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Charge Transfers of Lightning Discharge Detected by Lightning Location System (LLS) and Altitudes of -10 ºC isotherm in the Coastal Areas of the Sea of Japan

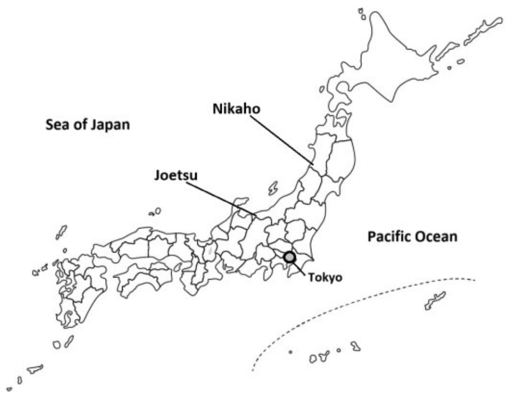
Michihiro. Matsui*(1), Koji Michishita (2), and Koji Takano (3)
(1) Franklin Japan Corporation, Sagamihara., Japan, 2520212, https://www.franklinjapan.jp/
(2) Shizuoka University, Hamamatsu, Japan, 4328561
(3) Kyushu Electric Power Co., Inc., Fukuoka, Japan, 8158520

Abstract

The authors have analyzed the seasonal characteristics of lightning discharges in the coastal areas of the Sea of Japan using the datasets observed by two slow antennas, the Japanese Lightning Detection Network (JLDN), and the Local Forecasting Model (LFM) provided by the Japan Meteorology Agency (JMA). We clarified that the frequency of lightning discharges with a charge transfer exceeding 50 C increased when the altitude of the -10°C isothermal layer descended below 2,500 meters.

1. Introduction

The coastal areas of the Sea of Japan are famous for winter lightning which causes catastrophic damage [1]. Approximately 4% of the lightning discharges hitting high structures such as wind turbines in winter had a charge transfer of 300C or larger [2]. The JLDN has outputted lightning in the stroke unit and detected return strokes and ICC_P (see Chapter 5) among CG lightning. Consequently, the lightning detected by the JLDN is expressed as "lightning discharge" in this study. Miyama et al. reported the observation of a lightning flash whose charge transfer exceeded 900 C at a wind turbine during the winter months in a coastal area of the Sea of Japan [3]. According to Berger et al. [4], the 50% value of downward negative flash charges was 7.5C. However, previous studies on winter lightning have demonstrated that charge transfers during winter lightning season are significantly higher compared to those during seasons other than winter [5, 6, 7]. Furthermore, bipolar upward discharges initiated from high structures tended to have large charge transfer values. Michishita et al. [8] reported that the median charge of upward bipolar discharges initiated by wind turbines was 107 C in a coastal area of the Sea of Japan in the winter months. The percentages of negative, positive, and bipolar lightning discharges on a wind turbine were 71%, 15%, and 14%, respectively [9]. Those previous studies have indicated winter lightning occurring in coastal areas of the Sea of Japan can cause energetic lightning and subsequent damage. This was caused by the low altitude of the cloud charge and the reduced or nonexistent lower positive charge regions [10, 11]. Neglecting high-energy upward lightning discharges in winter may significantly underestimate the actual damage by lightning discharges. The main reason is that the characteristics of upward lightning in winter are not fully understood. Therefore, clarifying the seasonal characteristics of lightning discharges and understanding the initiation conditions of upward lightning is very important. Matsui et al. [12] have already reported the relationship between the −10 °C isotherm altitudes on winter lightning and the occurrence of upward lightning discharges. The purpose of this study is to clarify the magnitude of the charge transfer of lightning discharge and the altitude of the -10 °C isotherm layer.



(a) Locations of slow antenna

(b) appearance of the slow antenna

Figure 1 The location of observation points by the slow antenna and appearance of those

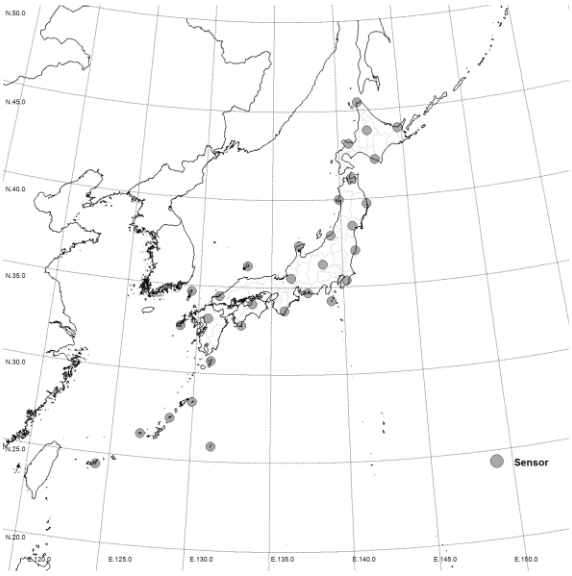


Figure 2 locations of the JLDN sensors

2. Estimation of Charge Transfer

In order to estimate charge transfer, we have used a dataset observed by slow antennas in Nikaho and Joetsu. We show their locations and a picture of the appearance of the slow antenna in Figure 1. We have estimated the charge transfer using the point charge model. Assuming that the electric field change (E-field) measured at a distance follows the point charge model, the change in the charge transfer (Δ Q) can be expressed by equation (1). shown in Equation 1.

$$\Delta Q = \frac{2\pi\varepsilon_0 D^3 \Delta E\{1+(H/D)^2\}^{3/2}}{H} \quad (1)$$

Where Δ E is the change in the e-field measured at the slow antenna, H is the vertical height of the charge above ground, and D is the horizontal distance from the slow antenna to the lightning position located by the JLDN.

We estimated H as the altitude of the -10°C isothermal layer by assuming that the charge associated with lightning exists in the -10°C isothermal layer using the LFM [13] distributed by the JMA. The -10°C isothermal layer height was subsequently calculated using interpolation from the potential height and air temperature of the LFM at the lightning position located by the JLDN operated by Franklin Japan Corporation (FJC) [14].

The JLDN is the largest commercial lightning detection network in Japan, with 31 sensors installed. Figure 2 shows the locations of the JLDN sensors. The JLDN was completed in early 2003 and has been observing lightning flashes in and around Japan for over 20 years. The median location error of lightning strokes that hit wind turbines in southern Akita Prefecture was approximately 190 meters for first and subsequent strokes in summer [15] and 155 meters in winter for subsequent strokes after Initial Continuous Current (ICC) [16].

3. Seasonal Change in Altitudes of -10 ºC isotherm

We have analyzed the dataset regarding the charge transfers of lightning discharges, as detected by the JLDN within a range of 5 to 50 kilometers from the slow antennas from October 21st, 2023, to January 30th, 2025. We show the seasonal changes in the altitude of the -10°C isothermal layer when the JLDN observed lightning discharges in Figure 3. The highest altitude of the -10°C isothermal layer was 7570 meters on August 29th, 2024, and the lowest one was 986 meters on January 17th, 2025. Figure 3 indicates that the altitudes of the -10°C isothermal layer concentrated between 1000 and 3000 meters in winter, and those concentrated more than 6000 meters in summer. The number of lightning discharges occurring in spring and autumn is smaller than in summer and winter. The reference [12] reported that the ratio of upward lightning increases concomitantly with a decrease in the altitude of the -10°C isothermal layer, particularly when it falls below 2000 meters during the severe winter season. Michimoto [17] suggested that as the altitude of the -10°C isothermal layer descends below 1,800 meters, the frequency of one-shot lightning, a characteristic of winter lightning, increases. This observation is in alignment with the results reported in Reference [17].

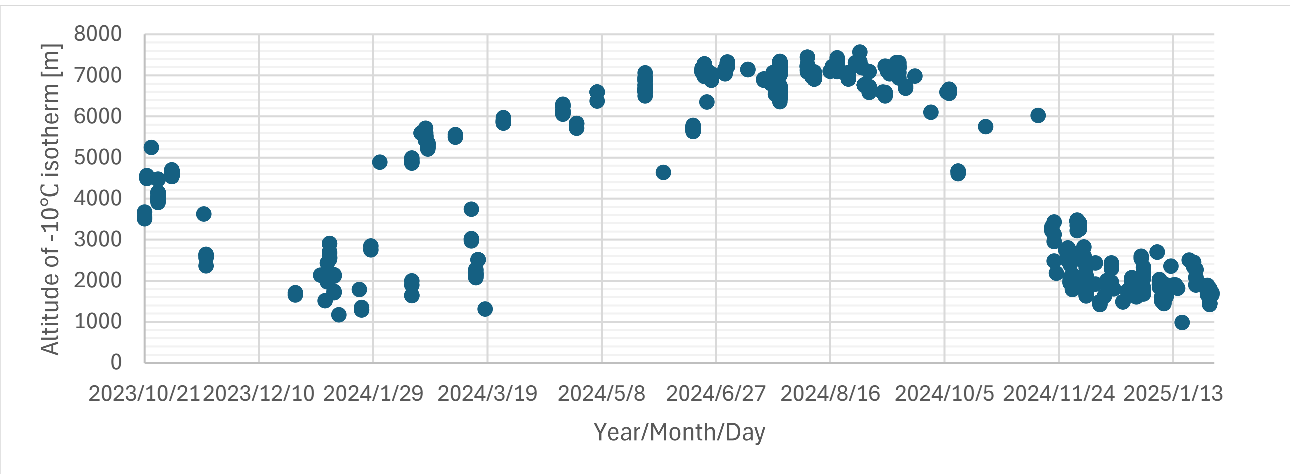


Figure 3 Seasonal changes in the altitude of the -10°C isothermal layer when the JLDN detected lightning discharges

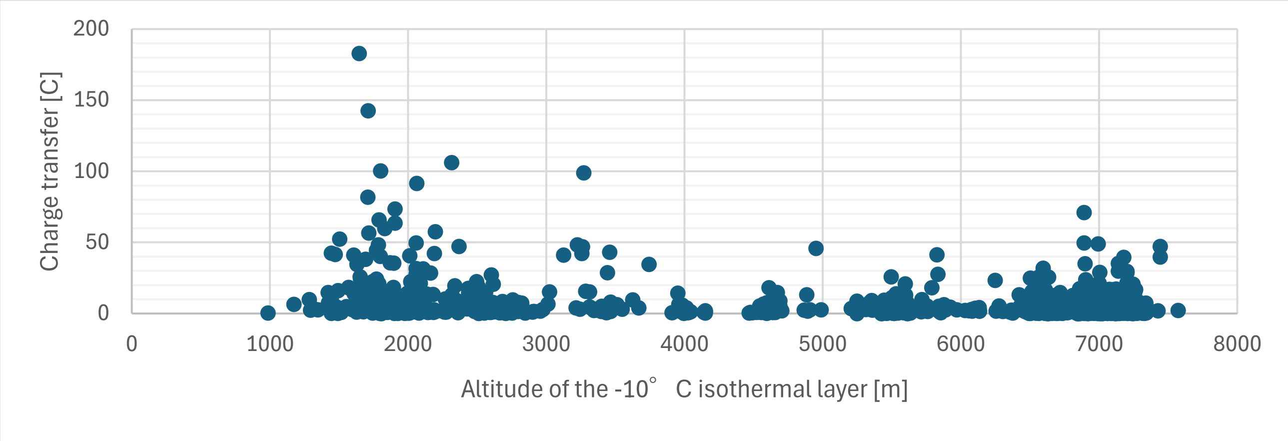


Figure 4 altitude of -10°C isothermal layer and a charge transfer of lightning flash detected by the JLDN in the period between October 21st, 2023, and January 30th, 2025

Table 1 Average charge transfer and altitudes of the -10 ºC isotherm

Altitude of -10°C isothermal layer [m]	Average charge transfer [C]	The number of samples
1000 - 2000	16.0	133
2000 - 3000	9.1	136
3000 - 4000	10.2	61
4000 - 5000	4.3	89
5000 - 6000	5.5	99
6000 - 7000	4.4	597
7000 - 8000	4.2	524

4. Relationship between Charge Transfer and Altitudes of -10 ºC isotherm

Figure 4 illustrates the relationship between the magnitude of charge transfer and the altitude of the -10°C isotherm when the JLDN detected a lightning discharge. The figure suggests a predominant occurrence of lightning discharges with charge transfers exceeding 50 C or more when the altitude of the -10°C isothermal layer falls below 2500 meters. This finding aligns with the results of a previous study by Michishita et al. [18], who reported that lightning discharges with charge transfers above 300C occur predominantly when the altitude of the -10°C isotherm is between 1000 and 2500 meters. The findings of this study also suggest that lightning discharges with charge transfer values greater than 50 C tend to occur more frequently during winter compared to other than winter. The maximum recorded charge transfer, estimated at approximately 183 C at a -10°C isotherm altitude of 1645 meters, further substantiates this observation. The relationship between the average charge transfer of lightning discharges detected by the JLDN and the altitudes of the -10 ºC isotherm is elucidated in Table 1. As illustrated in Table 1, the average transferred charge exhibited its maximum value when the altitude of the -10°C isothermal layer ranged between 1000 and 2000 m, amounting to approximately 3.7 times the magnitude observed when the altitude of the -10°C isothermal layer in summer exceeded 6000 m. According to references [8,9,12], the height of the -10°C isothermal layer along the coast of the Sea of Japan is lower during the winter months, resulting in upward lightning strokes with high-energy bipolar lightning. The findings of this study also demonstrated that lightning discharges along coastal areas of the Sea of Japan during winter have higher energy compared with the typical downward negative lightning strokes observed in summer.

5. High-Energy Lightning Discharges that could not be Observed by LLS

The maximum value of charge transfer obtained in this study was approximately 183 C. However, according to the references [2,3], we infer that lightning discharges with even larger charge transfers occurred along the Japan Sea coast in winter during the observation period of this study. For instance, a 900 C lightning flash documented in reference [3] transpired in November 2023, however, the JLDN could not detect it. We inferred the characteristics of lightning discharges with large charge transfers, which the JLDN could not detect. Diendorfer et al. [19] classified negative upward lightning into three types, as shown in the following,

(1) ICC_{RS}: The ICC followed by single or multiple return strokes.
(2) ICC_{P}: The ICC not followed by any return strokes and superimposed with a pulse current with an amplitude of 2 kA or higher.
(3) ICC_{ONLY}: The ICC not followed by any return strokes and not superimposed by ICC pulses with an amplitude of 2 kA or higher.

Michishita et al. [20] further classified ICC_{P} into two types and evaluated the detection efficiency (DE) of the JLDN for them. One is a fast pulse (ICC_{FP}) with a rise time of less than 8μs that is superimposed on the ICC, and the other is a slow pulse (ICC_{SP}) that occurs when the charge in the cloud due to the M component is neutralized [9,21]. According to the reference [20], the DE of the JLDN for ICC_{RS}, ICC_{FP}, ICC_{SP}, ICC_{ONLY} were 100%, 55%, 35%, and 0% respectively. Therefore, we assume that the JLDN failed to detect a high-energy lightning flash when the rise times of return strokes or ICC_P of that were not fast enough.

4. Summary

- The authors have analyzed the charge transfers of lightning discharges using the datasets obtained from the slow antennas, JLDN, and the LFM.
- The altitudes of the -10°C isothermal layer concentrated between 1000 and 3000 meters in winter, and most of those existed above 6000 meters in summer.
- The findings of this study showed that the charge transfer of lightning discharge that occurs during winter tends to be larger than that during summer.
- We assume that the JLDN failed to detect a high-energy lightning discharge when the rise times of return strokes or ICC_P of that were not fast enough.

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