Electrical charge associated with cloud-to-ground lightning discharge

in the Shonai area, Tohoku district, Japan

by

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Abstract

Electrical charges related to cloud-to-ground (CG) lightning discharge were investigated using ground electric fields measured around the Shonai area in the Tohoku district, Japan. First, the requirement for preciseness for least-squares fitting of the electric fields derived theoretically assuming a point electrical charge to the measured electric fields is discussed. The horizontal resolution needed to obtain appropriate solutions is proposed using a set of theoretical electric fields made by electrical charges at heights with intervals of 0.1 km. A numerical fitting with the proposed spatial resolution was applied to the measured ground electric fields, and the locations and amounts of charges were estimated for 19 negative CG lightning discharges that occurred around Shonai during the warm and cold seasons in 2012. The estimated locations of the charges were compared to the atmospheric temperature, Doppler radar measurements, and the distribution of very-high-frequency (VHF) radiation sources detected by a VHF-based lightning detection system for two events. In one of the analyzed events, the estimated electrical charge revealed the characteristics of a negative charge that could have caused the discharge. In the other event, the charge was estimated to have been located at low altitude, and the event could not be interpreted by the usual negative CG lightning discharge model. The discussion concerning the numerical fitting presented in this study may be useful for future investigations of the electrical charge related to lightning discharges based on a small number of ground electric field measurements.

1. Introduction

Thunderstorms are extremely interesting and important phenomena for meteorological and technological research. Lightning, itself, is a very dangerous phenomenon that can cause damage to humans and technology via power-line breakdowns and disturbances in aeronautical operations. Because thunderstorm activity is strongly related to cumulonimbus development, scientific interest in thunderstorms is not limited to electrical processes. Recent studies have discussed the rapid increase in lightning occurrences immediately before severe weather phenomena such as tornadoes; this feature is known as a “lightning jump” (Steiger et al., 2007; Gatlin and Goodman, 2010; Nishihashi et al., 2015).

The mechanism that causes lightning is strongly related to convective motions and atmospheric conditions in thunderclouds. In other words, the electrical status in thunderclouds is important for studies of cloud dynamics and investigations of weather impacts associated with active cumulonimbus including studies based on numerical simulations (Mansell et al., 2005; Hayashi, 2006). The recent development of three-dimensional monitoring of lightning flashes via very-high-frequency (VHF)-based detection systems has greatly contributed to thunderstorm research (Ushio et al., 2015). The Lightning Mapping Array (LMA; e.g., Rison et al., 1999; Thomas et al., 2001, 2004) and other similar lightning detection systems have been used to systematically investigate the nature of thunderstorms. An important contribution of the LMA observations has been to clarify the nature of thunderstorms in that the LMA provides information concerning the status of electrical charges in clouds. Radiation sources often show horizontal layered structures inside clouds related to intra-cloud (IC) and/or cloud-to-ground (CG) lightning discharges. Previous
studies have demonstrated that these layers correspond to charge layers formed in clouds, and extended discussions of electrical characteristics based on that assumption have been published (Krehbiel et al., 1979; Williams, 1989; Bateman et al., 1999; Shao and Krehbiel, 1996; Thomas et al., 2001; Coleman et al., 2003; Riousset et al., 2007; Yoshida et al., 2014). These results have demonstrated the usefulness of three-dimensional monitoring of lightning discharges using electromagnetic waves of VHF or other bands.

Three-dimensional monitoring of radiation signals to detect the electrical charge structures in thunderclouds is now regarded as an effective continuous monitoring technique. However, it is important to compare the radiation signals captured by radio-wave-based lightning detection systems with other observation methods that can estimate electrical charge to validate radio-wave detection techniques.

Our group previously reported a field observation project known as “The Shonai Area Railroad Weather Project” (Kusunoki et al., 2008). In an area near the coast of the Japan Sea in northern Japan, tornadoes are often observed (Niino et al., 1997); this region is also subject to characteristic thunderstorm activity (Brook et al., 1982). The project was designed in 2007 to investigate the fine-scale structure of wind gusts and to develop an automatic strong-gust detection system for railroads using two X-band Doppler radars and a network of 26 surface weather stations (Kusunoki et al., 2008; Inoue et al., 2011). As part of the project, Nishihashi et al. (2013) developed a three-dimensional VHF-based lightning mapping system around the Shonai area to monitor the total lightning activity in winter to investigate the mechanism of the winter lightning discharge process and its application to the prediction of strong wind gusts. They also deployed field-mill sensors around the area to measure the electric field variations.

Measurements of the electric fields can provide information concerning the electrical charge status related to CG lightning discharges in thunderclouds. However, the number of electric field measurements in the Shonai area is close to the minimum required to estimate the charge status. In this study, we discuss a procedure to estimate the charge status based on a small number of ground electric field measurements and examine the estimated results compared to other observations in the Shonai area.

2. Data

The three-dimensional lightning mapping system deployed by Nishihashi et al. (2013) in the Shonai area is based on a direction-of-arrival technique applied to a set of three antennas at each measurement site. The system is capable of detecting radiation sources radiated by lightning flashes, similar to LMA and/or lightning detection and ranging (e.g., Lennon, 1975), which uses time-of-arrival (TOA) technology (Proctor, 1971, 1981). In this study, we call this system N-LMA. Figure 1 shows the locations of the sensors used to detect 23–200 MHz VHF signals from the lightning leaders. Each site was equipped with an N-LMA antenna and a field-mill sensor (EFM-100 Atmospheric Electric Field Monitor, BOLTEK Corp.) to measure electric field changes. The response time of an EFM-100 is 0.1 s, and its resolution is 0.01 kV/m (Boltek Corp., 2015). Instantaneous 1-s values picked up from the original signals with 0.05-s time resolution were archived on a personal computer at each site. Figure 2 is a photograph of the EFM-100 at observation point L3. The sensors were calibrated by placing them between a parallel plate capacitor at the Kakioka Magnetic Observatory. Prior to the actual observations, the field-mill sensors were calibrated via an intercomparison of their measured values and the simultaneously measured values of a reference field-mill mounted at the earth’s surface. We used data from locations L1–L4. There is also a field-mill sensor at point L5; however, we did not use its data because the site is not in a good environment for electric field measurements, and there is another...
measurement site, L2, nearby.

In this study, we analyzed the electric field variations related to CG lightning discharges based on the time variations in the 1-s value after a ground stroke with respect to the previous data. CG lightning discharges are usually attributed to the neutralization of a monopole charge (e.g., Wilson, 1916; Krehbiel et al., 1979; Maier and Krider, 1986; Koshak and Krider, 1989; Krider, 1989). Using the time-difference values at the four stations, it was possible to estimate the position and amount of charge aloft because the number of unknown values (the three components of the position of a single charge in three-dimensional coordinates and the amount of charge) and the number of measured values were the same.

To detect the events, we used data obtained by the routine lightning detection system, Lightning DEtection Network system (LIDEN), operated by the Japan Meteorological Agency (JMA). LIDEN was installed in 30 airports throughout Japan to serve as an aeronautical weather service in July 2000 (JMA, 2001). LIDEN is a hybrid system consisting of a time-of-arrival method in the low-frequency band for return strokes (involved in CG flashes) and an interferometric technique in the VHF band for VHF radiation sources associated with lightning discharges within thunderclouds. The wave forms observed by the time-of-arrival method are used to estimate the polarities and amplitudes of the ground strokes. The typical estimated location accuracy given the technical specifications is a few kilometers in the Kanto Plain (Suzuki et al., 2012). The average detection efficiency deduced from the visual observations is 70% for CG lightning (Kasahara, 2011) and 83% for total lightning (JMA 2001, personal communication). From the list of CG lightning discharges obtained by LIDEN, we selected the negative polarity events that were detected near the N-LMA network. We only selected events that were composed of a single stroke or only a few strokes if they occurred at the same position during a 1 s interval. The data used in this study are listed in Table 1.

3. Analysis method for Point-charge fitting

Least-squares fitting is carried out finding a solution via numerical fitting based on the theoretical electric field produced by an aloft electrical charge. Because the number of sites was small in this study, it was necessary to perform the fitting carefully. Figure 3 shows profiles of ground electric fields driven by ideal charges located at heights of 3 km, 5 km, and 7 km normalized to the value just under the charge. The curves show the gradients at different distances from the charge. For a charge located at 3 km (low altitude) the curve has a steeper gradient than those for charges at 5 km and 7 km. The fitting process was performed by horizontally shifting the two-dimensional profile of the electric field generated by the point charge at each height to find the best position when searching for the least-squares difference. We

| Item                                   | reference                      |
|----------------------------------------|--------------------------------|
| 3-D lightning mapping system (N-LMA)   | Nishihashi et al. (2013)       |
| Atmospheric electric field (EFM-100)   | Boltek Corp. (2015)            |
| at L1, L2, L3, L4                      |                                |
| X-Band Doppler radar at JR Amarume Station | Kasunoki et al. (2008), Inoue et al. (2011) |
| Lightning detection data by LIDEN      | JMA (2001), Suzuki et al. (2012) |
prepared a table containing the electric fields of point charges at heights at every 0.1 km from 0.1 km to 15 km.

Next, we determined the necessary precision for the horizontal shifting of the electric field distribution needed to obtain stable solutions in the numerical fitting process. To this end, we performed test fittings of the generated electric fields for an ideal electrical charge at an arbitrary position. An ideal charge was placed at a height of 3.5 km at 38.84783°N and 139.8736°E. This is a position near the center of the observation network that does not coincide with any grid of the five tests, as shown in Table 2. Electric fields generated at the observation sites by this charge are regarded as ideal measurements, and the solutions were searched using least-squares fitting with the theoretical electric fields prepared above. For the numerical fitting, we set the search area of the latitudinal range from 38.66°N to 39.02°N and the longitudinal range from 139.75°E to 140.11°E.

Figure 4 shows the heights and the numbers of the charges representing the maximum correlation coefficient obtained in the five tests. As can be seen from Figure 4, the heights of the charges are not yet equal to the true height (3.5 km) in tests A and B but converge to the true height from tests C to E. The number of points increases with increasing resolution. For example, the number of points was seven for test E, and the correlation coefficients at these points took the same values by the double-precision calculations. Figure 5 shows the horizontal locations of the charges on a plane at a height of 3.5 km for tests C, D, and E. The results for tests D and E are the mean locations of the individual tests. The distance of the mean positions of the deduced charges in the three tests from the ideal charge is nearly the same (approximately 50 m). The distance derived from the algorithm proposed by Krehbiel et al. (1979), subsequently referred to as the Krehbiel algorithm, was also similar. Therefore, the horizontal resolution needed to estimate charges via numerical fitting using the prepared theoretical electric fields at every 0.1 km in height was determined to be higher than 0.002° in longitude and 0.001° in latitude for this observational network.

Figure 6 shows the longitude, latitude, height, maximum correlation coefficient, and movement of the charge with respect to the searching height for test E. It can be seen from the top and third panels that the charge estimated at each height moves roughly north-eastward with increasing height. This is the movement resulting from the theoretical curves, such as those shown in Figure 3, that are fitted to the measured values changing their horizontal profiles with height. The charge amount reaches a minimum at the true height (3.5 km) in Figure 6; however, the position of the actual minimum charge that gives a correlation coefficient greater than 0.999 was at a height of 2.8 km at 38.8695°N and 139.8520°E in test E, which is outside the area shown in Figure 6. We conducted an additional test shifting the ideal charge to a height of 3.43 km at the same horizontal position. The height of the charge was artificially kept away from the grid point to check whether the solution was obtained at the nearest grid. The estimated solution was located at the same horizontal position at the nearest height.

Finally, we conducted similar tests putting ideal charges at several other positions in the search area and confirmed that the numerical fit with the horizontal resolution in test E provided solutions at the horizontally neighboring grids and at the closest heights to the ideal charges. Therefore, a horizontal resolution of 0.0005° in longitude and 0.0002° in latitude for the horizontal shifting of the electric fields driven

| Table 2: List of the grid spacings used in the test fittings. |
|---------------------------------------------------------------|
| Latitudinal (°)     | Longitudinal (°) |
|---------------------|------------------|
| test A              | 0.005            | 0.01             |
| test B              | 0.002            | 0.005            |
| test C              | 0.001            | 0.002            |
| test D              | 0.0005           | 0.001            |
| test E              | 0.0002           | 0.0005           |

Fig. 4 The heights and numbers of charges that yielded the maximum correlation coefficients in the test fittings A–E with the horizontal resolutions shown in Table 2.

Fig. 5 The locations of the solutions in the horizontal plane in the test fittings C, D, and E; the position of the ideal charge is denoted by “True” and the solution of the Krehbiel algorithm is denoted by “Kreb”.

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by charges at every 0.1 km in height provide solutions with a horizontal accuracy of approximately 50 m and a vertical resolution of 100 m. In this study, we conducted our analyses using these vertical and horizontal resolutions and took the mean values of the points showing the maximum correlation coefficient for individual events. Figure 7 summarizes the flow of the proposed data processing.

4. Data analysis and Discussion

We analyzed 19 flashes, the solutions for which are listed in Table 3. Note that for some of the events in Table 3, the Krehbiel algorithm could not provide solutions (shaded columns); however, solutions were obtained for all the events via numerical fitting. As can be seen in the columns that are not shaded in Table 3, the values obtained via numerical fitting are nearly the same as those obtained via the Krehbiel algorithm. For the events where the Krehbiel algorithm could not provide a solution, the heights of the estimated charges via the numerical fitting are less than 1 km. The calculation processes diverged during the matrix calculation in the Krehbiel algorithm when the charges were situated at low altitudes. We checked the stability of the Krehbiel algorithm using test calculations with ideal charges and found that the stability condition depends on the horizontal location of the charge. If an ideal charge is set near the center of the network, the Krehbiel algorithm can provide a solution for the charge if it is situated higher than 0.3 km, whereas if the charge is set near borders of the range, a solution cannot be found for a charge at the height lower than 1 km.

For the events listed in the 14th−16th columns, both methods provided solutions at altitudes greater than 10 km. Radiation sources were not observed at these heights during these events. Only weak echoes, less than or equal to 10 dBZ, were seen by the JMA C-band routine weather radar, and the atmospheric temperatures near the charges in these events were less than −45°C. These features are quite different from the characteristics of negative charges in the conventional negative CG lightning discharge model. It is difficult to investigate the characteristics of the estimated charges for these events without other information and/or observational data. We would like to reserve a discussion concerning these events for a future study.

Of the events listed in Table 3, we would like to briefly discuss two events by comparing our findings to other observations. One event is a case where both the numerical and the Krehbiel methods provided solutions, and the other is a case where the Krehbiel method could not provide a solution.

4.1. The October 13, 2012 Event

Figure 8 shows the electric field variation with respect to a CG lightning discharge that occurred on October 13, 2012 (column 6 in Table 3). Clear negative pulse-like variations were observed at stations L2 and L4, and weak step-like vari-
Prepare a table of ground electric field profile by charges situated at the height at every 100m from 0.1 to 15 km.

Operate test fittings to evaluate the horizontal resolution needed to obtain appropriate solutions by least square fitting.

Find the best position by least square method and calculate the charge amount.

Fig. 7 Block diagram showing the algorithm used to deduce the electrical charge in this study.

Table 3. List of the solutions for the electrical charges and their ambient atmospheric temperatures related to the negative CG lightning discharges analyzed in this paper. Values in the latitude, longitude, height, and charge amount columns are those obtained using the method introduced in this study, while values in parenthesis are solutions based on the Krehbiel algorithm. The symbol “*” listed in the parenthesis denotes that solutions were not obtained by the Krehbiel algorithm and the columns containing such events are shaded.

| Date     | Time (JST) | Latitude (°N) | Longitude (°E) | Height (km) | Charge (C) | Temperature (°C) |
|----------|------------|---------------|----------------|-------------|------------|------------------|
| Jul. 05  | 05 21 16   | 38.825 (38.825) | 139.914 (139.913) | 0.8 (*)     | −28.4 (*)  | 17.1             |
|          | 06 50 02   | 38.817 (38.817) | 139.945 (139.919) | 0.2 (*)     | −132.9 (*) | 20.3             |
| Sep. 08  | 22 08 00   | 38.829 (38.830) | 139.886 (139.885) | 2.6 (2.8)   | −9.2 (−9.0) | 11.1             |
| Oct. 13  | 00 05 24   | 38.860 (38.860) | 139.821 (139.820) | 2.3 (2.3)   | −6.6 (−6.9) | −2.5             |
|          | 00 09 13   | 38.873 (38.872) | 139.855 (139.855) | 4.6 (4.8)   | −5.1 (−5.2) | −15.9            |
|          | 00 10 36   | 38.860 (38.859) | 139.856 (139.856) | 5.3 (5.3)   | −9.2 (−9.4) | −20.2            |
| Oct. 21  | 05 12 32   | 38.906 (38.904) | 139.851 (139.850) | 0.8 (*)     | −41.3 (*)  | 11.9             |
| Nov. 08  | 05 13 57   | 38.911 (38.911) | 139.854 (139.854) | 3.7 (3.7)   | −11.1 (−11.6) | −7.4       |
|          | 04 55 41   | 38.888 (38.888) | 139.863 (139.863) | 2.9 (2.9)   | −18.7 (−19.1) | −8.1       |
| Oct. 21  | 06 16 03   | 38.801 (38.811) | 139.885 (139.893) | 0.1 (*)     | −244.1 (*) | 12.2             |
|          | 06 21 12   | 38.803 (*)      | 139.996 (*)      | 0.8 (*)     | −250.0 (*) | 5.5              |
|          | 08 15 26   | 38.791 (38.791) | 139.910 (139.910) | 3.4 (3.3)   | −2.7 (−2.8) | −11.7            |
|          | 08 17 14   | 38.797 (*)      | 139.912 (*)      | 0.9 (*)     | −7.6 (*)   | 4.6              |
|          | 09 08 20   | 38.715 (38.715) | 139.793 (139.792) | 14.8 (14.7) | −13.4 (−13.5) | −52.5        |
|          | 09 10 28   | 38.721 (38.719) | 139.891 (139.890) | 10.7 (10.7) | −15.2 (−15.6) | −45.7        |
|          | 09 12 16   | 38.700 (38.706) | 139.930 (139.929) | 10.0 (10.2) | −28.1 (−26.4) | −45.1        |
| Nov. 20  | 09 17 21   | 38.747 (38.724) | 140.035 (140.069) | 0.1 (*)     | −114.1 (*) | 12.6             |
|          | 05 08 37   | 38.795 (38.799) | 139.918 (139.915) | 0.7 (*)     | −21.3 (*)  | 3.4              |
|          | 05 09 20   | 38.811 (38.820) | 139.966 (139.969) | 0.1 (*)     | −639.3 (*) | 9.3              |

Fig. 8 Time variations in the electric fields observed at stations L1−L4 at 00:10:25-45 JST on October 13, 2012. The upward direction in the figure denotes the vertically upward direction from the ground.
ations were observed at stations L1 and L3. The variations were caused by a CG lightning discharge that occurred at 00:10:36 JST from a cloud that developed in a low-pressure zone over the Japan Sea. For this event, LIDEN detected only one stroke. The measured negative variations, which imply downward electric field pulses, were caused by an equivalent positive charge that occurred as a result of the neutralization of a negative charge by a negative stroke. It is possible that several strokes actually occurred; however, they are likely related to the same cumulonimbus that caused the lightning discharge. In the analysis, we took the electric structure to be the neutralization of a single charge and investigated the difference between the electrical status before and after the variations.

Figure 9a shows the N-LMA data superimposed on the radar echo of the 3.0° elevation plan position indicator measured by the JR Amarume station radar for the event shown in Figure 8. The detected radiation measured by N-LMA (colored dots) in this example was determined based on observations at the L1 and L4 sites. The blue reversed triangle marks the position of the negative stroke detected by LIDEN, and the red plus-mark is the position of the estimated charge. The temperature profile was estimated from a routine objective analysis of the JMA mesoscale numerical model. The data were obtained from the nearest time prior to the lightning detection. As listed in Table 3, the height

![Figure 9a](image-url)

**Fig. 9a** The top panel shows the time variation of the heights of the VHF radiation sources (colored dots) detected by the L2 and L4 sites and the negative CG detected by LIDEN (blue, reversed triangle). The middle left and bottom right panels show the distribution of the VHF radiation sources (colored dots) and the negative stroke detected by LIDEN (blue, reversed triangles) in the vertical plane in the east-west and north-south directions, respectively. The middle right panel shows the number of N-LMA detections (black line) and the atmospheric temperature from the JMA operational mesoscale model analysis (blue line). The bottom left panel shows a mapping of the VHF radiation sources (colored dots), radar echo (colored areas) measured by the Amarume (JR) X-band Doppler radar (thin, black plus-mark), the estimated charge (thick, red plus-mark), and surface weather sensors (thin, black X-marks).
of the estimated charge was 5.3 km. The radiation sources detected by N-LMA before the stroke appeared at a height of approximately 3 km, that is, the starting point of the leader was near 3 km, lower than that of the estimated charge. In the horizontal plane, the estimated charge was nearly 3 km from the LIDEN point and was adjacent to the N-LMA detection points and the radar echo region. It is possible that the leader started just under the charge and then propagated westward resulting in the ground stroke detected by LIDEN. It is noted that there were some radiation sources at approximately 7–8 km, which may reveal the location of the upper positive charge layer.

The location of the charge is related to the ambient atmospheric temperature in the widely accepted non-inductive, graupel–ice interaction mechanism introduced by Takahashi et al. (1978). In that mechanism, charge separation is thought to be generated by updraft caused by convection around a region with a temperature range between −10°C and −20°C in the cumulonimbus. Based on in situ measurements by balloon-borne electrodes, Stolzenburg et al. (1998) demonstrated that the center of the primary negative charge is situated near the −22°C temperature layer in supercell updrafts, −16°C in convective updrafts in mesoscale convective systems, and −7°C in New Mexican mountain storm updrafts. The atmospheric temperature at the height of the estimated charge in this event was estimated to be −20.2°C. From the volume scan data of the JMA routine weather radar (not shown here), a clear echo of more than 50 dBZ at heights of 2–3 km and 35–40 dBZ echoes near this region were observed, showing high convective activity. Therefore, the conditions may be comparable to the first or second situations described by Stolzenburg et al. (1998).

Figure 9b contains a similar plot to Figure 9a, but for approximately 3 minutes earlier than Figure 9a, when only an IC flash had been observed. The detected radiation sources and the charge locations are nearly the same as those shown in Figure 9a. Figure 10 shows the ground electric field variations at this time. Clear positive variations were observed at
stations L2 and L4 while weak negative ones were observed at stations L1 and L3. These variations can be attributed to a dipole-like charge pair that is caused by an IC flash. Therefore, the radiation sources shown in Figure 9b might represent the manifestation of the IC flash inside the cloud before the CG lightning. In Figure 9b, the detected radiation sources primarily occur at a height of approximately 2 km. The peak is near the height of the 0°C atmospheric temperature. The layer near the 0°C atmospheric temperature height may be related to the positive charge region under the main negative charge (e.g., Dotzek et al., 2005).

In view of these results, we think that the position and the amount of the estimated electrical charge listed in Table 3 for this event represent the status of the negative charge that caused the CG lightning.

4.2 The November 20, 2012 Event

Figure 11 shows the ground electric field variations with respect to a CG lightning discharge that occurred on November 20, 2012 (the 18th event in Table 2). A clear negative pulse was observed at station L3, and weak pulses were observed at stations L2 and L4. The pulses were caused by a CG lightning discharge that occurred at 05:08:37 JST from a cloud that developed in a low-pressure zone accompanied by a front propagating from the Japan Sea. For this event, LIDEN detected only one stroke. As shown in Table 3, the height of the estimated charge via numerical fitting was 0.7 km. The atmospheric temperature at the height of the charge was estimated to be 3.4°C from the routine objective analysis of the JMA mesoscale numerical model. A solution could not be obtained using the Krehbiel algorithm because the square of the height became a negative value in the algebraic calculation used to solve the matrix equation. This may be due to the low height of the corresponding charge.

Figure 12a is a composite plot of this event that is similar to Figure 9a. The radiation sources detected by N-LMA before the stroke in this example were determined based on measurements at the L3 and L4 sites. At the other sites, preceding radiation sources were not observed prior to the CG lightning discharge. As can be seen in Figure 12a, the radiation sources appeared broadly near a height of 3 km where the atmospheric temperature was approximately −17°C. The starting point of the leader, which is usually expected to be located under a negative charge region, was near 3 km, higher than that of the estimated charge. The estimated charge was nearly 10 km from the LIDEN point and horizontally 5–6 km from the radar echo region.

Figure 12b contains a plot similar to Figure 12a, but at approximately 1.5 min earlier than Figure 12a, and its radiation sources were detected by the L2 and L4 sites. Here, only an IC flash was observed. The detected radiation sources and the charge locations are situated a little lower than those shown in Figure 12a. For this event, the ground electric field variations expected for an IC flash were observed (not shown here). These radiation sources may reveal the electrical conditions inside the cloud prior to the CG lightning event. In Figure 12b, the radiation sources appeared primarily at a height of approximately 1.3 km. The peak occurrence of the radiation sources was near the approximately −2°C atmospheric temperature height and may be related to the positive charge region under the primary negative charge.

With these observational signatures, it is difficult to interpret whether the charge estimated from the ground electric field variations was the negative charge that caused the CG lightning discharge in this event. Because the pulse observed at L3 was sharp, there is a possibility that the 1-s time resolution is not sufficient to catch the exact signal of the CG. It is possible that different solutions would be obtained for these events if the original electric field signals of the 0.05 s sampling had been archived and could have been used. Another possible interpretation of the estimated charge obtained for this event is that an upward positive leader occurred at this time resulting in the allocation of a positive charge at a height near 700 m. If such a process occurred, the signal would be detected as a negative CG by LIDEN. However, these are only speculations and we lack the necessary data to examine them.
5. Conclusions

In this study, we discussed the precision of the numerical fitting required to estimate the position and the amount of electrical charge related to negative CG lightning discharges using ground electric field variations measured by Field-mill sensors deployed by Nishihashi et al. (2013) in the Shonai area of the Tohoku district in Japan. When preparing theoretical electric fields with electrical charges situated at every 0.1 km from a height of 0.1 km to 15 km, we found that numerical fittings with horizontal resolutions higher than 0.002° in longitude and 0.001° in latitude provided nearly the same results as the Krehbiel algorithm. It is notable that the numerical fitting can provide solutions even when the Krehbiel algorithm fails.

In one of the case study events, the electrical charge estimated from the 1 s measurements of the Field-mill network revealed the characteristics of the negative charge that caused the CG lightning discharge. In the other event, for which the Krehbiel algorithm could not provide a solution, the charge estimated by the numerical method could not be interpreted as the negative charge that would have caused the negative CG in the framework of the usual negative CG model. Electric field measurements with a higher sampling rate are necessary to investigate that event more precisely.

These results indicate that the electrical charge estimation proposed in this study potentially provides a realistic solution even when the number of electric field measurements is small. The discussion given in this study may be useful for future studies of electrical charges related to CG lightning discharges based on ground electric field measurements.

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東北地方庄内地域付近の落雷に係る電荷

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落雷に係る電荷について、東北地方庄内地域での地上電場観測に基づき調査した。最初、理論値を観測値に最小二乗法で合わせるため要求される細かさについて議論した。高度0.1 km毎の電荷による理論的な電場を与え、適切な解を得るため必要となる水平方向の分解能を提案した。提案された空間分解能により2012年の暖・寒候期に庄内で発生した19の落雷に係る地上の電場により電荷の位置と量を推定した。推定された負極性落雷の電荷の推定位置の2事例を大気温度、ドップラーレーダーおよびVHF帯雷標定システムで検知された電磁波放射源の分布と比較した。1つの事例では、推定された電荷は落雷を引き起こす負電荷の性質を表していた。他方では、電荷が低高度に求まり、通常の負極性落雷モデルでは説明できなかった。本研究で記された数値的電荷推定の議論は、少ない地上電場観測を元にした落雷に関係する電荷の今後の研究にとって有効な情報になると考えられる。