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PROCEEDINGS

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STUDIES ON THUNDERSTORM ELECTRICITY

TOSIO TAKEUTI

CONTENTS

I. Cloud Discharge

Abstract

To study the electric process in cloud discharge and charge distribution in thundercloud, the electrostatic field changes due to a cloud discharge were recorded simultaneously at three field sites. Atmospherics, thunder, etc. were the assisting means for the study. It has be found that there are three types of thundercloud: Type I predominantly produces an upper-positive vertical dipole discharge, Type II an inclined or horizontal discharge, Type III an upper-negative vertical one. Type III was found likely to have more or less thin distribution of negative electric charge on top or just above it. Streamer velocities range mostly in $1\sim2\times10^6$ cm/sec, and are nearly kept constant through the whole duration of a discharge. The path length of a vertical discharge is usually 2 km or less, while that of a horizontal one is mostly longer than this value. The electric charge neutralized in a cloud discharge often exceeds 100 coulomb, which is in a good agreement with Hatakeyama's report, while it is appreciably larger than the value presented in other reports. The cloud discharge consists of many local discharges being distributed on its path at 200 m interval in average. The charge dissipated by a local discharge is estimated at about 1 coulomb or more.

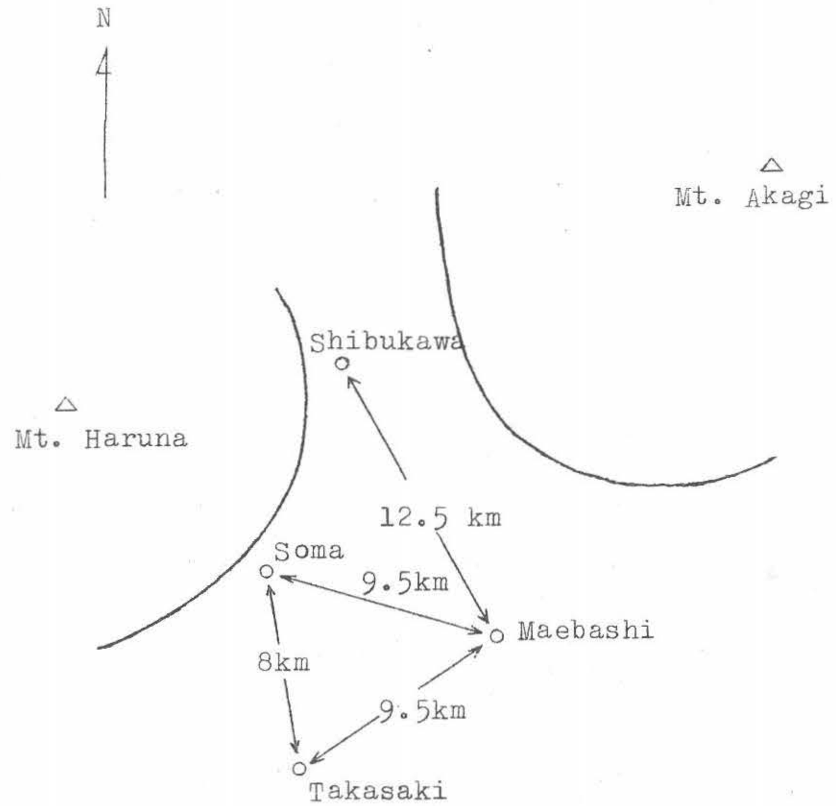
1. Introduction

Supposing that a cloud discharge is simulated by dissipation of an electric dipole, charge and position of it can be determined by the simultaneous observation of electrostatic field change at seven points. For this reason, many workers have made this kind observation at several points. For example, in Japan, Hatakeyama (1958) carried it out at five points, Tamura (1958) at eight points, in U.S.A. Workman et al. (1942) at eight points, Reynolds et al. (1955) at eleven points, but their observations did not concerned with the detailed structure of the discharge. Smith (1957) recorded the field change at two points and succeeded in analyzing the motion of electricity through a discharge. Barnard (1951) and Hacking (1954) each independently made three points observations, but their measurements were confined only to ground discharge. Many other workers who estimated charge and position of an individual discharge, or studied the charge distribution in a thundercloud did not make any multi-point observations. We made the field change observations at Maebashi and Shibukawa in 1960 and extended it to three points, Maebashi, Takasaki, and Soma in 1961. The results obtained from these observations were already published in 1961 and 1963. (1961) (1963) Thereafter the observation were repeated at Maebashi, Takasaki, and Soma in 1962 and 1963. It is the purpose of this paper to describe the detailed character of a cloud discharge which is deduced from the measurements of field change, thunder, flash, and cloud observation at the three points.

2. Apparatus and field sites

The apparatus used in the field measurement is an antenna type field meter which has been improved a little from the previous one. (1962) The voltage induced on a vertical antenna is either amplitude-modulated or frequency-modulated, then it is fed on to the first channel of a multi-track magnetic tape recorder. The time response of the system is ranged from 10 s. to 1 ms. Identification marker pulses sent from a key station on the air were put on the second channel, by means of which we can secure the identification of the individual field changes at three points. Thunder and vocal notice of a flash were recorded on the second or the third channel. An atmospheric waveform recorder with the frequency response from 1 kc to 100 kc was also employed. (1956) The field sites are located in Gunma-ken, one of the most thunderstorm active district in Japan. The

Fig. 1. Observation sites



sites were selected so as to have nearly a regular triangle shape on the map as shown in Fig. 1.

3. Method of analysis

In the analysis, we firstly tried that the data fit or not to an upper-positive vertical discharge, because this type of discharge is thought to be of more common than the other types, that is, lower-positive vertical, horizontal, and inclined discharges. The data which did not succeed in the analysis were then examined if they could be interpreted as a lower-positive vertical discharge or a horizontal one. We must have five variables to describe a vertical dipole discharge. These are horizontal co-ordinates, heights of positive and negative charge, and quantity of electric charge. The variable increase to six in the case of horizontal discharge and in the most general case, of an inclined discharge, we must have seven variables. The difficulty in ~~the~~ data analysis increases with number of unknown variables. For this reason, the data analysis largely succeeded for vertical discharge, while only a small number of the data were analyzed for horizontal one. A little knowledge was obtained for the nature of an inclined discharge.

3.1. Vertical discharge

If h_1, h_2, d, and Q denote the height of upper charge, that of lower charge, horizontal distance between discharge and observation site, and the quantity of neutralized charge respectively, the field change F produced by a dipole discharge at an observation site can be written as:

$$F = 2QY \qquad (1)$$

where

$$Y = h_1/(h_1^2 + d^2)^{3/2} - h_2/(h_2^2 + d^2)^{3/2} \qquad (2)$$

It is convenient for the data deduction to prepare the electrostatic field intensity maps having h_1, h_2, and d as parameter in every two km interval. That is 10, 8, and 6 km were selected for h_1, and 8, 6, 4, and 2 km for h_2 in 1962; 12, 10, 8, 6, and 4 km for h_1, and 10, 8, 6, 4, and 2 km for h_2 in 1963. We drew three concentric circles with radii r_i, r, and r_0 given by respective equation (3), (4), and (5) on the maps. The centers of the circles coincide with the projection of a discharge on a horizontal plane.

$$r_i = \sqrt{2}h_2 \qquad (3)$$

$$r = h_1^{1/3} h_2^{1/3} (h_1^{2/3} + h_2^{2/3})^{1/2} \qquad (4)$$

$$r_0 = \sqrt{2}h_1 \qquad (5)$$

Fig. 2 shows an example.

Let us consider an upper-positive discharge first.

a) If the site is located inside r_i, the field change must show a monotonous increase.

b) If the site comes to be in the section between r_i and r, the field change should have an extreme value and the net field change must be positive.

c) If the site come to be on r, the field change has an extreme value and the net field change is zero.

d) If the site is found between r and r_0, the field change has an extreme value and the net field change must be negative.

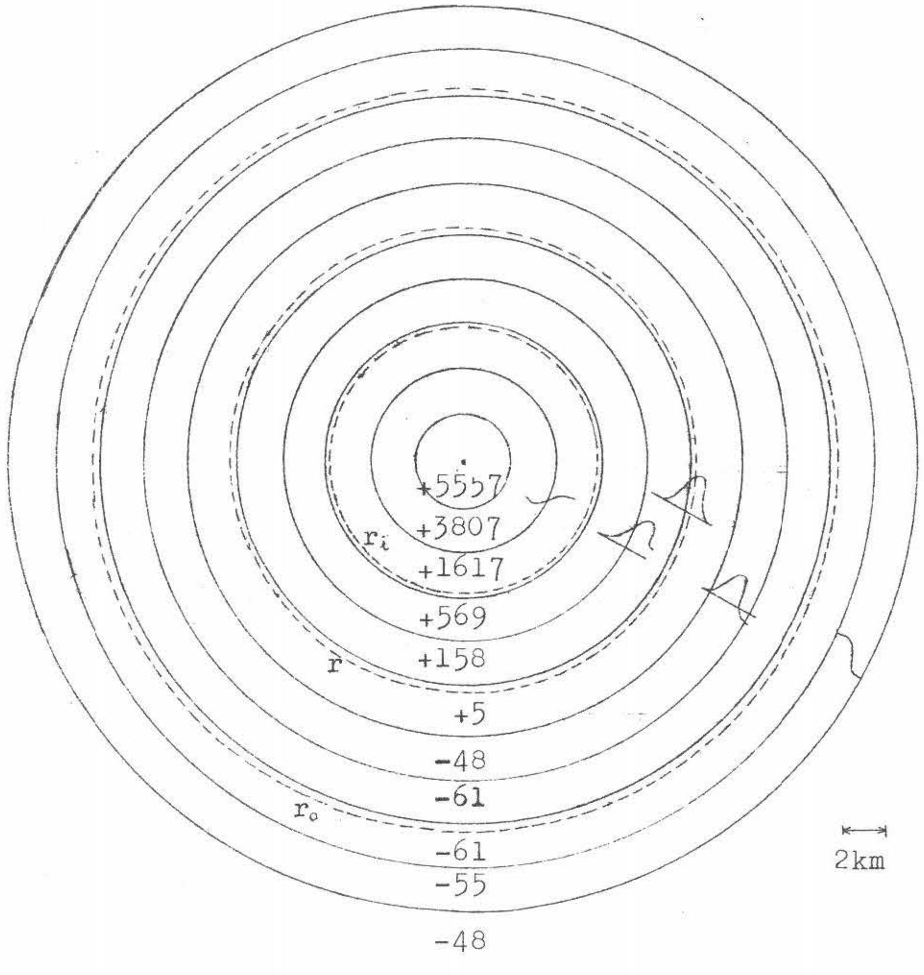
e) If the site is found outside of r_0, the field change must show a monotonous decrease.

In analyzing the data, we examined each map in turn taking into account the relative net field change and shape of it at the respective site. Moreover only the maps satisfying the following condition were accepted for the later discussion.

a) Discharge point estimated from the map trial must coincide with the location obtained from thunder, flash and cloud observations.

b) For example let us consider an upper-positive discharge, and assume that the observation site

Fig. 2. An example of field intensity map for vertical discharge.
This map shows the case of h_1 = 12 km and h_2 = 4 km. The values on the map mean $Y \times 10^5$ which are computed by unit of km for all parameters. If positive charge descend in the discharge, the field changes observed at each regions divided with the three circles must result as shown in the Figure.



is found in the section between r_i and r_0 , and the positive charge moves down during the process. The field change produced at the site must show an increase as it moves down from h_1 to $d/\sqrt{2}$, thereafter a decrease as it moves from $d/\sqrt{2}$ to h_2 . Now let us denote A and B the above two field changes respectively, then we get the following equations

$$A = 2Q\{ h_1/(h_1^2 + d^2)^{3/2} - 2/3\sqrt{3}\, d^2\} \qquad (6)$$

$$B = 2Q\{ 2/3\sqrt{3}\, d^2 - h_2/(h_2^2 + d^2)^{3/2}\} \qquad (7)$$

$$A/B = \frac{h_1/(h_1^2 + d^2)^{3/2} - 2/3\sqrt{3}\, d^2}{2/3\sqrt{3}\, d^2 - h_2/(h_2^2 + d^2)^{3/2}} \qquad (8)$$

Computing the ratio A/B from the field change record, we can estimate the value d for each combination of h_1 and h_2 using the equation (8). The value d obtained are then applied for the map trial. Some value d showed that it were unfavorable for map trial. The combination of h_1 and h_2 corresponding the unfavorable d must be abandoned for the further discussion.

3.2. Horizontal discharge

A group of maps, one each referring to the combination of a height value and a horizontal distance value between the two charges composing of the dipole, were prepared in a similar way as before. The height value were selected from 2 to 12 km at every 2 km interval, and the horizontal values from 2 to 10 km at same interval. An example is shown in Fig. 3. Two straight lines r_n and r_p on the map pass through the respective projection of negative and positive charges and these are pararell to r.

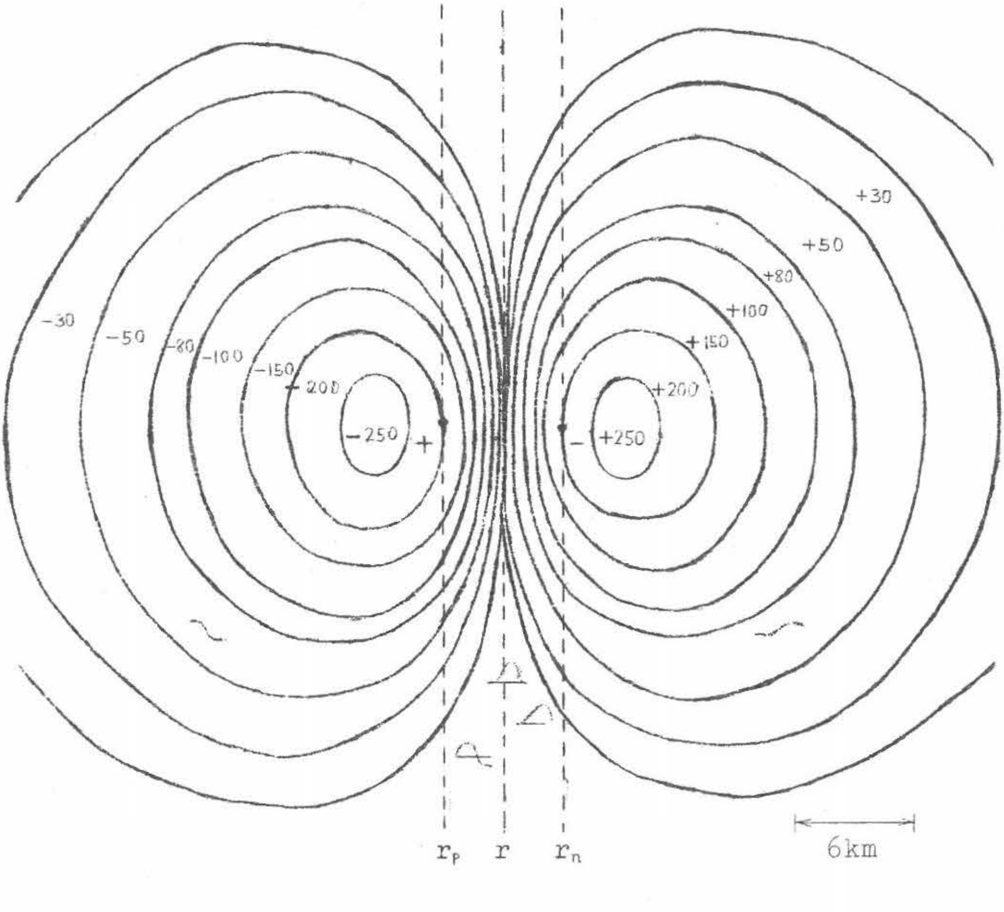
Let us consider the case of positive charge movement discharge.

a) If a site is located outside of r_n or r_p , the field change shows a monotonous increase or decrease.

b) If a site is located on r, the field change shows an extreme value and the net field change comes to zero.

c) If a site is located between r_n and r, the field

Fig. 3. An example of field intensity map for horizontal discharge.
This map shows the case that heights of both charges are each 12 km and horizontal distance between both charges is 6 km. The values on the map mean $Y \times 10^5$ as same as Fig. 2. If positive charge move in the discharge, the field changes observed at each regions divided with three lines r_n , r, and r_p must result as shown in the Figure.



change has an extreme value and the net field change comes to positive.
d) If a site is located between r and r_F , the field change has also an extreme value and net field change comes to negative.

We analyzed the horizontal discharge on these maps as before. Data of thunder, flash, and cloud observation were used for aid of the analysis.

3.3. Inclined discharge

From the thunder observations at two or three site, it was shown that some discharges are neither vertical nor horizontal. They must be treated as an inclined discharge. However the small number of the site made it very difficult to analyze. Only a limited knowledge could be obtained about the discharge.

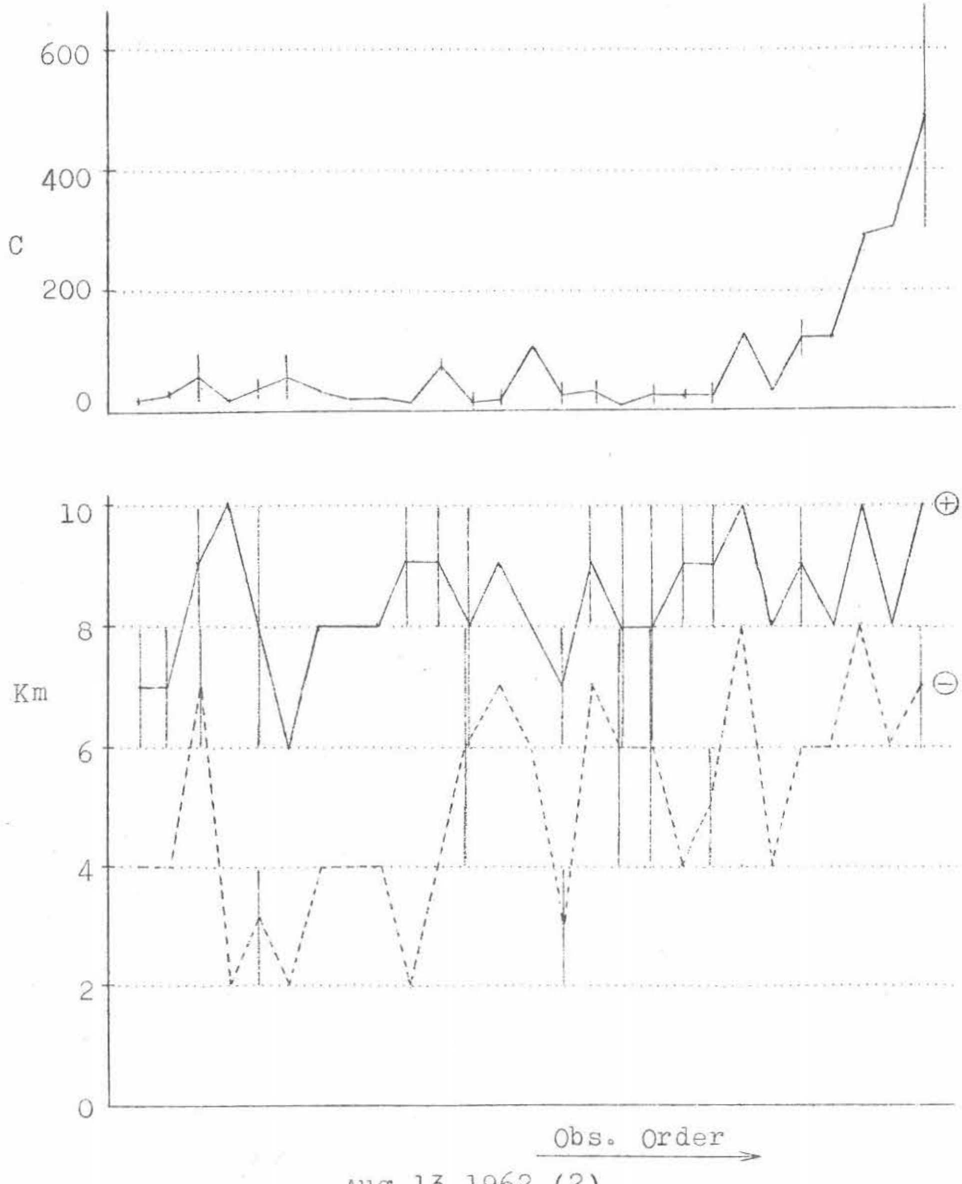
4. Charge distribution in thundercloud

The charge distribution in the thundercloud deduced from the cloud discharge analysis can be assorted into three types. They are Type I cloud in which most cloud discharges show upper-positive vertical discharge, Type II cloud where major part of discharge have the horizontal or inclined character. Type III cloud where plenty of upper-negative vertical discharges take place.

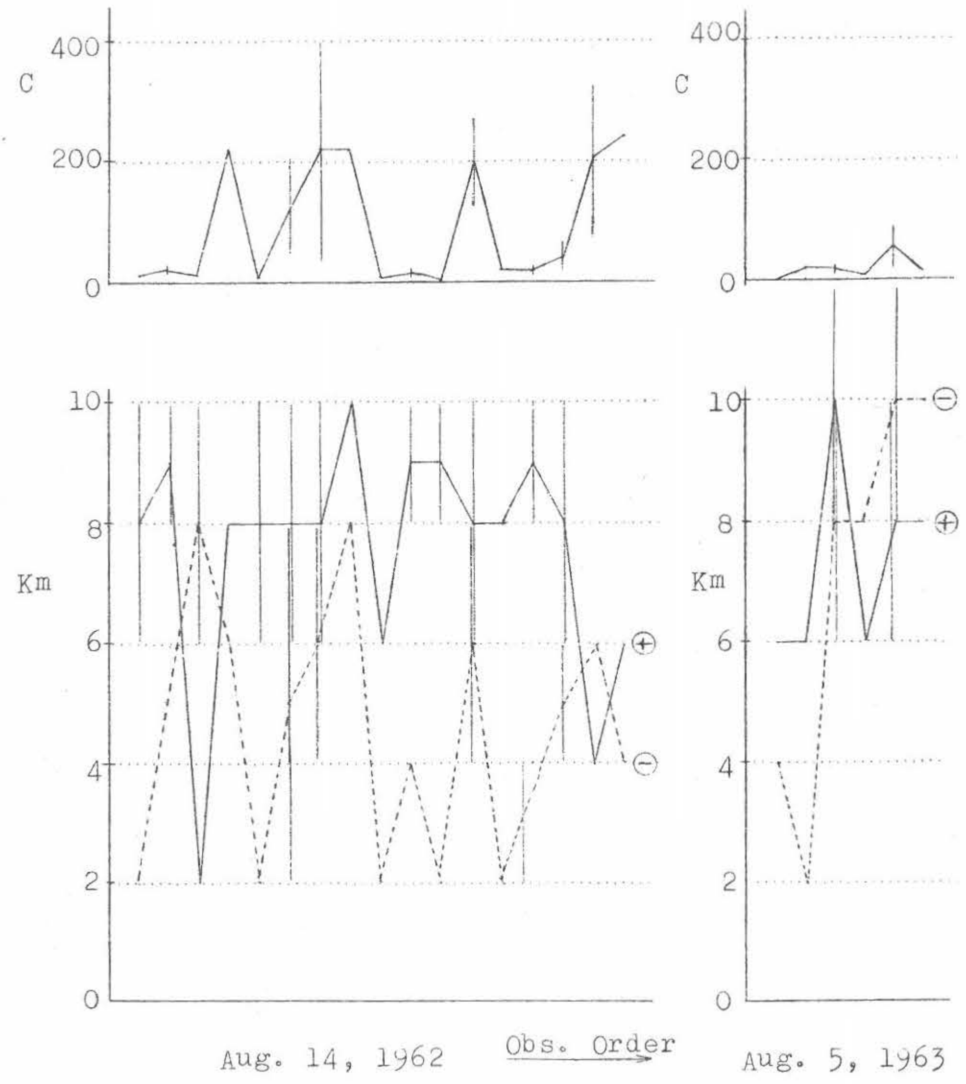
4.1. Type I cloud

We have four Type I cloud samples which are three storms and one group compsed of two storms. Heights and charge quantities of discharges relating to Type I cloud are shown in a time sequence in Fig. 4. The histograms of the charge quantities are shown for each storm in Fig. 5. The following results can be obtained from the Figure.
a) The charge quantity and the height vary in wide range. This shows the complexity of thundercloud with respect to an electrical structure.

Fig. 4. Heights and charge quantities on discharges in Type I clouds.
The vertical fine lines show limits of errors. The results of Aug. 14, 1962 are composed of two storms.



Aug. 13, 1962 (2)


400
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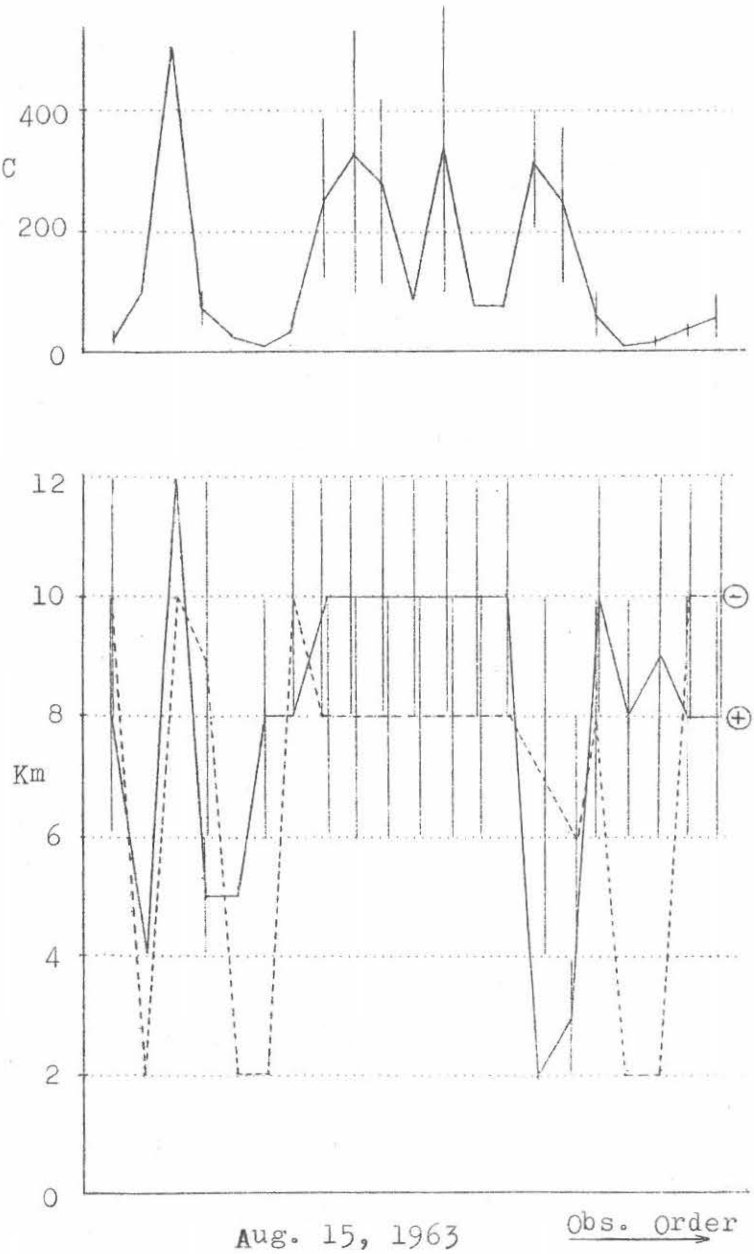
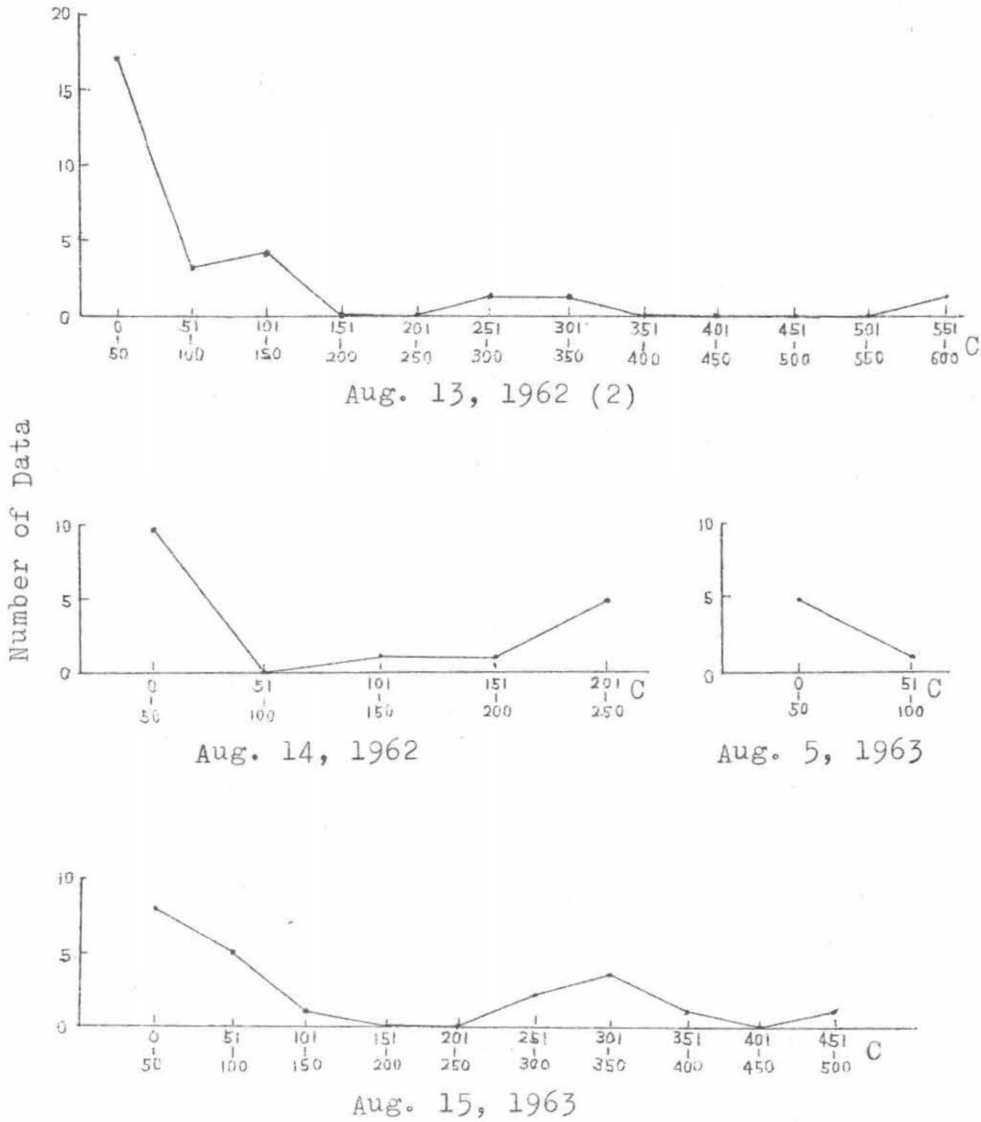
Obs. Order
Aug. 5, 1963



Aug. 15, 1963

Fig. 5. Histogram of charge quantities on cloud discharges in Type I cloud.
The results of Aug. 14, 1962 are composed of two storms.



b) Charge quantity often exceeds 100 coulomb, the magnitude agrees well with Hatakeyama's report (1958), but it is appreciably larger than the value given in other reports.

4.2. Type II cloud

We observed two storms which belong to the type.

a) Storm on Aug. 13, 1962 (the 1st storm)

No vertical discharge was recorded in the storm. Ninteen discharges seem to be horizontal at about 10 km height and the dipole moment are from 10 c-km to 25 c-km. We could get the reasonable values for only two discharges as shown in Table 1.

Table 1. Fundamental values for horizontal discharge.

Obs. No.	Height	Length	Charge quantity
5	8-12 km	2-6 km	10 coul.
9	6-10 km	2-8 km	5 coul.

b) Storm on Aug. 3, 1963 (the 1st storm)

Cloud discharge in the storm are assorted into four types as shown in Table 2.

Table 2. Number of data for each type discharge.

Vertical discharge with upper-positive	2
Vertical discharge with upper-negative	7
Inclined discharge	7
Horizontal discharge	1
	No. of Data

Table 3 gives the result of computation for the horizontal discharge in Table 2.

Table 3. Fundamental value for the horizontal discharge

Height	Length	Charge quantity
8 km	4-6 km	130-250 coul.

Concerning the inclined discharge, we can only estimate the height from thunder and flash observation data. The result of analysis on the storm is shown in Fig. 6. The Figure shows that all types of discharges can not be characterized by their height and charge quantity.

4.3. Type III cloud

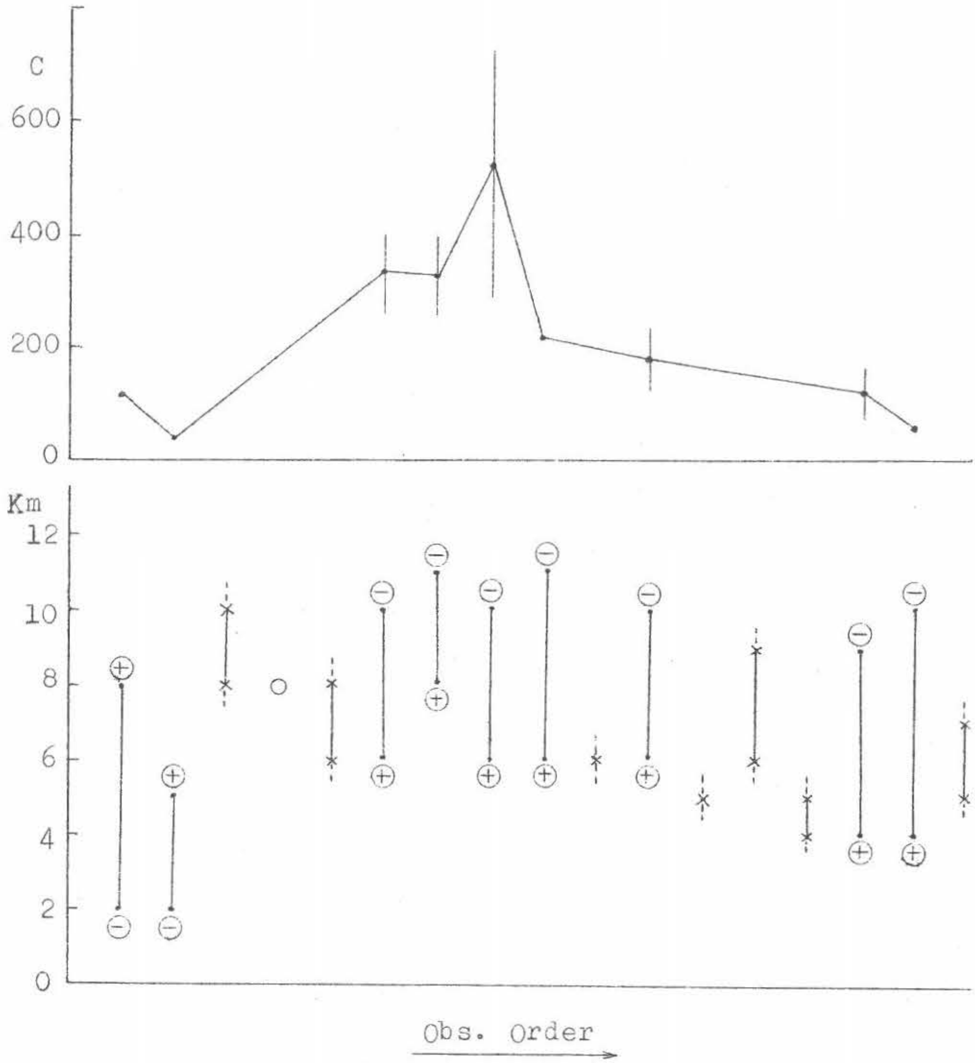
This type has not been reported by other workers yet, but we observed two storms of this type. Charge quantity and height of the upper-negative vertical discharge are shown in Fig. 7. This type discharge occurs in the higher part of a cloud, and the charge quantity is smaller than other type discharges. It is reasonable from the values shown in the Figure to conclude the existence of more or less thin negative charge distribution on top of or just above the cloud. This height is in good agreement with the altitude of cloud top measured with radar and photographic method. (1963) (1950)

5. Fine structure of discharge

5.1. Movement of electric charge in a discharge path

If the field change shows a maximum, it is due to a movement of positive electric charge in a discharge process, and if the change shows a minimum it is due to a movement of negative one. Table 4 indicates the number of discharge by movement of positive or negative electric charge. Smith (1957) reported that most discharges are performed by the movement

Fig. 6 Heights and charge quantities for storm on Aug. 3, 1963 (the 1st storm).
. show the vertical discharge. o show the horizontal discharge. × show upper limit of lower charge and lower limit of upper charge on the inclined discharge. The vertical fine lines show limits of errors.



Aug. 3, 1963 (1)

Fig. 7 Heights and charge quantities on discharges in Type III clouds.
The vertical fine lines show limits of errors.

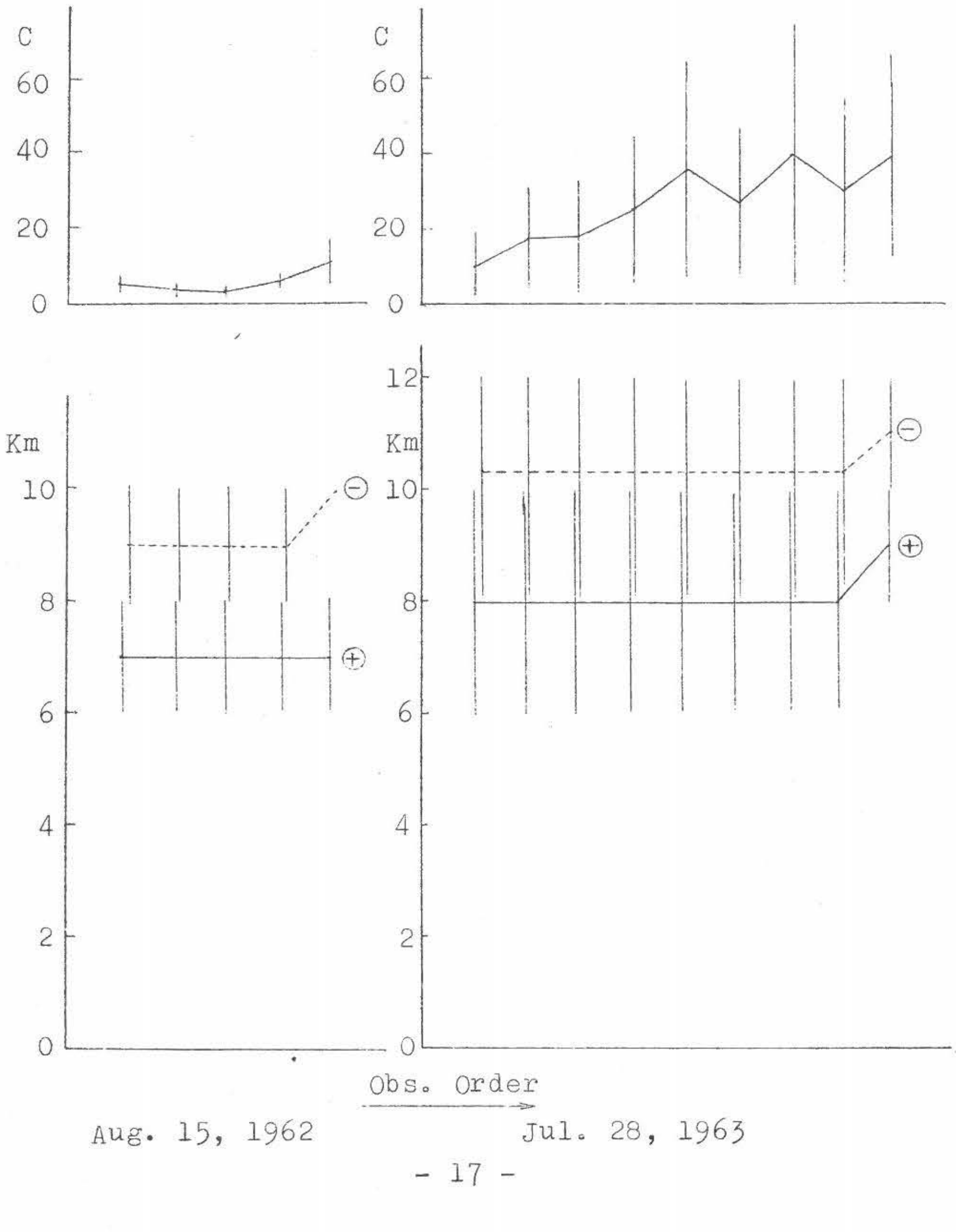


Table 4. Direction of charge movement

Positive descend	12	4	1	1	1	5	9
Negative descend	0	1	0	0	0	2	6
Positive ascend	0	1	0	0	0	0	9
Negative ascend	2	9	0	1	1	1	30
	8.13,62(2)	8.14,62	8.3,63(1)	8.3,63(2)	8.5,63	8.15,63	Smith

of lower charge, but our results shows that the direction of the movement differs a storm to another. This may be relate closely to the charge distribution in each cloud.

5.2. Streamer velocity

The velocity of streamer in the cloud discharge can be estimated from the path length of a discharge and the duration of it. Fig. 8 shows the relation between velocity and discharge path length in general. Fig. 9 shows the same relation with respect to the positive streamer. They indicate that the polarity of a streamer and path length of the discharge has no significant influence to the progressive velocity. When field change record shows extreme value, we can get $d/\sqrt{2}$ by using the equation (8). Let us difine L_1, L_2, t_1, and t_2 as follows.

L_1 : Discharge path length between the onset point and $d/\sqrt{2}$.

L_2 : Discharge path length between the onset point and the end point.

t_1 : Duration from the onset to the time when the field change is reached to an extreme value.

t_2 : Total duration of a discharge.

Then we can obtain Fig. 10 showing the linear relation between L_1/L_2 and t_1/t_2 . The Figure tells that the streamer velocity is kept constant through the discharge process.

5.3. Discharge path length

5.3.1. Vertical discharge

A histogram of vertical discharge path length in general and that with positive streamer are shown in Fig. 11 and 12 respectively. We see that most discharges have the path length of 2 km. Since we estimate the path length using the field maps with the parameter value of h_1 and h_2 in every 2 km interval, the real path length may be less than 2 km in most case.

Fig. 8 The relation between streamer velocity and discharge path length in general.
The dotted line show the relation including one extraordinary high velocity, that is 1×10^{7} cm/sec.

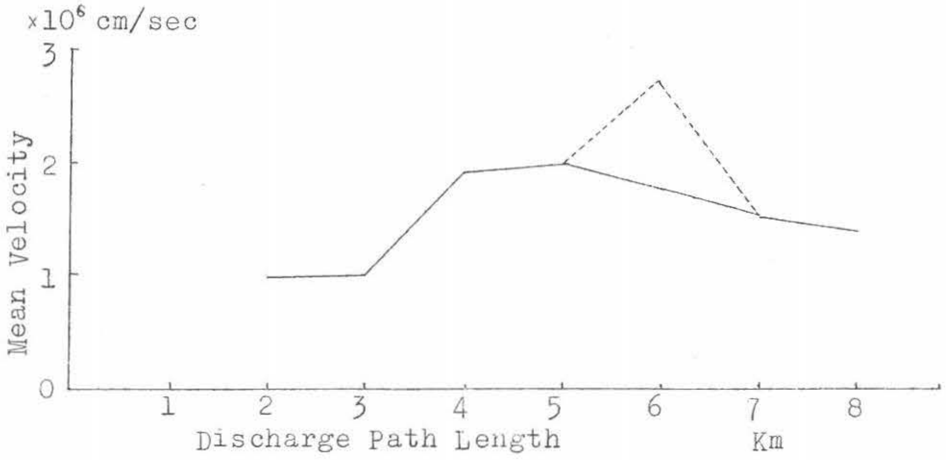


Fig. 9 The relation between streamer velocity and discharge path length with respect to the positive streamer.

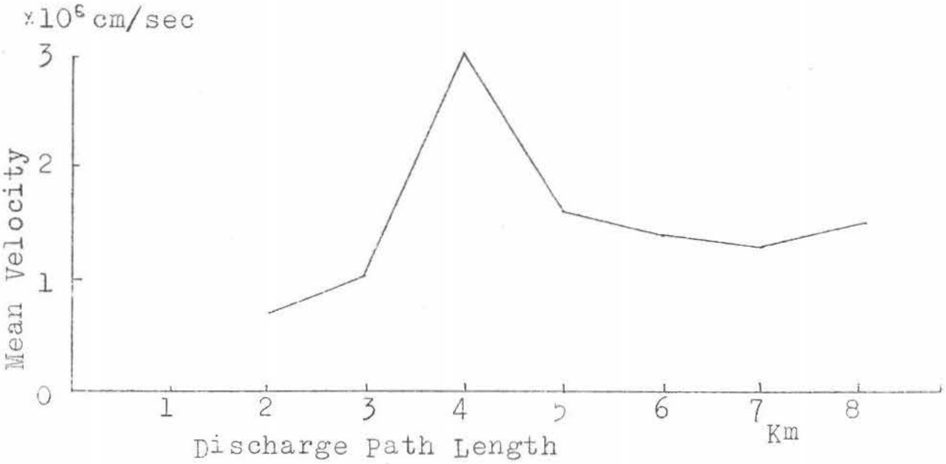


Fig. 10 The change of streamer velocity in discharge path.

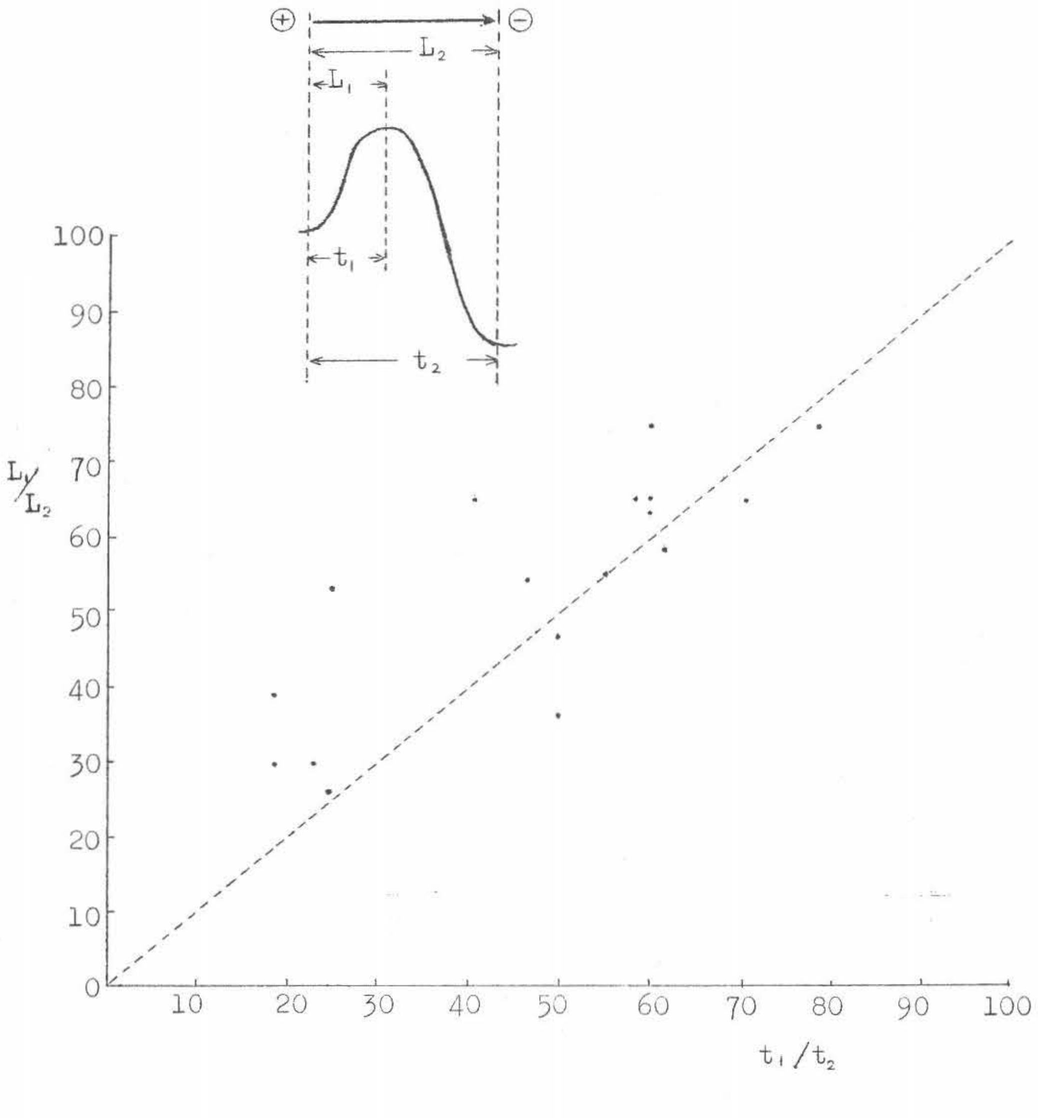


Fig. 11 Histogram of vertical discharge path length in general.

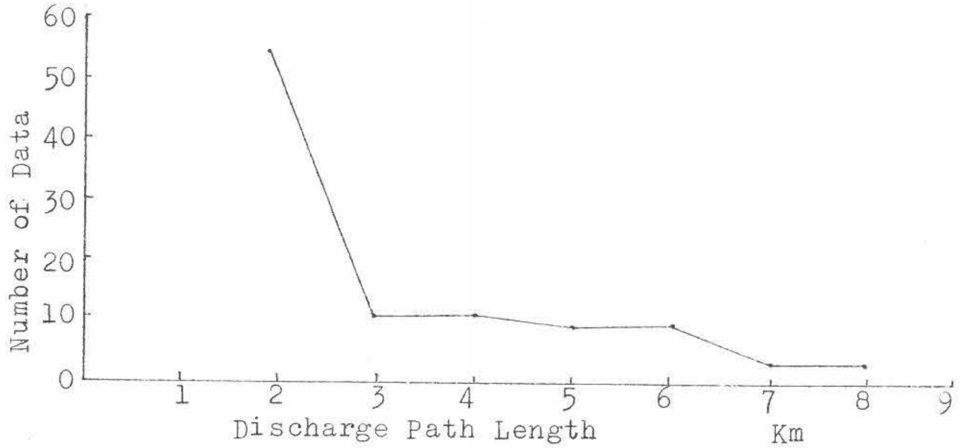
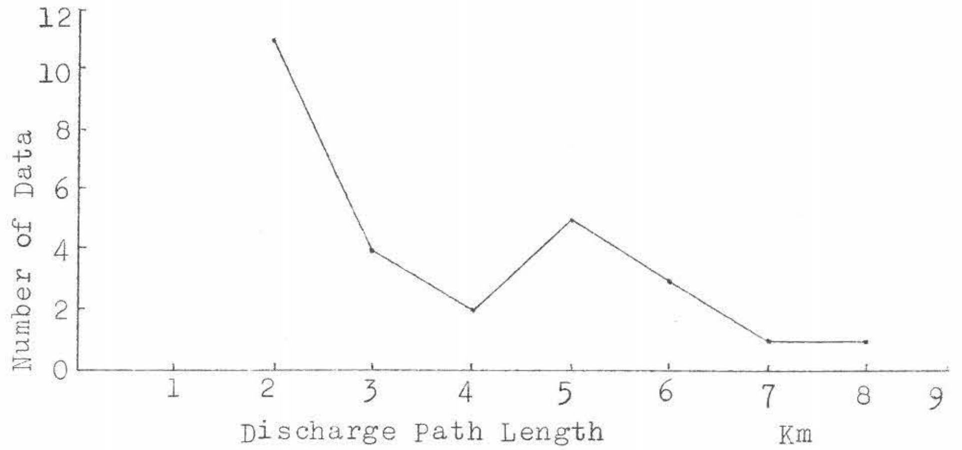


Fig. 12 Histogram of vertical discharge path length with respect to the positive streamer.



5.3.2. Horizontal discharge

Though we have got only three data on the horizontal discharge, the mean path length of them is about 5 km, and longer than that of a vertical discharge. It is our experienced evidence that a long horizontal discharges can often be seen during a storm with our eyes, and this is in a good agreement with the above results.

5.4. Charge quantity and discharge path length

Fig. 13 shows how the charge quantity is influenced by the discharge path length in Type I cloud. Here we see that the charge becomes smaller as the length come to be long.

5.5. Multiple cloud discharge

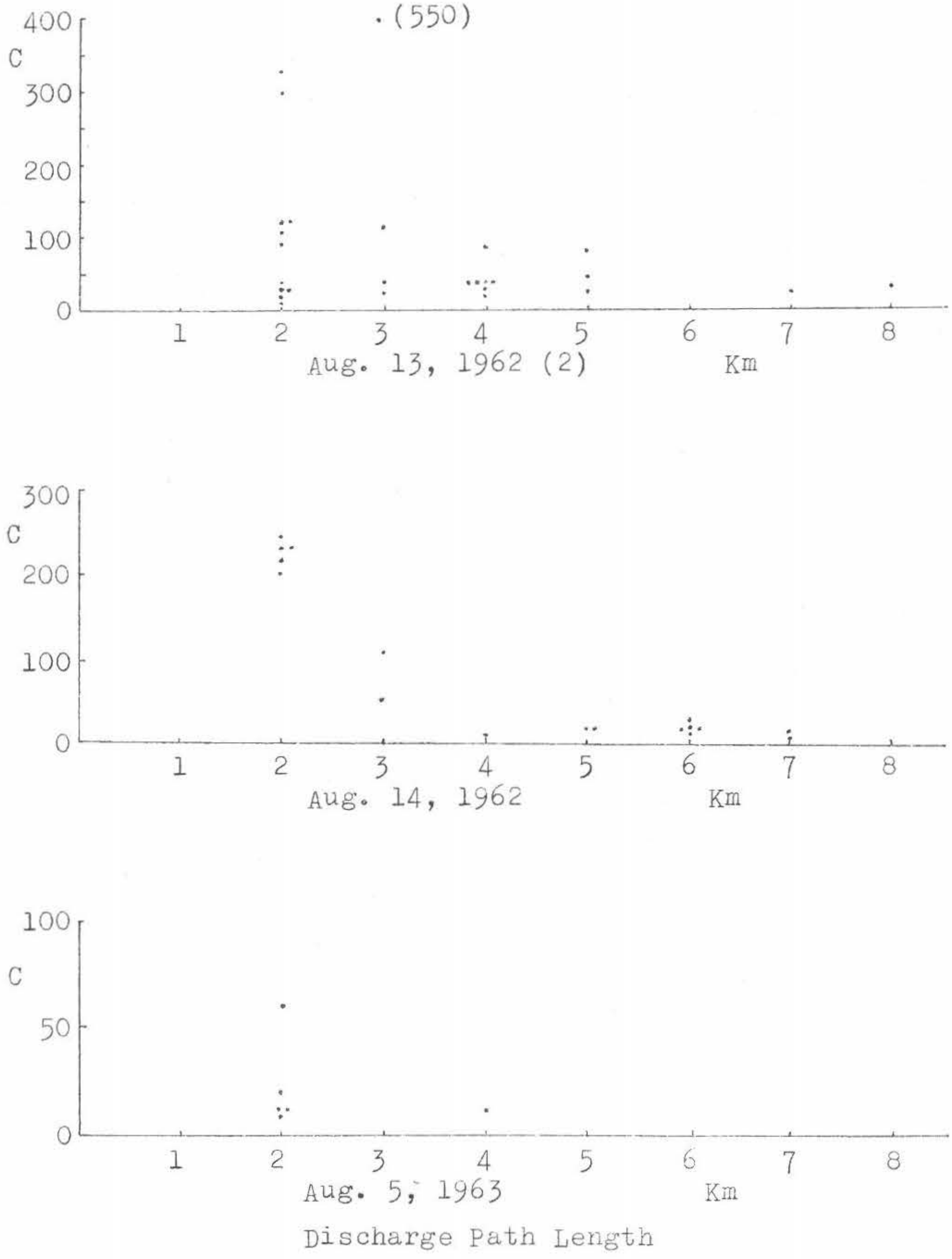
Some of field changes show a large stepwise fashion as shown in Fig. 14. We will call it a partial discharge. Mean number of partial discharges in a cloud discharge are two as shown in Table 5. The results of analysis

Table 5. Multiple cloud discharge

Multiplicity	No. of Data
2	8
3	1
4	1

of a partial discharge is shown in Fig. 15. It likely tells that a partial discharge is of multiple character repeating the same path and not a discharge neutralizing row of a local charge center on the path.

Fig. 13 The relation between discharge path lengths and charge quantities in Type I clouds.



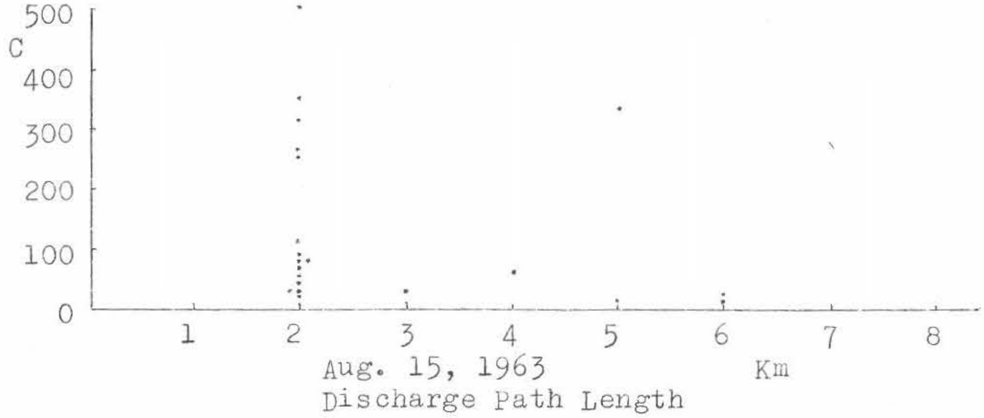


Fig. 14 An example of field change due to multiple cloud discharge.

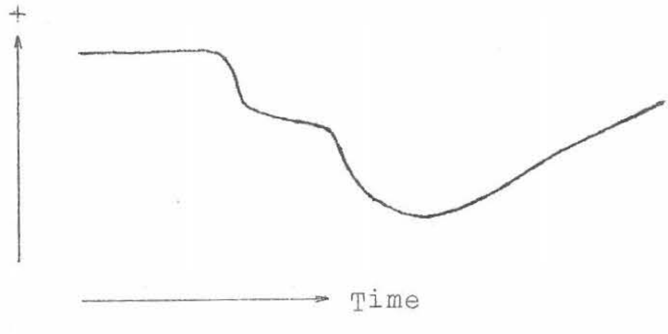
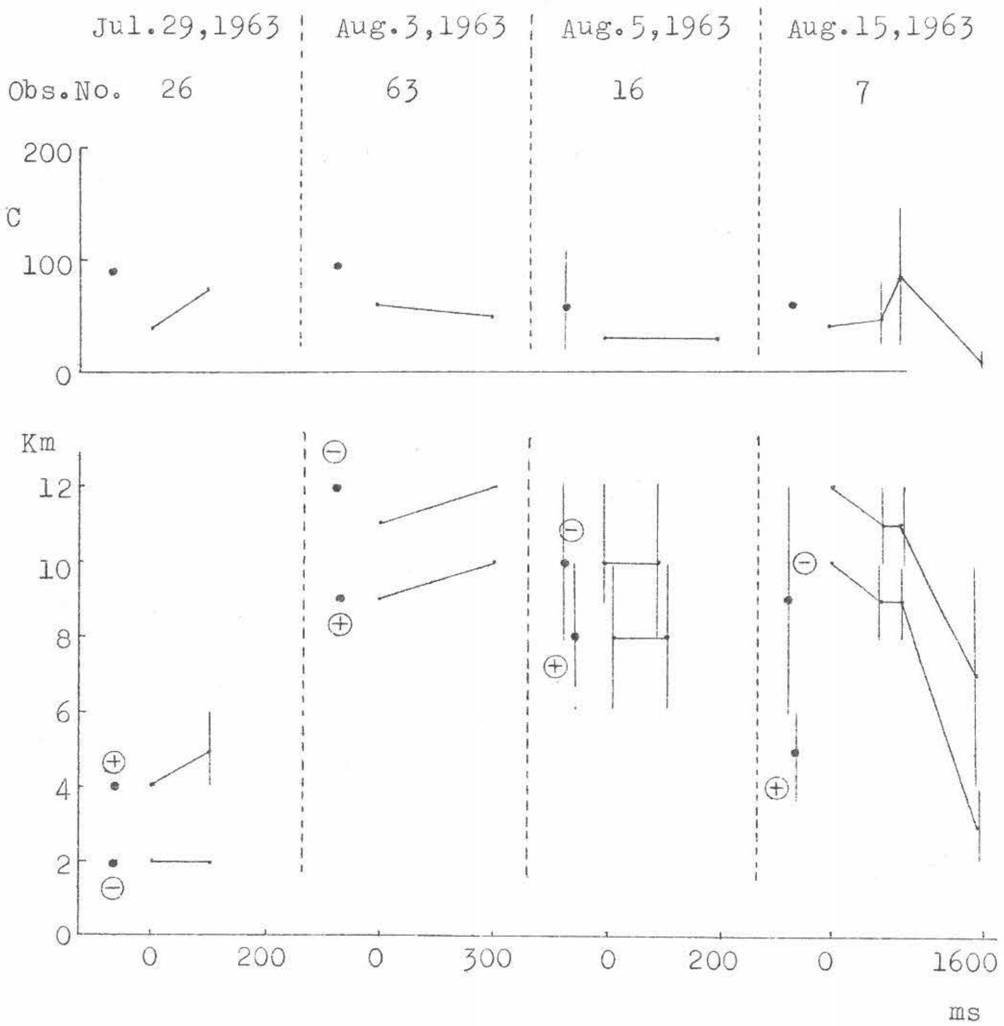


Fig. 15 Heights and charge quantities on multiple cloud discharges.
The data at each left side are results obtained by field change analysis which are ignored the partial discharges. The data at each right side show heights and charge quantities of partial discharges with respect to time sequences in each cloud discharges. The vertical fine lines show limits of errors.



5.6. Local discharge

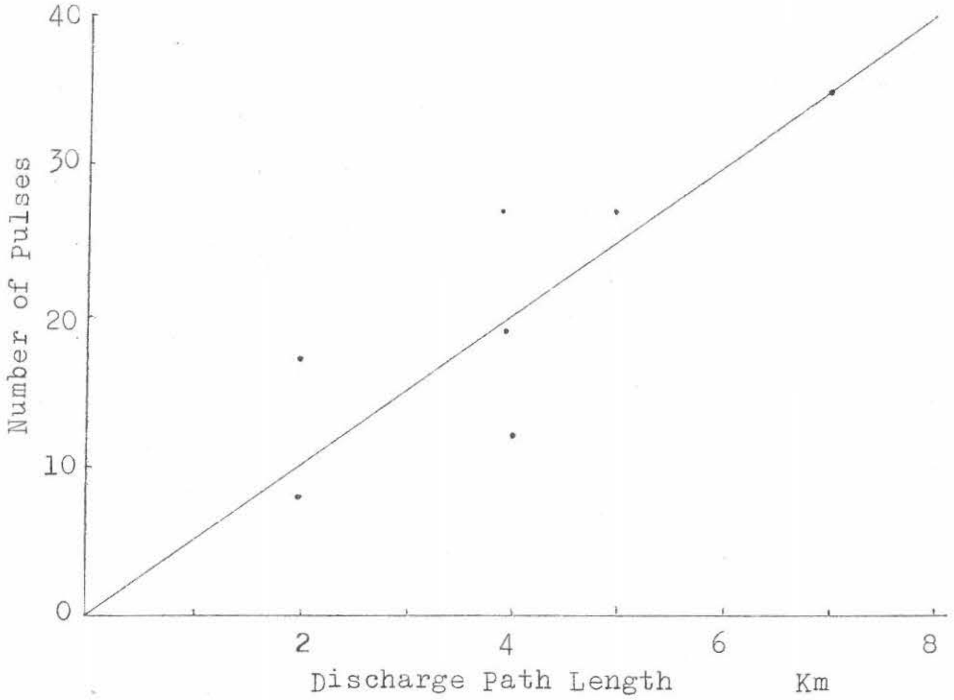
The storm on Aug. 13, 1962 (the 2nd storm) stayed around Soma throughout its storm period. The atmospherics originated from the storm were recorded on a waveform recorder at Takasaki. We picked up the electrostatic pulses exceeding 2V/m on the record. The relation between number of electrostatic pulses and path lengths of the discharges is shown in Fig. 16.
It is clear that electrostatic pulses are occurring at a rate of 5 pulses per km. Therefore we would conclude that local discharge center generating the pulse is distributed on the discharge path at an interval of 200 m as a mean.

Next let us compute the charge quantity of the local charge. Horizontal distance between the discharge and the observation site is 8 km which is the distance between Soma and Takasaki. The two charge centers composing a local vertical dipole are assumed to have the respective altitude as follows: 10 and 10.2 km; 8 and 8.2 km; 6 and 6.2 km; 4 and 4.2 km; 2 and 2.2 km. In the case of combination 6 and 6.2 km, the radii of circles r_i and r_o are calculated as 8.5 and 8.8 km respectively, so that Takasaki must be located near to r_i and r_o. The record of an electrostatic pulse can only indicate a net field change, so that we can not compute exactly the charge on this bassis. By the other combination the observation site are found inside of the circle r_i or outside of circle r_o, so that we can compute the charge quantity from the pulse. Results of the computation show that charge quantity exceed 0.3 coulomb, if the altitude are 2 and 2.2 km, and exceed 1.25 coulomb for combinations of 10 and 10.2 km, 8 and 8.2 km, and 4 and 4.2 km. We may estimate the charge to be roughly 1 coulomb or more.

6. Conclusion

The electrostatic field change analysis of cloud discharge give us the evidence about existence of the three types of thundercloud, i.e., Type I cloud

Fig. 16 The relation between number of electrostatic pulses and discharge path lengths.



where most cloud discharges are of upper-positive vertical dipole, Type II cloud where they are mostly of horizontal or inclined dipole, Type III cloud where mostly of upper-negative dipole. Type I and II may be considered to be a normal cloud with respect to charge distribution, but Type III is the one which has not been reported yet. We may deduce the existence of thin distribution of negative charge on the top of or just above Type III cloud. For studying the negative charge distribution on Type III cloud, we shall need more direct measurement by an airplane or ballon. Of the cloud discharges in Type I cloud, the charge quantity, path length of the discharge, and position of it vary in a very wide range. They reflect the diversity of thundercloud in electrical structure. The path length of most vertical discharges are 2 km or less, while horizontal ones have 5 km as a mean. The mean streamer velocity of the cloud discharges seems to have $1 \sim 2 \times 10^6$ cm/sec. The polarity of a streamer and path length of the cloud discharge seems to have no significant influence to the velocity, and in fact, the streamer progresses with constant speed throughout the path. A cloud discharge are found to superpose some local discharges on it. The charge center of a local discharge is distributed on the discharge path at about 200 m interval and the mean charge quantity of it is 1 coulomb or more.

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II. Ground Discharge

Abstract

The nature of ground discharge was studied by means of field change analysis with aid of thunder observation, flash photographing, etc. The studies are divided into two main parts, i.e., the discussion on the probability of ground discharge in thunderstorm and on the structure of ground discharge. The probability exhibits a variation in a wide range in every storm and it depends on the type of a thundercloud. The probability in Type I cloud is generally larger than that in Type II and III, because the charge height in Type I is generally lower than in Type II and III. The successive stroke channel in the cloud progresses sideward or spreads out widely and does not progress upward as observed in South Africa. The leader model given by Schonland and Malan can not explain our field change records, so that we have to modify a leader model so as to have a twig-like structure in a cloud and the charge distribution on it is uniform everywhere.

1. Introduction

The method of analysis of field change due to ground discharge measured on ground opens a way to studying the nature of the discharge as well as cloud discharge to research workers, and indeed many papers adopted the method can be found. It is true that some aspect of a ground discharge can be investigated on the basis of single field site observation, however, there are many others which require the simultaneous observation at several sites. Four field sites are the minimum demand for the dipole model analysis of a ground discharge when we have no other auxiliary means.
It is for this reason that some workers tried to investigate the structure of the discharge actually making simultaneous observation at several field sites. (Workman et al. 1942; Barnard 1951;

Hacking 1954; Reynolds et al. 1955; Tamura et al. (1958) In the early period of our storm observation untill 1959 we used single site to record field change, thunder, flash, etc. The number of field site were increased to two in 1960 and to three from 1961 to 1963. Some of the results being described in this paper are the deduction of single site observation, while the others depends on two or three sites simultaneous observations.

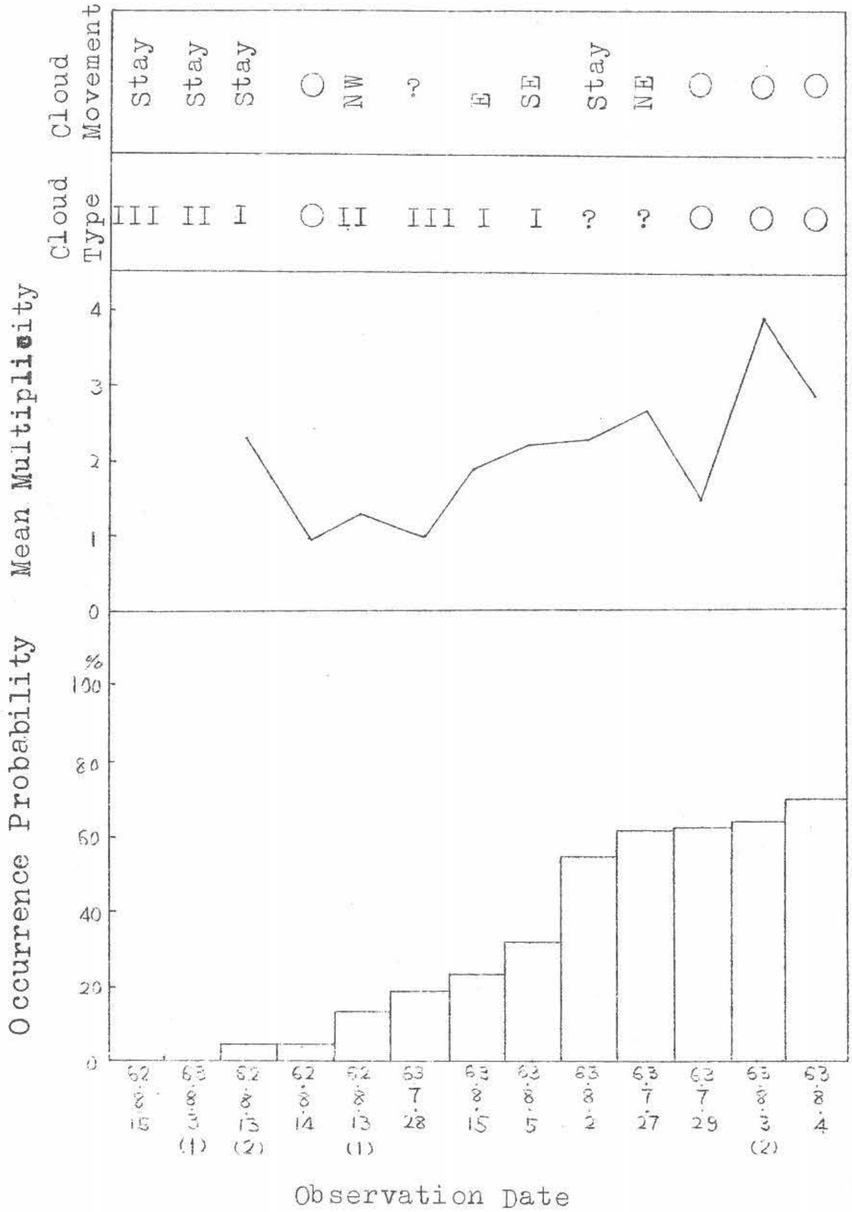
2. Apparatus and field sites

The single site observation was carried out at Maebashi untill 1959. In 1960 Shibukawa was added to Maebashi, and from 1961 to 1963 Soma, Takasaki, and Maebashi were selected for the three sites. The map of field sites has already been illustrated in Chapter I. Apparatus used for the observations included mill type field meter, antenna type field meter, VLF atmospheric waveform recorder, VHF atmospheric recorder, Boy's camera, etc. (1958) (1962) (1956) (1963) (1961)

3. Occurrence probability of ground discharge

Occurrence probability of a ground discharge has been investigated for thirteen groups of thunderstorms, of which four group consisted of two storms simultaneously occurred at two different places and nine group consisted of single storm. The probabilities are shown in Fig. 1. It can be found that the probability varies from 0 to 70% depending on a storm group. Moreover the largest value was obtained indeed from a group consisting of two storms, so that the upper limit of the value must be larger than 70%. We tried to find the correlation between several plausible meteorological factors and the occurrence probability. As the charge separation in thundercloud closely relates to the vertical temperature distribution in it, we firstly investigated the correlation between the probability and the altitude of freezing level measured by radio

Fig. 1 Occurrence probability and multiplicity for ground discharge.
○ means a group consisting of two storms occurred different places at same time.



sonde at Tateno Meteorological Observatory, about 100 km apart from the field sites, at 9 p.m. on the storm day. However this did not give any correlation. It is very possible that the temperature measurements were made at the too distant place from the thunderstorms to correlate. Secondly, we checked the correlation between the probability and the storm appearing time of the day. If a storm occurs at night, the temperature on earth's surface would be lower than what we would expect in daytime and meteorological conditions influencing a thunderstorm activity should be different from those in daytime. Notwithstanding the prospect the investigation again did not give any successful result. Next we investigated the correlation between the probability and the fact whether a storm moved or stayed. It is surprising to note that the probability for a staying storm is smaller than that for a moving storm. This must be due to some meteorological condition influencing the charge distribution in the cloud, but it is difficult for us to point it out at present. In Chapter I we have classified thunderclouds into three categories, i. e., Type I, II, and III, which predominantly produce cloud discharge with structure of upper-positive vertical dipole, inclined or horizontal dipole, and upper-negative vertical dipole respectively. It has been found that the occurrence probability of ground discharge is smaller in Type II and III than in Type I as shown in Fig. 1. On the other hand we have an experimental evidence that the charge distribution in Type II and III occupies a higher part in the cloud than that in Type I. See Fig. 2. Therefore it is evident that the larger probability for Type I is due to the charge distribution in lower part of the cloud in comparison to Type II and III. The variation of probability with time was measured in every ten or twenty minutes interval for each of the four groups as shown in Fig. 3. The probability was actually kept roughly constant through the life of the 2nd storm on Aug. 13, 1962, while the probability gradually increase on the storm on Aug. 15, 1963 and it decreased on

Fig. 2 Charge distributions in thunderclouds deduced from cloud discharges with respect to cloud type.

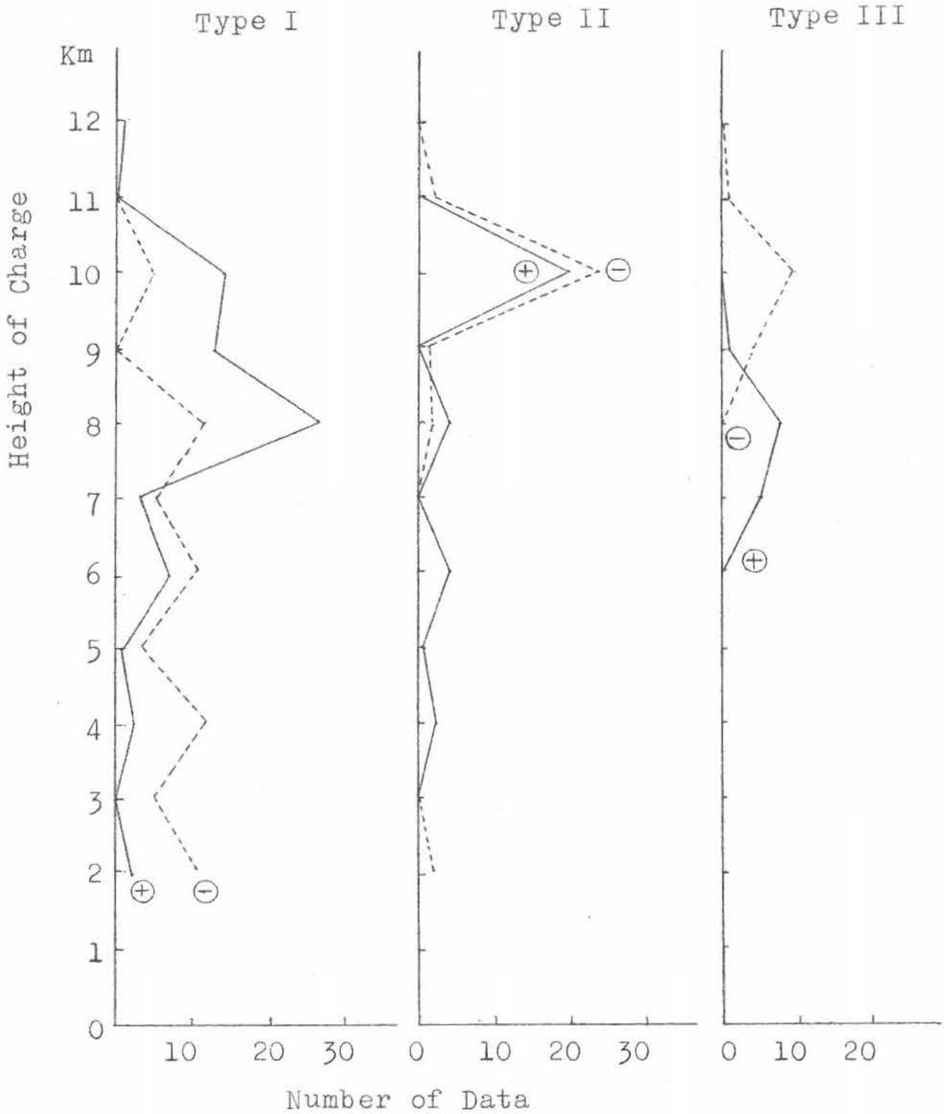
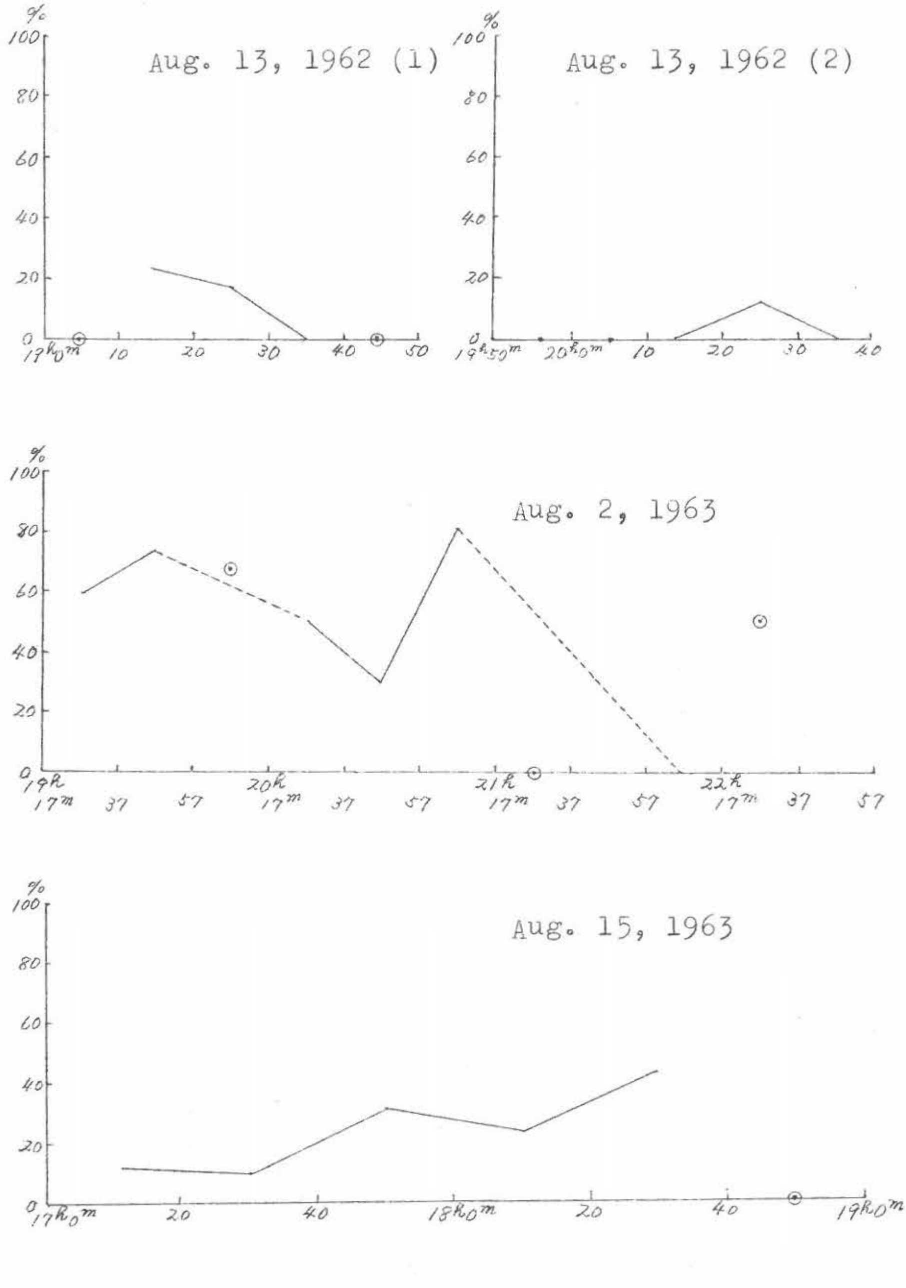


Fig. 3 Variations of occurrence probabilities of ground discharges with time.
⊙ is result from data whose number is smaller than 5.



the 1st storm on Aug. 13, 1962. The probability of the storm on Aug. 2, 1963 did not show any regularity. Therefore it is evident that the developmental aspect of a storm is very variable from a storm to another. The smaller probability value in 1962 than that in 1963 would not have any significance in this respect.

4. Structure of ground discharge

4.1. Multiplicity

Fig. 1 shows that multiplicity of ground strokes is roughly in a proportional relation to the probability. Brook and Kitagawa (1960) showed that the number of cloud discharges, if a storm activity exceed a certain level, come to be nearly equal to the total number of ground strokes. If the principle is applicable to our case, the multiplicity of ground stroke must increase as the probability decreases. Thus the result obtained here seems to correspond to their abnormal case on which they reported the existence of some storms aparting from the rule. Histograms of multiplicity obtained from field changes and from Boy's camera photographs are shown in Fig. 4. The agreement of the histograms is fairly good with the report in other countries. (Pierce et. al. 1962)
The multiplicity measurement on Boy's camera photograph may often bring a confusion of M component with ground stroke, so that the multiplicity deduced by means of Boy's camera generally results a higher value than the field method.

4.2. Time interval between ground strokes

Fig. 5 is the probability distribution of interval between strokes occurring in a ground discharge obtained from field change.

4.3. VHF emission from various stage of a ground discharge

Fig. 4 Histogram of multiplicity of ground discharge.
× : Data from field change record
o : Data from Boy's camera photograph

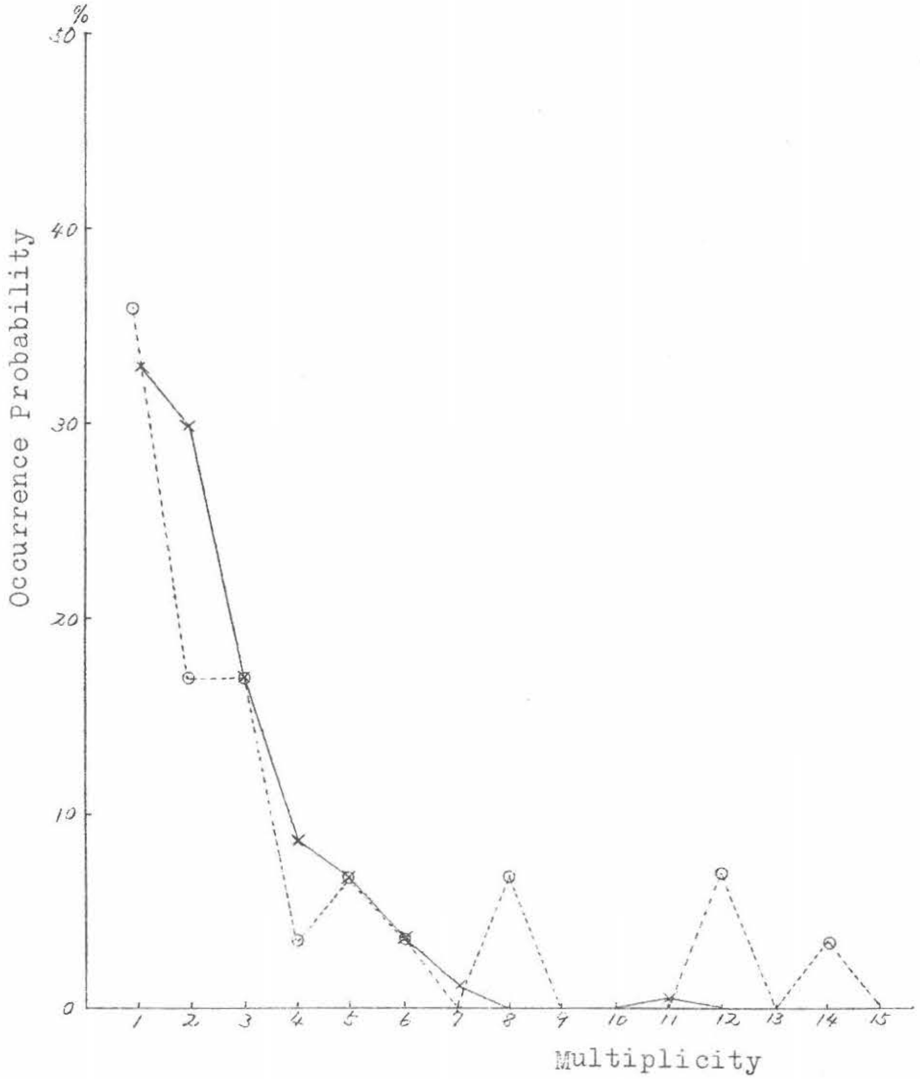
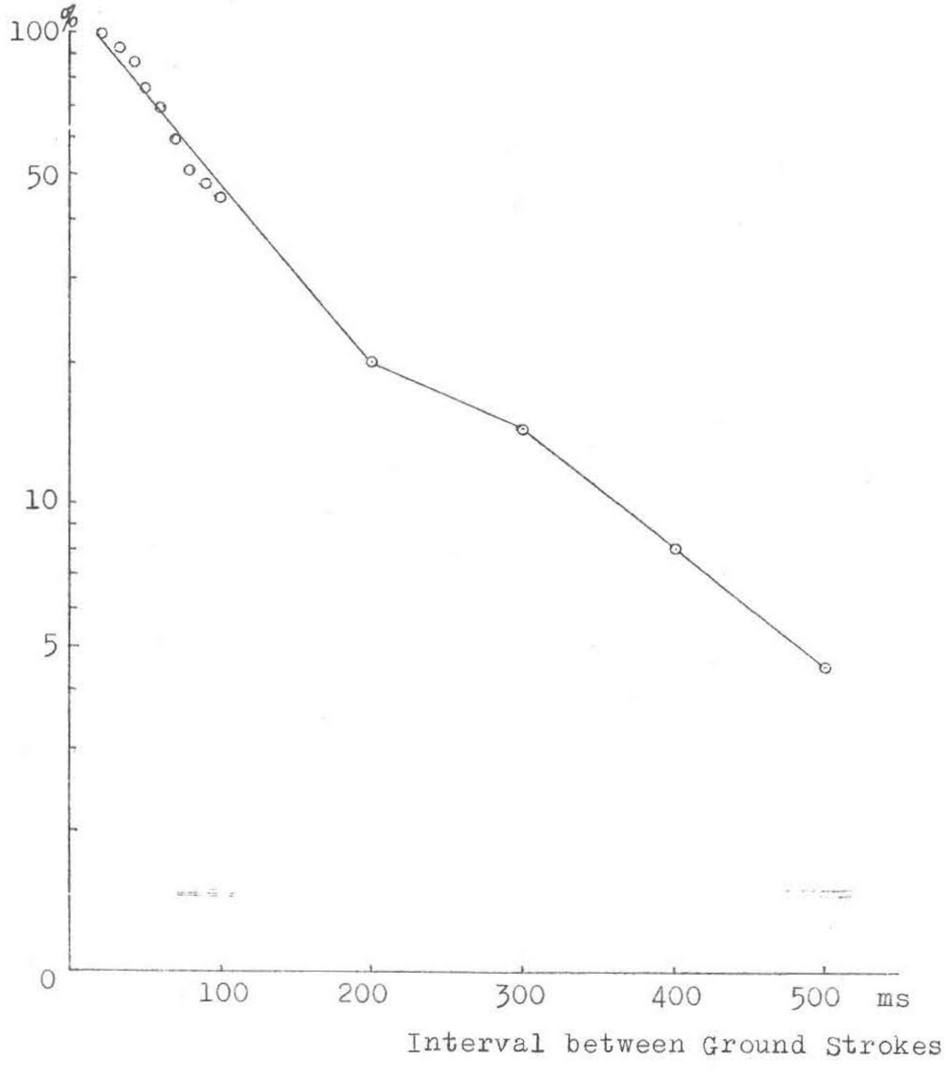


Fig. 5 Probability distribution of time interval between ground strokes occurring in a ground discharge obtained from field change.



We have made some simultaneous records of field changes and VHF emissions from 1.3 mc to 150 mc, as well as the record of atmospheric waveforms and VHF emission at many frequencies. Intensities of VHF emissions from various stages of a ground discharge process are shown in Table 1.

Table 1. Intensities of VHF emission from ground discharge.

Freq.	Successive Leader	Between Strokes	After Stroke
500 mc	13,0		
150 mc	5,0	1,4	1,1
100 mc		0,1	
27 mc	2,0	0,1	0,1
3 mc	0,2	0,1	0,1
1.3 mc	1,4	0,5	1,3
0.5 mc	2,2		
0.3 mc	11,0		
0.1 mc	11,6		

The left number in each column means the number of records, intensity on which equals roughly to that on the 1st leader record. The right one in each column means the number of records, intensity on which is weaker than that on the 1st leader record. The VHF emission intensity from the 1st leader has been never exceeded by that from other stage at the region observed by us.

We did not succeed in recording the VHF emission from a ground stroke because of too slow speed of the record in comparison with the stroke duration. It has been found that the emission from 500 kc to 10 mc by the 1st leader is more intence than that by successive leaders. Emission from 1 mc to 150 mc in the interval between successive strokes and in the period after the last stroke are generally weaker than that of the 1st leader irrespective of accompaniying field change. This seems to mean that the mechanism of emitting radio wave is different among the 1st leader, the successive leader, and the discharge between or after ground strokes.

4.4 Position and quantity of charge producing a ground discharge.

4.4.1 Field change method of estimating the quantity and the position.

If we denote quantity, horizontal co-ordinates, and height of charge neutralized by a ground stroke with Q, x, y, and h respectively, a field change F produced at the co-ordinate origin will be given by equation (1)

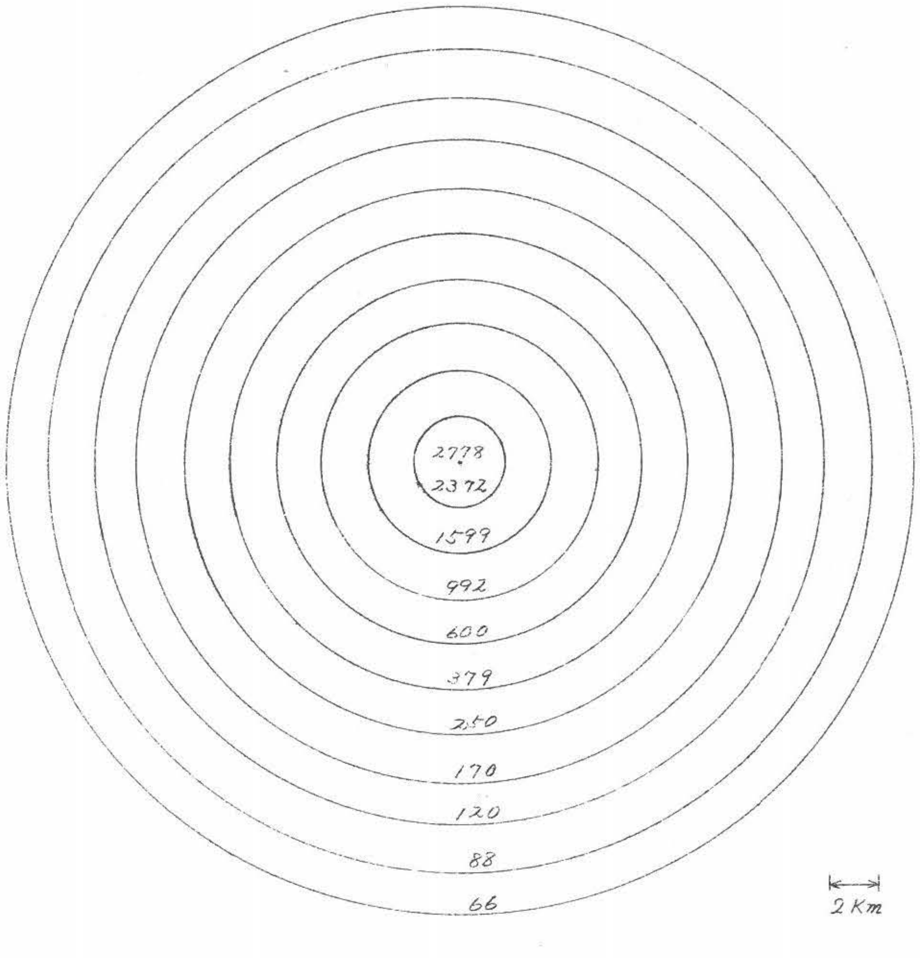
$$F = 2QY \qquad (1)$$

where

$$Y = h/(h^2 + x^2 + y^2)^{3/2} \qquad (2)$$

If we have a set of four simultaneous F's obtained at four respective different sites, we can estimate Q, x, y, and h using equation (1). We analyzed the ground stroke by means of map trial as we had done it on a cloud discharge. A contour, which indicates Y value respectively corresponding to horizontal distances in every 2 km interval from the charge center projection, was prepared on the map for each of the h value 2, 4, 6, 8, 10, and 12 km. Fig. 6 is

Fig. 6 An example of field intensity map for ground stroke.
This map show the case of 6 km of charge center height. The values on the map mean $Y \times 10^5$ as same as Fig. 2 in Chapter I.



example of the map.

4.4.2 The results analyzed

The height and quantity of charge neutralized by ground strokes with respect to their stroke orders are shown in Fig. 7. It can be found that the height of the successive stroke does not increase with stroke order in contrast to the results given by Malan and Schonland (1951), while it is in a good agreement with the report given by Ishikawa. (1961) Ishikawa estimated the ground stroke height from duration measurement of leader strokes recorded at Maebashi. It is very likely that in Maebashi district, the ground stroke channel does not strech straight upward in thundercloud as the stroke order increases, but it progresses sideward or spreads widely. We have here the experimental evidence which support this point as follows;

a) We succeeded in fixing the position of each stroke belonging the same ground discharge in three cases as illustrated in Fig. 8., which shows that there are some ground discharges whose stroke channel developes not upward but sideward as the stroke order increase. It must be noticed further that the horizontal distance between successive strokes is about 1 km.

b) Fig. 9 a and b are to suggest a possibility that a stroke channel progress sideward in thundercloud and Fig. 9 c a channel spreading in the cloud.

Hacking (1954) reported that the height of a stroke channel makes a gradual increase, but at same time the channel often progresses sideward. Brook and Vonnegut (1960) observed visually J streamer and reported the deflection of it from vertical. Malan (1961) also noticed the horizontal spreading of J streamer.

4.5 Continuing current in ground discharge

Fig. 7 Height and quantity of charge neutralized by ground stroke with respect to stroke order.
o———o : Data by sign of leader field change
x- - - - - -x : Data by return field change
•——-——• : Data by leader duration (Ishikawa)
Number of data is indicated in each parenthesis.

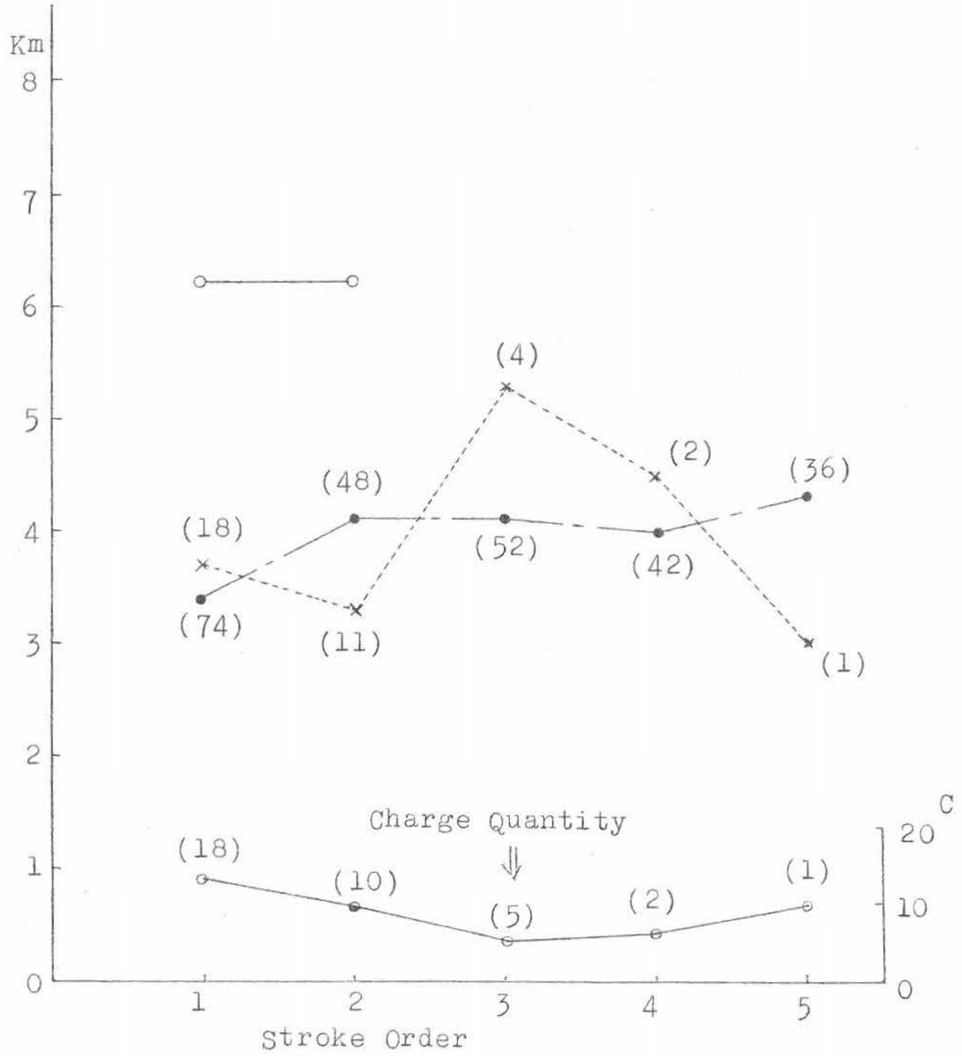
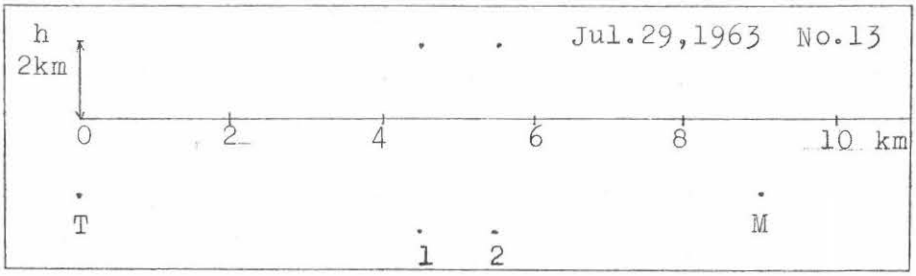
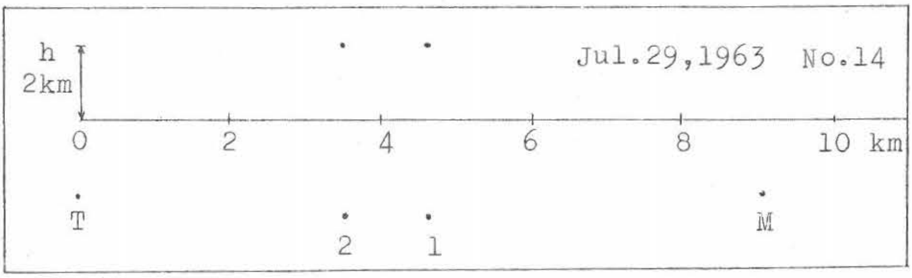


Fig. 8 A projection chart of charge centers neutralized by ground strokes in a discharge.
T: Takasaki observation site
M: Maebashi observation site
→ means limit of error and ⊙ means struck point on a ground.
Numbers in the Fig. show stroke order.





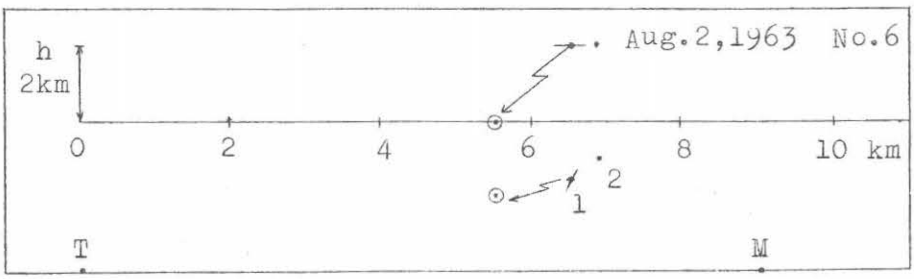
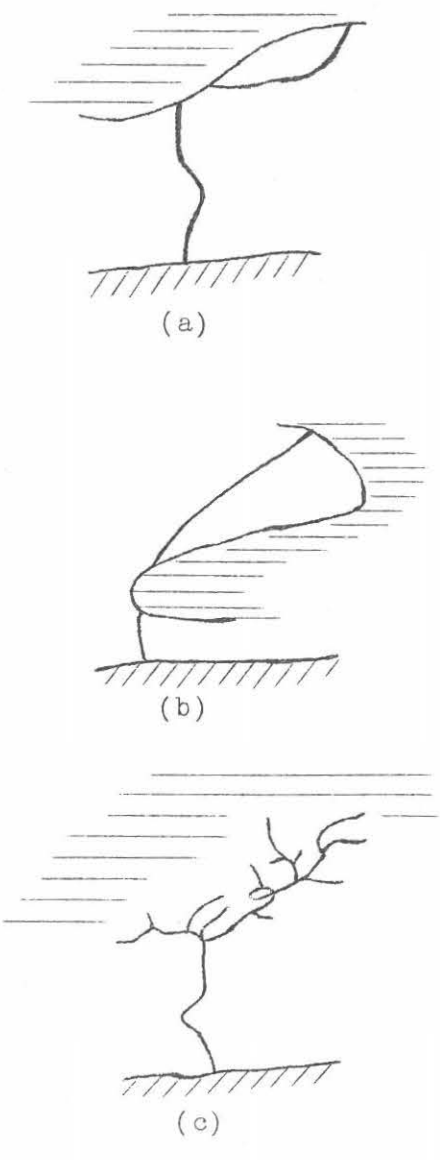


Fig. 9 Sketches from the photographs of ground discharge.



Malan (1954) reported the existence of a continuing current from the ground after the last stroke, and designated "F change" to it. Kitagawa, Brook, and Workman (1962) reported about the continuing current appearing in the interval between ground strokes. We investigated the after grow duration of a ground stroke on our Boy's camera photograph. Fig. 10 is the histogram of the duration, which does not seem to indicate the existence of a long continuing luminosity. However it must be noticed that we have succeeded in finding out the two photographs which have continuing luminous lines on many points along a stroke channel as shown in Fig. 11. The maximum line duration on one of the two photographs is about 40 ms, the other is 70 ms. Five out of sixteen ground discharges investigated produced the field change due to continuing current. The currents estimated from the field change are ranged from 20 to 500 A, while the current due to return stroke is usually of order of 2×10^4 A, though 10^5 A is sometimes exceeded. (Chalmers 1957) The great difference in current value between continuing current and return stroke is the main cause of the difficulty for photographing a continuing current together with a return stroke. The height which the continuing current reached has been estimated only for three cases. Two of the three gave the height which is nearly the same as the height of a return stroke charge center. The data on continuing current are listed in Table 2.

4.6 Structure of leader stroke

The height of a charge center H relating to a ground stroke can be estimated using the equation (3) given by Malan and Schonland (1947), provided the leader field reversal distance D being known.

$$H = D/0.79 \qquad (3)$$

Fig.10 Duration of aftergrow of ground stroke

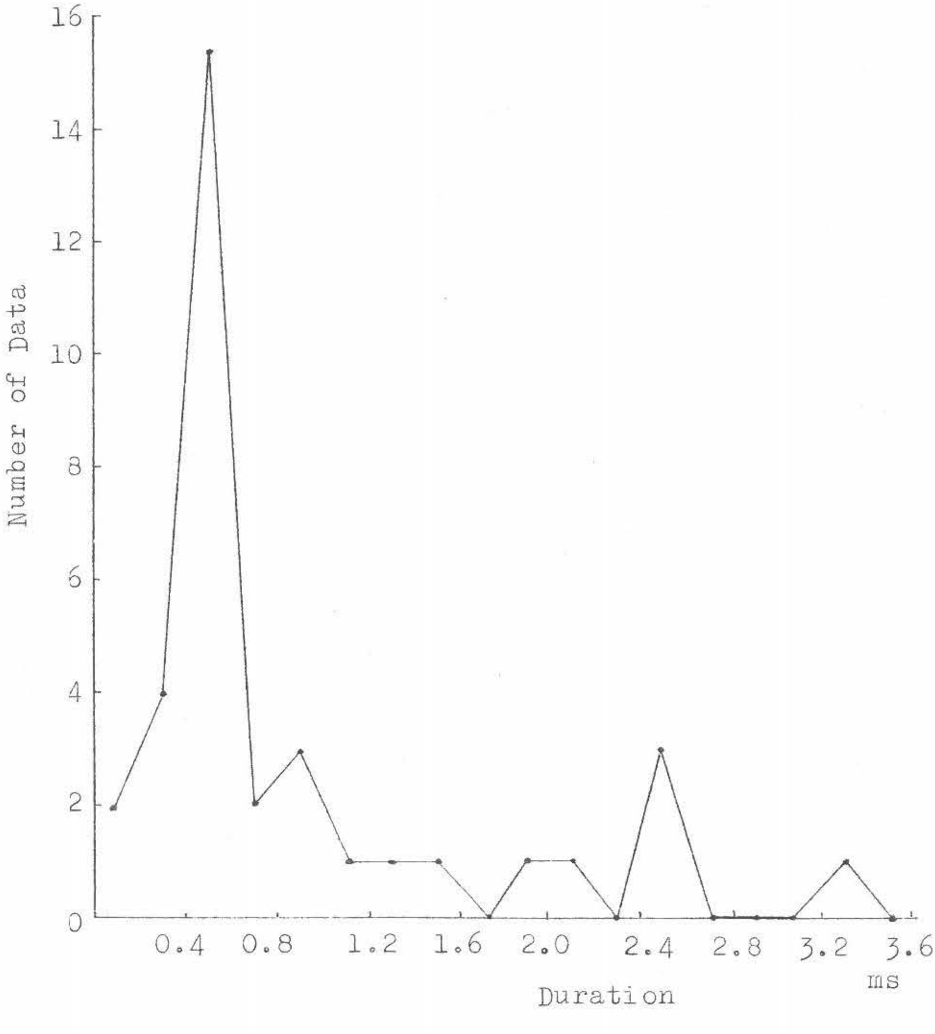


Fig. 11 Sketch for the photograph of ground stroke showing long luminous lines. Dotted lines mean image of after grow.

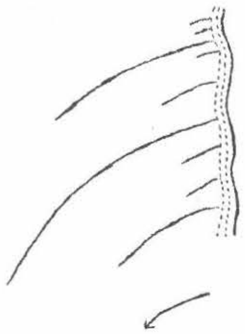


Table 2. Data on continuing current

Discharge No.	Occurrence Time	Charge Quantity	Current	Height Reached	Height of Charge of Ground stroke just before the Current
1	After Last Stroke	36-72 C.	180-360 A.	?	?
2	After Last Stroke	5-8 C.	20-32 A.	2-4 km	2 km
3	After Last Stroke	4 C.	27 A.	2 km	2 km
4-1	Between Strokes	27 C.	104 A.	10 km	2 km
4-2	After Last Stroke	84-156 C.	252-468 A.	?	2 km
5	After Last Stroke	?	?	?	2 km

Fig. 12 represents the relation of the sign of a leader field change to the distance from the site to leader, and the reversal distance is found to be 5 km. The computed height 6.3 km of the 1st and 2nd ground stroke is indeed larger than what was obtained using the field change method or the leader duration method. (Ishikawa 1961) An explanation of the difference in the estimated stroke height in the two method will need a new model of a leader structure. Let us assume the height of a stroke charge center to be 4 km in Maebashi district following the result deduced from field change analysis and from leader duration measurement. Suppose that a leader has the structure illustrated in Fig. 13, and the charge distribution is everywhere uniform along the leader track, then the macroscopic charge transport along the track will be equivalent to the negative charge center transport from 4 km to 3 km in height. Suppose a charge center moves down from h_1 to h_2, the reversal distance will be given as follows;

$$r = h_1^{1/3} h_2^{1/3} (h_1^{2/3} + h_2^{2/3})^{1/2} \qquad (4)$$

Putting respectively 4 and 3 km to h_1 and h_2, we can get 4.9 km for r. By this method, we can bring the height given by the return field change method equal to the height given by the leader stroke sign method. Fig. 14 is the relation of stroke order to height of charge center neutralized by ground stroke in South Africa. (Malan and Schonland 1951) Comparing Fig.14 and Fig. 7 we can know the evidence that the two method, i.e. the leader duration and the return field change, give the same result for two country, while the other method i.e. leader field sign and the ratio of leader field change to return field change give the other same result for both country. In the previous discussion we saw that each charge center height value obtained respectively by three different method can be made identical with each other in Japan. If there is no much difference in electrical structure of a thundercloud

Fig. 12 Relation between the sign of leader field change and distance from site to the leader deduced by thunder observation.
The ordinate means the following value;
(Number of negative field change)/(Number of negative and positive field change)
• : The 1st leader
× : The 2nd leader

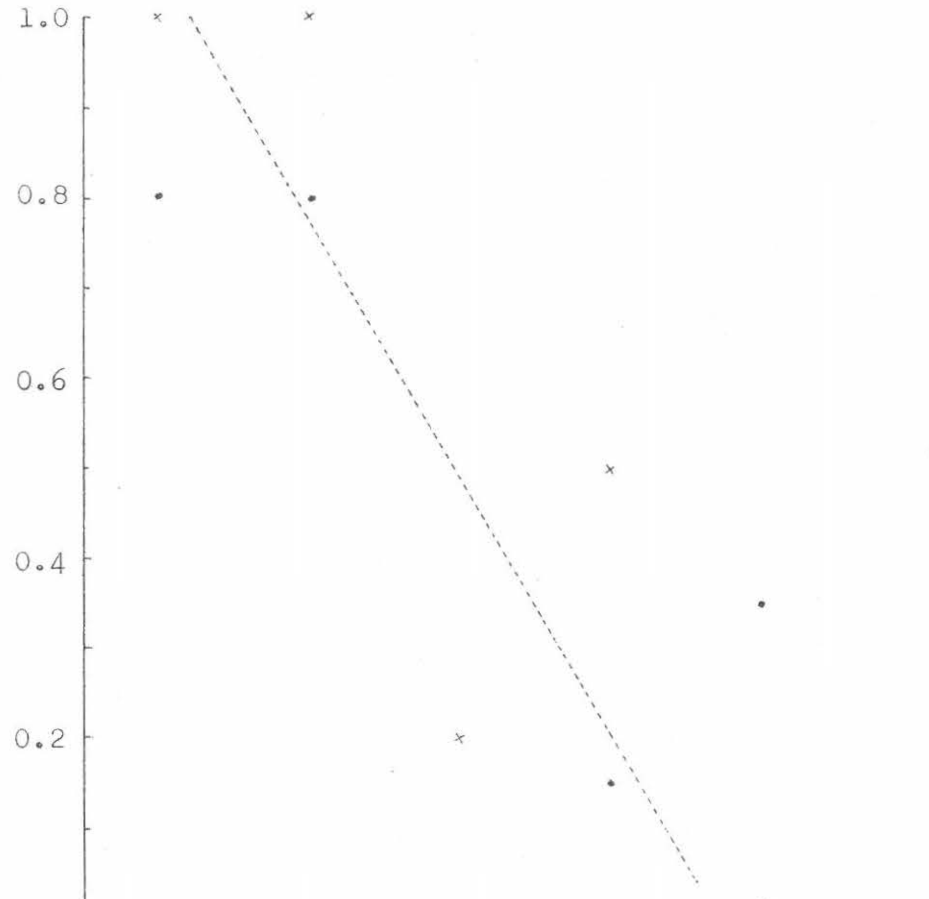


Fig. 13 New model of leader stroke

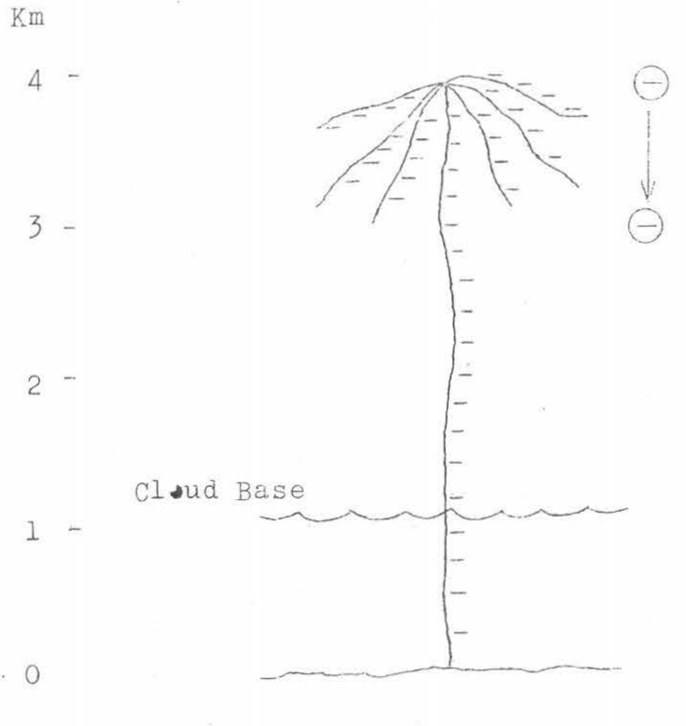
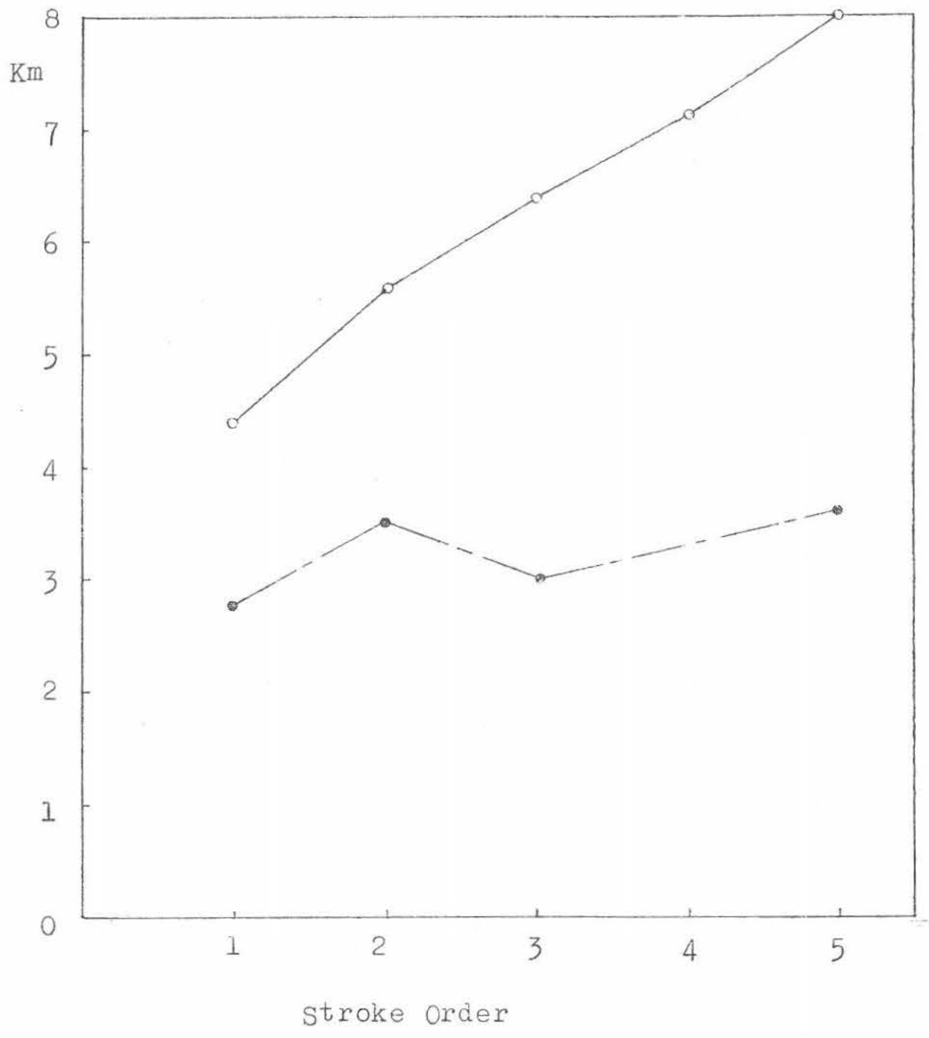


Fig. 14 Height of charge neutralized by ground stroke with respect to stroke order in South Africa.

o——o : Data by sign of leader field change and by ratio between leader field change and return field change

●—-—● : Data by leader duration



between Japan and South Africa, the same should be true for South Africa too. Therefore it is very probable that the true height of a charge center in South Africa may be lower than that reported by Malan and Schonland (1951) and roughly identical with the value in Japan.

5. Conclusion

(1) The occurrence probability of a ground discharge can vary in a wide range from 0 to larger than 70 %, and depends on the type of a thundercloud. The negative charge in Type II and III cloud is distributed in a higher part of a thundercloud than in Type I, so that the probability in Type II and III cloud is generally smaller than that in Type I. (2) The height of a charge center neutralized by successive ground stroke does not increase as the stroke order increases, but progress sideward. (3) The model of a leader stroke must be changed from that already given by Schonland and Malan who assumed a uniform negative charge distribution in a simple vertical channel. The new model has channel spreading like a tree in a thundercloud. If the electrical condition in a thundercloud is the same between in South Africa and in Japan, the charge center height reported by Malan and Schonland must be reduced to a lower value like that in Japan.

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III. Thunderstorm Observation by Radar

Abstract

The thunderstorm observation with PPI radar using 3 cm wave length was carried out at Tochigi-ken in 1964. Though the radar echo did not indicate anything further than a precipitation region, we have succeeded in obtaining the some nature of behavior of thunderstorm.

1. Introduction

As the radar is a very useful method of studing thunderstorms, many worker have used it for the study. We have made storm observation with PPI radar together with simultaneous recording of the field change, thunder, etc. on the ground. The analysis of the data have not thoroughly been completed at present, so that we will limit our description only to the discussion on the radar observation in this Chapter.

2. Radar and field sites

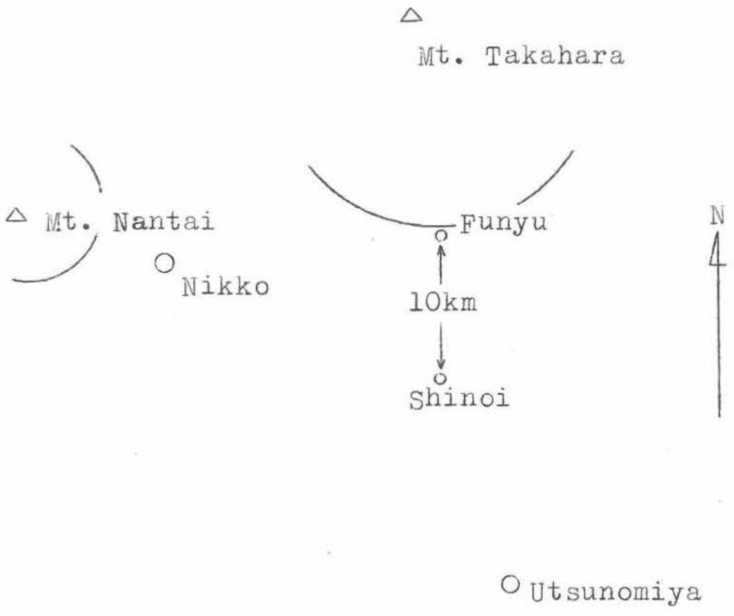
2.1. Radar

The radar with 3 cm wave length mounted on a trailer displays a PPI scope which has a maximum detectable range of 50 km. The echoes are automatically photographed on 35 mm film at a constant time interval.

2.2. Field sites

In 1964 we recorded some elements of thunderstorm effect, such as field change due to lightning discharge etc., at Funyu and radar echo at Shinoi with 10 km separation distance between them. The sites are located in Tochigi-ken, one of the most thunderstorm active district in Japan as well as Gunma-ken. The map showing the sites is given in Fig. 1.

Fig. 1 Observation site



3. PPI radar echo

Although the radar echo in our case is limited to indicating a precipitation region, still they are very useful for investigating the behavior of a thundercloud. To go without possible ambiguity in the following, we left out the echoes from our discussion in accordance with the following criteria.

The echoes showing complex aspect are omitted because of the difficulty in analysis.

If the location of an echo coincides with the storm location informed by the Utsunomiya Meteorological Observatory, the echo is brought to a check whether the distance from the sites to a discharge point deduced from thunder observation can roughly explaine the corresponding distance on the PPI scope.

The echo data which satisfied the above criteria were collected for four storms. The echoes are illustrated in Fig. 2. The general nature of the echoes investigated will be described in the next.

3.1. The investigated storm echoes were found to move or to disappear after staing at an initial appearing point for 20 minutes or more.

3.2. In one case the echoes were seen to come together to a large echo, while in another case there was a large echo divided into a few smaller echoes.

3.3. Duration of an echo is generally ranged from 20 minutes to longer than 2.5 hours, but discharges are found not always to occur without interruption through the life of an echo.

3.4. The track of a moving echo is found generally to be along the lower portion of the land, something like a valley, river, etc. and the advance of an echo is often stopped even by the existence of a small mountain of a few hundred meter in height. The relation between the general track of an echo

Fig. 2 a Radar echoes by the thunderstorm on Jul. 28, 1964. The diameter of inner circle is 20 km and that of outer one is 40 km. The radar site Shinoi locates at the center. • indicates the position of Funyu site.

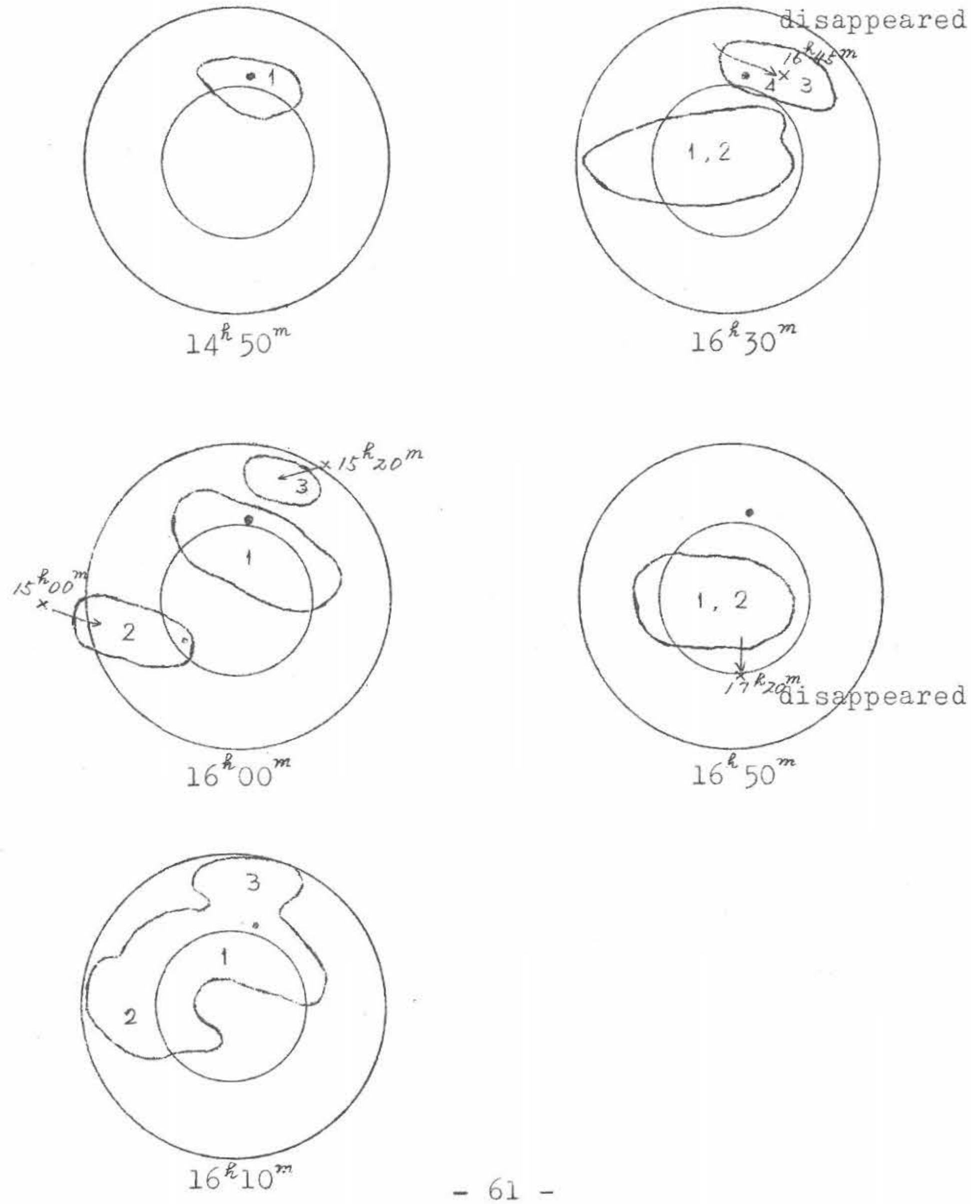


Fig.2. b Radar echoes by the thunderstorm on Aug. 2, 1964. The diameters of the circles are 20, 40, and 60 km respectively. The radar site Shinoi locates at the center. • indicates the position of Funyu site.

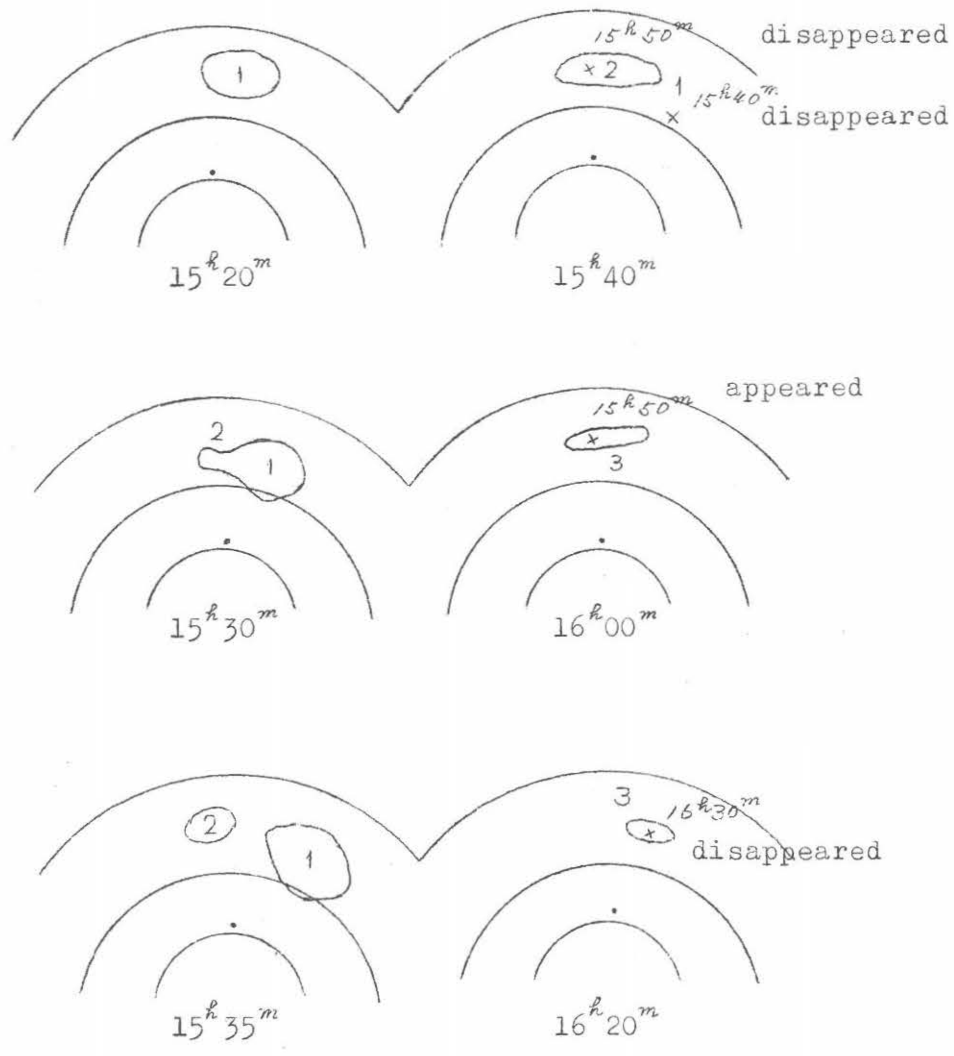


Fig. 2. c Radar echoes by the thunderstorm on Aug. 12, 1964. The diameter of inner circle is 20 km and that of outer one is 40 km. The radar site Shinoi locates at the center. • indicates the position of Funyu site.

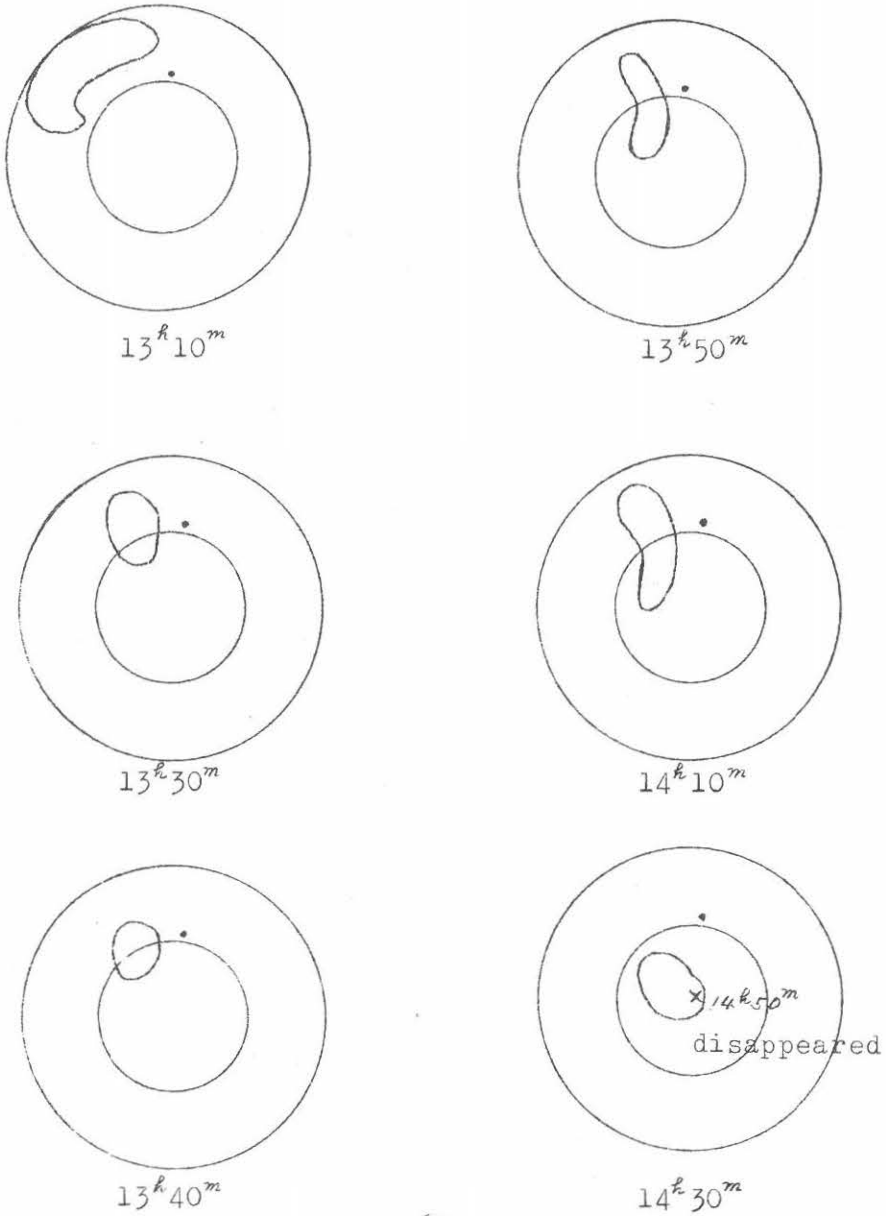
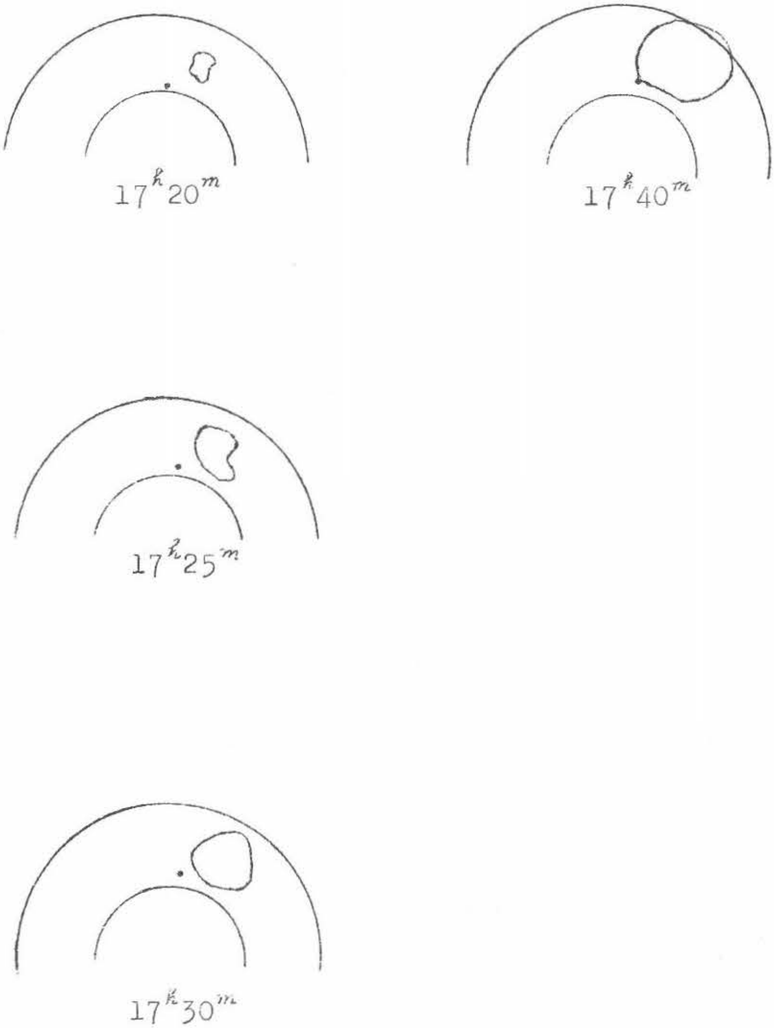


Fig.2.d Radar echoes by the thunderstorm on Aug. 17, 1964. The diameter of inner circle is 20 km and that of outer one is 40 km. The radar site Shinoi locates at the center. • indicates the position of Funyu site.



motion and the feature of the land are illustrated in Fig. 3 and 4. The result is in good agreement with Kitaoka's report. (1950)

3.5. Fig. 5 illustrates the corelation of an echo center to the storm center inferred from discharge-thunder time-interval. It can be seen that the most discharge active portion in a thundercloud is always be involved in a precipitating region.

Reference

Kitaoka T., Kaminari no Kenkyu, Denki Shoin Press, 16-30 (1950)

Fig.3 The natural feature around observation sites.
● and ◎ indicate the Shinoi and Funyu site respectively.
The numbers in the map show the height with unit of m.

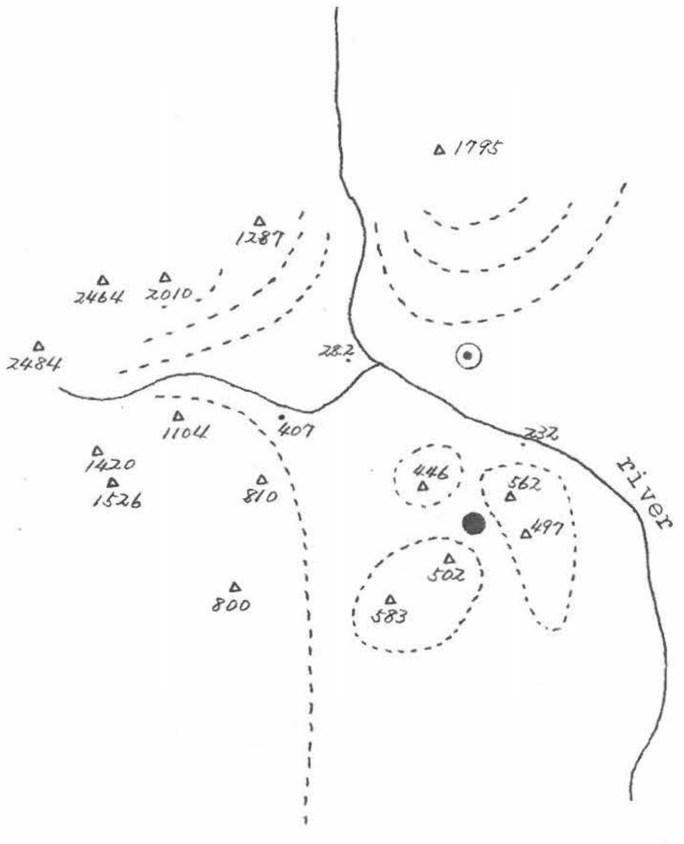


Fig.4 Courses of thunderstorms. Terminals of each arrow show where the storm disappeared. There was no discharge in the storm on Jul. 27, but the cloud had charge.

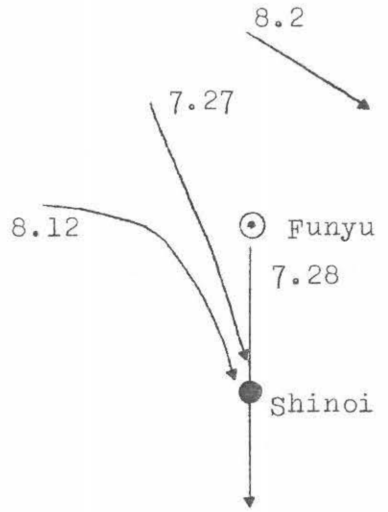
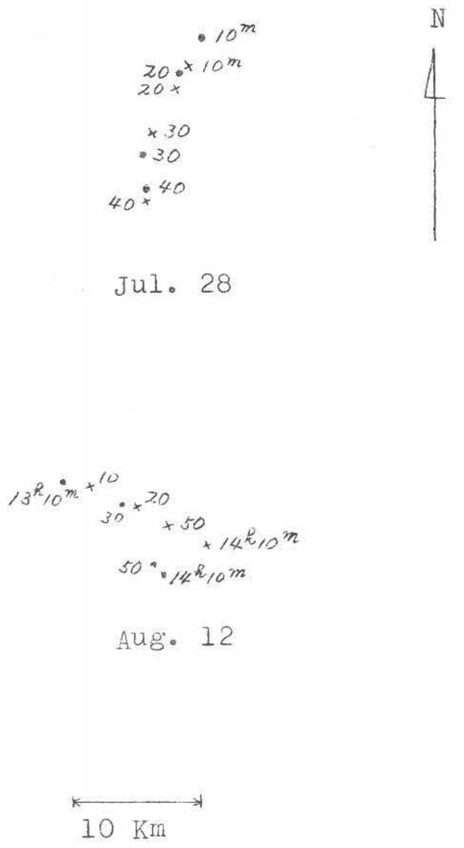


Fig. 5 Relation between center of echo and thunder.
• indicates the center position of echo and × indicates that of thunder.



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Map of Central Japan