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Droplet charging by high voltage discharges and its influence on precipitation enhancement

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ABSTRACT

Laboratory experiments were performed to determine the effect of electrical charges transferred on droplets by electrical discharges on their growth by collision and coalescence. A twin cloud chamber was built inside a large cold room and was filled with cloudy air. One chamber was used as the control chamber and, therefore, was left unperturbed. On the other hand, in an experimental chamber, electrical discharges were produced. Droplets grow during a free fall of 1 m, and the droplet spectrum was sampled by microscope slides covered in Formvar. The experimental arrangement could also measure charge on individual drops between 325 and 415 μm in diameter by using small induction rings.

After comparing the spectra from both chambers, a shift towards larger sizes was observed in the cloud that sustained electrical discharge. Also, by measuring the charge on the droplets, it could be observed that the electrical discharge transferred charges of both signs. Discussions about the relevance for cloud seeding and fog elimination are carried out.

1. Introduction

A gush of rain in thunderstorm has often been observed shortly after a nearby lightning stroke (Schonland, 1950; Moore et al., 1962, 1964; Szymanski et al., 1980; Piepgrass et al., 1982). Several mechanisms have been proposed to explain how lightning can trigger precipitation.

One of the early theories was put forward by Schonland (1950) where charged hydrometeors are levitated by cloud's electrical field. When an electrical discharge occurs, the field is reduced and the particles start to accelerate downwards. A numerical model that couples the growth of the particles in a cloud with electrical development was used by Ziv and Levin (1974) to explain the rain gush. They demonstrated that electrical forces in clouds decrease the fall velocities of hydrometeors and inhibit particle interaction, thus when a lightning strike occurs, a rain gush takes place. However Vonnegut (1975), Kamra (1975) and Colgate (1975) suggested that Ziv and Levin's (1974) hypothesis was not completely correct. Next, Jayaratne and Saunders (1984) suggest a different view, precipitation initiates lightning and not vice versa.

Another theory proposed to explain this phenomenon was suggested by Goyer (1965a,b) where radial wind produced by acoustic waves (explosions or lightnings) result in an increase on the rate of coalescence of water droplets, triggering precipitation. Vuković and Ćurić (1998) analyzed the influence of the acoustic waves on rain gushes using a one dimensional numerical model. Their results suggest that the acoustic wave generated by a lightning can shift the mean volume radius of the spectrum from 10 to 25%. According to the authors that increase of the droplet size could be important for further gravitational driven coalescence. This result agrees with the observations by Goyer (1965a,b) carried out in the Old Faithfull Geyser, where gushes of rain were formed after detonating explosive cords near the Geyser plume.

Moore et al. (1964) proposed an interesting rain gush explanation. They suggest that a ground flash leaves a tree-like pattern of electric charge opposite in sign to the original one within the cloud. After this interaction, droplets get charged

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with different signs within the cloud, and by electrical forces they attract each other and coalesce. After becoming neutralized, these droplets have a greater mass and continue growing by collisions and coalescence while falling through the cloud. The interaction of droplets and streamers has been documented by Oladiran (1981, 1982), Phelps and Vonnegut (1970) and Phelps (1972). These results show that the droplet can have a direct interaction with the streamers where the latter can be completely absorbed, re-emitted, or interact indirectly. This direct interaction between streamers and droplets is not considered by Moore et al. (1964) hypothesis. Laboratory measurements of charge acquired by droplets when they interact with positive corona streamers were carried out by Barker et al. (1983). But the experimental setup in this work could only measure positive charged droplet, thus, it neglected any droplets charged with negative charge.

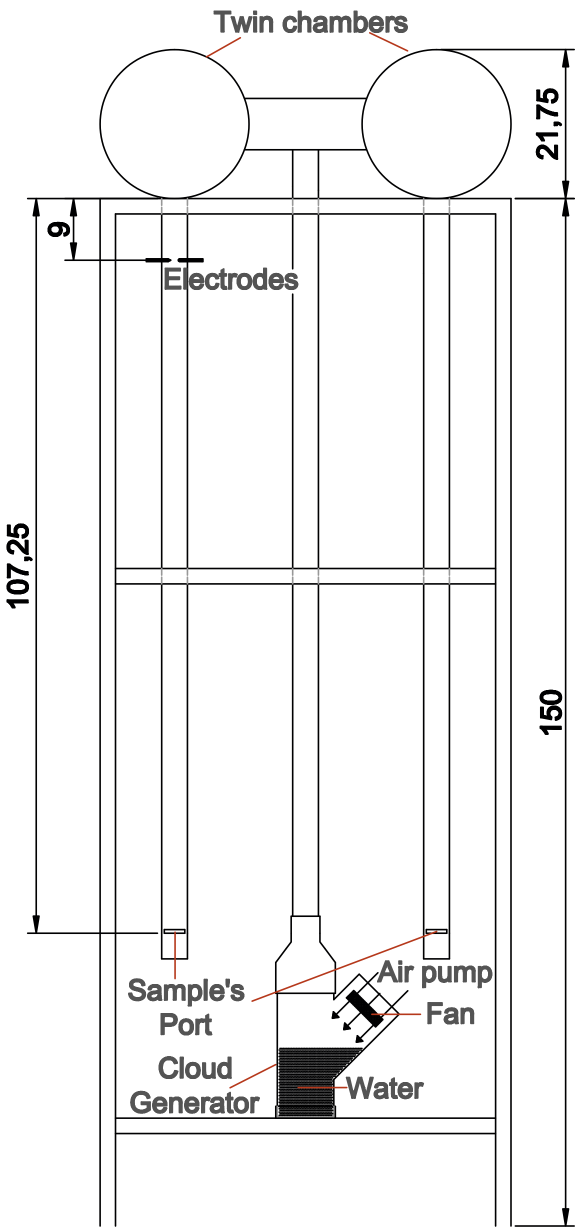


Fig. 1. Experimental setup.

In order to test the importance of Moore et al. (1964) theory, a twin cloud chamber was built inside a large cold room to measure the influence of electrical discharges in droplets growth. One chamber was used as the control chamber and, therefore, was left unperturbed. On the other hand, in an experimental chamber, electrical discharges were produced. A comparison between the spectra of both chambers shows that electrical discharges shift the spectrum towards larger sizes. In addition, charge measurements on individual drops show that electrical discharges transferred charge of both polarities to the drops. The results obtained support Moore et al.'s (1964) theory.

2. Experimental setups

2.1. Cloud droplet spectrum measurements

Fig. 1 shows the twin chamber setup which was mounted in a walk-in cold room of 2.6 m long, 1.6 m wide and 2.3 m high. This room can reach a minimum temperature of −25 °C and maintain a desired temperature within a range of ±1 °C. The experimental setup consists in two cylindrical chambers with 29 cm in diameter and 50 cm depth. They are connected with a cylindrical pipe of 10 cm in diameter. Through this connecting pipe, the chambers were simultaneously filled with cloud produced by the cloud generator at the bottom.

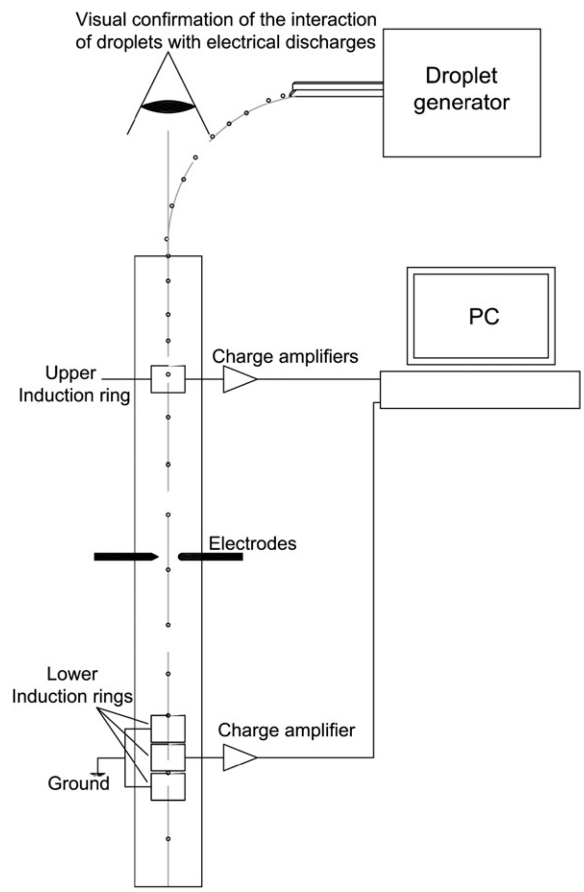


Fig. 2. Charge transfer measurement setup.

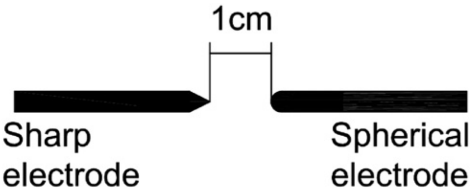


Fig. 3. Electrodes geometry.

Therefore, both chambers received cloud of the same characteristics. The cloud generator produces cloud by heating water and, with a soft air flow, the cloud was pumped in the chamber after thermalizing.

A vertical cylindrical pipe of 5 cm in diameter and 1 m long is connected with each chamber as shown in Fig. 1. These pipes allow the study of the droplet growth by collision and coalesce as they fall at terminal velocity. Samples of the droplets spectrum were taken through an opening in the pipes using microscope slides covered with a solution of 1% of Formvar® (polyvinyl formal) and 99% of 1,2-dichloroethane (ethylene dichloride).

The pipe on the left has two insulated electrodes (Fig. 3) where impulsive electrical discharges of both signs can be produced. Conversely, if a longer exposure to electrification is needed, a corona discharge can also be generated.

The high voltage generator has two leads with −7.5 kV and 7.5 kV (pulsed voltage used in electrical discharges) and one lead of 15 kV (continuous voltage used only for corona discharges). The electrode geometry (Fig. 3), allows the production of electrical discharges of both negative and positive polarities. For example, if the positive output is connected to the sharp electrode and the negative one to the spherical electrode, a 15 kV positive discharge takes place. The inverse connection gives a negative discharge. Although the threshold electric field for positive streamers is half of negative ones, the electric field near the sharp electrode is several times larger than the field in the spherical one. Therefore the electric discharge starts from the sharp electrode, regardless of the polarity of the applied voltage. This feature was chosen because the electrical discharges in nature can be either positive or negative and their behavior is different (Williams, 2006).

To measure the influence of an electrical discharge on the droplet size distribution (DSD) of a cloud, both cloud chambers and pipes were fully filled. Then the desired type of electrical discharges were produced. After some time, slides covered with Formvar® were inserted on the opening mentioned above, and to ensure that the smaller droplets enter in the Formvar® solution a faster flow (~1 m/s)) of about 2 s long were produced by means of the fan of the cloud generator (see Fig. 1).

Afterwards, the liquid water content (LWC) was measured by sucking a known volume V of cloudy air through a filter where the liquid droplets were caught. The filter was weighed before and after the aspiration was performed. LWC was determined by means of the water weight and volume aspired. It was noticed that the filter mass also varied, probably by capturing aerosol particles or vapor condensation which put a limit of ($\pm$0.3 g/m^3) to the accuracy of the measurement.

2.2. Charge transfer measurements

Fig. 2 shows the setup used to quantify the amount of charge transferred to the drops by electrical discharges. The drops were produced by droplet generator with electronic control of production rate (Abbott and Cannon, 1972).

To measure the charge transfer by an electrical discharge into a drop, two induction rings were placed after and before the electrodes as shown in Fig. 2. The drop generator was placed so that the trajectory of the drops goes through the induction rings and the electrode area.

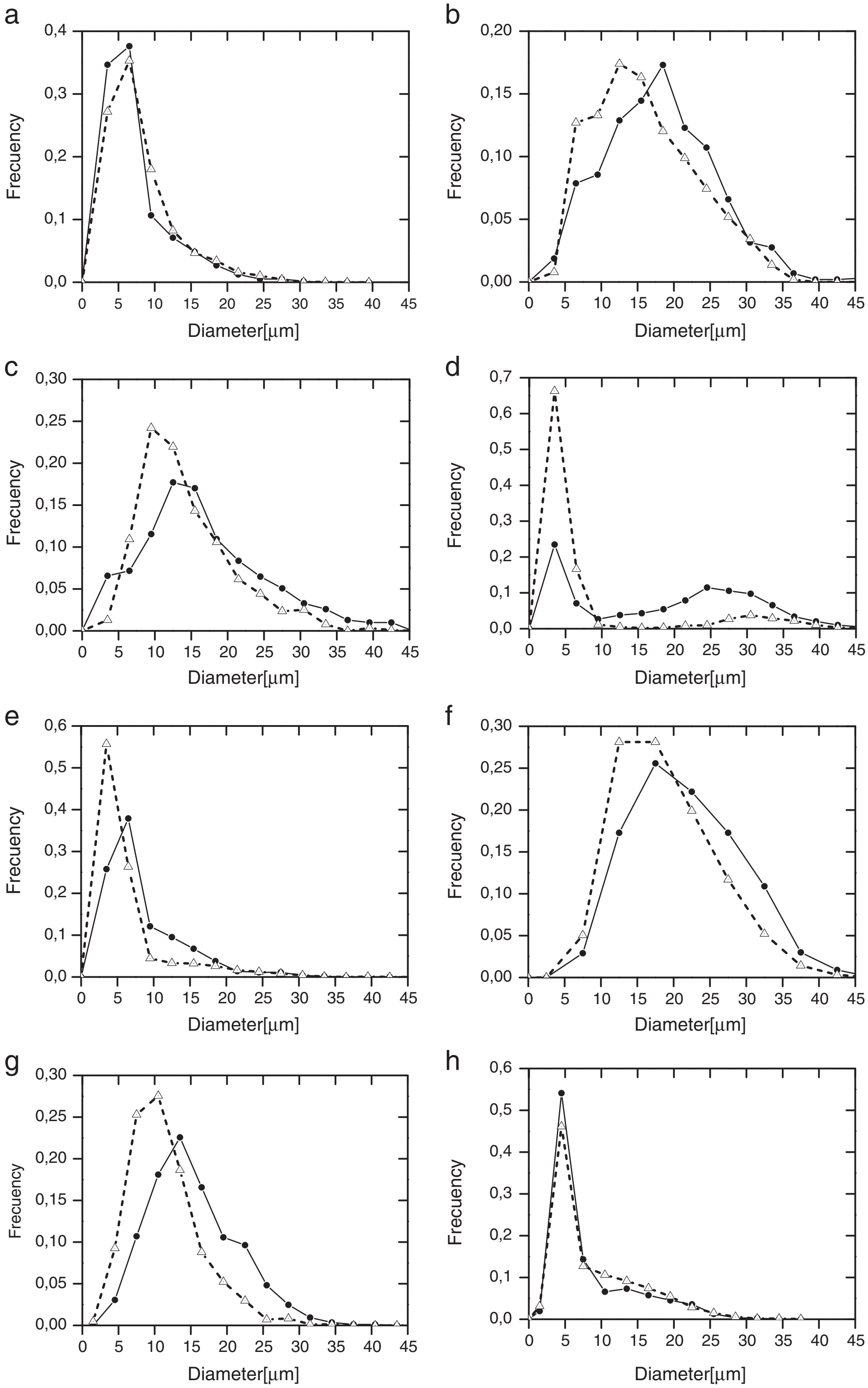
The rings were connected to charge amplifiers with a maximum noise of 2 fC. Both were inside a copper tube of similar diameter connected to electrical ground to reduce the ambient electrical noise. The dimension of the lower ring are 2 cm high and 2 cm in diameter, and 3 cm in diameter and 2 cm long of upper ring. The aspect ratio (height/width) of the lower ring ensures that if a charged particle goes through it, an opposite charge is induced with a slightly smaller magnitude. In the case of the upper ring the aspect ratio used was smaller, because the bigger diameter used which allowed us to see the situation in the electrode area in good detail.

The system induction ring-amplifier was calibrated by forming a capacitor with a rod centered and connected to a known voltage. Since the capacitance of this cylindrical capacitor can be calculated, and the applied voltage was known the charge induced in the ring was obtained. The better aspect ratio of the lower ring gives a more precise measurements of the charge in the drops, therefore, it was used as reference for the upper ring (see below).

To measure the charge transferred by an electrical discharge to a drop, its trajectory was followed visually and the discharge

Table 1
Characteristics of the measurements done. N denotes the number of experiment. The error of the LWC is $\pm$0.3 g/m^3. The temperature of the cloud chambers T has an error of $\pm$1 °C. P denotes perturbed chamber and U the unperturbed one. $\bar{r}$ and σ are the mean diameter and the standard deviation of the DSD. ts is the time after the discharge when the DSD was sampled.

					$\bar{r}$ [μm]		σ [μm]		Droplets measured	
N	Type of discharge	ts [s]	LWC [gr/m^3]	T [°C]	P	U	P	U	P	U
1	No discharge	–	0.7	7	7.5	8.2	4.4	4.6	1933	2016
2	Positive	31	1	8	18.1	16	7.5	6.9	1017	1023
3	Positive	15	0.7	7	16.6	14.3	8.3	6.3	1005	1152
4	Positive	24	0.7	8	19	8.6	11.7	10.1	976	1039
5	Negative	20	0.8	7	8.6	6.8	5.3	5.2	1082	964
6	Corona	55	–	–	21.6	18.9	7.3	6.7	851	842
7	Corona	50	–	8	15.3	11.4	6	4.8	1001	633
8	Negative	12	0.7	7	8.3	5.8	9	6.1	1920	2052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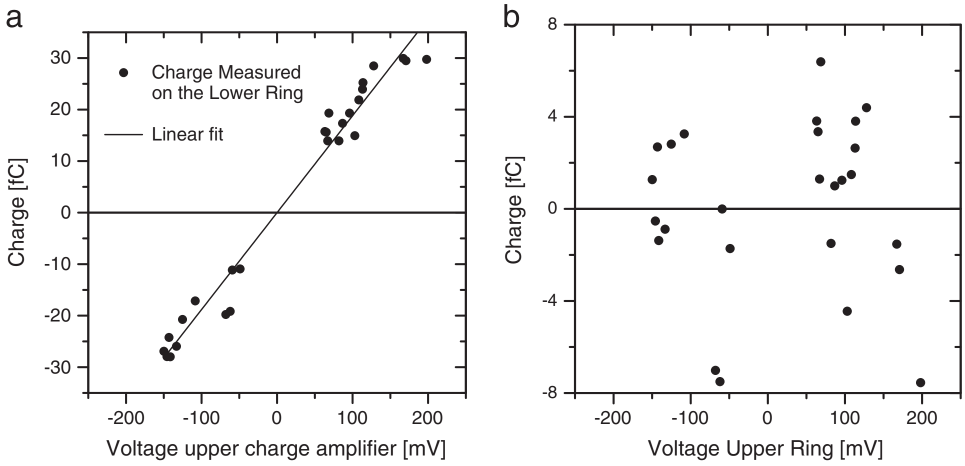

Fig. 5. (a) Voltage measured in the upper charge amplifier vs. charge measured on the lower ring. The line represents the linear fit of the data. (b) Residues of the linear fit of (a).

was triggered manually as it approached the electrode area. Since the initial charge on the droplets was measured by the upper induction ring and the final charge by the lower induction ring, the charge transferred can be obtained. Terminal velocity was determined from the time difference between charge pulses measured by both rings. In turn, the diameter of the droplet was deduced from the terminal velocity.

3. Results

3.1. Influence of electrical discharges on droplets growth

One measurement was made without electrical discharges in the left chamber in order to test that there were no significant differences in the DSD between the chambers.

Two types of measurements were carried out, one with corona and another with electrical discharges. In the measurements with corona, the 15 kV continuous output of the high voltage generator was connected to the sharp electrode and the experimental setup to electrical ground. The spherical electrode was removed in these measurements. On the other hand, the experiments with impulse discharges used bursts of 3 spaced by 0.25 s. The duration of the discharges, with the electrical connection was described earlier, were a few μs) each. Table 1 shows the characteristics of the measurements made.

The Fig. 4 shows DSD of all the experimental runs. Fig. 4a shows the results of DSD of experiment No 1 where no discharge was applied. No significant differences between DSD of both chambers were found. Instead, in all the other measurements where electrical discharges were applied, the perturbed chamber shows a shift of DSD towards larger sizes with respect to the control one.

In cases No 2, No 3 and No 4 (Fig. 4 b, c, d) positive discharges were applied and DSD were sampled at 15, 24 and 20 s respectively. Cases No and No3 show an increase of the percent of droplets with sizes bigger than 17 μm in diameter. Case No 4, in contrast, where both chambers have a bimodal DSD. An increase of droplets of sizes bigger than 10 μm is shown.

Negative discharges were applied in No 5 and No 8 measurement. Samples were took at 20 and 12 s (Fig. 4e and h). In the first of these experiments an increase of the number of droplets bigger than7 μm is seen. While in the other no shift in the spectrum was observed. A reason why this was observed could be that sampling time was very small, and droplets in the electrode area did not reach the sampling port.

With positive corona discharges applied for 15 to 55 s on case No 6 and No 7 during 15 and 55 s (Fig. 4f and g respectively), a displacement towards bigger sizes of DSD of the perturbed chamber respect the unperturbed one also takes place.

3.2. Interaction of droplets with electrical discharges

Using the set up shown in Fig. 2 the charge captured by a drop could be quantified. First a "calibration" of the upper ring-amplifier system was done by producing several drops with random initial charge and reading the output of the amplifiers as they went measuring the charge on them as they went through the induction rings. As the lower ring was previously calibrated, a curve (output voltage vs. charge) for the upper ring was obtained by a linear fit as shown in Fig. 5a. The correlation coefficient was 0.97 and the ranges of residuals is −7.5 to 6.4 fC (Fig. 5b).

As mentioned above the discharges were produced after the drops went through the first ring, in order to measure the initial charge on it. After the drops passed the electrode area, their final charge was measured. The drops diameter used ranged from 325 to 415 μm. The initial charge of the drops was between −128 and 164 fC and the minimum magnitude 23 fC. 32 events were measured. A histogram of charge transfer measurement is shown in Fig. 6a. The gray area denotes the range of the residuals

Fig. 4. Normalized droplets size distributions measured under different types of discharges. Experiments No 1 to 6 corresponding to figures (a) to (f) respectively. In (f) LWC measurements were not carried out. Perturbed chamber is shown with lines and the unperturbed one with dots. Histogram step 3 μm for (a) to (e) 5 μm (f).Normalized droplets size distributions measured under different types of discharges. Experiments No 7 and 8 corresponding to figures (g) and (h) respectively. In (g) LWC measurements were not carried out. Perturbed chamber is shown with lines and the unperturbed one with dots. Histogram step 5 μm for (h) and 3 μm (i).

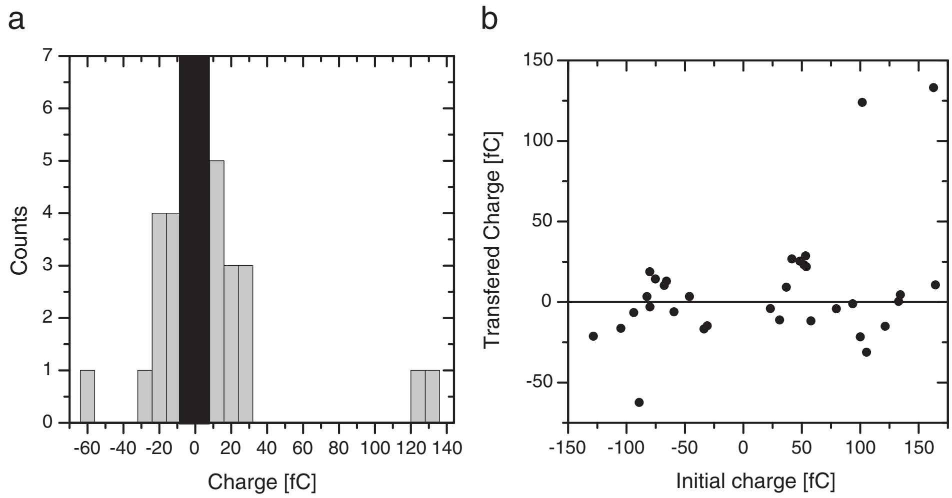

Fig. 6. a) Histogram of charge transferred to drops by positive electrical discharges. The black area denotes the range of the residues of the linear fit of the upper ring's calibration. The histogram step size is 8 fC. b) Plot of initial charge of the drops vs. the charge transferred by the electrical discharge.

of the calibration. Charges outside that range can be regarded as transferred by the electrical discharges, and not to measurement errors. The charges transferred were between −62 and 133 fC. As Fig. 6b shows, the charge transferred to the droplet has no dependence on the initial charge of the drops.

4. Discussions and conclusions

The natural process of collision between cloud droplets starts when DSD has a significant concentration of droplets bigger than 50 µm in diameter. Since the collision and coalesce growth mechanism is not efficient at smaller radii and the diffusion droplet growth is low, the times needed to have droplets big enough to trigger precipitation can be too long. Therefore, these droplets continue to grow by condensation and can reach higher altitudes and lower temperatures where they freeze and spread over a large area, having no significant contribution to the precipitation.

The charge in the cloud is dispersed over a large volume (Tao et al., 2009; Zhang et al., 2009; Hou et al., 2009; Rust et al., 2005). To neutralize charge, a lightning must tap this charge by tree like branching, interacting with many droplets that results charged with positive or negative sign. Since the precipitation drop concentrations are of the order of a few per liter, charging a small percent of the cloud droplets could be enough to enhance precipitation. This idea was tested in a numerical model by Khain et al. (2004). In their model by charging a small percentage of droplets in a non precipitating cloud they found precipitation initiation.

Khain et al. (2004) proposed a new method for rain enhancement and fog elimination, according to which either some fraction of droplets in the cloud get charged or charged droplets are injected by means of a droplet generator. Using numerical simulations they found that charging droplets with one sign only is more efficient for rain enhancement, while charging droplets with both signs is preferably for fog elimination. Our laboratory measurements agree with these simulations.

Our results together with the early observations of the rain gush phenomenon suggest that thunderstorm electrification could play an important role in the development of precipitation, especially in view of the short times needed to observe a noticeable effect on the droplets growth. This is consistent with the observations by Moore et al. (1962, 1964) and Szymanski et al. (1980) that a lightning discharge is followed by a radar echo intensification.

This work shows that the charge transferred to individual droplets by electrical discharges can be of both polarities, which suggests a modification to Moore et al. (1964) hypothesis. Besides interacting with a charged cloud, the lightning can interact with a neutral cloud as well. Faster collisions of droplets can be achieved between the opposite charged ones.

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