On the Electric Charge of Relatively Large Natural Cloud Particles

By Choji Magono and Katsuhiro Kikuchi

Dept. of Geophys., Hokkaido University

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Abstract

Results are described of measurements of the electric charge of individual cloud particles of diameter ranging from 15μ to 200μ carried out at the top of Mt. Teine from 1957 to 1959. The cloud particles are classified into warm cloud particles, supercooled cloud particles, frozen cloud particles and ice particles.

Both positive and negative cloud particles were observed but the portion of negative cloud particles was larger than that of positive ones through the cloud particles of all types. Mirror image relation like that in rainfall held in most cases. The magnitude of charge of cloud particles was roughly proportional to the cube of their diameters. In liquid state, charged cloud particles were considerably larger than non-charged ones.

Considering those results, the mechanism of electrification of relatively large cloud particles was considered to be as follows. In initial state of electrification, cloud particles are charged to the sign opposite to that of the prevailing electric field as a result of Wilson's ion capture process. Then larger cloud particles grow by uniting with smaller charged cloud particles of same sign produced by Wilson's process. After freezing of cloud particles, further charge generation by mutual friction will occur.

Introduction

It was expected that the electric charge of individual cloud particles would be important in studying the mechanism for the electrification of clouds, but no measurements have been made, perhaps owing to some difficulty in practical technique. Since electric power came into use at the top of Mt. Teine, 1023 m peak, in 1957, the authors began to measure the charge of individual cloud particles. During the course of the measurement, Twomey¹⁾ published results for the charge of individual cloud droplets in stratocumulus and stratus obtained at Mt. Wellington, Tasmania, Australia. According to his paper, a large portion (80% or more) of charged cloud droplets were positive in liquid phase, but when ice phase was present in the clouds, a majority (40~100%) of droplets sampled were negatively electrified. He stated also that ice phase in cloud is important in the electrification of cloud particles,

but data on the cloud particles in ice phase were not distinguished in his results. Later, Phillips and Kinzer²⁾ measured the charge of individual droplets of cumulus warmer than 0°C , and stated that in non-precipitating cloud, the number of positive droplets was roughly equal to that of negative droplets and that the magnitude of the charge agreed with that calculated theoretically by Gunn³⁾ who used thermal diffusion phenomenon of ions. The size of cloud droplets measured by them was as small as several microns. However, active clouds generally contain cloud droplets much larger than 20μ in diameter, and such cloud droplets have close relation to the electrification of thunder clouds. It is therefore considered that the charge of those large cloud particles would be more important than that of small cloud particles in studying the electrification phenomenon of clouds.

The results obtained by the present authors were considerably different from Twomey's.

The present paper is mainly concerned with the charge of relatively large cloud particles of cumuli and strato forms both in liquid and solid phases. Not charged cloud particles are discussed as well as charged cloud particles in this paper.

1. Measuring method and apparatus

Wells and Gerke's⁴⁾ method was used for measuring the charge of individual cloud particles in this study. When a cloud particle falls into a horizontal electric field of alternating current, it leaves a trajectory of sine wave type. If a direct current field is overlapped to the alternating current field, the trajectory deflects to the left or the right according to the sign of the charge of the particle. Thus e/m of the particle is measured from amplitude of the sine curve, using the following formula,

$$e/m = 2\pi^2 A f^2 \frac{300d}{\sqrt{2}V} \sqrt{1 + \left(\frac{g}{2\pi\lambda f^2}\right)^2} \quad (1)$$

where e is charge of a particle, m its mass, A amplitude of sine curve, f frequency of alternating current, d distance between two electrode plates, V potential difference in volts between the two plates, g gravitational acceleration, and λ wave length of the sine curve. The magnitudes other than V are represented in c.g.s. units. The mass (m) of cloud particle can be calculated from the wave length (λ) using Stokes' law.

The apparatus used is shown diagrammatically in Fig. 1. A hood in the roof was designed to be rotated around a vertical axis according to prevailing wind direction so that cloud particles would fall easily into the apparatus. It was expected that cloud particles would fall freely in the vertical metallic cylinder as shown in the center of Fig. 1. The trajectory of the cloud particles was photographed from a window of the cylinder using a close-up camera. The field of view of the camera is shown in the upper left side with magnification. A dark field illumination was made by the lighting system of a slide lantern. This illumination method was useful since the slide lantern had both heat absorbing filters and light condensers.

Sometimes, a suction fan was used as seen in the bottom of Fig. 1, because it was dif-

Fig. 1. Measuring apparatus.

icult under natural conditions to introduce small cloud particles into the apparatus without use of such a fan. It was of course true that in this case the cloud particles did not fall freely. Therefore, in order to stop the air current within the cylinder caused by the suction, two diaphragm shutters were devised to close them just after introduction of the small cloud particles. In spite of this procedure, it was difficult owing to turbulence to make sure of the free falling of the particles since their free falling speed was too low. Thus the accurate measurement of free falling velocity, in other words, of mass, could not be realized easily. This difficulty in the measurement of mass became one cause of lowering the accuracy of charge measurement of cloud particles as described later.

2. Accuracy and measurable range

The resolving power of the close-up camera used was 15μ in particle's diameter, and the lower limit in amplitude of wave length was 50μ . Accordingly, the resolving power in

Fig. 2. Measurable range.

e/m of the apparatus was about 20 c.g.s. where $f=50$ cycle/sec, $d=2$ cm and $V=5000$ volts. For examples, the lower limit of measurable charge was 1×10^{-5} e.s.u. in the case of diameter 100μ , and 1×10^{-7} e.s.u. in the case of diameter 20μ . Thus the measurable range was limited to an area as shown by hatching in Fig. 2.

Another cause of errors in the measurement of charge is concerned with inaccuracy in measuring the diameter of cloud particles. When free fall of cloud particles was not sure, Stokes' law was not useful; in addition to that, wave length could not be measured if cloud particles were not charged. In those cases, the width of traces of cloud particles in photograph was used to measure diameters of cloud particles, although this method was considered of low accuracy.

The reliability of this method was examined as follows. Regarding frozen cloud particles which left traces of normal sine wave type, both their wave lengths and widths were measured, and the diameters calculated by the two methods were compared with each other as shown in Fig. 3. In the figure one sees that the plotted data are scattered around a straight line which passes the origin of coordinates and is of inclination 45° to the abscissa within the error margin of $\pm 20 \mu$. The errors perhaps resulted from the inaccuracy in measuring the width of traces. But it is considered that systematic errors were not accompanied by the measurement of the width of the traces, since the plotted data were distributed symmetrically around the 45° line. It may be therefore accepted that the data of diameter obtained by this method is reliable from the statistical point

Fig. 3. Diameter calculated by wave length vs diameter obtained by use of width of trajectory.

of view, if data are sampled sufficiently. If cloud particles are of irregular shape, their width in falling path does not show their spherical diameter but their maximum dimension, particularly in ice particles.*

3. Results

In this paper, the term "not charged cloud particles" means not only uncharged cloud particles but slightly charged particles whose charges were too small to be detected.

According to weather conditions in which cloud particles were observed, they were classified into four types as in Table 1.

3.1 Warm cloud particles

"Warm cloud particles" were observed through the period from Sept. to Oct. 1957. Most of the cloud particles observed were not charged or charged so slightly as not to be detected. It was true of most cases that charged cloud particles of same sign occurred in group. The results of measurement of the charge of individual cloud particles are shown in Fig. 4. The abscissa of the figure shows the charge of individual particles, and the upper and lower ordinates represent the diameter of positively and negatively charged particles respectively. The measurable

* See Table 1.

Table 1. Classification of cloud particles.

Nominations	Weather conditions	Plate
a. Warm cloud particles	Air temperature was higher than 0°C.	Plate 1a
b. Supercooled cloud particles	Air temperature was below 0°C and icing phenomena were recognized on branches of trees nearby.	Plate 1b
c. Frozen cloud particles	Air temperature was much colder than 0°C but icing phenomena were not observed. This means that cloud particles were considered to be frozen, although freezing of the particles was not confirmed by their traces in photograph owing to their extreme thinness.	Plate 1c
d. Ice particles	The freezing of cloud particles was confirmed by the occurrence of periodic glittering of their traces in photograph. They were fairly large reaching about 200 μ in diameter. They were often observed in snowfall.	Plate 1d

Plate 1. Trajectories of charged cloud particles under a horizontal electric field.

A. C. field is overlapped to D. C. field shown to the left side.

ranges are also shown by solid lines. One sees that the data plotted are distributed within the measurable range.

It is noted that fairly many negative cloud

particles were observed. The number of negative cloud particles was rather more than that of positive ones. This was the important difference in the present measurements from

Table 2. Charge of warm cloud particles (Sept.~Oct., 1957).

Electrification	Numbers	Mean diameters (μ)	Signs	Numbers	Mean charges (e.s.u.)
Charged	79	58	+	19	1.0×10^{-5}
			-	38	1.6×10^{-5}
			unclear	22	2.4×10^{-5}
Not charged	362	40			

Table 3. Charge of supercooled cloud particles (Jan.~March, Oct.~Dec., 1958).

Electrification	Numbers	Mean diameters (μ)	Signs	Numbers	Mean charges (e.s.u.)
Charged	137	60	+	16	9.4×10^{-6}
			-	63	2.3×10^{-5}
			unclear	58	7.0×10^{-6}
Not charged	2642	45			

Twomey's results¹⁾. The range in which his results were distributed is indicated by the area enclosed by dotted line in the positive side.

Comparing the results with each other, it is noted that the cloud particles observed by the authors contain larger particles but there is deficiency in smaller particles. It is also noted that data plotted are distributed roughly parallel to straight lines $e/m = \pm 20$ c.g.s. both in the positive and negative sides. This means that the charge of warm cloud particles is roughly proportional to the cube of the diameter of cloud particles. Twomey's results showed that the charge was proportional roughly to the square of the diameter of particles.

Fig. 4. Charge of warm cloud particles.

The data shown in Fig. 4 are tabulated in Table 2 including those of not charged particles.

Sometimes it was difficult to determine the deflection direction of particles' trajectories owing to turbulence in the measuring cylinder, even if the cloud particles left traces of sine type. The term "unclear" in sign in the table means those particles whose signs were not determined. One may see that the mean diameter of charged particles was considerably larger than that of not charged particles. The fact that charged cloud particles were larger than not charged ones is seen not only in mean diameter but over a wide range as shown in Fig. 5. In the figure, the frequencies of charged and not charged particles are represented by dotted lines and

Fig. 5. Size distribution of charged and not charged warm cloud particles.

solid lines respectively. The diameter of cloud particles of the figure were all calculated from the width of traces only.

3.2 Supercooled cloud particles

The charge of "supercooled cloud particles" was measured during the periods Jan. to March and Oct. to Dec. 1958. The results are shown in Figs. 6, 7 and Table 3.

It is seen that the general properties of

Fig. 6. Charge of supercooled cloud particles.

Fig. 7. Size distribution of charged and not charged supercooled cloud particles.

supercooled cloud particles are similar to those of warm cloud particles described in Section 3.1. The excess in number of negative particles over positive particles is larger than in the case of warm cloud particles. This tendency seems to agree qualitatively with Twomey's finding that negative cloud particles were observed in winter season although they were absent in summer. It is seen also in Table 3 that not charged particles were much more numerous than charged particles. When charged cloud particles were not observed, the measurement of charge was stopped for a period. Therefore the true number of not charged particles would be much greater than shown in Table 3. And the data of those not charged particles would be distributed in ranges out of the measurable ranges shown in Fig. 6 if all the slight charge of particles could be measured.

3.3 Frozen cloud particles

The charge of frozen cloud particles has not been measured hitherto. But in the present observations, it was somewhat easier to measure the charge of "frozen cloud par-

Fig. 8. Charge of frozen cloud particles.

Table 4. Charge of frozen cloud particles (Jan.~March, 1958).

Electrification	Numbers	Mean diameters (μ)	Signs	Numbers	Mean charges (e.s.u.)
Charged	227	71	+	53	3.0×10^{-5}
			-	89	3.9×10^{-5}
			unclear	85	3.2×10^{-5}
Not charged	188	67			

Table 5. Charge of ice particles (Jan.~March, 1958).

Electrification	Numbers	Mean diameter (μ)	Signs	Numbers	Mean charges (e.s.u.)
Charged	31	203	+	12	4.3×10^{-4}
			-	10	2.0×10^{-4}
			unclear	9	8.6×10^{-4}
Not charged	9	205			

ticles" than that of not frozen particles, since the charges of the former were fairly large and were not crowded compared with those of not frozen cloud particles as seen in Plate 1. The results of frozen cloud particle charge measurements obtained in winter season of 1958 are shown in Fig. 8. In the figure, it appears that the relation of charge *vs* diameter, in frozen cloud particles, is not so different from that of cloud particles in liquid phase, but the following marked differences are noted from Table 4.

1. The portion of charged particles in ice phase increased as compared with that in liquid phase. The portion is rather more than that of not charged particles.
2. The mean diameter of charged particles is roughly equal to that of not charged particles.

Those facts different from those in liquid phase seem to show that the freezing phenomenon of cloud particles has some effect to increase both the growth and electrification of the cloud particles. The former effect is expected from cloud physics theory and the latter effect was suggested by Twomey¹⁾. As stated in Table 1, it was determined by indirect method whether the "frozen cloud particles" were actually frozen or not. The two marked differences described above may be also evidence that the "frozen cloud particles" were actually frozen.

3.4 Ice particles

It was confirmed from the periodic glittering of traces in the photograph that "ice particles" were already frozen. They were in most cases observed during snowfall, therefore, they may belong to the precipitation element. However it may be also considered that they are in the last stage of cloud particles, in other words, in the stage of ice

crystals. The ice particles were the largest among the cloud particles of four types, reaching 200 μ in maximum dimension.

Observation data are insufficient, however, it may be seen in Fig. 9 and Table 5 that the electrical properties of ice particles are not far different from those of frozen cloud particles except that the size* and charge** of ice particles were much larger than those of frozen cloud particles.

Fig. 9. Charge of ice particles.

For convenience, the electrical properties of cloud particles described above are summarized in the form of ratio in Table 6.

One sees in the table that n_+/n_- and Q_+/Q_- are smaller than unity through all the types except n_+/n_- of ice particles.*** In other words, the portion of negative cloud particles was larger than that of positive ones and the mean charge of negative cloud particles was larger

*, ** The size and charge are overestimated because the size is not the diameter of a sphere but maximum dimension.

*** The exception is not important because the data sampled were not sufficient, as seen in Table 6.

Table 6. Properties of charged cloud particles observed.

Classification	n_+/n_-	Q_+/Q_-	n_c/n_0	d_c/d_0
Warm cloud particles	0.50	0.63	0.22	1.45
Supercooled cloud particles	0.25	0.41	0.05	1.33
Frozen cloud particles	0.59	0.78	1.21	1.05
Ice particles	1.20	0.21	3.44	0.99

n_+ =total number of positive cloud particles measured,
 n_- =total number of negative cloud particles measured,
 Q_+ =mean charge of positive cloud particles,
 Q_- =mean charge of negative cloud particles,
 n_c =total number of charged cloud particles measured,
 n_0 =total number of not charged cloud particles measured,
 d_c =mean diameter of charged cloud particles,
 d_0 =mean diameter of not charged cloud particles.

than that of positive ones. But on other hand, this fact shows clearly that considerable positive cloud particles were observed even in solid state, although Twomey's results indicated that positive cloud particles were absent in clouds containing ice phase.

It is seen that in liquid state the number of charged cloud particles was much smaller than that of not charged particles but in solid state charged cloud particles were more numerous than not charged. Regarding mean

diameter, it may be seen that in liquid state charged cloud particles were larger than not charged particles but in solid state charged particles were roughly equal in size to not charged particles.

4. Charge of cloud particles and prevailing atmospheric electric field

When atmospheric electric field is strong, it is usual in rainfall that falling raindrops are intensively electrified to opposite sign to

Fig. 10. Charge of supercooled cloud particles under atmospheric electric fields.

Fig. 11. Charge of supercooled cloud particles under atmospheric electric fields.

that of the electric field. This is so called "mirror image relation." The relation is also expected to hold in the charge of cloud particles. In order to examine this assumption, the atmospheric electric field near the snow cover surface was measured during the period of observation of the charge of cloud particles. Examples of the results for supercooled cloud particles are given in Figs. 10 and 11. In the figures, solid lines represent time change of the electric field, and white dots show charges of supercooled cloud particles observed in each corresponding time. The sign and magnitude of the charge are shown by ordinates on the right hand. Data of not charged particles are plotted as dark points on the zero line. Each small and large dark point represents data of 1 to 20 cloud particles and of more than 21 cloud particles respectively.

As seen in Fig. 10, electric field changed violently positively and negatively during snowfall in the midnight of 11-12 Dec. 1958, but positive field was prevailing. Corresponding to the strong positive fields, negative cloud particles of charge 10^{-5} to 10^{-4} e.s.u. were predominant. After 04^h00^m the snow-

fall stopped and the positive field decreased gradually. After 05^h00^m fog only continued and the strength of the fields was about +100 volt/m which agreed with the mean value of surface electric field on normal fine days at this observation point. Corresponding to the later weak fields, all the cloud particles observed were not charged.

Fig. 11 shows three examples of short periods (11a, 11b, and 11c). In Figs. 11a and 11c, it may be seen that negative charged particles of 10^{-6} to 10^{-4} e.s.u. were observed under weak positive field; mirror image relation held. But the relation did not always hold in cloud particles, as seen in Fig. 11b. In spite of this exception, it was found in most cases that cloud particles charged intensively were to be observed under strong electric field. Such results had also been obtained by Phillips and Kinzer²³. Anyhow those relations between charge of cloud particles and electric field are very similar to the relations in the case of raindrop electrification.

5. Considerations

For convenience in consideration, the electrical properties of relative large cloud par-

ticles are summarized as follows.

- a) Through all the types of cloud particles, both positive and negative cloud particles were observed; the number of negative cloud particles was larger than that of positive ones.
- b) In liquid state, the mean diameter of charged cloud particles was considerably larger than that of not charged ones.
- c) It seemed that the freezing of cloud particles has some effect such as to accelerate the electrification and growth of cloud particles.
- d) Mirror image relation held in most cases between the charge of cloud particles and the prevailing surface electric field. Charged particles of same sign seemed to appear in a group for a short period.
- e) The magnitude of charge of cloud particles was roughly proportional to the cube of their diameters.

Since cloud particles of all types included both positive and negative charged cloud particles, and the cloud particles of the two signs were observed alternately under nearly the same meteorological conditions, it is probable that the electrification of the cloud particles was made by a mechanism by which cloud particles could be charged both positively and negatively according to conditions. It is therefore not likely that such a phenomenon as selective absorption of positive ions due to dipole layer of droplets' surface (Pannetier⁵⁾), bursting of sea water (Blanchard⁶⁾), of freezing of supercooled cloud droplets (Lueder⁷⁾) is the main mechanism responsible for the electrification of cloud particles, because as a result of the former two phenomena cloud particles can be electrified positively only. From other considerations Twomey also reached the same conclusion. By the later phenomenon cloud particles can be electrified negatively only as shown by Lueder's experiment. Regarding his experiment, one should note that from recent experiments of Reynolds, Brook and Mary⁸⁾ and Magono and Takahashi⁹⁾, no appreciable electrification was recognized in riming phenomena of supercooled cloud particles only, but to generate any appreciable charge, some friction between bodies in ice phase was needed.

The thermal diffusion of ions can produce both positive and negative charges on cloud particles, but the magnitude of charge is, at highest, of the order 10^{-7} e.s.u. only. Therefore some other selective diffusion mechanism is required to explain the charge ranging from 10^{-7} to 10^{-4} s.e.u. Here one may remember that mirror image relation holds in the present observations in most cases. The free falling velocity of cloud particles in gravity field was larger than, or of comparable order with, the vertical component of velocity of cloud particles due to mobility. It is therefore considered that the electrification process of Wilson's selective ion capture was caused to occur more or less under an electric field and cloud particles were electrified to the sign opposite to that of the prevailing electric field. Thus the sign of electrification of cloud particles was determined by the sign of prevailing electric field. However, the magnitude of charge of cloud particles observed was much larger than the maximum charge expected from the field strength: $Q = -3Er^2$ ¹⁰⁾ where Q is maximum charge of cloud particles of radius r under electric field of magnitude E . This contradiction may be explained if it is assumed that larger cloud particles grew by coagulation with smaller charged particles of the same sign. This assumption may be supported by the finding that the magnitude of the charge of cloud particles was roughly proportional to r^3 of the particles.

From Cochet¹¹⁾ the effect of charge on the acceleration of coagulation between cloud particles is not large, however it is considered that the effect is important in the initial stage of growth of the cloud particles, because larger cloud particles, even in small excess, will grow by coagulating with smaller particles. This mechanism will explain why charged cloud particles were considerably larger than not charged ones in liquid state.

Although the process of electrification of cloud particles suggested by Lueder is not considered to be the main one, the effect of freezing of supercooled cloud particles on the electrification is too large to be ignored. As to the effect, the present authors feel that electrification by mutual friction between frozen cloud particles occurs in solid state.

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比較的大きな雲粒の電荷について

孫野 長治・菊地 勝弘

(北海道大理学部地球物理学教室)

1957年から1959年にかけて手稲山頂において直径 $15 \sim 200 \mu$ の雲粒の電荷の測定を行なった。雲粒を温暖雲粒、過冷却雲粒、凍結雲粒および氷粒に分類して結果を述べた。

すべての型の雲粒を通じて、正・負両符号の雲粒が観測されたが、しかし負の雲粒の数が多かつた。また降雨の場合と同様な鏡像関係が雲粒電荷と空中電位の間にたいてい成立した。雲粒の荷電量はだいたい直径の3乗に比例した。凍結しない液相の雲粒では荷電したものは荷電しない雲粒よりも相当大きい。

これらの結果から比較的大きな雲粒の荷電機構は次のように考えられる。荷電の初期において Wilson のイオンの選択吸収機構によつて、その時の空中電場とは反対符号に荷電する。次に比較的大きな雲粒はすでに Wilson の機構により荷電している小さい雲粒と衝突することにより成長する。雲粒が凍結した後には雲粒相互の摩擦による電気発生がこれにかわる。