 1, 2 and 3 mm radius could be charged with rates of 5, 20, 45 $\mathrm{fC\,min}^{-1}$ respectively; and in 30 min (which is a characteristic time of residence of particles within the clouds) they could acquire charges of 0.15, 0.6 and 1.4 pC, respectively.

Although the values of the charges that soft hail pellets could acquire via this mechanism are relatively small, they are of the same order of magnitude as many of the charges on precipitation particles of mm-size reported in measurements made in real clouds. For instance, Mo et al. (2007) performed aircraft measurements of the electric field, and hydrometeor size and charge in a precipitation shaft beneath the base of a small convective cloud which was electrified. They were able to detect precipitation particles larger than 0.2 mm and charges greater than 0.5 pC and found that 70% of the particles carried charge greater than 0.5 pC, most of the particles carried charge between 0.5 and 10 pC and the maximum charge was 25 pC. They also found that 98% of the charged particles were charged positively.

Williams (1989) proposed that the electrical structure of thunderstorms can be represented as a vertical tripole consisting of three charge regions, an upper positive charge region, a midlevel negative charge region, and a lower positive charge region. The lower positive charge region plays a key role to enhance the electric field at the bottom of the main negative charge region, thus important lightning activity can be induced between negative and positive charge regions located in middle and lower parts of a thunderstorm respectively. Nag and Rakov (2009) suggested that the lower positive charge region could help the discharge of a negatively charged leader propagating downward; also the presence of a large amount of lower positive charge may avoid the occurrence of negative CG discharges.

The mechanism of ejection of charged particles could, in principle, explain the positive charge smaller than 5 pC acquired by individual precipitation particles of mm-size in the lower part of the cloud. By assuming that the undetected charged particles ejected from the graupel (charges <1 fC) are also negatively charged due to the temperature difference between the freezing droplet and the rime surface, they could contribute to the positive charge acquired by the graupel growing by riming. For instance, in the case that every undetected charged fragment carry 0.5 fC, then the charge acquired by the graupel particle could increase by a factor 4.5. However, we cannot quantify more precisely this contribution so far.

In addition, charges larger than around 5 pC found on the precipitation particles could also be acquired by collisions with other ice particles such as ice crystals or other graupel pellets (Takahashi (1978); Saunders at al. (1991, 1999, 2001); Saunders et al. (2006); Avila et al. (1995, 1996, 1998); Pereyra et al. (2000, 2008), etc).

An important observation is that the sign of the charge acquired by the rime was positive in agreement with the sign of the charged precipitation particles found in the lower region of clouds. Bateman et al. (1999) suggested that the charge of the lower positive charge region should be produced almost entirely by precipitation particles. Thus, we can conclude that the current results suggest that the mechanism of ejection of charged particles under conditions of secondary ice crystal production is a viable mechanism to contribute to the formation of the lower positive charge region.

Acknowledgements. This work was supported by Secretaría de Ciencia y Tecnología de la Universidad Nacional de Córdoba, Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET), and Agencia Nacional de Promoción Científica (FONCYT). We want to thank Jose Barcelona and Rodrigo Bürgesser for their technical assistance.

Edited by: S. Buehler

References

Avila, E. E., Aguirre Varela, G. G., and Caranti, G. M.: Temperature dependence of static charging in ice growing by riming, J. Atmos. Sci., 52, 4515–4522, 1995.

Avila, E. E., Aguirre Varela, G. G., and Caranti, G. M.: Charging in ice-ice collisions as a function of the ambient temperature and the larger particle average temperature, J. Geophys. Res., 101, 29609–29614. 1996.

Avila, E. E., Caranti, G. M., Castellano, N. E., and Saunders, C. P. R.: Laboratory studies of the influence of cloud droplet size on charge transfer during crystal-graupel collisions, J. Geophys. Res., 103, 8985–8996, 1998.

Avila, E. E., Castellano, N. E., and Saunders, C. P. R.: Effect of cloud droplet spectra on the average surface temperature of ice accreted on fixed cylindrical collectors, Q. J. R. Meteorol. Soc., 125, 1059–1074, 1999.

Avila, E. E. and Pereyra, R. G.: Charge transfer during crystal graupel collisions for two different cloud droplet size distributions, Geophys. Res. Lett., 27, 3837–3840, 2000.

Avila, E. E., Longo, G. S., and Bürgesser, R. E.: Mechanism for electric charge separation by ejection of charged particles from an ice particle growing by riming, Atmos. Res. 69 99–108, 2003.

Bader, M., Gloster, J., Brownscombe, J. L., and Goldsmith, P.: The production of sub-micron ice fragments by water droplets freezing in free fall or on accretion upon an ice surface, Q. J. Roy. Meteorol. Soc., 100, 420–426, 1974.

Bateman, M. G., Marshall, T. M., Stolzenburg, M., and Rust, W. D.: Precipitation charge and size measurements inside a New Mexico mountain thunderstorm, J. Geophys. Res., 104, 9643–9653, 1999.

Bürgesser, R. E., Pereyra, R. G., and Avila, E. E.: Charge separation in updraft of convective regions of thunderstorm, Geophys. Res. Lett., 33, L03808, doi:10.1029/2005GL023993, 2006.

Castellano, N. E, Avila, E. E., Saunders, C. P. R.: Dependence of the average surface temperature on cloud droplet spectra for rime ice accreted on fixed spherical collectors, J. Geophys. Res. 104, 23399–27406, 1999.

Choularton, T. W., Latham, J., and Mason, B. J.: A possible mechanism of ice splinter production during riming, Nature, 274, 791–792, 1978.

Choularton, T. W., Griggs, D. J., Humood, B. Y., and Latham, J.: Laboratory studies of riming and its relation to ice splinter production, Q. J. Roy. Meteorol. Soc. 106, 367–373, 1980.

Dong, Y. Y. and Hallett, J.: Droplet accretion during rime growth and the formation of secondary ice crystals, Q. J. Roy. Meteorol. Soc., 115, 127–142, 1989.

Foster, T. and Hallett, J.: A laboratory investigation of the influence of liquid water content on the temperature dependence of secondary ice crystal production during soft hail growth, Am. Met. Soc. Cloud Physics Conference, Chicago, 123–126, 1982.

Griggs, D. J. and Choularton, T. W.: Freezing modes of riming droplets with application to ice splinter production, Q. J. Roy. Meteorol. Soc. 109, 243–253, 1983.

Harris-Hobbs, R. L. and Cooper, W. A.: Field evidence supporting quantitative predictions of secondary ice production rates, J. Atmos. Sci., 44, 1071–1082, 1987.

Hallett, J. and Mossop, S. C.: The production of secondary ice particles during the riming process, Nature, 249, 26–28, 1974.

Hallett, J., Sax, R. I., Lamb, D., Ramachandra Murty, A. S.: Aircraft measurements of ice in Florida cumuli, Q. J. Roy. Meteorol. Soc. 104, 631–651, 1978.

Hallett, J. and Saunders, C. P. R.: Charge separation associated with secondary ice crystal production, J. Atmos. Sci. 36, 2230–2235, 1979.

Latham, J. and Mason, B. J.: Generation of electric charge associated with the formation of soft hail in thunderclouds, Proc. R. Soc., A 260, 537–549, 1961.

Latham, J. and Stow, C. D.: The distribution of charge within ice specimens subjected to linear and non-linear temperature gradients, Q. J. Roy. Meteorol. Soc., 93, 121–125, 1967.

Macklin, W. C. and Payne G. S.: A theoretical investigations of the ice accretion process, Q. J. R. Meteorol. Soc., 93, 195–214, doi:10.1002/qj.49709339606, 1967.

Mason, B. J.: The rapid glaciation of slightly supercooled cumulus clouds. Q. J. Roy. Meteorol. Soc. 122, 357–365, 1996.

Mo, Q., Detwiler, A. G., Helsdon, J. H., Winn, W. P., Aulich, G., and Murray, W. C.: Hydrometeor charges observed below an electrified cloud using a new instrument, J. Geophys. Res., 112, D13207, doi:10.1029/2006JD007809, 2007.

Mossop, S. C. and Hallett, J.: Ice crystal concentration in cumulus clouds: Influence of the drop spectrum, Science 186, 632–633, 1974.

Mossop, S. C.: Production of secondary ice particles during the growth of graupel by riming, Q. J. Roy. Meteorol. Soc. 102, 45–57, 1976.

Mossop, S. C.: The influence of drop size distribution on the production of secondary ice particles during graupel growth, Q. J. Roy. Meteorol. Soc. 104, 323-330, 1978.

Nag, A. and Rakov, V. A.: Some inferences on the role of lower positive charge region in facilitating different types of lightning, Geophys. Res. Lett., 36, L05815, doi:10.1029/2008GL036783, 2009.

Pereyra, R. G., Avila, E. E., Castellano, N. E., and Saunders, C. P. R.: A laboratory study of graupel charging, J. Geophys. Res 105, 20803–20813, 2000.

Pereyra, R. G. and Avila, E. E.: Charge transfer measurements during single ice crystal collisions with a target growing by riming. J. Geophys. Res., 107(D23), 4735, doi:10.1029/2001JD001279, 2002.

Pereyra, R. G., Bürgesser, R. E. and Avila, E. E.: Charge separation in thunderstorm conditions, J. Geophys. Res., 113, D17203, doi:10.1029/2007JD009720, 2008.

Rayleigh, L.: On the equilibrium of liquid conducting masses charged with electricity, Phil. Mag. 14, 184–186, 1882.

Saunders, C. P. R., Keith, W. D., and Mitzeva, R. P.: The effect of liquid water on thunderstorm charging, J. Geophys. Res. 96, 11007–11017, 1991.

Saunders, C.P.R.: Thunderstorm electrification laboratory experiments and charging mechanisms. J. Geophys. Res., 99, D5, doi:10.1029/93JD01624, 1994.

Saunders, C. P. R., Avila, E. E., Peck, S. L., Castellano, N. E., and Aguirre Varela, G. G.: A laboratory study of the effects of rime ice accretion and heating on charge transfer during ice crystalr-graupel collisions, Atmos. Res. 51, 99–117, 1999.

Saunders, C. P. R., Peck, S. L., Aguirre Varela, G. G., Avila, E. E., and Castellano, N. E.: A laboratory study of the influence of the water vapour and mixing on the charge transfer process during collisions between ice crystals and graupel, Atmos. Res., 58, 187–203, 2001.

Saunders, C. P. R. and Hosseini, A. S.: A laboratory study of the effect of velocity on Hallett-Mossop ice crystal multiplication, Atmos. Res., 59–60, 3–14, 2001.

Saunders, C. P. R., Bax-Norman, H., Avila, E. E., and Castellano, N. E.: A laboratory study of the influence of ice crystal growth conditions on subsequent charge transfer in thunderstorm electrification, Q. J. Roy. Meteorol. Soc., 130/B, 1395–1406, 2004.

Saunders, C. P. R., Bax-Norman, H., Emersic, C., Avila, E. E. and Castellano, N. E.: Laboratory studies of the effect of cloud conditions on graupel/crystal charge transfer in thunderstorm electrification, Q. J. Roy. Meteorol. Soc., 132/B, 2655–2676, 2006.

Saunders, C. P. R.: Charge separation mechanisms in clouds, Space Sci. Rev., 137, 335?353, 2008.

Takahashi, T.: Riming electrification as a charge generation mechanism in thunderstorms, J. Atmos. Sci. 35, 1536–1548, 1978.

Williams, E. R.: The tripole structure of thunderstorms, J. Geophys. Res., 94, 13151–13167, 1989.