Electric conductivity of rain water in the cloud over the island of Hawaii

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ABSTRACT

On the basis of observations by means of radiosonde equipment utilizing a rain water collecting funnel and an electric conductivity cell, it has been found that the electric conductivity of rain water in a cloud decreased with increasing height above the cloud base over the Island of Hawaii during the summer in 1965.

At the ground very near to the cloud base, the variation of the electric conductivity of rain water with respect to time during a shower was observed for each size of raindrop by means of raindrop spectrographs.

Introduction

For studies of rainfall mechanisms, observations of salt concentration in rain water has provided much information concerning the growth of rain and cloud drops. Especially, as the maritime airmass over the Island of Hawaii is relatively free from industrial air pollution, the role of cloud nuclei in the formation of rainfall may be inferred from the concentration of the salt in rain water more easily here than in most other places of the world. In fact, there has been much study of the rainfall on the Island of Hawaii from this point of view (Woodcock, 1952; Mordy & Eber, 1954; Woodcock & Mordy, 1955; Woodcock & Blanchard, 1955; Turner, 1955; Eriksson, 1957; Junge, 1957; Squires & Warner, 1957; Woodcock & Spencer, 1957; Duce *et al.*, 1963).

The purpose of the present work is to observe the concentration of salt in rain water aloft by means of a special radiosonde and to obtain the variation with time of the salt concentration in rain water at the ground as a function of raindrop size by means of many raindrop spectrographs. As was reported by Eriksson (1957), the electric conductivity of rain water on the Island of Hawaii has a high correlation with the concentration of sodium and chloride ions in rain water.

Description of equipment

A. Radiosonde of electric conductivity of rain water

The radiosonde equipment for the measurement of electric conductivity of rain water consists of a rain water collecting funnel (polyvinyl, diameter of base 113 cm), a siphon chamber which contains platinum electrodes (AC 30 volts, 150 cycles $\cdot$ sec^{-1}) and which empties automatically after collection of 20 ml of water, an electric conductivity meter, a transmitter (1680 Mc) and a pressure switch which gives a particular signal at about every hundred millibar level (Fig. 1). The value of the AC voltage of the platinum electrodes (30 volts) has been chosen so as to be suitable to measure the conductivity of water at the range below 200 $\mu℧ \cdot$ cm^{-1}. According to Eriksson (1957), the electric conductivity of rain water collected at the ground lay in this range during the observation period of "Project Shower". The orientation of the funnel used is inverted from that of the ordinary funnel. This configuration has been used so as to keep the air streamlines around the funnel smooth and to avoid having a dynamic pressure influence disturb the operation of the siphon. Rain water collected on the surface of the funnel is drained into the siphon chamber. When rain water is stored in a sufficient amount

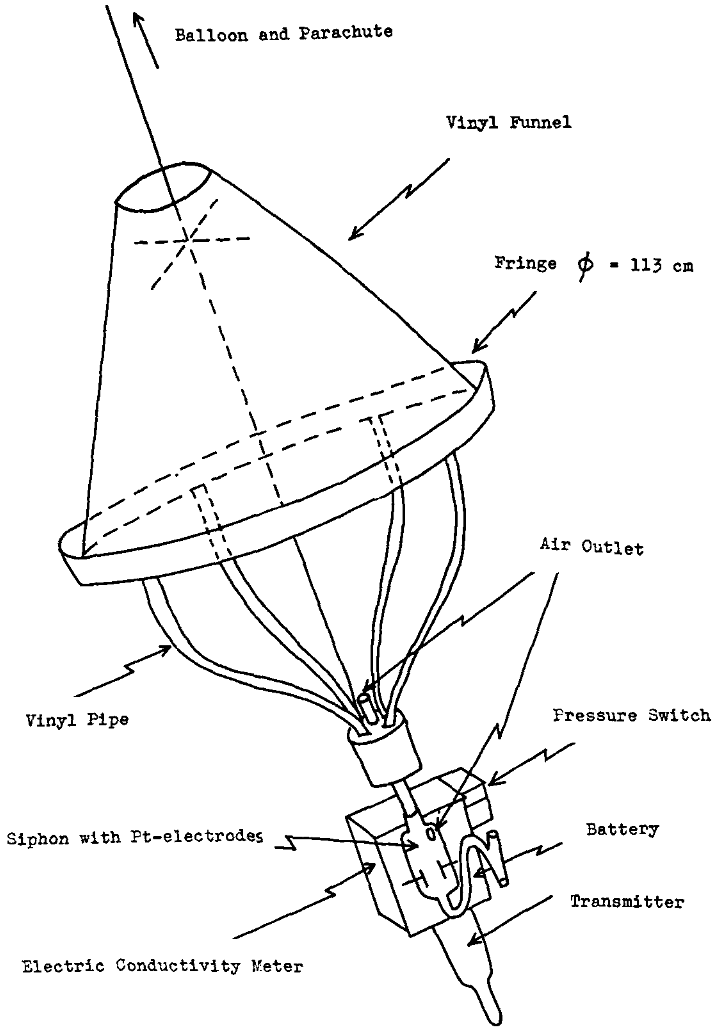

Fig. 1. Radiosonde equipment of electric conductivity of rain water.

in the chamber, the electric current between the electrodes indicates the conductivity of the water. When the stored water exceeds 20 ml in volume, it flows away by the siphon action. Hence, the chamber becomes empty, and the conductivity meter indicates zero. Values of the conductivity measurement are continuously transmitted from the radiosonde. Accordingly, the conductivity of rain water and the intensity of rainfall (frequency of emptying of the siphon chamber) can be recorded at the ground.

Rain water captured by the balloon and the parachute runs along the rope and drops away without mixing into the water collected on the funnel.

B. Raindrop spectrographs

The raindrop spectrographs used are similar to that devised by Bowen & Davidson (1951) and nearly the same as that used by Komabayasi & Gonda (1964). Raindrops which have entered the inlet are sorted by the horizontal airstream during the fall to the bottom dishes. There are five dishes on the bottom each of which drains into corresponding bottles. Raindrops are separated into five size classes A, B, C, D and E (Table 1). The horizontal cross section of a raindrop inlet in the raindrop spectrograph is $20 \times 4 = 80$ cm². Six raindrop spectrographs were used at the same place and at the

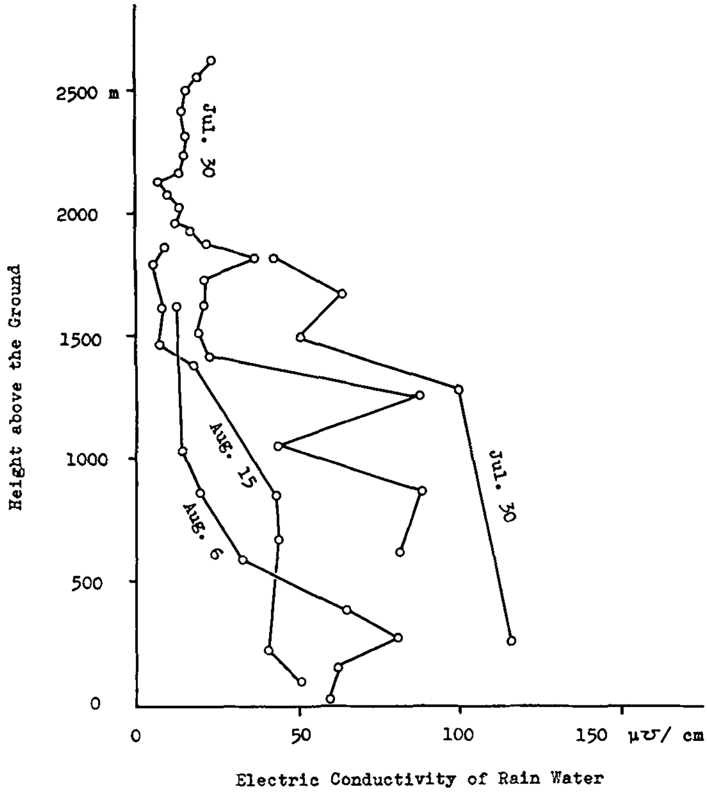

Fig. 2. Electric conductivity versus height observed at the nine mile site.

same time. Five of them were used to collect rain water samples as fast as possible and the sixth was used to obtain a control against aerosol contamination. The raindrop inlet of this latter instrument was covered with a polyvinyl sheet so that raindrops did not enter the apparatus. Except for this cover on the inlet all parts were identical to those of the other five raindrop spectrographs, dishes of the control spectrograph were washed frequently with distilled water and the conductivity of this water was measured. This contamination was not due to salts contained in raindrops, but rather to salts contained in the air in the form of dry fallout or of very small fog droplets. For every sampling period, the amount of this contamination was recorded. Data on the conductivity of rain water collected by means of the raindrop spectrographs have been reduced by the amount of this contamination.

Table 1. *Sorting in raindrop spectrograph*

Class	Raindrop diameter (mm)
A	$d > 1.0$
B	$0.6 < d < 1.0$
C	$0.4 < d < 0.6$
D	$0.2 < d < 0.4$
E	$0.1 < d < 0.2$

In order to increase the time resolution, the rain water samples were collected as rapidly as possible. The volumes of the samples were sufficient for measurement of electric conductivity, but in most cases they were too small to allow the elements of Mg, Ca and K to be analysed chemically.

Observations and results

The radiosonde instruments designed to measure the electric conductivity of rain water were launched both from the so-called nine mile site, located 9.5 miles from Hilo toward Mauna Kea,

Table 2. *Electric conductivity of rain water observed by means of radiosonde*

Height above the ground, m	Electric conductivity of rain water, μ℧/cm	Temperature of the air, °C
22 July, 1530–1656. 9 mile site		
150	Cloud base	14.0
950	13	13.7
1130	15	13.6
1300	8	13.5
27 July, 1615–1715. 9 mile site		
200	Cloud base	17.6
300	100	17.5
2300	12	8.3
27 July, 1803–1853. 9 mile site		
200	Cloud base	16.2
200	100	16.2
400	80	14.0
30 July, 1600–1623. 9 mile site		
200	Cloud base	17.0
300	120	17.0
1200	120	16.0
1400	50	15.0
1600	80	14.0
1700	40	13.0
30 July, 1635–1728. 9 mile site		
200	Cloud base	17.0
1000	80	12.5
1050	95	12.3
1100	38	12.0
1200	110	12.0
1300	20	12.3
1400	11	12.5
1700	10	12.7
1730	10	12.7
1850	45	12.7
1880	15	12.7
1910	10	12.6
1970	6	12.3
2090	4	11.9
2120	3	11.7
2180	3	11.5
2240	4	11.3
2280	4	11.1
2300	5	11.0
2400	8	10.3
2500	12	10.3
6 August, 1500–1548. 9 mile site		
0	60	18.0
50	Cloud base	17.5
200	80	16.8
300	100	16.2
400	80	16.0
700	40	14.5
800	20	14.1
1000	16	13.1
1700	6	15.4
15 August, 1646–1843. 9 mile site		
50	Cloud base	20.0
70	50	18.5
140	38	18.2
700	45	14.5
850	40	14.2
1300	16	10.9
1420	6	10.8
1600	8	9.8
1800	5	7.5
1850	7	7.3
20 August, 1905–2117. Hilo Airport		
0	48	21.0
500	60	18.9
600	55	17.8
670	50	17.2
720	33	16.9
780	30	16.5
830	31	16.0
900	30	15.6
1200	24	14.0
1300	23	13.4
1325	23	13.1
1350	21	13.0
1400	18	12.8
1425	21	12.7
1450	23	12.6
1800	22	11.2
1900	18	10.4
1950	23	10.3
2000	24	10.0
2400	21	8.1
2500	17	7.8
21 August, 0348–0530. Hilo Airport		
400	85	19.6
1100	63	14.6
1500	48	12.3
2100	36	9.5
2600	25	7.0
24 August, 2256–2423. Hilo Airport		
0	20	21.0
900	34	16.6
2000	18	10.6
2090	16	10.0
2180	14	9.8

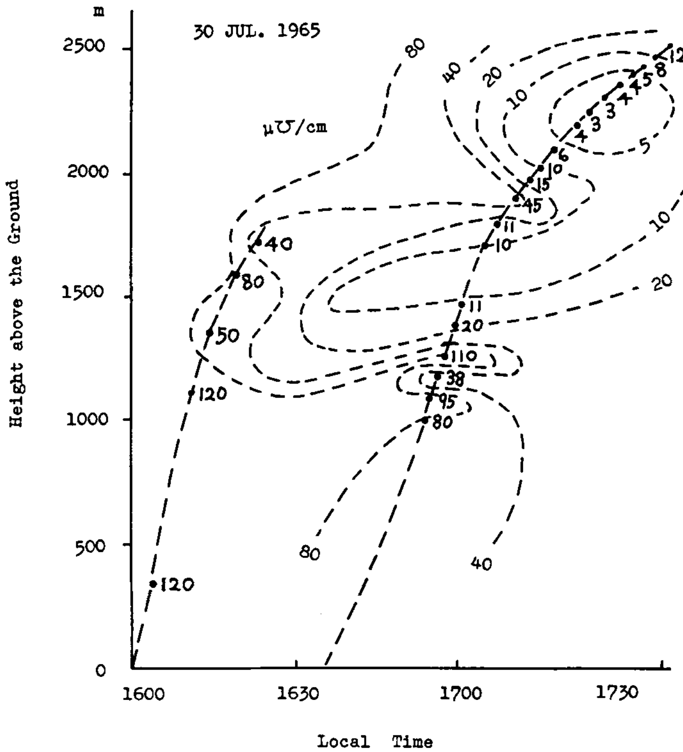

Fig. 3. Vertical cross section of the electric conductivity of a shower.

and from the Hilo Airport. The average ascent speed was one meter per second. Elevation of the former site is about 750 m above sea level and coincides with the average height of the base of rain clouds. The raindrop spectrographs were exposed at the nine mile site.

All data on the electric conductivity of rain water aloft, from the ground to the top of rain clouds, are tabulated in Table 2. Some sample soundings are illustrated in Figs. 2, 3 and 4. At the nine mile site as well as at Hilo Airport, despite a few irregularities, it can be seen clearly that the electric conductivity of rain water decreased with increasing height in the precipitating cloud. At the nine mile site, at levels around 2000 m above the ground the conductivity of rain water was very near to that of distilled water. On 30 July 1965, two radiosondes were successively launched into the same shower cloud. Time isopleths are drawn and illustrated in Fig. 3. Isopleths of the electric conductivity of rain water are tentatively illustrated and they suggest that a portion of minimum salinity (< 5 μ℧/cm) might have been present near the top of the rain cloud on that day.

In some cases the electric conductivity of rain water at the ground was lower than that in the portion of the cloud near the cloud base (Aug. 6, Aug. 20, and Aug. 24).

The raindrop spectrographs were operated during 14 showers. Some typical examples are illustrated in Figs. 5 through 9. On 17 July, heavy rain fell from a very thick cloud. A M-33 radar[1] placed on the Hilo Campus of the University of Hawaii detected the echo top to have reached 10,000 m above sea level. In this case (Fig. 5), the maximum electric conductivity of rain water of each size class appeared at successively later times with decreasing size of raindrops.

On 15 and 16 July (Figs. 6 and 7), weak showers occurred. As the intensity of rainfall

[1] See the article presented by Semonin & Stout in this issue.

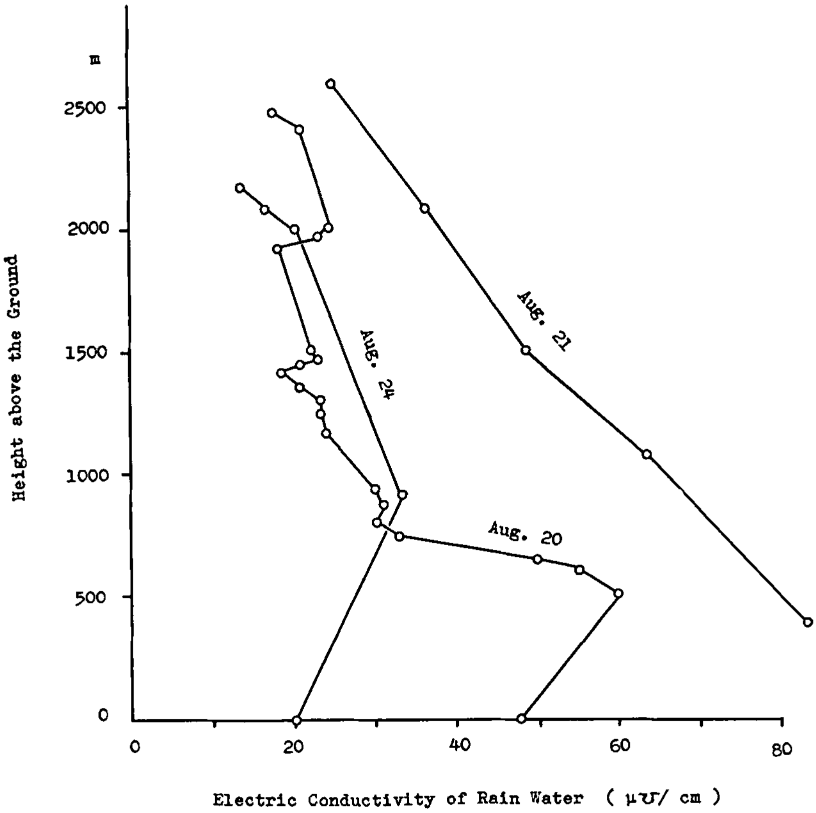

Fig. 4. Electric conductivity versus height observed at the Hilo Airport.

was small, the time resolution of the water samples was small (only two samples for most size classes). During these showers, the electric conductivity of rain water of the smallest size (E: 0.1 $< d <$ 0.2 mm) decreasee from the beginning to the end of the shower, while the electric conductivities of rain waters of all other sizes (larger than 0.2 mm in diameter) increased with time. On 30 July, a weak shower occurred. In this case (Fig. 8), in contrast to the former two examples, the electric conductivity of rain water of the smallest size (E) increased with time, while those of all other classes decreased with time.

During these weak showers, bulk samples of rain water were collected by means of a large ordinary funnel. The electric conductivity of bulk rain water of all three showers changed with time in the form of a U-shape. The conductivity was high at the beginning and at the end of the shower. The minimum value appeared at an intermediate time. It seems likely that the salinity of large raindrops and that of small raindrops in the shower had opposite trends with respect to time from the beginning to the end of the shower and that the composite salinity (salinity of bulk sample) had a minimum value at the intermediate time where both large and small raindrops had a relatively small salinity. The U-shape variation of the electric conductivity of bulk rain water was observed always to occur in moderate and weak showers. There were no exceptions. Turner (1955) reported the existence of salinity minima in certain size ranges of raindrops in warm rain on the Island of Hawaii. During the present observations, this type of dependence of the salinity upon the diameter was observed twice: on 5 August, 1347–1515 and 1628–1756 local standard time, two different showers in the same day. On that day, weak showers occurred from well stratified layer cloud. In other cases, the

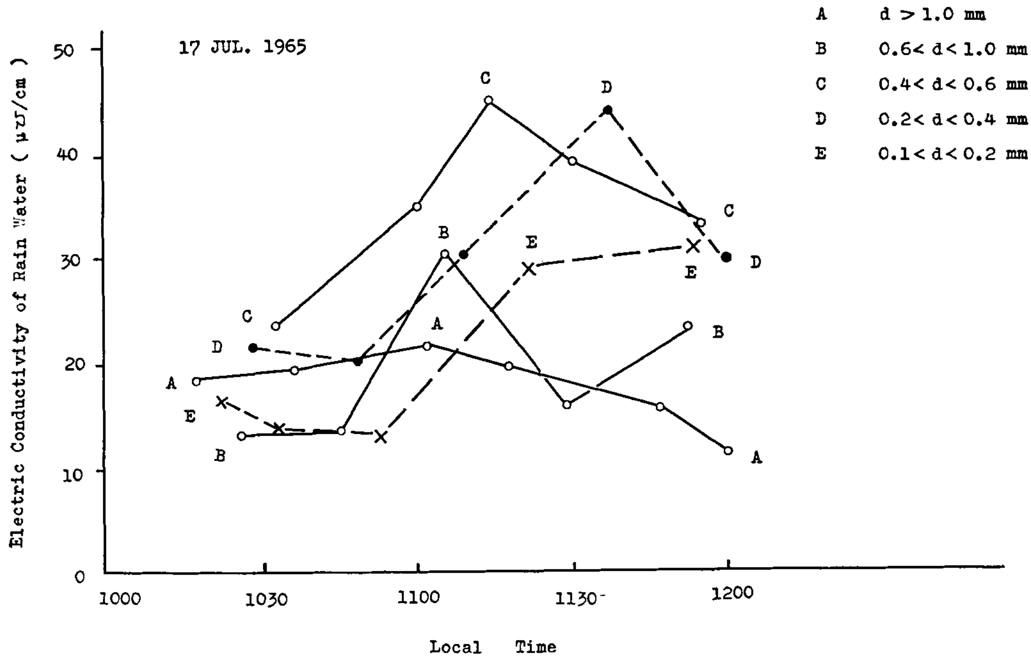

Fig. 5. Electric conductivity of rain water with time and with raindrop size (heavy rainfall).

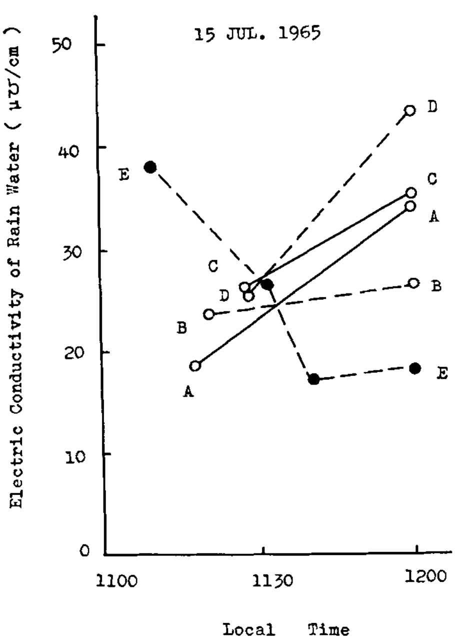

Fig. 6

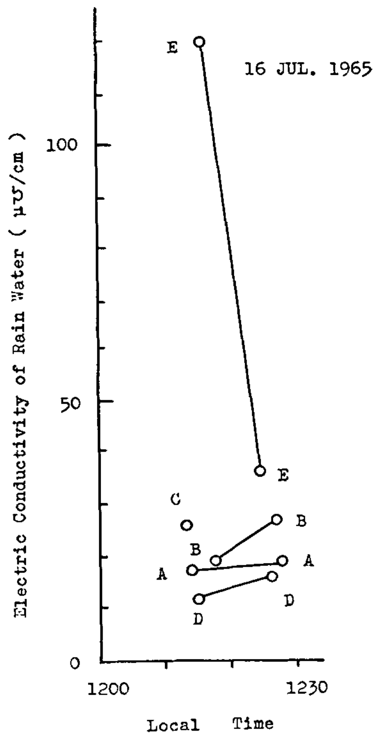

Fig. 7

Fig. 6. Electric conductivity of rain water with time and with raindrop size (weak shower).
Fig. 7. Electric conductivity of rain water with time and with raindrop size (weak shower).

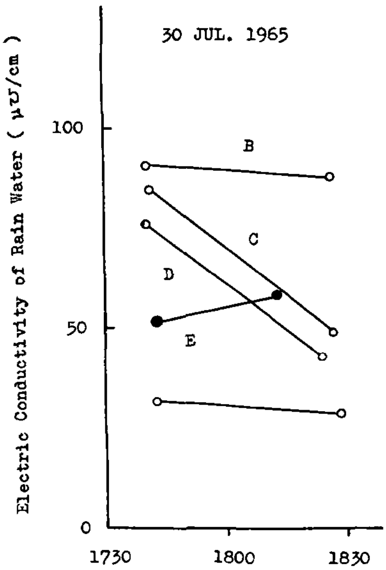

Fig. 8

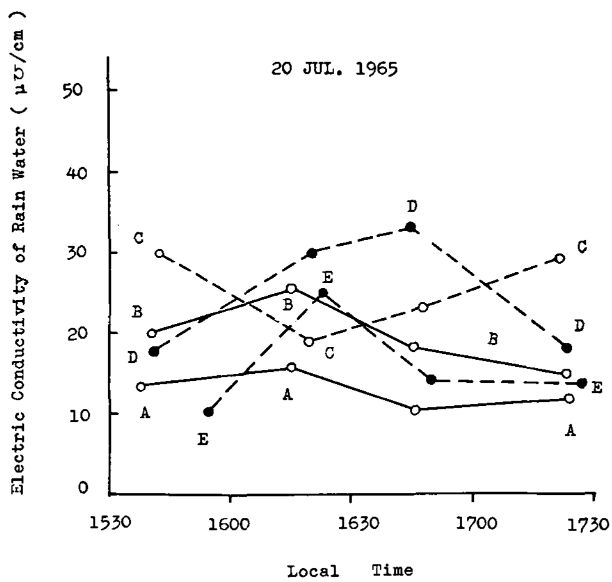

Fig. 9

Fig. 8. Electric conductivity of rain water with time and with raindrop size (weak shower).

Fig. 9. Electric conductivity of rain water with time and with raindrop size (heavy rainfall).

dependences of the salinity of the rainfall upon the diameter were different from time to time during one shower and from shower to shower.

Discussion

One of the significant facts apparent from our data is that the electric conductivity of rain water in a cloud decreased with height within the cloud in every instance. This fact does not conflict with the result reported by Eriksson (1957) that the concentration of the salt in rain water collected at the ground decreased rapidly from Hilo (coast) to Mauna Kea, provided that the portion of rain water near the cloud base falls earlier and the portion of rain water near the cloud top falls later during the movement of the cloud from the coast to the mountain.

The decrease of the electric conductivity of rain water with respect to height, hence, the decrease of the salinity of rain water with respect to height, should be explained from a consideration of the history of growth and trajectories of raindrops, cloud drops and giant salt particles. First, we confine our discussions to rainfall by the non-freezing process. If the motion of the air is, with some over simplification, assumed to be a uniform updraft and if all the salt particles and the water vapour are assumed to enter the cloud through the base such as in the convective cloud model adopted by Bowen (1950) and Ludlam (1951), the number of large salt particles per unit volume of air within the cloud space is large near the cloud base and decreases with increasing height. This is because the larger salt particles become raindrops sooner than the smaller ones and cannot reach the higher levels because of their greater fall velocities.

On the other hand, if the air parcels and the salt particles are assumed to enter the cloud through its upwind side, lateral boundary such as in the orographic cloud model adopted by one of the present authors (Komabayasi, 1957), the population of large salt particles per unit volume of air in the cloud is more or less uniform with respect to height initially, because the air containing the salt particles enters the cloud at all altitudes. After that, as rapid growth of saline drops takes place and the fall of these drops begins, the population of salt particles becomes

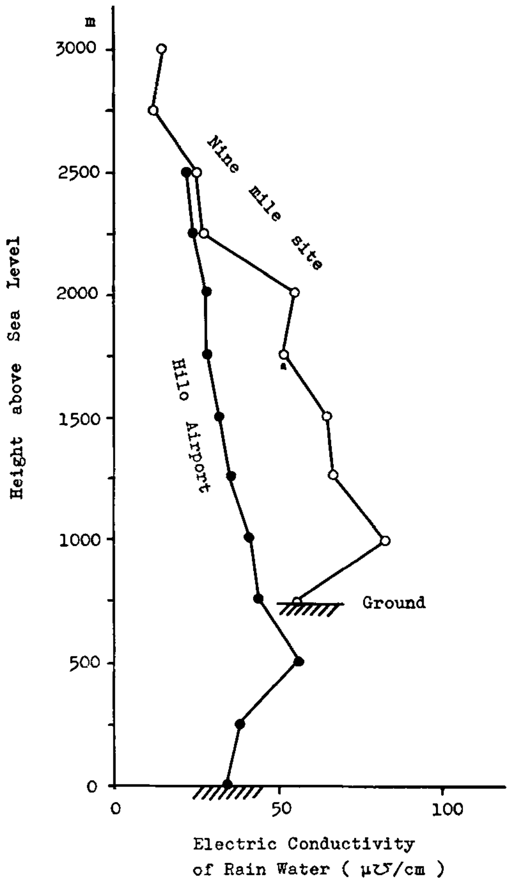

Fig. 10. Average electric conductivity of rain water versus height.

sparse in the upper portion of the cloud following the downward transfer of the saline drops.

Accordingly, the ratio of the total mass of the salt per unit volume of air to the total mass of the liquid water per unit volume of air is considered to decrease with increasing height above the cloud base in the model where the air enters tbe cloud through the base. In the model where the air enters the cloud through the lateral boundary, this ratio is considered to be uniform with respect to height initially, thereafter it will begin to decrease with height. Accordingly, if all water drops were captured by the radiosonde funnel, it would be reasonable to expect the salt concentration of rain water to decrease with height as our observations revealed. Fig. 10 indicates the average concentration of the salt in rain water observed at the nine mile site and at the Hilo Airport respectively. It can be seen that the salt concentration was more uniform at the Hilo Airport which is located at the upwind side of the nine mile site. If the cloud above the Hilo Airport was nearer to the formative stage, this uniformity may be understandable by the use of the latter model.

However, it seems to be unrealistic to assume that all water drops in the cloud were completely collected by the funnel. If it is permitted to assume that water drops larger than drizzle size, for example larger than 100 microns in diameter, were collected completely, but drops smaller than this size were not collected by the funnel, the argument concerning the salt concentration in rain water with respect to height will be much different from the above. This is because the rain water content of the cloud (drops larger than 100 microns) will decrease more rapidly with height than the mass of the salt per unit volume of air will decrease. Therefore, in both cases of the two models of cloud cited above the salt concentration of rain water should increase with height instead of decreasing.

The observations show that this was not the case. In addition to this, sometimes the rainfall intensity was observed to be greater near the cloud top than near the cloud base. In fact, in Fig. 2, the rainfall intensities on 30 July between 2000 m and 2500 m levels were estimated to be 2.4 mm per hour from the frequency of siphoning action. Accordingly, it seems necessary to adopt some composite model to explain the observed result, so far as the salt hypothesis in which each raindrop is assumed to originate from a corresponding giant salt nucleus is concerned.

On the other hand, if not only the salt hypothesis but also other rainfall mechanisms are assumed to be at work in the warm cloud over the Island of Hawaii, the argument concerning the salt content of rain water with height will be different again. If some mechanism can form raindrops from cloud water without the aid of the giant salt particles near the top of the cloud, this rain water would be captured by the radiosonde funnel as well as the rain water which originated from the giant salt nuclei. The salt concentration of rain water collected by the funnel, is, in this case, considered to decrease with height as the present observations revealed, because the ratio of the salt mass to the liquid water content of the cloud is considered to decrease with height.

During the period of the present observation, the population of cloud drops were observed to be small and their average diameter were observed to be larger than the cloud drop size of the continental cumuli.[1] This agrees with the observational result in "Project Shower" (Squires & Warner, 1957; Squires & Twomey, 1957). The possibility can not be fully ruled out that a random coalescence mechanism between these large cloud drops was at work. Neither can the possibility that some electric effect was at work to form raindrops without the aid of the giant salt nuclei be denied since radiosonde measurements[2] revealed that the electrification of drops in the warm cloud was not always weak.

It was often observed that the electric conductivity of rain water collected at the ground was lower than that at levels a little above the cloud base. Probably this is due to substantial rain water having originated from the upper portion of the cloud where the salt concentration of water was very small and having reached the ground after penetration of the salt rich layer above the cloud base without being much contaminated.

These cloud models and explanations should be consistent with the results of the observations obtained by the raindrop spectrographs. In some cases of weak and moderate showers of short duration such as in Fig. 6, the rain water of the smallest drop size (E) had the highest conductivity and the rain water of the largest drop size (A) had the lowest conductivity initially. If it is considered that the smallest raindrops came to the ground from the lowest level in the cloud, and the larger raindrops came from the higher levels in the cloud, this could be consistent with the above explanation for the lower conductivity of rain water at the ground than that at the levels a little above the cloud base. The height of the cloud base was about 100 m above the ground and the humidity of the air at the ground was very near saturation. It is unlikely that evaporation below the cloud base altered much the salt concentration of raindrops.

But, it cannot be denied that the evaporation of drops in the cloud within the downdraft area might have had some influence on the salt concentration of raindrops. A doppler radar detected a downdraft sometimes at the leading edge of the shower at the nine mile site.[3] It is possible that the high electric conductivity of bulk rain water at the initial stage of the weak or moderate shower may be explained by the effect of evaporation in the downdraft.

The high electric conductivity of bulk rain water at the final stage of the weak or moderate showers may be explained by the view that the population of salt particles in the cloud was high near the trailing edge due to the lateral influx of air and particles. But, we have yet no way to explain why the smallest raindrops had the lowest salt concentration at the final stage of the shower.

Next, brief discussion is given of the rainfalls which appeared to involve the ice mechanism. On 22 July (Table 2), a deep convective cloud of thunderstorm type occurred near Mauna Kea. The M 33 radar (loc. cit.) detected a light rain beginning at high altitude. The radiosonde funnel was launched before the rain reached the ground. As the core of the shower was far from the nine mile site, the radiosonde funnel was unable to collect much rain water. Although only three values of electric conductivity were obtained, these values seem to indicate a typical example. On that day, there was a layer of stratus cloud above the nine mile site, below which broken fractocumuli were present, the height of cloud base of the former being about 1000 m above the ground, that of the latter being 150 m above the ground. The highest cloud was the spread anvil of the thunderstorm flowing from Mauna Kea to the nine mile site. Probably the low conductivity of $8\ \mu\mho \cdot cm^{-1}$ at the 1300 m level was that of the rain water coming from the freezing anvil, the high value of $15\ \mu\mho \cdot cm^{-1}$ was that of the stratus cloud in which cloud drops were probably about drizzle size so that the radiosonde funnel was able to collect them, and the intermediate value of 13 $\mu \cdot \mho cm^{-1}$ was that of rain water having passed through the stratus.

If this interpretation is correct, the variation of the salt concentration in the case of the heavy rainfall with a high echo top (beyond 10,000 m) illustrated in Fig. 5 may be tentatively explained as follows. Snowflakes and graupel pellets which had a low concentration of salt came down from the upper part of the cloud. They became raindrops of various sizes at the

[1] See the article presented by Jiusto in this issue.

[2] See the article presented by Takahashi & Isono in this issue.

[3] See the article presented by Rogers in this issue.

melting level. Among these raindrops, some drops fell to the ground without accretion of many saline cloud drops, while other drops fell to the ground with accretion of many saline cloud drops. Here, it has been assumed that the saline cloud drops are densely populated in the lower part of the cloud. Let a particular size class, for instance, B ($0.6 < d < 1.0$ mm) in Fig. 2 be considered. The raindrops which had already reached a size of class B before passing the layer populated with the saline cloud drops were able to enter the B dish of the raindrop spectrographs, provided that they did not capture many saline cloud drops and thereby grow into another size class. On the other hand, raindrops which had been smaller than size B before passing the layer populated with the saline drops were able to enter the B dish of the raindrop spectrographs, provided that they captured many saline drops during the fall and grew up to the size B. As the initially larger raindrops are considered to reach the ground earlier than the initially smaller raindrops, the concentration of the salt in rain water of the size class B will be more dilute at the earlier stage and will become more concentrated with increasing time. In addition to this, if the decrease in the population of the saline cloud drops with time is taken into consideration, the observation illustrated in Fig. 5, that is the successively later occurrences of the peak for each size class from the largest to the smallest size classes, may be explained.

On July 20, the continuous rain took place at the nine mile site. During this period, snowfall took place at Mauna Loa Observatory. Also the top of Mauna Kea was observed to be covered with snow. Therefore, the rainfall at the nine mile site on that day was considered to involve the ice mechanism. The observation during this rainfall is illustrated in Fig. 9. The case illustrated in Fig. 9 is more or less similar to the case explained above though much irregularity occurred. Probably this is due to the irregular distribution of saline drops with time and space. However, it should be noted that these explanations are only tentative and less consistent each other and that definite explanations are still open questions.

Conclusion

On the basis of radiosonde measurements of the electric conductivity of rain water in the cloud over the Island of Hawaii, the following results have been obtained.

(*a*) The concentration of salt in rain water decreased with increasing height above the clouds base.

(*b*) The gradient of this decrease with height was steeper in the cloud above the nine mile site (inland) than in the cloud above the Hilo Airport (coast) on the average.

(*c*) The concentration of the salt in rain water collected at levels a little below the cloud top was sometimes as low as that of distilled water.

(*d*) The concentration of salt in rain water collected at the gound was lower than that at levels a little above the cloud base.

(*e*) In the cases of moderate or weak showers which were considered to occur due to a non-freezing process, the concentration of the salt in bulk rain water collected at the ground always showed the U-shaped variation with time from the beginning to the end of the shower, having a minimum at an intermediate time.

(*f*) On the other hand, the concentration of the salt in rain water collected by raindrop spectrographs at the ground showed a monotonous decrease or increase with time for each drop size and these tendencies were opposite for large raindrops and small raindrops respectively resulting in the U-shape variation with time for the bulk rainfall.

(*g*) In the cases of heavy rainfalls which were considered to involve the ice crystal process, the concentration of salt in each rain drop size class had a peak value at an intermediate time during the rainfall, and the peak occurred first for the largest raindrops, then at successively later times for successively smaller raindrops.

(*h*) Tentative explanations and models for these observed phenomena are discussed though definite conclusions are still open questions.

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ЭЛЕКТРОПРОВОДНОСТЬ ДОЖДЕВОЙ ВОДЫ В ОБЛАКАХ НАД ОСТРОВОМ ГАВАЙИ

На основе радиозондовых наблюдений с использованием воронки, собирающей дождевую воду, было найдено, что электропроводность дождевой воды в облаке уменьшается с увеличением высоты над основанием облака. Наблюдения производились над островом Гавайи в течение лета 1965 г.

На уровне земли вблизи основания облака с помощью спектрографов дождевых капель наблюдались временные вариации в течение проливного дождя для электропроводности дождевой воды в каплях всех размеров.