Determination of Lightning Origins in a Thunderstorm Model

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Abstract

The origins of lightning are determined through a thunderstorm electricity model (Takahashi, 1984) with inclusion of a discharge process.

Lightning origins are found to vary greatly with microphysical parameters. The calculations successfully simulate the following: the initial appearance of lightning at the cloud top followed by low level lightning; two layers of origin in maritime thunderstorm lightning as opposed to only one layer of origin in continental thunderstorms; the maintenance of a negative charge source at -10°C; and shallow level lightning due to interactions between the main cloud cell and the induced second cloud cell in maritime thunderstorms.

1. Introduction

Thunderstorm electrification is one of the most exciting research topics in the atmospheric sciences. However, the involvement of several different fields (electric discharge of gases, dynamics, cloud physics, and solid physics) makes the research difficult and often provides contradictory conclusions, especially with regard to electric charge separation processes. Fortunately recent advances in computer models have helped to combine results from these different fields and allow selection of practical theories when combined with observational data.

Takahashi (1984, hereafter called paper T) uses an axisymmetric cloud model with detailed microphysics. With riming electrification as the dominant mode of charge separation, this earlier model succeeds in the simulation of many observations including the modes of electrical activity during the thunderstorm life cycle and electric space charge distribution with height. The 1984 model proposes space charge separations at two locations, one near the cloud top created by the gravitational separation of graupel and snow crystals, and the second at around -10°C. This second area of charge separation results in a large negative space charge at this same level. The critical factor in explaining this charge accumulation is the reversal of graupel and snow crystal charges at around -10°C during riming electrification. This phenomenon has been studied recently by Saunders and Jayaratne (1986) whose findings confirm those of Takahashi (1978b).

During riming electrification, falling graupel acquires a negative charge above the -10°C level (Takahashi, 1978b) while rising snow crystals acquire a negative charge below this same level. The negative charges of the rising snow crystals and the falling graupel and to each other resulting in the observed strong negative charge accumulation. We call this process, “dynamic charge separation”. In addition, the model shows “dynamic charge separation” to be more powerful than “gravitational separation” in producing charge accumulation.

The 1984 model further shows the magnitude of the space charge to greatly depend upon cloud physical parameters, especially the number concentrations of cloud nuclei and ice nuclei. Using aircraft in the field, Dye et al. (1986) demonstrated that electrical activity in Montana clouds is in fact very dependent upon ice crystal concentration, especially graupel.

Origins of lightning discharge have been deter-
mined either by the use of arrival time differences of thunder of VHF at different ground locations or with multi-electric field measurements at the ground. Although the origins of lightning discharge range widely from the $-4^\circ$C to $-30^\circ$C levels (Jacobson and Krider, 1976; Proctor, 1981; and others), there is some tendency for cloud-to-cloud lightning to occur first near the cloud top, with cloud-to-ground lightning following from lower levels (MacGorman et al., 1986). Lightning in a typical Florida thunderstorm has two layers of origin at $-30^\circ$C and $-10^\circ$C, while an average Colorado thunderstorm has only one layer (MacGorman et al., 1981). Most lightning originates at around $-11^\circ$C in New Mexico thunderstorms (Krehbiel et al., 1979).

In the present study, a charge neutralization process during lightning discharge is included in the model discussed in Paper T. The results are compared with observations, and physical interpretations are proposed that determine lightning origins.

2. Model construction

a. Basic assumptions

It was assumed that discharge occurs when the maximum electric field in space is higher than the critical value, 3400 V cm$^{-1}$, which was the maximum electric field observed just before lightning struck the aircraft used to make the observation (Gunn, 1948). The discharge amount was set at 20 Coulombs which is the typical value in a New Mexico thunderstorm (Workman et al., 1942). In the model, space charges in each of the nearest grid points (ring shaped except at the cloud center because the model is axisymmetric) are calculated around both the positive and negative maximum space charge centers. The smallest region where the accumulated space charge is just over 20 Coulombs is selected and space charges are neutralized by 20 Coulombs in equal rates among charged particles only in this selected volume. Around a positive (or negative) maximum space charge region, only positive (or negative) space charges are used to calculate the potentially discharged total space charge.

Rimming electrification is included as the main charge separation process for reasons discussed in Paper T. As was done previously, it is assumed that charge separation processes that are practically effective only in the near-discharge field do not change the fundamental electrical profiles calculated without them.

b. Model setup

The model setup is similar to that in paper T. Briefly, the model includes riming electrification, ion-related charge separation processes, and point discharge from the ground. The riming electrification process includes a dependence on snow crystal size for electrification (see Appendix). The ion-related processes include ion diffusion, interaction with aerosol particles, and field-driven ion capture processes.

Microphysical processes include nucleation of cloud nuclei, condensation and collection growth of liquid drops, nucleation on ice nuclei and ice particles produced by ice multiplication during collisions between graupel and large drops, freezing of supercooled drops, and the deposition and riming growth of snow crystals and graupel. Liquid drops and graupel are classified by diameter and thickness.

The dynamic equations are for a deep-anelastic axisymmetric model with a diffusion term for a first-order closure system. Equations are for vorticity, potential temperature, water vapor, number density functions of Aitken nuclei, cloud nuclei, ice nuclei, ice particles, liquid drops (33 classes), graupel (45 classes), snow crystals (21 classes of size, 5 classes of thickness), electric charge functions of drop charge (33 classes), graupel charge (45 classes), snow crystal charge (21 x 5 classes), and large and small ion concentrations.

The environmental and initial conditions are chosen to simulate a moderate cloud size in the domain of 8 km in height and 6.4 km in radius. A backward scheme is extensively used during the latter period of calculation to maintain stable calculations.

c. Model runs

Two cases are chosen for simulation. Case A is for a thunderstorm which develops in an environment influenced by maritime air, case B is for a thunderstorm which develops over the U.S. Great Plains. The initial cloud nuclei number concentration is set at 100 cm$^{-3}$ in case A and increased
to 1000 cm$^{-3}$ in case B. The initial cloud droplet size distribution, which is assumed to be formed instantaneously from cloud nuclei, is broader in case A than in case B (Takahashi, 1978a). The maximum ice nucleus concentration with nuclei fully activated is set as 1 cm$^{-3}$ in both cases.

3. Results

a. Case A

(1) First lightning discharge (17 m 40 s)

In the early stages of cloud development, snow crystals grown near the cloud top fall along

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**Table 1. Lightning discharge locations and time in case A (above) and case B (below).**

<table>
<thead>
<tr>
<th>CASE</th>
<th>TIME</th>
<th>LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DISCHARGE FIELD</td>
<td>MAX POSITIVE SPACE CHARGE</td>
</tr>
<tr>
<td>A</td>
<td>17:40*</td>
<td>(0**, 4.8***s)</td>
</tr>
<tr>
<td></td>
<td>31:40</td>
<td>(0, 2.0)</td>
</tr>
<tr>
<td></td>
<td>53:00</td>
<td>(2.0, 1.6)</td>
</tr>
<tr>
<td></td>
<td>55:00</td>
<td>(2.0, 1.6)</td>
</tr>
<tr>
<td></td>
<td>60:00</td>
<td>(2.0, 1.6)</td>
</tr>
<tr>
<td></td>
<td>65:10</td>
<td>(1.8, 1.4)</td>
</tr>
<tr>
<td>B</td>
<td>17:40</td>
<td>(0, 4.8)</td>
</tr>
<tr>
<td></td>
<td>18:40</td>
<td>(0.2, 4.8)</td>
</tr>
</tbody>
</table>

* min : sec ** radial distance (km) *** vertical distance (km)

| discharge effective size (km) |
the cloud boundary and re-enter the cloud. These snow crystals are large enough to collect cloud droplets and form graupel (Fig. 1). Through collisions between graupel and snow crystals, graupel are mainly electrified negatively and ice crystals positively. At the cloud top, however graupel are electrified positively and snow crystal negatively because of low liquid water content. Gravitational separation creates a strong electric field at the main charge separation region between the lower negative space charge carried by graupel and the upper positive space charge carried by snow crystals at the upper part of the cloud. Between the two major space charges, positive electric potential gradients develop and the electric field rises to the magnitude of the discharge field at 4.8 km in the cloud center (Table 1). Discharge occurs between the two space charges (positive, \( X_p = 0.2 \) km, \( Z_p = 4.8 \) km, negative, \( X_n = 0.2 \) km, \( Z_n = 4.4 \) km, Fig. 2). After discharge, the main space charge is for the most part neutralized and the positive potential gradient disappears at the upper part of the cloud. Near the cloud top, a positive space charge slightly dominates since positively charged snow crystals in the main space charge form positively charged graupel during riming growth while large negative graupel falls along cloud boundary. A rather weak negative potential gradient develops around this positive space charge. The small positive space charge around the \(-20^\circ C\) level is due mainly to the positive snow crystals transported into the cloud through cloud boundaries.

(2) Second lightning discharge (31 m 40 s)

The accumulation of precipitation particles in the cloud suppresses the updraft allowing large graupel to then fall into the cloud center (Fig. 3). In the cloud center, graupel carries a strong negative charge due to riming electrification. The graupel changes sign from negative to positive during riming electrification at lower levels due

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Fig. 2. Case A. Model-derived magnitude and direction of the electric potential gradient as functions of the height and radial distance at 17 m 40 s (Left) and 18 m 0 s (Right). The net positive space charge is denoted by thin solid lines and the net negative space charge is denoted by thin dashed lines. The thin dash-dotted lines denote lines of neutral space charge. The number in the lower right-hand corner of each diagram is the magnitude of the maximum vector denoting the potential gradient. Thick bold lines connect the discharge centers through discharge field location.
to the warmer temperatures present there. Snow crystals electrified negatively at this level are carried upward and their space charge is added to that of the falling negative graupel. Thus the negative space charge increases in magnitude. The electric field between the mid-level negative space charge carried by graupel and snow crystals and the low-level positive space charge carried by...
graupel reaches the critical discharge field in 31 min 40 sec at H=2 km in the cloud center. Discharge occurs between those two space charges \((X_p=0\text{ km}, Z_p=1.6\text{ km}, X_n=0\text{ km}, Z_n=2.2\text{ km}, \text{ Fig. 4})\). After the discharge, both the mid-level negative space charge and the low-level positive space charge are neutralized. Only the negative electric potential gradient remains between the upper negative snow crystals and the lower positive graupel at the upper part of the cloud.

A positive electric potential gradient at the ground induces point discharge and a negative space charge is built up near the ground.

(3) 3rd lightning discharge (53 m 0 s)

Precipitation particles falling along cloud boundaries induce a downdraft and form a small convection current surrounding the main cumulus cloud (Fig. 5). The snow crystals from the main cloud which seed this second cloud cell enhance the formation of small graupel. Because the temperature is mostly above \(-10^\circ\text{C}\), graupel are electrified positively and snow crystals negatively during riming electrification. Gravitational separation of graupel and snow crystals produces a negative charge above and a positive charge below creating a strong negative potential gradient between them. The discharge field reaches at \(X=2\text{ km} \text{ and } Z=1.6\text{ km} \text{ in } 53\text{ min. \ Discharge in the second cloud cell occurs between the main negative space charge carried by snow crystals and the positive space charge carried by graupel (Fig. 6, } X_p=1.4\text{ km, } Z_p=0.4\text{ km; } X_n=1.6\text{ km, } Z_n=2.0\text{ km). The low-level positive space charge is for the most part neutralized after lightning occurs.}

A positive space charge at the right edge of the main negative space charge in Fig. 6 is due to snow crystals which are electrified positively by field-driven charging within a negative potential gradient area. The upper negative space charge is due to negative snow crystals while the uppermost positive space charge is due to small ions.

(4) Fourth lightning discharge (55 m 0 s)

Meanwhile a negative space charge re-forms at around the \(-10^\circ\text{C}\) level in the main cloud cell (Fig. 7). A lightning stroke occurs between the snow crystal-carried negative space charge in the main cloud cell and the graupel-carried positive space charge in the second cloud cell at 55 min (Fig. 8). The discharge field origin is still at \(X=2.0\text{ km} \text{, } Z=1.6\text{ km} \text{ between the upper negative snow crystals and the lower positive graupel in the second cell. The locations of the positive and negative space charges are } X_p=1.6\text{ km, } Z_p=1.6\text{ km, } Z_n=2.0\text{ km}\).

Fig. 5. Same as Fig. 1 except at 53 min 0 s (Left and Center) and 53 min 20 s (Right).
Fig. 6. Same as Fig. 2 except at 53 min 0 s (Left) and 53 min 20 s (Right).

Fig. 7. Same as Fig. 1 except at 55 min 0 s (Left) and 55 min 10 s (Right).
Fig. 8. Same as Fig. 2 except at 55 min 0 s (Left) and 55 min 10 s (Right).

0.8 km; \( X_n = 0.2 \text{ km}, Z_n = 1.6 \text{ km} \). After this discharge, both space charges are almost neutralized.

(5) Fifth lightning discharge (60 m 0 s)

Space charges recover their magnitude by gravitational separation between graupel and snow crystals in the second cell (Fig. 9). A discharge occurs again between them (Fig. 10). The discharge field location is still the same at \( X = 2.0 \text{ km}, Z = 1.6 \text{ km} \). The positive and negative space

Fig. 9. Same as Fig. 1 except at 60 min 0 s (Left and Center) and 60 min 10 s (Right).
charge locations are $X_p = 2.0$ km, $Z_p = 1.4$ km, and $X_n = 1.8$ km, $Z_n = 1.8$ km. Graupel-held charges are highly neutralized at lower levels.

(6) Sixth lightning discharge (65 m 10 s)
At the center of the main cloud, positive ions are supplied from the ground by point discharge.

Fig. 10. Same as Fig. 2 except at 60 min 0 s (Left) and 60 min 10 s (Right).

Fig. 11. Same as Fig. 1 except at 65 min 10 s (Left) and 65 min 20 s (Right).
They attach themselves to the snow crystals. A relatively strong positive space charge is thus formed near the ground (Fig. 11). A lightning stroke occurs between the negative snow crystal-carried space charge in the second cloud cell and this positive snow crystal-carried charge near the ground below the main cloud center (Fig. 12). The discharge field is located at $X=1.8$ km and $Z=1.4$ km. Positive and negative space charge centers are $X_p=0$, $Z_p=0$, and $X_n=2.0$ km, $Z_n=1.8$ km.

Fig. 12. Same as Fig. 2 except at 65 min 10 s (Left) and 65 min 20 s (Right).

Fig. 13. Same as Fig. 1 except case B and 17 min 40 s (Left and Center) and 18 min 0 s (Right).
km. The negative snow crystal space charge in the second cloud cell is highly neutralized by the lightning stroke.

As the graupel mixing ratio decreases in magnitude (<0.1 g kg⁻¹), space charge separation does not effectively occur and electrical activity weakens gradually with time.

b. Case B

(1) First lightning discharge (17 m 40 s)

In case B, because the cloud droplet size is small, the growth rate of graupel slows due to the low collection efficiency of cloud droplets on snow crystals (Fig. 13). Most graupel is formed near the cloud top where the water content is relatively high. Graupel and snow crystals, as separate groups, are therefore mostly electrified in unipolar signs; graupel negatively and snow crystals positively. Due to gravitational separation of graupel and snow crystals, the space charge distribution is carried by negatively charged graupel below and positively charged snow crystals above. A positive electric potential gradient between them rises causing discharge at 17 min 40 sec (Fig. 14). The discharge field location is X=0, Z=4.8 km. The positive and negative discharge space charge locations are X_p=0.6 km, Z_p=5.0 km and X_s=0.4 km, Z_s=4.4 km. The discharge reduces the high space charge densities near the cloud top. The reason for the slight dominance of a positive space charge near the cloud top is the same as that in a-(1). The uppermost negative space charge is due to the negatively charged snow crystals which are attached by negatively charged small ions flowing in from above.

(2) Second lightning discharge (18 m 40 s)

The space charges of both graupel and snow crystals quickly recover near the cloud top during convection (Fig. 15). The second stroke occurs at 18 min 40 sec. The discharge field location is X=0.2 km and Z=4.8 (Fig. 16). The positive and negative discharge space charge centers are X_p=0.4 km, Z_p=5.2 km, and X_s=0.8 km, Z_s=4.2 km. Both space charges are highly neutralized after the second stroke.

Since most graupels are formed within the narrow area where negative electrification of graupel occurs, the graupel carry a strong nega-
Fig. 15. Same as Fig. 13 except at 18 min 40 s (Left) and 18 min 50 s (Right).

Fig. 16. Same as Fig. 14 except at 18 min 40 s (Left) and 18 min 50 s (Right).
ative charge. Even when they fall within the cloud cell at a later time, riming electrification below $-10^\circ$C does not alter their original electric sign sufficiently enough to build a low level positive space charge. The electric field at low levels is thus weak and no lightning discharge occurs there.

Also, due to the slow rate of graupel formation, only half as much graupel is produced in the second cloud cell as in case A. There is no space charge separation between the graupel and snow crystals strong enough to trigger lightning in the second cloud cell. Neither does lightning develop between the main cloud cell and the second cloud cell.

4. Discussion

Model results (Fig. 17) demonstrate two layers of lightning origin in case A, which may simulate Florida thunderclouds, while only one layer is found in case B which may simulate a typical Colorado thunderstorm. The former case has not only a high charge separation within the main cloud cell and within the second cloud cell in themselves, but also a strong interaction between both cells in producing lightning strokes at lower levels. The model results will be further compared with observations.

a. Time sequence of lightning discharges

As has been observed (Krehbiel et al., 1984, MacGorman et al., 1986), lightning discharges occur initially near the cloud top and then at lower levels. Gravitational charge separation acts near the cloud top at the early stages while dynamic charge separation occurs at around $-10^\circ$C in mature stages in the main cloud cell. In the dissipating stage, small second cells are activated and gravitational charge separation induces lightning strokes. Point discharge helps to induce the ground stroke in the last period.

b. Single and double layers of lightning origins

The calculations of two layers of lightning origin in case A and one layer in case B are similar to observations (MacGorman et al., 1981). The calculated temperatures of the two layers in the model were $-30^\circ$C and $-10^\circ$C as has been observed.

However, the calculated temperature is colder in case B when lightning occurs than has been seen in observations, although observational data varies widely with height for the area of lightning in Colorado thunderclouds.

According to the model, the reason for the
difference between lightning origins in these different cloud types is the differences in graupel growth rates. In case B, a large cloud nuclei concentration results in slow graupel growth. They grow, therefore, primarily near the cloud top. Since graupel carry a strong negative charge, they rarely change electric sign below $-10^\circ C$ as explained previously. The positive pocket of space charge near $0^\circ C$ is thus small, producing an electric field so weak that no lightning discharge occurs at low levels. This slow graupel growth rate also hinders a strong charge separation in the second cloud cell.

The lightning discharge location is lowered in continental cases by lessening the ice nuclei concentration. As was discussed in Paper T, when the ice nuclei concentration is of one order less than occurs in case B, the graupel concentration becomes small. Here, the electric charge does not separate strongly enough to trigger lightning near the cloud top. Instead, a negative space charge accumulates at around $-10^\circ C$ due to dynamic charge separation. In this case, lightning occurs between the mid-level negative space charge and the upper positive space charge. The mean height of lightning strokes is thus lowered.

c. Low-level lightning

Proctor (1983) observed low-level lightning (3–5 km, $-5^\circ C$ to $-16^\circ C$) when a high radar echo (9.5 km) leans toward the low level main echo (3–4 km). In case A, snow crystals from the main cloud cell seed the shallow second cloud cell. Graupel formation is thus enhanced in the second cloud cell. Gravitational charge separation produces a greater charge separation in the second cell. Lightning discharges not only occur in the second cloud cell but also occur between the main cloud cell and the second cloud cell. Lightning origins are at low levels here, as has been observed.

d. Inclination of discharge centers

Although discharge centers are vertical in the main cloud cell in case A, they are somewhat inclined in case B due to the wider distribution of graupel caused by the small size. A very large inclination was calculated for low level lightning in case A, especially in discharges between the main cloud cell and the second cloud cell. The discharge location is determined by the gravitational separation between graupel and snow crystals in the second cell and does not vary with time. In these cases the discharge electric field location highly deviates from the line-connected discharge centers (Fig. 8). Here, fairly horizontal lightning paths are expected. This may be related to the rather horizontal lightning observed near the cloud base (Proctor, 1983).

e. Others

In case A, the discharge space charge was increased to 50 Coulombs. However, no significant difference in the sequence of lightning discharges was observed except in a larger neutralized volume. The electric term in the dynamic equation helped only slightly in the maintenance of the convection and made no significant changes in electrical activity.

Although calculations compare well with observations, limitations in the model should be discussed. Due to the assumption of discharge between maximum space charges, a discharge path was selected between them although a discharge field was built among other space charges (Figs. 8 and 12). However it is not clear at this moment whether discharge occurs among the space charges which then creates a breakdown of the field, or whether leaders extending from the breakdown field find the maximum space charges.

Another point concerns the limitation of a two-dimensional model. Because the model is axisymmetric, the space charge distributes itself in the form of a ring. A three-dimensional model is necessary to improve the calculations. In this three-dimensional model, wind shear effects on charge distribution can be included.

5. Conclusions

Lightning origins are determined in a numerical thunderstorm model. The origins are greatly dependent on microphysical processes. Gravitational separation between graupel and snow crystals near the cloud top creates a large space charge separation there; lightning, then, is first triggered near the cloud top (1 in Fig. 18). Subsequent charge separations are caused by dynamic charge separation at around $-10^\circ C$ triggering low-level lightning (2 in Fig. 18). However, in continental thunderclouds, slow graupel formation and unipolar charging discourages low-level
lightning. In maritime thunderclouds, additional graupel formation occurs in induced second cloud cells when snow crystals are seeded from the main cloud cell. Gravitational separation creates a charge separation strong enough to trigger low level lightning (3 in Fig. 18). The discharge between the main cloud cell and the second cell shows as a horizontal lightning bolt (4 in Fig. 18). Finally, cloud to ground lightning occurs between the space charge of the second cell and the space charge originating in point discharge below the main cloud domain (5 in Fig. 18).

Acknowledgments

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References


Appendix

The Dependence of Ice Crystal Size Upon Electric Charge Rate During Rimming Electrification

1. Apparatus

A separated charge tends to increase in strength when larger ice crystals are present in collisions between ice crystals and an ice sphere. However, the data summarized by Marshall et al. (1978), was obtained mostly without the presence of cloud droplets. Temperatures varied during these experiments. It is necessary to conduct new experiments with cloud droplets present and in a stable environmental condition.

A 3-m tall cylinder, used to grow large ice crystals, was set in the cold room (Fig. A1). Its construction was similar to Furukawa et al. (1980). Air circulated gently through the main and sub cylinders. The proper blocking on the floor of the main cylinder made sure that the air speed was at a minimum in the center of the cylinder. To prevent frost formation on the cylinder wall to minimize depletion of moisture into the cylinder metal, a black cloth was placed 1-cm from the cylinder wall. A riming rod was

Fig. A1. Apparatus used to study riming electrification.
inserted in the main cylinder, and experiments were conducted in preparation of small and large ice crystals.

A. Small ice crystals

Cloud droplets were supplied from the sides of the main cylinder by 3 humidifiers. Although the droplets were electrified negatively, the charging rate during riming electrification was much greater than that found with sole cloud droplet collection. Ice crystals were nucleated on dry ice in a separate box, and seeded ice crystals were supplied into the main cylinder at a rate controlled by regulation of a shutter opening. Ice crystals as large as 1 mm grew in the cylinder. The ice crystal concentration was measured by a special device (Fig. A2).

A rectangular polyethylene box has an opening at both top and bottom. A thin brass leaf with a center opening covers the top. One side of the leaf is connected to a spring while the other is connected to a metal piece. This piece is inserted into a hole below polyethylene box. To measure ice crystal concentration, this box is inserted into the main cylinder. Ice crystals fall freely through this box. An ebonite block is then placed at the bottom of the box. This block has groove in its top surface. A glass slide coated with replica solution is placed in the groove. This ebonite block is pushed by a long rod from the side of the cylinder and it closes the lower opening. A small metal piece at the side of the ebonite block releases the metal piece connected to the brass leaf. The leaf closes the top opening instantly. All the ice crystals in the box fall onto the glass plate where they can be enlarged through a microscope and then photographed.

B. Large ice crystals

Frost was used for large ice crystals. A large wire mesh plate was connected to a rod at the top of the cylinder which could move the mesh horizontally. The mesh plate was thus periodically shaken and frost was torn loose. Its charge was small enough not to disturb the riming electrification. Humidifiers were placed 1 meter from the cylinder bottom and were used only to grow frost. The riming rod was placed at 70 cm in height. Due to the low frost concentration the charging rate was small, and the electric charge from the humidifier generated cloud droplets hindered the identification of true riming electrification. At the bottom of the cylinder, a heating pan was installed to supply water vapor for the riming. The cloud droplets formed from this vapor were only weakly charged and did not disturb the charging experiment. Frost was collected on glass plates coated with replica solution.
2. Results

Experiments were conducted at $-15^\circ$ to $-20^\circ$C with cloud water contents of 1.8 to 2.3 g m$^{-3}$. The experimental procedures on electrification were the same as in previous work (Takahashi, 1978). The mean separated charge is the total charge amount divided by the total collided ice crystal number. In order to determine a true representative size, ice crystal size distributions were first determined. Since separated charge is considered to be proportional to the mass, size distribution was converted to the number times the cross-section assuming that the thickness is constant. A modal size for ice crystals in a new distribution could thus be selected (Fig. A3).

Although charging rates increase with larger ice crystals below 100$\mu$m in diameter, the charging rate seems to level off in the larger size range.

The present experimental values are smaller than other experimental values cited by Marshall et al. above 100$\mu$m. A smoothed curve connecting experimental values was used in the present numerical simulation.

The separated charge was proportional to the rotation speed of the riming rod in the range of 7 ms$^{-1}$ to 10 ms$^{-1}$.

References