Radar-Echo Structure of Middle-Level Precipitating Clouds and the Charge of Raindrops (I)
—Processes of Mixing of Precipitation Particles Falling from Generating Cells—

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Abstract

Observations of middle-level precipitating clouds were made using a vertically pointing radar, a field mill and an optical spectrometer with a charge detector. It was studied how the electrical properties of raindrops varied with the fine structure of clouds and micro-physical processes in clouds.

Main results are as follows. In a part of the cloud system in which most of generating cells were in a vigorous stage and in which a large increase in echo intensity with decreasing height was found between the levels of $-10^\circ$C and $0^\circ$C, positively charged raindrops were predominant on the ground and averaged charges were observed to be quite large. In the whole cloud system averaged values of positive charge per raindrop varied almost in phase with those of negative charge and both absolute values were nearly equal each other. But the number flux of positively or negatively charged drops did not necessarily vary with time in phase with the averaged charge of each sign. There was a rather good correlation between the time variation of maximum diameter of raindrops and that of the value of raindrop charge.

Main results can be accounted for reasonably if we suppose that positively charged particles falling from the generating cell of a vigorous stage were mixed with negatively charged ones falling from the cell of a decaying stage in the region above $0^\circ$C level and that precipitation particles grew by aggregational process and they were recharged through friction process.

1. Introduction

Fine structure of middle-level precipitating clouds on the northern part of a warm front has been studied primarily by radar observations. Two types of clouds are most frequently observed—the one is observed as an echo of relatively uniform pattern and the other is observed as cellular echoes. Though micro-physical processes in these clouds are different with each other (Boucher, 1957; Browning, 1974; Hobbs and Locatelli, 1978; Takeda and Fujiyoshi, 1978), the electrical properties of raindrops from middle-level clouds have been generally put into only one type—“continuous rain”. Processes of charging are closely related to micro-physical processes in clouds, as is suggested by studies of snow clouds (Kikuchi, 1973 and 1975; Magono and Orikasa, 1966 a and b). Even though the charge on raindrops were measured for different types of clouds (Bradley and Stow, 1974 a and b; Selvam et al., 1977; Smith, 1955; Takahashi and Fullerton, 1972), the time variation of the charge on raindrops was hardly discussed in relation to that of fine structures of clouds. This will be partly because many authors used only information of precipitating particles aloft which was collected intermittently by means of an airplane or a radiosonde.

In the case of ice particles we could speculate the processes or conditions of their growth in clouds from their types. On the other hand, in the case of raindrops it is difficult to discuss the processes of their growth and charge generation
only on the basis of the charge and the size distribution of raindrops observed on the ground.

Our concerns are to make the simultaneous observation of the charge on raindrops and the structure of clouds and to study how the electrical properties of raindrops vary with the fine structure of clouds and micro-physical processes in clouds.

2. Instruments and data

Observations were made in 1978 at Disaster Prevention Research Institute of Kyoto Univ., Uji. Instruments are a vertically pointing radar of 3.2 cm in wavelength, a field mill and a raindrop-spectrometer which is specially designed for the simultaneous measurement of the charge on raindrops.

We show the structure of the spectrometer schematically in Fig. 1. When a falling raindrop interrupts the beam of light, its size is determined by measuring the change in transmitted intensity of the beam detected by a phototransistor. The spectrometer allows raindrops of 0.2 to 6.0 mm in diameter to be detected. In this paper we will call the raindrops whose diameters lie between \( D - 0.1 \) and \( D + 0.1 \) mm “raindrops with \( D \) mm in diameter”. An apparatus for measuring the charge on raindrops is attached to the spectrometer. It is similar to apparatus devised by Ratcliffe et al. (1969) and Wishart (1978). When a charged raindrop passes through the inside of a brass cylinder, the charge induced on the cylinder is measured by an electrometer. The minimum amount of measurable charge is \( 10^{-2} \) pC. In this paper we will call the raindrops whose magnitude of the charge is below the detection limit of the instrument “non-charged raindrops”.

Observational site was situated on the northern part of a warm front as seen from the surface weather map shown in Fig. 2. It rained continuously with the intensity of a few mm/hr from 15.30 JST on April 11 to 4.00 JST on April 12 (Fig. 3). The results of analyses on continuous rain observed from 17.14 to 23.33 JST on April 11 will be described in following chapters.

There is no upper air station near Uji and we used aerological data at Yonago, Shionomisaki and Hamamatsu in our analyses. Aerological data at 21.00 JST are shown in Fig. 4. Freezing levels shown by open circles are around the level of 750 mb. A cloud layer defined by relative humidity of 100% is inferred from data at Yonago and Hamamatsu to lie between 780 and 560 mb over the observational site.
3. Radar-echo structure observed by a vertically pointing radar

Fig. 5 shows the time-height cross section of 10 Log Ze (Ze is the equivalent radar reflectivity factor) from 17.50 to 23.50 JST. Hereafter, we will call 10 Log Ze “echo intensity”. A bright band, which means the occurrence of melting of falling ice particles, was observed constantly at a height of about 2 km. An echo top defined by 20 dBZ was higher from 18.00 to 20.30 JST than that observed during other periods and rainfall intensity was also larger from 18.00 to 20.30 JST as seen in Fig. 3. Echo intensity was observed to be high intermittently from 20.30 to 23.00 JST. It became weak after 23.00 JST.

As seen in Fig. 5 the height of echo top defined by 10 dBZ varies with time. There are regions of high echo intensity between the levels of 4.0 and 6.4 km and some of them are depicted by closed contours—that is, Cell B and Cell C. These closed contours indicate that there are larger particles in higher concentrations in the regions than in surrounding regions. Distinct sloping streamers are recognized in Fig. 5, such as emanating from 5 km level at 18.00 JST, 19.25
JST and 19.50 JST. Traces of streamers can be also recognized after 20.30 JST. It has been postulated that for cellular echoes seen above the upper part of streamers are the regions where ice particles are produced and these regions have been termed "generating cell" (Marshall, 1953; Langleben, 1956). Echo patterns of closed contours (Cells B and C) would show the existence of generating cells which are in a vigorous stage as stated by Langleben (1956), Wexler and Atlas (1959) and Heymsfields (1977). In contrast, distinct streamers or their traces would suggest the existence of generating cells of a decaying stage as stated by the same authors (Cells A, D, E, F, G, H and I). It can be said that middle-level generating cells which were imbedded in a stratiform cloud passed in different stages of development over the radar site. As shown in Fig. 5, the streamer of Cell A is quite long and it passes just under Cells B and C. It is highly probable that graupel-like particles of large falling velocity which had been originated from Cells B and C felled through the streamer of Cell A. Though such a mixing process could not be clearly detected in the echo pattern obtained by the vertically pointing radar, it would be detected if we observe the time variation of echo pattern using a RHI radar in detail.

Fig. 6 shows the vertical profiles of echo intensity averaged for one hour with the height interval of 400 m. Echo intensity in the layer below the level of 5 km was larger during the period of 18.00 to 21.00 JST than during other periods. It became weak with time after 21.00 JST. It is interesting that larger increase in echo intensity with decreasing height is found between the levels of 4.6 and 2.6 km in the vertical profiles from 18.00 to 21.00 JST than those of any other periods. This fact indicates that precipitating particles grew also large in falling through the layer from −10°C level to 0°C level. Such a large increase is not found during other periods.

4. Electric field and precipitation current measured on the ground

Time variation of electric field showed a waved pattern seen in Fig. 7. The magnitude of electric field was ±2000 V/m at the highest. Comparing with Fig. 5, the electric field seemed to change its sign when generating cells (cells A to I) passed over the radar site. Though the largest amplitude of electric field were observed between 19.00 and 19.30 JST, rainfall intensity shown in Fig. 3 did not change so much during the same period. The second highest value of electric field was observed between 22.30 and 23.30 JST, but rainfall intensity was weaker.
during this period than before the period. Thus the time variation of electric field did not necessarily correspond to the variation of rainfall intensity.

Time variations of positive \( I_{\text{pr}^+} \), negative \( I_{\text{pr}^-} \) and net \( I_{\text{pr}^\text{net}} \) precipitation currents averaged for every one minute are shown in Fig. 7. The net precipitation current was mainly positive before 22.00 JST and it was always negative after 22.00 JST. An inverse relation between the polarity of electric field and that of net precipitation current hardly held. Especially after 22.00 JST the net precipitation current was always negative independently of the polarity of electric field. Occasionally the inverse relation seemed to hold such as from 20.00 to 21.00 JST and from 21.30 to 21.50 JST, though there were some time-lags in the appearance of their peak values. There seems to be a tendency that the absolute value of the precipitation current was large when the variation of electric field showed a large amplitude. Quite large precipitation currents were also observed between 19.00 and 19.30 JST in the same way as electric field.

There were two types of time variations of precipitation currents. In one type both \( I_{\text{pr}^+} \) and \( I_{\text{pr}^-} \) increased and decreased almost simultaneously as seen during the period of 18.00 to 19.30 JST. It is to be noted that it rained heavily and generating cells were in close vicinity to each other during this period, as seen in Figs. 3 and 5. In another type the increases in \( I_{\text{pr}^+} \) and \( I_{\text{pr}^-} \) occurred by turns as seen before and after the period of 18.00 to 19.30 JST.

As stated above rainfall intensity had not so good correlation both with electric field and with precipitation current. This fact indicates that rainfall intensity was not related directly to the electrical activity of clouds. On the contrary there was a rather good correlation between the time variation of maximum diameter of raindrops (Fig. 3) and that of precipitation current. The largest diameter of raindrops (3.2 mm) was observed between 18.50 and 19.20 JST when both \( I_{\text{pr}^+} \) and \( I_{\text{pr}^-} \) were quite large. It is suggested that the electrical activity of clouds was more closely related to the processes which produced large particles than the processes which caused the increase in rainfall amount, though more cases of observation will be needed for this suggestion to be verified more conclusively.

5. Electric charge and number flux of raindrops

1) Electric charge on raindrops

It is expected that the charge on individual raindrop would give more useful information than the precipitation current to study the processes of growth and charging of precipitation particles. We tried to average the positive charges and negative ones on raindrops obtained for one minute separately. Averaged positive and negative charges \( \bar{q}_+ \) and \( \bar{q}_- \) per one raindrop are shown for each size range in Fig. 8. Number fluxes of positively \( (N_+) \) and negatively \( (N_-) \) charged raindrops are also shown in Fig. 8 (we do not show number fluxes for all size ranges to avoid the complexity).

In all size ranges both positive and negative charges can be found out independently of the polarity of electric field. Though there was a little time-lag, the magnitude of averaged positive charge varied almost in phase with that of averaged negative charges. The time-lag between time variation of \( q_+ \) and that of \( q_- \) can be seen clearly between 18.00 and 18.30 JST for drops with 2.0 and 2.4 mm in diameter. There were not so large differences between the magnitudes of averaged positive and negative charges at each time, though number fluxes of positively charged raindrops were not the same as those of negatively charged raindrops. It seems that the larger the diameter of drops was, the larger magnitude of averaged charge was and the earlier the increase in the magnitude started, as clearly seen from 18.00 to 18.30 JST and from 19.00 to 19.30 JST. Apparently Wilson's induction theory alone could not explain the charge-size relation of raindrops reported here.

It seems that there was an inverse relation between \( N_+ \) and \( N_- \). For example, \( N_+ \) of raindrops with 1.2 mm in diameter gradually increased from 17.20 to 17.30 JST and it decreased from 17.30 to 17.40 JST. On the other hand \( N_- \) of raindrops gradually increased from 17.30 to 17.40 JST and it decreased from 17.40 to 17.50 JST. It is interesting that \( N_+ \) (or \( N_- \)) does not necessarily vary with time in phase with \( \bar{q}_+ \) (or \( \bar{q}_- \)).

Between 18.00 and 20.00 JST number fluxes of raindrops smaller than 0.8 mm in diameter were quite small, and between 18.50 and 19.30 JST number fluxes of drops with diameter larger than 1.6 mm were also larger than those during any other periods. The magnitude of electric field and that of precipitation current were also large. The magnitude of charge on raindrops observed from 18.50 to 19.30 JST was larger for all size ranges by one or two orders than that...
Fig. 8 Time variations of averaged positive ($\bar{q}_+$; full circles) and negative ($\bar{q}_-$; crosses) charges per one raindrop and those of number fluxes of positively ($N_+$) and negatively ($N_-$) charged raindrops in each size range. The scale of the ordinate during the period of 18.35 to 19.40 is larger by one order than that of any other periods.
Table 1. Typical values of raindrop charge observed by us and those by other authors.

<table>
<thead>
<tr>
<th>Cloud and rainfall type or time</th>
<th>Raindrop charge</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain showers (thundery)</td>
<td>+1.30 pC</td>
<td>Smith (1955)</td>
</tr>
<tr>
<td>Continuous rain (thundery)</td>
<td>+0.18 pC</td>
<td></td>
</tr>
<tr>
<td>St, Sc</td>
<td>+0.54~0.02 pC</td>
<td>Ratcliffe et al. (1969)</td>
</tr>
<tr>
<td>Shallow cumulus cloud (warm cloud)</td>
<td>+0.0042~0.0008 pC</td>
<td>Takahashi and Fullerton (1972)</td>
</tr>
<tr>
<td>Towering Cu, Cb (pre-monsoon)</td>
<td>+1.79 pC</td>
<td>Selvam et al. (1977)</td>
</tr>
<tr>
<td>Sc and St (monsoon)</td>
<td>+0.66~0.37 pC</td>
<td></td>
</tr>
<tr>
<td>Towering Cu, Cb (post-monsoon)</td>
<td>+0.74 pC</td>
<td></td>
</tr>
<tr>
<td>17.50 JST</td>
<td>+0.06 pC</td>
<td></td>
</tr>
<tr>
<td>18.17 JST</td>
<td>+0.54 pC</td>
<td></td>
</tr>
<tr>
<td>19.10 JST</td>
<td>+0.18 pC</td>
<td></td>
</tr>
<tr>
<td>19.14 JST</td>
<td>+2.54 pC</td>
<td></td>
</tr>
<tr>
<td>23.07 JST</td>
<td>+0.52 pC</td>
<td></td>
</tr>
<tr>
<td>23.09 JST</td>
<td>~1.51 pC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>~0.14 pC</td>
<td></td>
</tr>
</tbody>
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observed at any other periods. These facts suggest again that electrical activity of clouds is closely related to the processes which produce large particles.

We showed our typical values of charge together with those obtained by other authors in Table 1. Though the value varies with drop size, we chose the values of charge on raindrops with 1.2 mm in diameter, for precipitation current was largest in this size range. We observed the largest magnitude of negative charge and that of positive charge at 19.10 and 19.14 JST, respectively. Our values are nearly equal to those of continuous rain obtained by other authors (e.g. Ratcliffe et al. (1969) and Selvam et al. (1977)), except for the values at 19.10 and 19.14 JST, which are as large as the charge on drops from thunderclouds. This fact indicates that precipitation particles in such clouds as observed by us could be charged to the same magnitude as particles in thunderclouds, even if the rain seems to be a continuous-rain type, under certain circumstances which will be discussed later.

2) Ratio of number fluxes of charged and non-charged raindrops to total number flux

Many authors reported that both positively and negatively charged raindrops were observed simultaneously. However, it is not apparent whether they are mixed at random or regularly. In our case there seemed to be a regular time variation in number fluxes of positively and negatively charged raindrops as mentioned before. In order to clarify this, we showed the ratios of number fluxes of positively charged ($N_+$), negatively charged ($N_-$) and non-charged raindrops to total number flux ($N$) every one minute in Fig. 9. Solid and dotted lines indicate $N_+/N$ and $N_--/N$, respectively. Full circles in the figure mean that all raindrops were non-charged at that time.

It is to be noted that the increase and the decrease in ratios of $N_+/N$ and $N_--/N$ occurred alternately. Positively charged raindrops were observed predominantly before 17.30 JST, negatively charged ones were predominant in turn around 17.40 JST, positively charged ones were predominant again around 18.00 JST and so on. It is also found that for larger raindrops $N_+/N$ and $N_--/N$ tend to be replaced more completely, and that with decreasing diameter positively and negatively charged drops tend to be mixed and further the ratio of number flux of non-charged raindrops to total number flux increased. It is interesting that the peak value of $N_+/N$ (also $N_--/N$) appeared earlier with increasing diameter. There seemed to be a tendency that $N_+/N$ (or $N_--/N$) became large with the increase in the negative (or positive) value of electric field only for the raindrops with diameter less than 0.8 mm.

All of facts written in this chapter also indicate that the charge of larger raindrops could not be explained by Wilson’s induction theory alone.
Fig. 9  Time variation of ratios of number fluxes of positively charged, negatively charged and non-charged raindrops to total number flux. Dotted and solid lines indicate $N^-/N$ and $N^+/N$, respectively. Full circles mean that all raindrops are non-charged at that time.
6. Discussion

Observed rainfall would be roughly classified into following three periods on the basis of the results stated above.

Period A (18.00 to 20.00 JST)

Echo intensity was high, especially in the layer below the level of 5 km, and a large increase in echo intensity with decreasing height was found between 4.6 and 2.6 km. Generating cells at middle levels were in close vicinity to each other and some of them were observed to be in a vigorous stage. During the period it rained heavily and number fluxes of large raindrops were larger than those during any other periods. These facts suggest that the cloud system would have mainly composed of generating cells of a vigorous stage in this period. Both the magnitude of electric field and the charge on raindrops were also larger. Positive and negative precipitation currents increased and decreased almost simultaneously, but net precipitation currents were mainly positive.

Period B (22.00 to 23.33 JST)

The height of echo top defined by 10 dBZ was almost the same as other periods, but that defined by 20 dBZ was lower than those during other periods. Traces of streamers (in other words, generating cells of a decaying stage) were observed intermittently. It rained lightly and the diameter of raindrops was smaller than those during other periods. These facts suggest that the cloud system would have mainly composed of generating cells of a decaying stage in this period. Though electric field changed its polarity with time, net precipitation currents were mainly negative because positively charged raindrops were very few.

Period C (17.14 to 18.00 JST and 20.00 to 22.00 JST)

A distinct streamer and traces of streamers (namely, generating cells of a decaying stage) were observed intermittently. The increase in the positive and negative precipitation currents occurred by turns.

We will discuss the origins of positively and negatively charged raindrops.

1) Melting effect

As noted before Wilson's induction theory could explain only a part of observational results. It was stated by Magono and Kikuchi (1963, 1965) that when ice particles melt, they lose some part of negative charge and the magnitude of lost negative charge varies with their types. However this would not be the main process which caused raindrops to be charged positively in present case, because such a large difference in magnitude of charge among raindrops as observed by us could not be produced only by the melting process.

2) Processes in the falling of particles

Fig. 10 shows rainfall intensity and precipitation currents in each size range during the periods of 18.30 to 18.39 JST and 20.20 and 20.29 JST. It is shown in Fig. 5 that during the periods the lowest part of the streamers, which were associated with Cell A and Cell E, passed over the radar site. Though both of streamers seem to have originated from the same height of 5 km and the values of surface electric field were negative during both periods, there is a contrast between the charge-size distributions of two streamers. Positive precipitation currents are larger than negative ones for all of size ranges between 18.30 and 18.39 JST. In contrast, negative ones are predominant for drops with diameter larger than 1.4 mm between 20.20 and 20.29 JST.

The increase in echo intensity with decreasing from 4.2 km (−10°C level) to 2.6 km (0°C level) along the streamer quite larger in the former streamer than in the latter streamer. The large increase in echo intensity seen in the former streamer could not be given by sublimational process and the accretion of cloud droplets. Aggregation among ice particles would have been active in the former streamer. It is possible to account for such an active aggregation as a result of supply of ice particles from other generating cells, as suggested before. It is to be noted that the region (between the −10°C and 0°C isotherms) where aggregation process is inferred to have been active was in the layer where charge generation is generally said to be active. In the former streamer the charge-size
distribution of particles would have been modified remarkably by the processes which particles underwent during their falling.

3) Stages of generating cells
   As stated before, during Period A the cloud system mainly composed of generating cells of a vigorous stage passed over the radar site and positively charged raindrops were predominant on the ground. During Period B the cloud system in which most of generating cells were in a decaying stage was observed and negatively charged raindrops were predominant. These facts suggest that positively charged particles would be supplied from generating cells of vigorous stages and that negatively charged particles would be originated from generating cells of decaying stages.

4) A hypothetical model
   Our simultaneous observations of electric field and radar echo structure, which were made for middle-level precipitating clouds in 1978 and 1979, show that electric field seemed to vary with time roughly in two ways—steady pattern and waved one. In the former pattern the sign of electric field remained positive or negative and the amplitude of variation was rather small. In the latter pattern electric field changed its sign and its amplitude was large such as seen in the present case. Especially in the case that electric field changed its sign very frequently and its amplitude was quite large, generating cells were observed to have been in close vicinity to each other in the same way as shown in Period A. As an example of the latter pattern we show the case of Feb. 23 in 1979 in Fig. 11 and Fig. 12. The electric field showed the waved pattern after 19.00. The vertical cross section of radar echo at 19.20 is shown in Fig. 12. The bright band appeared at the height of 3 km and there were some streaks which imply the existence of generating cells aloft. When generating cells were in close vicinity to each other as seen on the left side of Fig. 12, there were echoes of large intensity even between the cores of streaks and it would be expected that the mixing of precipitation particles from different generating cells occurred there.

   On the basis of observational facts, a following hypothetical model can be proposed so as to interpret the relation between the radar-echo structure of precipitating clouds and their electrical features.

   It will be reasonable to say that generating cells produced densely rimed crystals and graupels predominantly in or near the centre of the updraught in their vigorous stage and they produced non-rimed crystals predominantly in their decaying stage. Magono and Orikasa (1966 a) and Kikuchi (1975) observed that rimed crystals or graupels were positively charged and that non-rimed snow crystals were negatively charged. Takahashi (1978) gave the charge of a graupel as a function of temperature and cloud water content from the laboratory experiment. It would be reasonable, even if taking into this result, to say that graupel were charged positively in our case. Because generating cells are suggested to have been between the levels of 4.0 and 6.4 km (that is, −5 and −15°C) and cloud water content in these cells would
not have been so large as in the thunder cloud. Now we will suppose the hypothetical situation shown schematically in Fig. 13. In this situation three generating cells which are in a decaying stage (a), in a vigorous stage (b) and in a decaying stage (c), respectively, are lined closely, and positively charged particles are falling predominantly from the cell of a vigorous stage and negatively charged particles are falling predominantly from the cells of a decaying stage continuously. Falling particles would be sorted in prevailing wind with vertical shear in accordance with their sizes, and particles of smaller falling velocity would have a large chance to be dispersed into a broad area in their falling. Therefore it is expected that smaller particles charged positively or negatively are distributed more widely on the ground than larger particles and that they are mixed easily with each other. If such a cloud system passes over the observational site without a remarkable change, the number fluxes of positively and negatively charged particles and the ratio between them would vary with time at the site in the rate shown in Fig. 13. The time variations of the fluxes are qualitatively in good agreement with the results shown in Figs. 8 and 9. It is tempting to suppose that the situation of clouds observed at Period A was similar to that shown in Fig. 13.

During Period A positive and negative charges per one raindrop \((q_+\) and \(q_-)\) which were averaged every one minute were quite large and they were nearly the same each other. Both values varied almost in phase. But the number flux did not vary with time in phase with averaged charge. As discussed before there was a rather good correlation between the time variation of maximum diameter of raindrops and that of the electrical activity of clouds. We can account for these results reasonably in the following way, provided that particles supplied from generating cells of different stage are mixed in their falling.

Laboratory experiments of Magono and Takahashi (1963) suggest that if rimed crystals or graupels are mixed with non-rimed crystals in their falling in the region lying between the \(-10^\circ\)C and \(0^\circ\)C isotherms, the former particles would be recharged positively and the latter would be recharged negatively through friction process. Even if the size of particles is the same, the magnitude of their charges would differ greatly in accordance with the degree of recharging. Therefore the peak values of averaged charges \((\bar{q}_+, \bar{q}_-)\) would appear naturally between the peak values of \(N_+\) and \(N_-\), and the increase in averaged positive charge would occur in nearly the same time as that in averaged negative charge (Fig. 14). The good correlation of averaged charges with maximum diameter of raindrops, which is seen in Fig. 3 and Fig. 8, would imply that the aggregational growth of ice particles and the frequent occurrence of frictional charging are closely related to.

5) **Particles from stratiform cloud**

Until now we did not take into account particles falling from stratiform cloud in which generating cells were imbedded. Most of raindrops observed on the ground would be ascribed
Fig. 14 Supposed time variations of charge (a), number flux of particles (b) and the ratio (c).

6) Inverse relation

The inverse relation between the polarity of electric field and that of charge on raindrops or the precipitation current was hardly seen in present case. It could not be also seen in other cases which will be reported in another paper. However the inverse relation between the polarity of electric field and the ratio of the number flux of positively charged raindrops to that of negatively charged ones was seen for the raindrops smaller than 0.8mm in diameter (Figs. 7 and 9). Although small ice particles are easy to change the polarity of their charge through melting process, the inverse relation would not be explained only by the effect of melting. It might be possible to interpret that the polarity of their charge changed by ion capture process suggested by Smith (1955). More detailed discussion on this problem will be done in another paper.

7. Summary

Observations of middle-level precipitating clouds were made in order to study how the electrical properties of raindrops vary with the fine structure of clouds and micro-physical processes in clouds, using a vertically pointing radar, a field mill and an optical spectrometer with a charge detector. Clouds were situated on the northern part of a warm front and it rained continuously for about twelve hours.

Main observational results are as follows. Generating cells of various stages were imbedded in the cloud system and surface electric field showed a waved pattern. When the cloud system in which generating cells were in a decaying stage passed over the radar site, negatively charged raindrops were predominant. When the cloud system in which most of generating cells were in a vigorous stage passed over the radar site and in which a large increase in echo intensity with decreasing height was found between 4.6 ($\sim -10^\circ$C level) and 2.6 km ($0^\circ$C level), positively charged raindrops were predominant and quite large averaged charges were observed. It is an observational fact to be noted that a quite long streamer originated from a generating cell passed just under other cells. Averaged values of positive charge per raindrop were nearly equal to those of negative charge and they varied almost in phase with averaged values of negative charge. But the number flux of positively or negatively charged drops did not vary with time in phase with the averaged charge of each sign. There was a rather good correlation between the time variation of maximum diameter of raindrops and that of electrical activity of clouds. The inverse relation between the polarity of electric field and the ratio of the number flux of positively charged raindrops to that of negatively charged ones was seen only for raindrops smaller than 0.8 mm in diameter.

Wilson's induction theory could explain only a part of these observational results. We can account for the results reasonably if we suppose that positively charged particles supplied from the generating cell of a vigorous stage are mixed with negatively charged ones supplied from the cell of a decaying stage in their falling and that the mixing occurs in the region lying between the $-10^\circ$C and $0^\circ$C isotherms. That is, in this case precipitation particles would grow by aggrega-
tional process and they would be recharged through friction process.

Acknowledgements

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中層降水雲のレーダーエコー構造と雨滴電荷 (I)

--- Generating cells からの降水粒子の混合過程 ---

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中層降水雲の観測を、垂直レーダー、電場計、雨滴粒度・電荷測定装置を使用して行ない、雨滴の電気的特性が雲の微細構造及び雲内の微物理過程の変化と共に、どのように変化するかを調べた。
主な結果は次の通りである。generating cell の多くが活発な状態にあり、−10℃ 高度から 0℃ 高度にかけてニューグル强度が大きく増加するような降水雲系からは、正に帯電した雨滴が卓越して降り、帯電量の平均値も極めて大きかった。観測した降水雲系全体として、雨滴個数の正の電荷と負の電荷とは、ほぼ同位相で、その大きさは変化し、帯電値も互いにほぼ等しかった。然し、正又は負に帯電した雨滴の数フラックスは、帯電量の変化とは必ずしも同位相ではなかった。雨滴の最大直徑の時間変化と雨滴の帯電量の大きさとは、比較的良い相関が見られた。

これらの主な観測結果は、活発な generating cell から降る正に帯電した粒子が、衰弱した generating cell から降る負に帯電した粒子と、落下中に高度より上で混合し、これらの降水粒子が併合過程により成長すると共に、摩擦過程によって再帯電したと考えることにより説明される。