Electric charge on raindrops grown in warm clouds over the island of Hawaii

By TSUTOMU TAKAHASHI and KENJI ISONO, *Water Research Laboratory, Faculty of Science, Nagoya University, Nagoya, Japan*

(Manuscript received January 27, 1967)

ABSTRACT

Measurements of electric charge on raindrops in and beneath warm clouds over the Island of Hawaii were carried out with the use of radiosonde and ground equipment in the summer of 1965. In the case of shower type rain, raindrops were observed to have a considerable amount of positive electric charge while a reversal of the normal fair weather electric field intensity was observed at the ground level.

Radiosonde observations revealed that raindrops with positive charge were present in the lower part of clouds and that raindrops with negative charge predominated in the upper part.

In the case of continuous rain, the electric field intensity at the ground level showed increased positive values, and raindrops with negative charge were sometimes observed at the ground stations. The features of the electrification of raindrops in these different precipitation types are described.

Introduction

Measurements of electric charges on raindrops in clouds aloft and at the ground stations were made during the Japan–U.S. cooperative program in Hawaii in the summer of 1965. The purpose of our measurements was to obtain basic data important in the elucidation of electrification mechanisms in warm clouds. It has been widely believed that precipitation particles of the ice-phase play a weighty part in the charge generation in the thundercloud (Workman, 1950; Brook, 1958; Mason, 1953, etc.). Vonnegut (Vonnegut, 1954), on the other hand, observed that there was lightning even in warm clouds, and proposed a mechanism for the electrification of a warm cloud by atmospheric ions.

Measurements of electric charges on raindrops beneath warm clouds will give us an important clue as to the role which precipitation particles of the liquid phase play in the electrification process.

In middle latitudes, raindrops usually grow from particles of the ice phase and electrification occurs in both the ice-stage and the liquid stage. In order to elucidate the electrification processes it is desirable to learn more about electrically charged precipitation particles in a pure solid-state and in a pure liquid-state separately.

The electric charge measurements of snow crystals and graupel pellets were carried out in the Hokuriku region during the winters of 1963 and 1964 by our group (Isono, Komabayasi & Takahashi, 1966).

The result of the present study on the electrification of raindrops will give us an important suggestion on the electrification process even in cold clouds.

Description of the instruments used

(a) *Electric charge radiosonde*

The radiosonde transmitter used for measuring the electric charge on precipitation elements (Takahashi, 1966) consists of a receiving dish for collection of precipitation particles and a D.C. electrometer amplifier with sufficient power to drive a radiosonde transmitter. The collecting dish is 7 cm in diameter and 15 cm in depth and contains a sheet of filter paper in order to minimize the splash of raindrops. This dish is held coaxially within an outer aluminium cylinder 15 cm in diameter and 100 cm in height and is insulated from the outer cylinder by teflon (Fig. 1). In order to avoid splashing of raindrops at the outer aluminium wall onto the dish, an aluminium cap with a 5×5 cm^2 opening

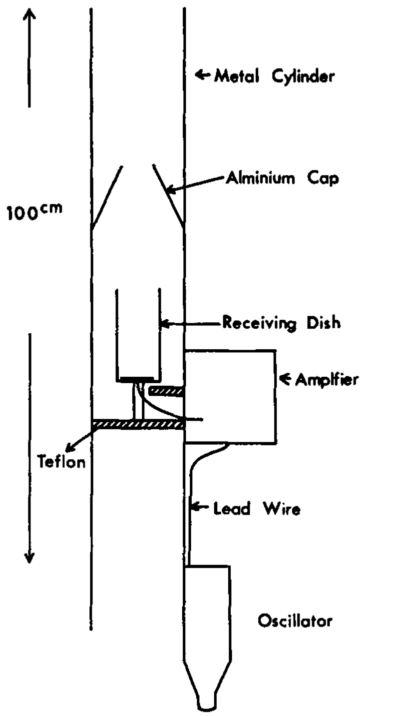
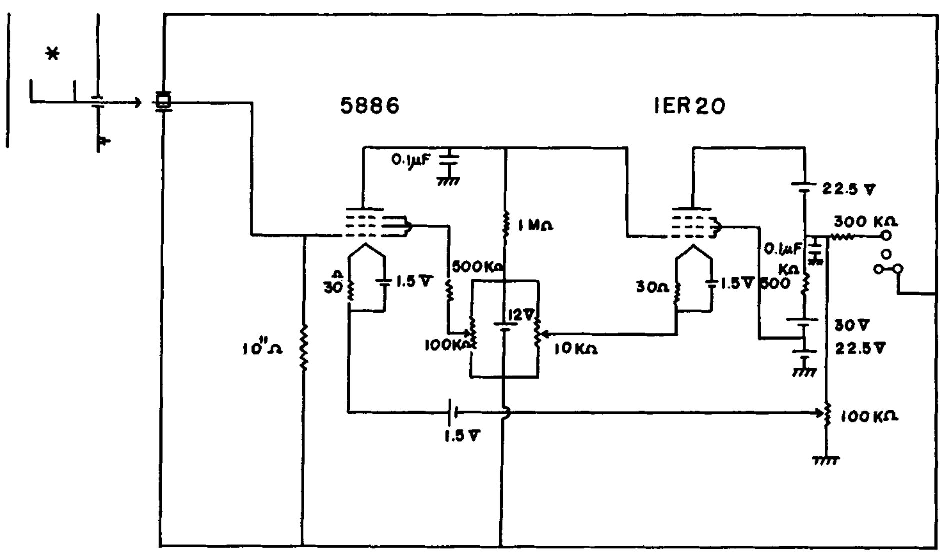


Fig. 1. Schematic diagram of radiosonde transmitter for measuring electric charge on raindrops.

at the center is mounted over the collecting dish. The voltage across the resistor ($4 \times 10^{10}\Omega$) between the dish and the outer cylinder is measured with a D.C. electrometer amplifier which has nearly the same electronic network as that used for measuring potential gradient in the atmosphere by Hatakeyama and others (1958).

A circuit diagram of the amplifier of the radiosonde transmitter is shown in Fig. 2. The time constant of the input part of this sonde is 1 second. A radiofrequency oscillator operates at 1680 MC and the modulator for imposing information on the radiofrequency carrier is a blocking oscillator whose repetition rate of 20 c/s to 200 c/s is controlled by the output voltage of the D.C. electrometer amplifier. The modulator works at a frequency of about 110c/s when a water drop without charge falls onto the inner dish and works between 110 c/s and 200 c/s for positively charged drops and between 110 c/s and 20 c/s for negatively charged drops. An electric charge of 5×10^{-4} e.s.u. is the limit of detection of this radiosonde. The signals are received by a GMD-IA type receiving set with a recorder. The relation between the indication of the recorder and the amount of electric charge was calibrated before each ascent by using water drops having various values of



ELECTRIC CIRCUIT

Fig. 2. Circuit diagram of the electric charge radiosonde.

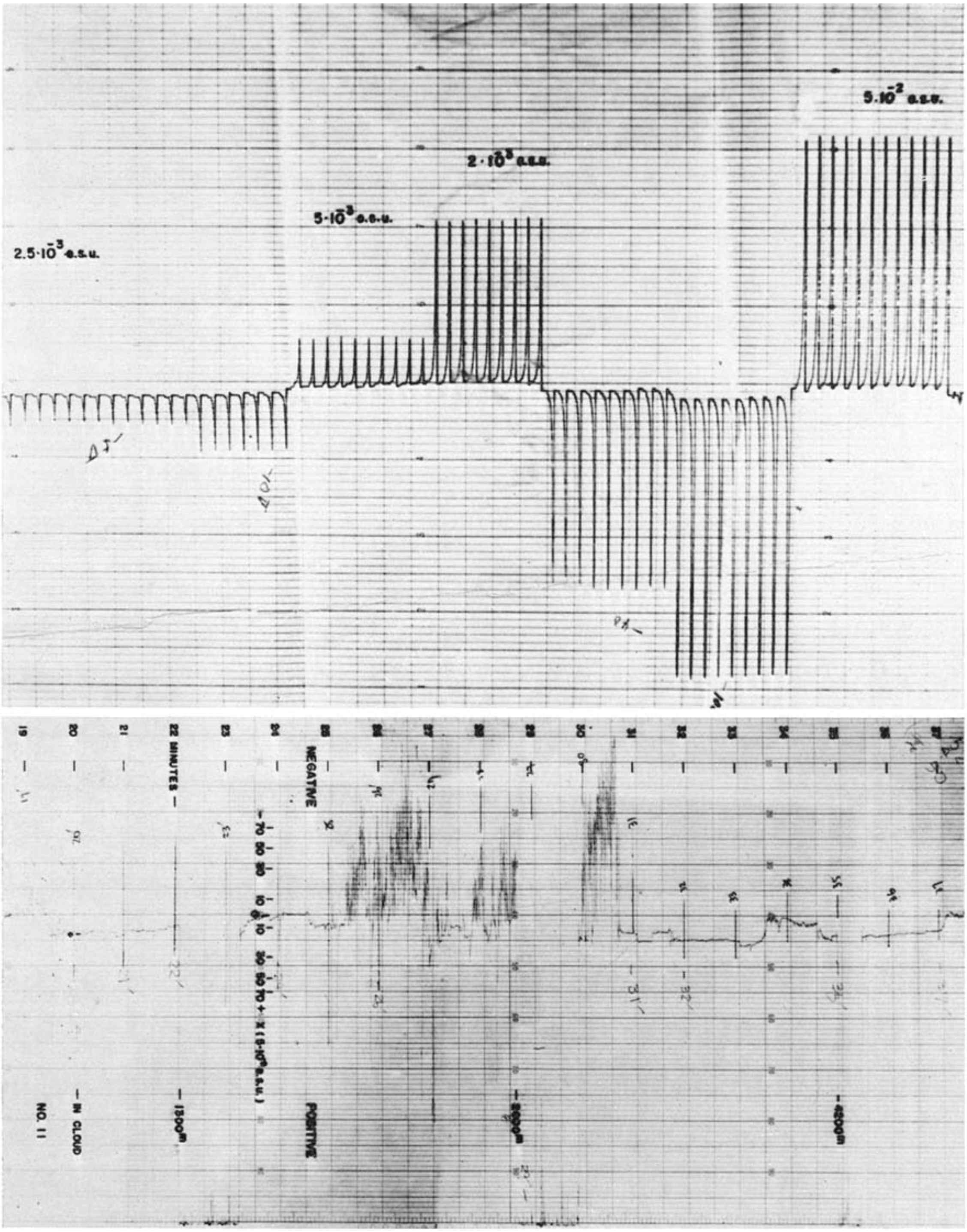


Fig. 3. An example of records for calibration of the electric charge radiosonde (*upper*). An example of records of the electric charge radiosonde, Ascent No. 11 (*lower*).

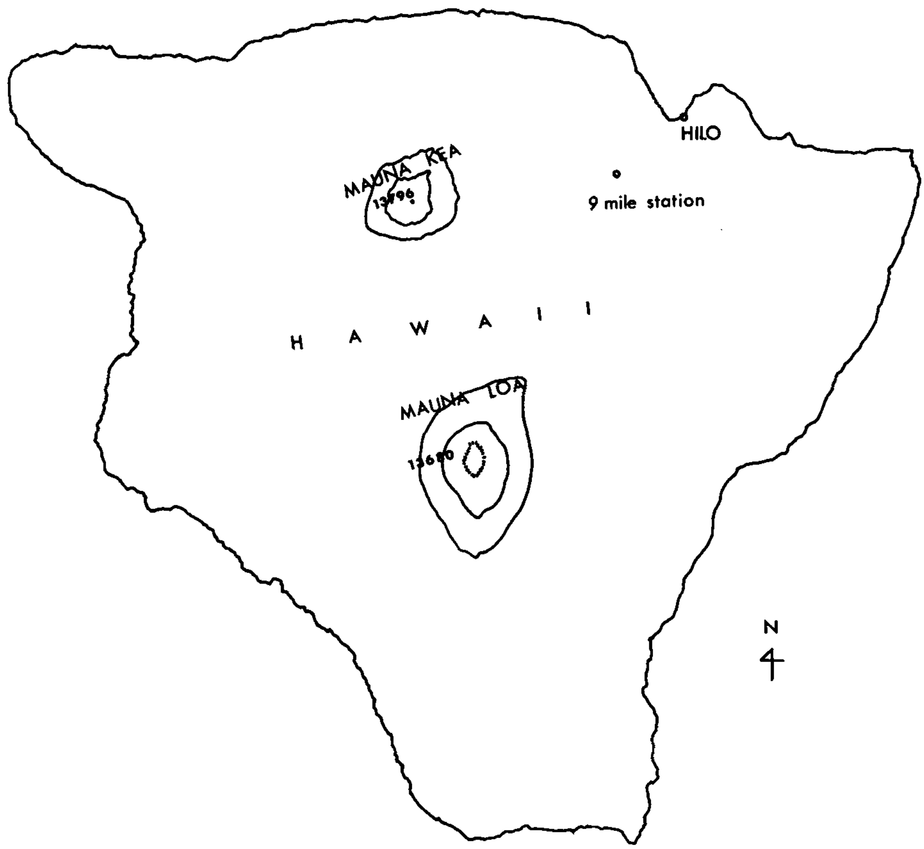


Fig. 4. Sites of Observation, the 9 mile station and Hilo Weather Bureau.

electric charge. An example of the calibration is shown in Fig. 3. The radiosonde transmitter is hung 50 m below the balloon to avoid large water drops shed by the balloon.

(*b*) *Instrument for continous recording of electric charge on raindrops at the ground station*

The voltage across the resistor, a 1 Q19 tube ($10^9\Omega$), between the collecting dish for raindrops and ground is amplified by a UX54B tube and a 12AT7 tube. The electric power of this signal is amplified and recorded by a Mini-writer. 10^{-4} e.s.u. of electric charge is the limit of detection of this instrument. In order to avoid the induction effect due to abrupt variations of electric field, an aluminium cylinder of 19 cm in diameter and 150 cm in height was mounted over the inner collecting dish and connected to ground. A sheet of filter paper was put in the inner dish (7 cm in diameter and 1 cm in depth) to minimize the effect of splashing of raindrops. The number of raindrops was counted by use of a filter paper soaked with dyes (water blue).

(*c*) *Instrument for measuring the electric field*

The instrument for measuring of electric field is the field mill type (see Chalmers, 1949).

Observation sites

The ascent of electric-charge radiosondes, measurements of electric charge on raindrops and measurements of electric field were mainly carried out at the 9 mile station, which was on the slope of Mauna Kea, 9 miles to the southwest of Hilo city, Hawaii Island (Fig. 4). Such observations were also made at the Hilo Weather Bureau for one week at the end of the period of the observations.

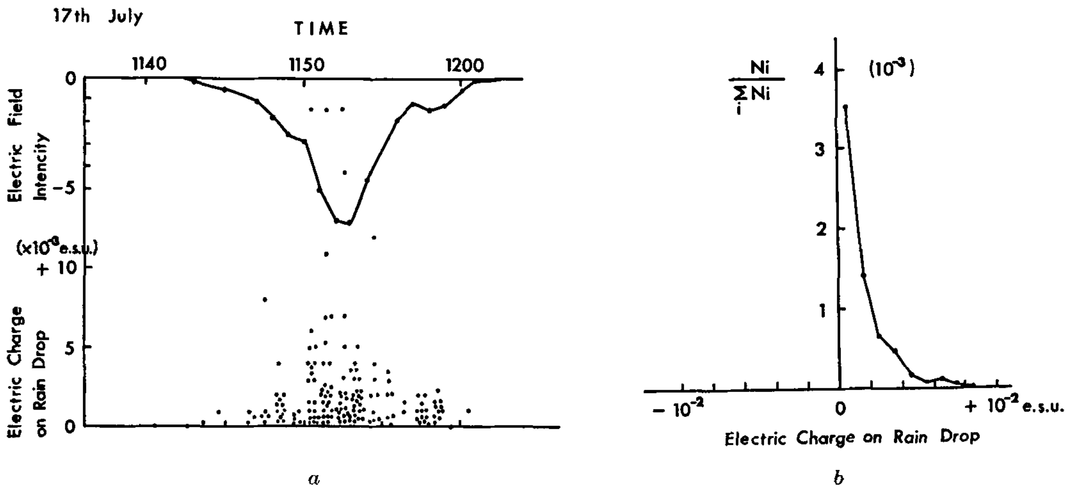


Fig. 5. (*a*). Electric charges on individual raindrops (*dots*) and electric field intensity observed at the 9 mile station during a shower, 17th July 1965. (*b*) Frequency of electric charge on single raindrops.

Observational results

(a) Shower

A typical example of the mode of time variation of electric charge on individual raindrops and of the electric field obtained at the ground station (9 mile station) measured in units of electric field intensity in fine weather are shown in Fig. 5*a*.

The time variation of electric field showed a concave curve and the field was negative during the shower. Positively electrified raindrops were recorded while the electric field was negative. The maximum electric charge on raindrops was 10^{-2} e.s.u. The relative frequency of raindrops as a function of the amount of electric charge per drop is shown in Fig. 5*b*. About one per cent of raindrops (limit of diameter ascertained by the filter paper soaked with dyes was 0.2 mm) had an electric charge larger than 5×10^{-4} e.s.u.

The results of three electric charge radiosonde observations are shown in Fig. 6. The first two radiosonde transmitters were launched from the 9 mile station and the third was launched from Hilo Weather Bureau. The electric field and the precipitation current at the ground are shown below the figures for each electric sign separately. In every case of shower type rains, the electric field showed a concave parabolic curve. Both negative and positive electric charges were observed on raindrops at the ground station on 29th July, 1965. Those cases in which raindrops were negatively electrified while the electric field was also negative, was very small in number for shower type rain, and the ratio of the number of such cases to those cases having positively electrified raindrops combined with negative fields was 1/12.

Positively charged raindrops were observed by radiosonde ascent No. 3 on 29th August. The height of maximum electric charges and the maximum number of electrified raindrops was at a level of nearly 2.5 km. No electrified raindrops were found above the 3 km level.

The results obtained on 9th August are shown in the middle of Fig. 6. Negative electric field intensity and raindrops with positive charge were observed at the ground station. The radiosonde ascent, No. 9, also showed raindrops with positive charge up to the 2.1 km level, above which raindrops with negative charge were observed. No charged raindrops were found above 3.2 km.

Radiosonde transmitter No. 11 was launched on 22nd August from the Hilo Weather Bureau near the coast. The electric field intensity record showed a concave curve with negative values. At levels between 2 km and 3 km negatively charged raindrops were observed in this sounding. Above the 3 km level electric charges on raindrops decreased abruptly. Transmitter No. 10, launched from the 9 mile station, was tracked by the radar of the Illinois Group. The

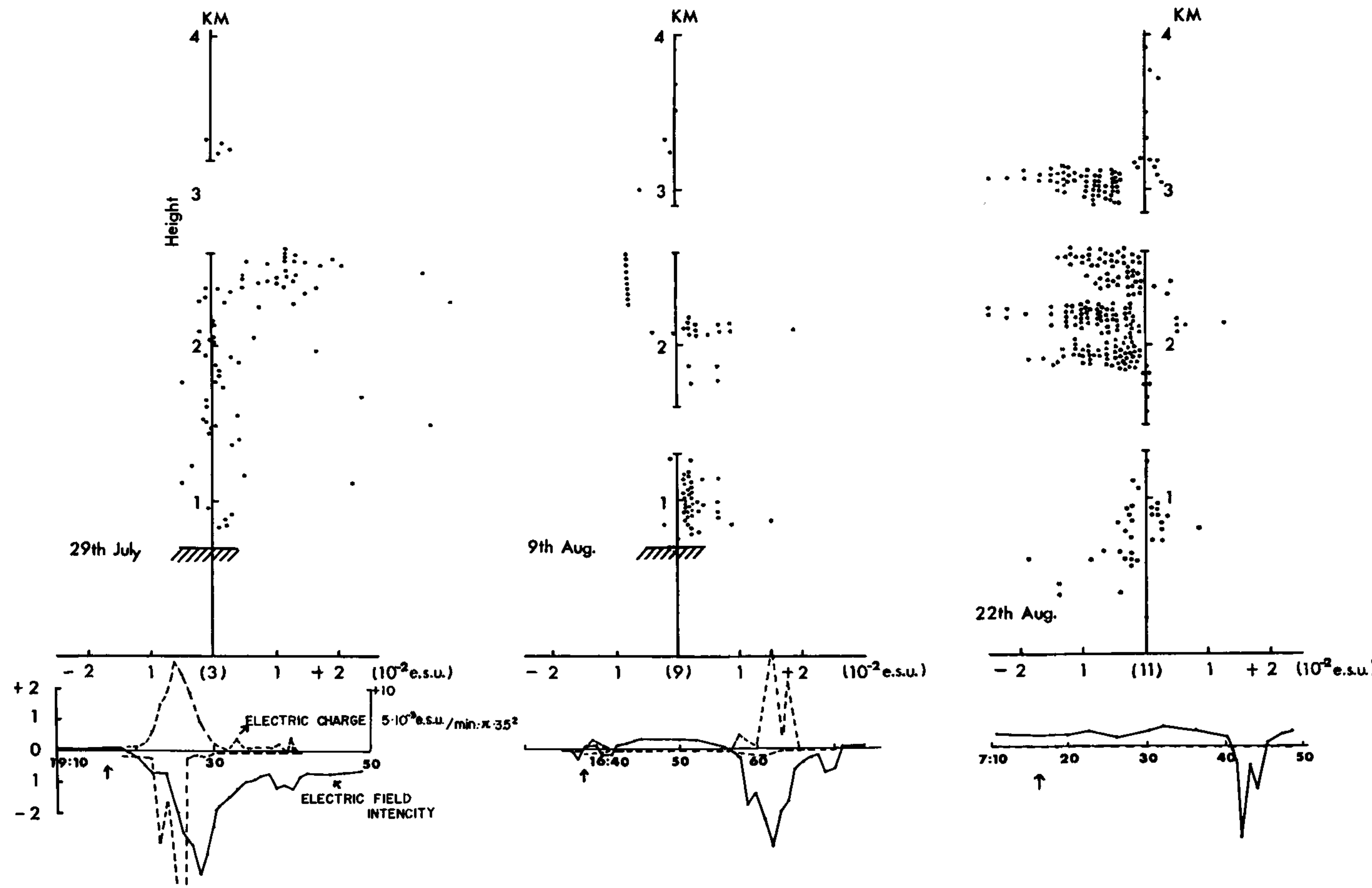


Fig. 6. Vertical distribution of charge on raindrops (*dots*) during showers on 29th July, 9th August, 22nd August 1965 (*upper*). Electric field intensity (*full line*), positive and negative charge on single raindrops (*dotted*) during the respective showers.

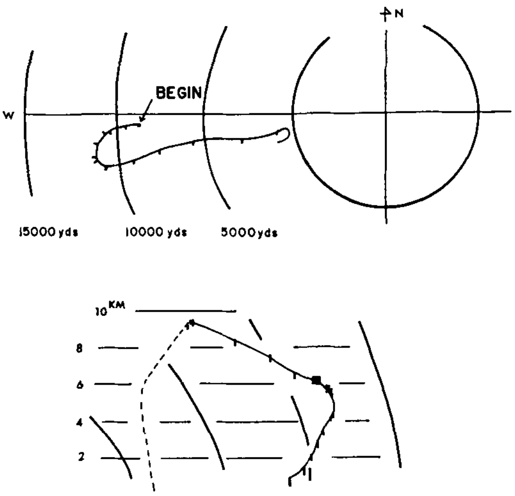
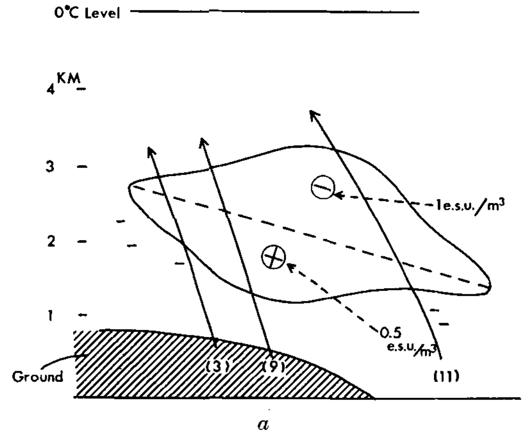
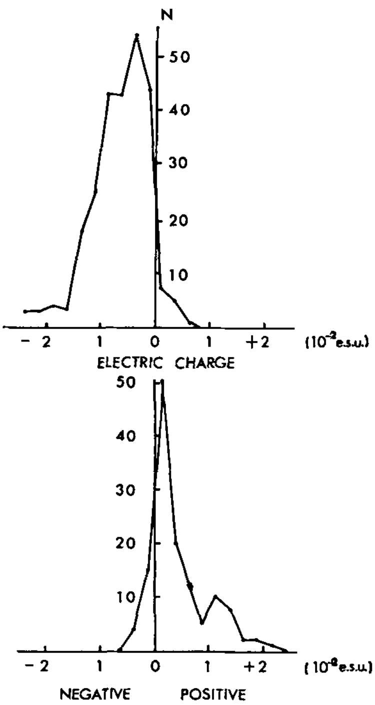


Fig. 7. The locus of radiosonde transmitter No. 10; horizontal projection (*upper*) and vertical projection.

locus of the transmitter is shown in Fig. 7. The transmitter at first was carried toward the west and came back toward the east at a height of 5 km. Radar observations showed that echoes over the sea were of the solid type and that they became diffused over the 9 mile station. From this information, transmitter No. 10 may be presumed to have ascended across the top part of a cumulus cloud. Similar consideration of the flight paths of transmitters No. 13 and No. 9 launched from the 9 mile station lead to the inference that they passed through the upper part of clouds and measured the electric charge distribution in that part. Further it appears that transmitter No. 11 launched from the Hilo Weather Bureau passed through the middle part of clouds. A model of electric charge distribution deduced from these radiosonde observations is shown in Fig. 8. As shown in the figure, raindrops with positive charge were found in the upper part of the cloud. The height of the boundary between positive and negative domains in shower type clouds was above 2 km in height. Electric charge densities in each part were -1 e.s.u./m.^{3} and $+0.5$ e.s.u./m^3 respectively, values which are one order of magnitude smaller than would be expected in a thundercloud. These rather large values of electric charge density indicate that there is some possibility of having lightning even in warm rain clouds by the electrification of raindrops. The frequency distribution of charge magnitude in



a



b

Fig. 8. A model of electric charge distribution of shower type clouds composed from results obtained by soundings by the electric charge radiosonde. The diagrams on the left side shows the frequency distribution of positive and negative charges respectively.

electrified raindrops is shown in Fig. 8 *b*. The upper diagram is the result of radiosonde 3 and the lower diagram is that of radiosonde 11. Negative electric charges of 5×10^{-3} e.s.u. in the upper part of the cloud and positive

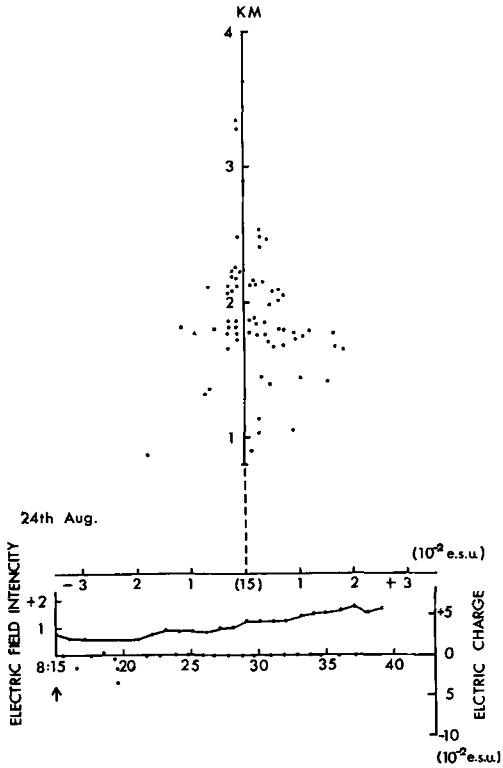


Fig. 9. Vertical distribution of charges on raindrops (*dots*) (*upper*) and electric field intensity (*full line*) and electric charges on raindrops (*dots*) during a continuous rain.

electric charges of 1×10^{-3} e.s.u. in the lower part of cloud were the modal values.

(*b*) *Weak shower type cloud*

When a shower was light, the electric field intensity was positive during the shower and showed a slight concave curve as shown in Fig. 9. Radiosonde transmitter No. 15 launched during this period indicated both positive and negative electric charges in the cloud. This cloud may be at the premature stage of a shower cloud and it is felt that electric charge separation in the cloud was still poorly developed at this stage.

(*c*) *Continuous rain*

A case of continuous rain which fell over an extensive region is shown in Fig. 10. Electric field intensity became more positive during the precipitation in contrast with the cases of shower type rains described above. Negative electric charge was sometimes observed at the ground station. Radiosonde ascent No. 13 at the Hilo Weather Bureau indicated large positive electric charges at a height of 1.5 km, and there were no electrified raindrops above 2 km. In this case, the electric charge distribution may be considered to be such that positive electric charges existed in the upper part of the cloud with negative electric charges in the lower part. The electric charge distribution in cloud is in contrast with that of the shower type cloud.

Discussion

The inverse relation between the sign of electric charges on raindrops and field intensity, has been reported by many workers (cf. Chalmers 1957). Smith (1955) has suggested that the charge is produced by the splashing of the raindrops at the earth's surface with charged splash droplets remaining in the air. In the case of the apparatus used for measuring charge on individual raindrops at the ground station, the raindrops fell through an aluminium funnel (19 cm in diameter and 150 cm in height) before being measured. If there fell many small negatively charged droplets which were so small that they did not leave stains on filter paper, negative charge would still be detected by the charge recorder. But in the case of showers which were accompanied by negative electric fields such negative charges were usually not detected.

This seems to suggest that splashed droplets were not responsible for the negative electric field intensity near the ground. However, there is a possibility that splashed droplets were so small that they could not fall through the funnel and reach the collecting dish due to wind or evaporation.

Concerning the positive charges on raindrops, if the ion capture theory by Wilson (1929) and Chalmer (1944) is assumed to hold, the maximum amount of charge acquired by a raindrop of radius r during its fall is given by

$$Q = 0.52\ Fr^2,$$

where F is the electric field intensity. If we take the value of electric intensity observed at the ground station for F and if the radius of the raindrop is assumed to be 2 mm, the amount of charge will be given by the line plotted in Fig. 11. These values are very much smaller than

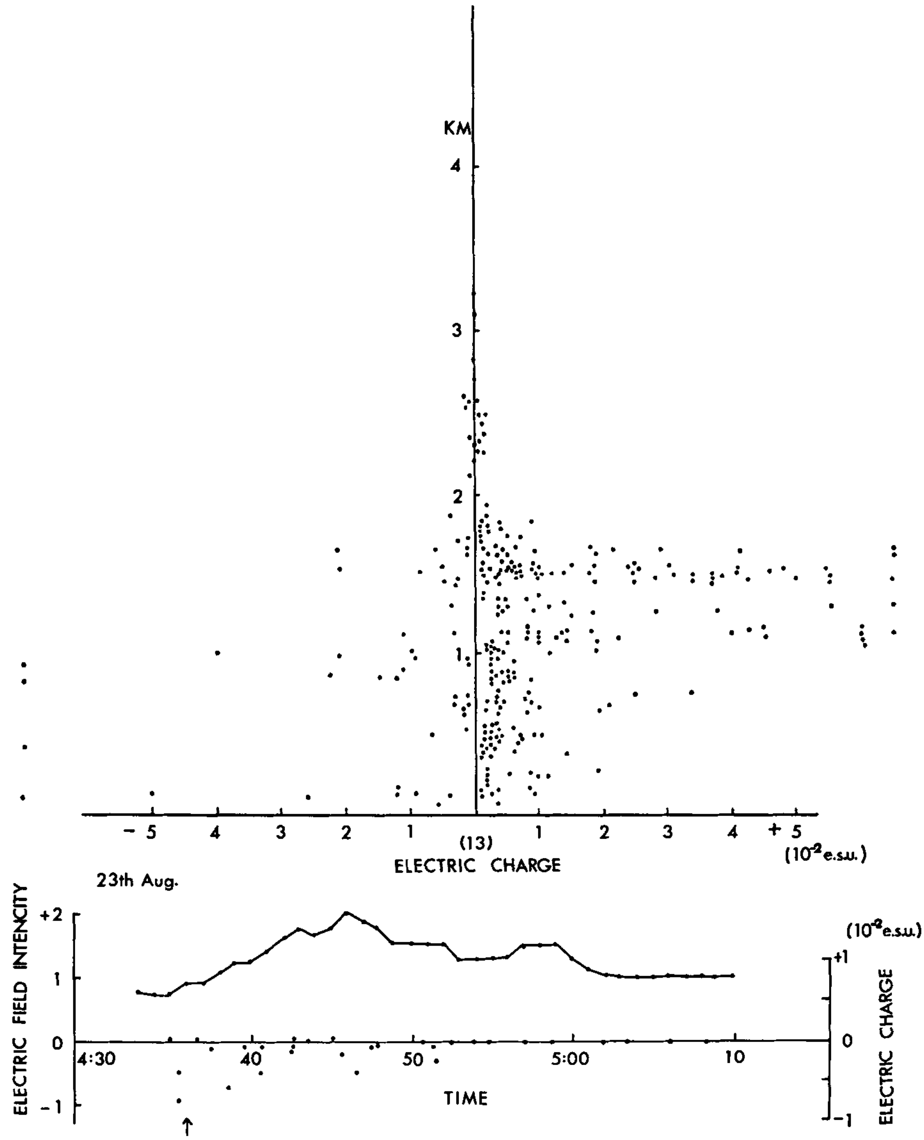


Fig. 10. Vertical distribution of charges on raindrops (*dots*) (*upper*) and electric field intensity (*full line*) and electric charges on raindrops (*dots*) during a continuous rain.

those observed. It is therefore difficult to consider the positive electric charges on raindrops as being due to the capture of ions below clouds.

Though the charging mechanism of raindrops has not been clarified, it seems likely that the negative potential gradient observed during showers was due to larger quantities of negative charge in the upper part of the cloud. A tentative crude model of electric charge distribution in cells of shower clouds based on our observations made at the ground stations and by radiosonde is shown in Fig. 12*a*. Some unspecified charge separation mechanism works at a certain level above the ground; raindrops are charged positively and smaller droplets negatively. The shower clouds move from the coast along the slope of the mountain. At the premature stage and the dissipating stage of a cell the

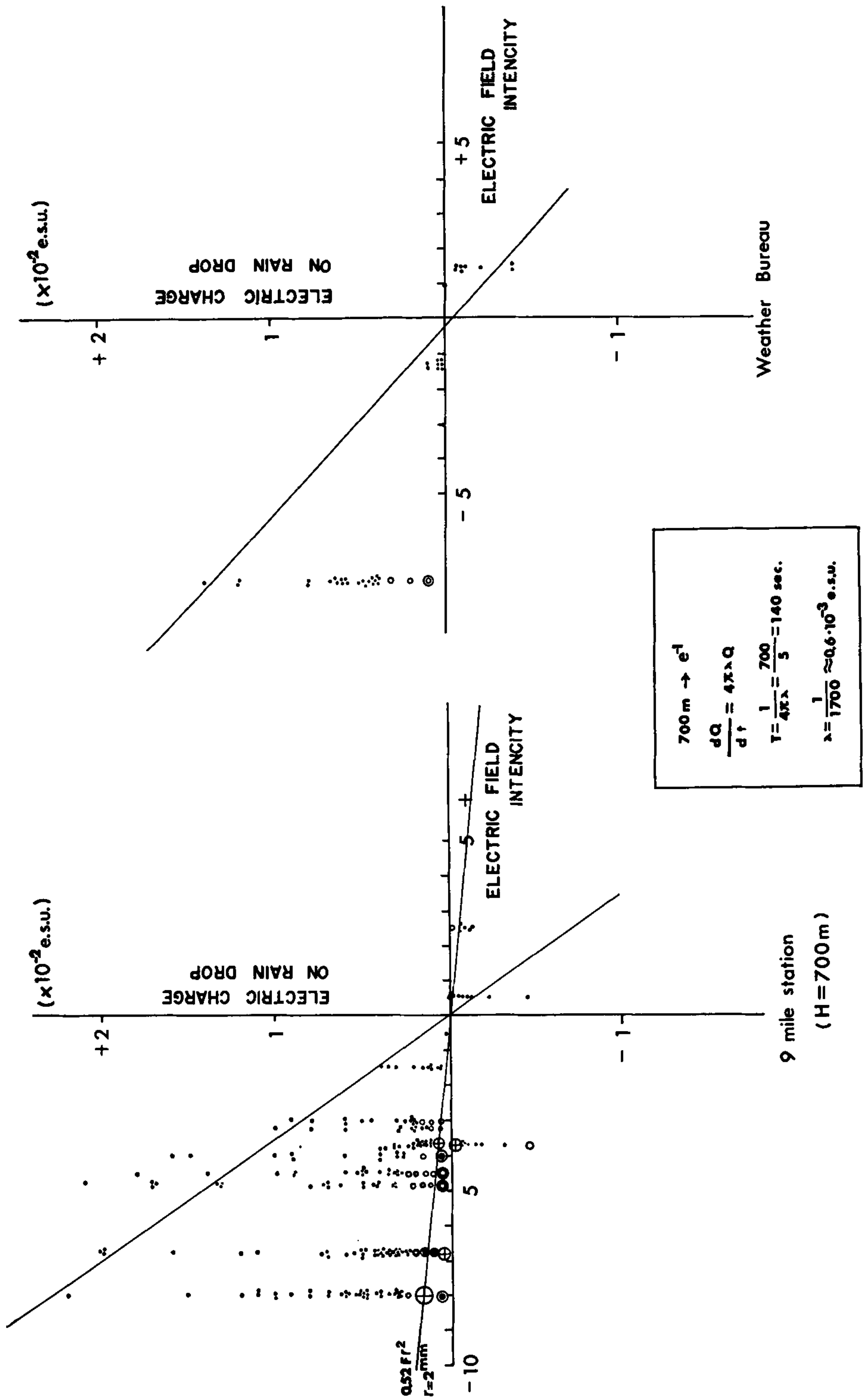


Fig. 11. Relation between electric charges on raindrops and electric field intensity. Circles indicate the values of charges that would be acquired by raindrops of 2 mm in diameter at the respective electric field intensity, based on the ion capture theory (see the text).

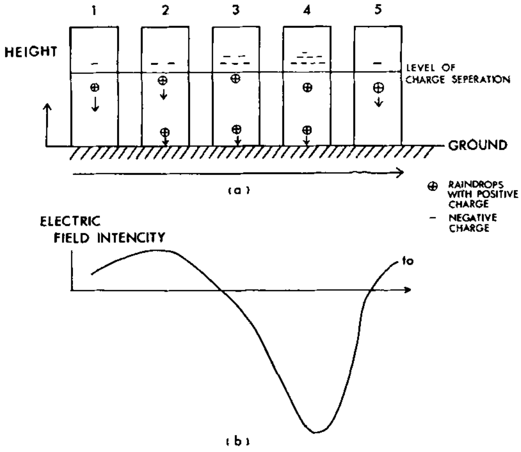


Fig. 12. A model illustrating the change in vertical distribution of charges on raindrops with development of convective warm clouds.

charge separation activity may be weak. At the mature stage the charging rate and the rainfall intensity may be intensive. Positive charges are carried down to the ground by raindrops, and consequently negative charges are accumulated in the upper part of the clouds.

As the result of such a process, the field intensity becomes negative under the cells at the mature stage because of the larger negative charge, while raindrops carry positive charge. Under the clouds at the premature and dissipating stage or under the clouds whose convective activity is weak, the field intensity may be less negative or slightly positive. The characteristics of the variation of electric field intensity observed at the 9 mile station and of the charge distributions aloft revealed by electric charge-radiosondes may be explained by this model.

The smaller charges on raindrops and correspondingly smaller variations of field intensity observed at the Hilo Weather Bureau Office as compared with the observations made at the 9 mile station cannot be explained only by the simple model described above. The discrepancy may be explained by assuming negative ions in the layer under clouds and neutralization of positively charged raindrops falling through this layer. If this effect is to be brought about during fall distance of 700 m, ionic conductivity should be about 6×10^{-4} e.s.u. This value is much larger than 10^{-5} e.s.u. over the Pacific Ocean obtained by Coroniti *et al.* (1953). For the elucidation of this problem, further measurements of the distribution of ions are needed.

Conclusion

Observation of electric charge on raindrops by use of radiosondes and ground observations of raindrop charges and electric field were carried out in Hawaii during summer 1965. Rains in Hawaii were classified with respect to electric charge distribution in clouds; shower, weak shower and continuous rain. A considerable number of electrified raindrops were observed in the clouds. In the case of shower type rains, the electric charge on raindrops reaching the ground was positive, while electric field intensity became negative and varied with time along a smooth concave curve. Positive electric charges were present in the lower part of clouds and negative electric charge in the upper part of cloud. The electric charge density was one order of magnitude smaller than that expected in thunderstorms.

In the case of continuous rain-type cloud, the electric charge distribution of positive and negative charge with height was the inverse of that described above for the shower type cloud.

Since the features of electric field intensity variations and charges on raindrops in Hawaii were much simpler than those usually observed in Japan and in continuous areas, further studies on the electrical characteristics of clouds in this region will provide us with important insight into the nature of the charge separation mechanism in clouds.

Acknowledgements

The authors would like to express their sincere thanks to Professor E. J. Workman, the Director of the Cloud Physics Observatory of the University of Hawaii, who provided us with necessary facilities for our works in this project and also to Professor R. L. Lavoie for his kind help throughout the program. Invaluable help was also provided by the Environmental Science Services Administration, especially Mr. Ray Busniewski, Technician in Charge, U.S.W.B., Hilo.

Acknowledgement is made of the financial support of this investigation through a grant from the Japan Society for the Promotion of Science as part of the Japan–U.S. Cooperative Science Program.

REFERENCES

Brook, M. 1958. Laboratory studies of charge separation during ice-ice contact. *Recent Advances in Atmospheric Electricity*, pp. 383–389.

Chalmers, J. A. 1947. The capture of ions by ice particles. *Quart. J. R. Met. Soc. 73*, 324–334.

Chalmers, J. A. 1957. "*Atmospheric Electricity*", chap. IV, par. 125, pp. 96–98. Pergamon Press, New York.

Coroniti, S. C. & Heaton, E. 1953. The electrical conductivity of the atmosphere over the Pacific Ocean. *Trans. Amer. Geophys. Un. 34*, 833–835.

Hatakeyama, H. Kobayashi, J., Kitaoka, T. & Uchikawa, K. 1958. A radiosonde instrument for the measurement of atmospheric electricity and flight results. *Recent Advances in Atmospheric Electricity*, 119–135.

Isono, K., Komabayasi, M. & Takahashi, T. 1966. A physical study of solid precipitation from convective clouds over the sea: Part III. Measurement of electric charge of snow crystals. *Jour. of Met. Soc. Japan, Ser. II 44*, 227–233.

Mason, B. J. 1953. A critical examination of theories of charge generation in thunderstorms. *Tellus 5*, 446–460.

Smith, L. G. 1955. The electric charge of raindrops. *Quart. J. R. Met. Soc. 81*, 23–47.

Takahashi, T. 1966. Measurement of electric charge in thundercloud by means of radiosonde. *Jour. of Met. Soc. Japan, Ser. II 43*, 206–207.

Vonnegut, B. 1954. Possible mechanism for the formation of thunderstorm electricity. *Proceedings on the conference on atmospheric electricity held at Portsmouth, New Hampshire*, 19–21.

Wilson, C. T. R. 1929. Some thundercloud problems. *Jour. Franklin Inst. 208*, 1–12.

Workman, E. J. & Reynolds, S. E. 1950. Electrical phenomena occurring the freezing of dilute aqueous solution and their possible relationship to thunderstorm electricity. *Phys. Rev. 78*, 254–259.

ЭЛЕКТРИЧЕСКИЙ ЗАРЯД НА ДОЖДЕВЫХ КАПЛЯХ, РАЗВИВШИХСЯ В ТЕПЛЫХ ОБЛАКАХ НАД ОСТРОВОМ ГАВАЙИ

Летом 1965 г. над островом Гавайи с помощью радиозондового и наземного оборудования были проведены измерения электрических зарядов на дождевых каплях внутри и под теплыми облаками. В случае дождей, типа проливных, было обраружено, что дождевые капли имеют значительный положительный заряд, в то время как на уровне земли наблюдался обратный ход интенсивности электрического поля хорошей погоды.

Наблюдения с радиозондов обраружили, что дождевые капли с положительным зарядом находятся в нижней части облаков, а капли с отрицательным зарядом — в верхней части облаков.

В случае непрерывных продолжительных дождей интенсивность электрического поля на уровне земли имела увеличенные положительные значения, и на наземных станциях иногда наблюдались капли с отрицательным зарядом. Описываются особенности процессов электрификации дождевых капель в названных различных типах осадков.