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VLF signatures of ionospheric perturbations associated with winter lightning in the Hokuriku area of Japan

Takuya Otsuyama, Tadao Kariya and Masashi Hayakawa

Department of Electronic Engineering, The University of Electro-Communications, Chofu-shi, Tokyo 182-8585

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Abstract: The VLF signature of ionospheric perturbations associated with winter lightning in the Hokuriku area (Japan) were investigated over a 3-month period (December 2000 to February 2001). During this observation period, no optical phenomena were observerd; thus, the presently reported observation period was not so active as the observatian period for the previous winter (Y. Hobara *et al.* ; Geophys. Res. Lett., **28**, 935, 2001). Based on the VLF subionospheric observations of the NWC (Australia) signal obtained at Moshiri (Hokkaido) and Kasugai (near Nagoya), we obtained the following results: (1) Trimpis tend to occur when lightning activity is enhanced, (2) Trimpis are observed when the causative lightning is very close to the great circle path, and (3) the amplitude of the scattered signal is in the range of -12 dB to -28 dB (with respect to the unperturbed signal), independent of the polarity. These characteristics lead us to conclude that the Trimpis in our observations are due to the electromagnetic pulse of lightning discharges occurring close to the great circle path and with sufficient charge transfer.

key words: VLF propagation, Hokuriku winter lightning, ionospheric perturbations

1. Introduction

Recent observations of ionosphere perturbations by means of VLF subionospheric VLF propagation have suggested the presence of a new type of Trimpi (the so-called early/fast Trimpi) that is directly related to lightning discharges in addition to the classical Trimpis produced by particle precipitation as a consequence of wave-particle interactions in the magnetosphere (see the recent reviews by Strangeways (1996) and Rodger (1999)). Several mechanisms have been proposed to explain a variety of the characteristics of early/fast Trimpis, including ionization changes that arise from the heating of the lower ionosphere by intense lightning electromagnetic pulses (Inan *et al.*, 1991; Taranenko *et al.*, 1993; Nickolaenko and Hayakawa, 1995) and/or a quasi-electrostatic field (Pasko *et al.*, 1995; Inan *et al.*, 1996). The most fundamental question in this area of research is related to the study of the characteristics of causative lightning, *i.e.*, what kinds of lightning conditions are essential for producing early/fast Trimpis, etc.

New observations are urgently needed to obtain a better understanding of the characteristics of these early/fast Trimpis and of their generation mechanism. The purpose of this paper is to provide a statistical study of the VLF signatures of ionospheric perturbations associated with winter lightning in the Hokuriku area (Japan Sea side) of Japan based on a relatively long-term (3 months) continuous measurement period.

2. Description of the experiment and observation

A network for observing ionospheric perturbations has been established in Japan to study seismo-ionospheric effects (in other words, seismo-Trimpis). These observations are continuously performed at seven stations throughout Japan (Hayakawa, 2001). Four VLF/LF transmitter signals are simultaneously received at each station (for details, see Hayakawa, 2001). To detect slow changes in the ionospheric parameters associated with earthquakes, the JAPAL system has been developed as an extension of the Omnipal system by Dowden and Adams (1998), which uses GPS as a phase standard to compare JG2AS (40 kHz standard wave in Fukushima prefecture) phase measurements made days or months apart. The JAPAL system which is normally operated with a time resolution of 20 s for the seismo-Trimpis, was also used for the present study. We increased the time resolution up to its highest value of 50 ms during the period of December 15, 2000, to February 28, 2001 (about 3 months) to detect winter lightning in the Hokuriku area (Japan Sea) of Japan, shown by the rectangle in Fig. 1. To cover the Hokuriku area, we used the Trimpi data observed at Moshiri in Hokkaido and

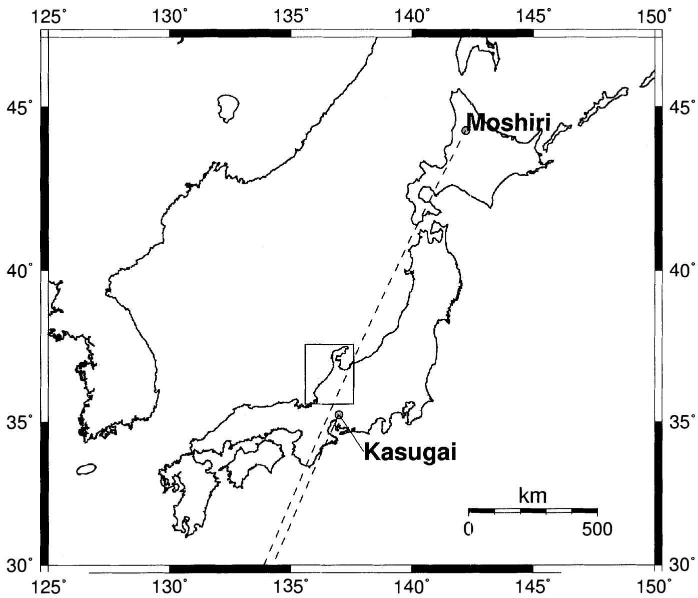

Fig. 1. Locations of two observation stations (Moshiri and Kasugai), together with the great circle path to the VLF transmitter of NWC (Australia). The rectangle indicates the area of interest.

Kasugai (in Aichi prefecture) together with the NWC data ($f = 19.8$ kHz in Australia). The VLF propagation path is illustrated in Fig. 1, together with the observation area.

The Japanese Lightning Detection Network (JLDN) is based on the combined time of arrival (TOA)/magnetic direction finding (MDF) technology for determining lightning direction (Cummins *et al*., 1998; Ishii *et al*., 2002) and provides the absolute time, location and peak current (together with the polarity) of most cloud to ground (CG) discharges. The accuracy of the time of lightning is ± 1 s in the JLDN data.

Winter lightning in the Hokuriku area is known to exhibit peculiar characteristics; that is, (1) the number of positive (+) CG discharges is about the same as the number of negative (−) CG discharges, and (2) the lightning carries a large electric charge (Brook *et al*., 1982; Takeuti and Nakano, 1983; Michimoto, 1993). We closely observed this particular winter period to compare differences in the occurrence of Trimpi associated with + and − causative CGs.

3. Analysis results

3.1. Result of optical observations

During the period of our analysis, optical phenomena associated with winter lightning in the Hokuriku area, such as red sprites and elves, were watched for at the Chichibu observatory (geographic coordinates: 35.93°N, 138.90°E). However no optical emissions were detected. This optical measurement was not continuous, since we visited the observatory at Chichibu only when the lightning forecast of the Hokuriku Electric Company reported that lightning activity was highly likely in Hokuriku (we visited the observatory several times during the observation period). Thus, we cannot confirm that no red sprites occurred during the observation period. Nevertheless, the Tohoku University group also reported that no optical emissions occurred the Hokuriku area during the observation period (Fukunishi, Takahashi, private communication), supporting our findings. Several sprites were detected in the Hokuriku area during the following winter 2001/2002 using the same optical sensor (Hayakawa *et al*., 2003). Thus, the lightning activity during the presently reported observation period was not so intense as that during the previous winter (Hobara *et al*., 2001).

3.2. Trimpi structure

Figure 2 shows an example of an early/fast Trimpi observed at Moshiri in Hokkaido on the subionospheric VLF signal from NWC ($f = 19.8$ kHz, Australia). The upper panel shows the phase, while the lower panel shows the amplitude. The accuracy of the JLDN lightning data is 1 s, and the time of the causative lightning is indicated by a downward arrow and the broken line. The time difference between the lightning and the Trimpi onset is difficult to estimate because of the one-second ambiguity, but the data definitely shows an early Trimpi. A statistical analysis of several datasets yielded an onset duration (from onset to maximum deviation) in the range of 0.05 to 0.55 s, with an average onset dination of 0.28 s. The recovery time ranged from 0.05 to 1.1 s, with an average recovery time of 0.33 s. All of the observed Trimpis were of this type, and were categorized as early/fast Trimpis (Inan *et al*., 1996). They also corresponded to RORDs, as defined by Dowden *et al.* (1994).

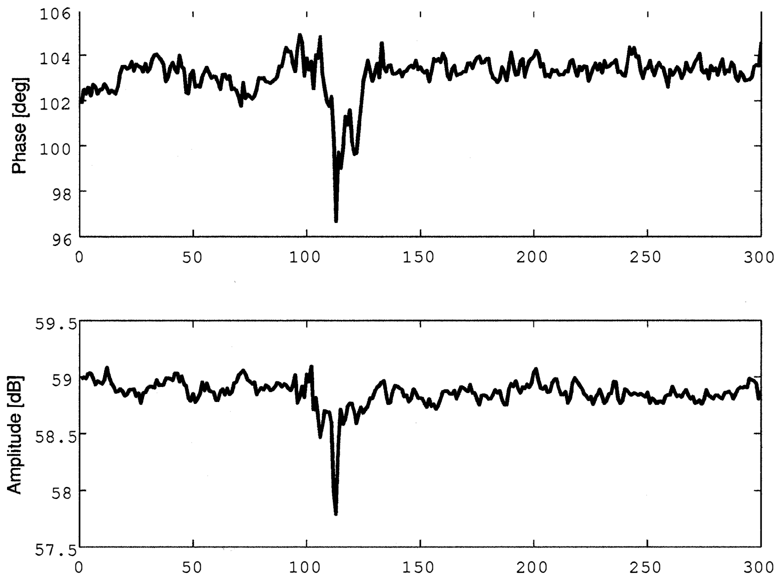

Fig. 2. A typical example of early/fast Trimpis observed at Moshiri (upper panel: phase, lower panel: amplitude).

3.3. Occurrence rate of Trimpis in relation to lightning activity

Figure 3 illustrates the temporal evolution of total lightning activity (including both + and −CGs) in the Hokuriku area (defined in Fig. 1) using the data obtained during a three-month observation period (December 2000 to February 2001). Lightning activity is indicated in blue, and the occurrence of Trimpis is indicated in red. A general comparison between lightning activity and the occurrence of Trimpis shows that Trimpis tend to occur when the lightning activity is enhanced. However, no Trimpis occurred in some periods even though the lightning activity was very enhanced (*e.g.* mid-December and beginning of January). Trimpis occurred in association with about 5% of the +CG discharges and with about 7% of the −CG discharges during the three-month observation period; these percentages are nearly the same.

Three particular days on which several Trimpis were observed (*i.e.*, December 23, 2000; January 28 and February 15, 2001; see Fig. 3) were further analyzed. Figure 4 shows a summary of the amplitudes of the scattered signals (with respect to the unperturbed signal) according to the phasor concept (Dowden *et al.*, 1994), plotted using the amplitude and phase data shown in Fig. 2. The polarity of the causative lightning can be seen from the polarity (+ or −) of the maximum discharge current in Fig. 4. The figure shows that the intensity of the scattered signals ranges from −28 dB to −12 dB for both polarities of the causative CG discharges with a mean value of −18.6 dB. No particular or significant difference in the scattered signal intensity was observed between the + and −CG discharges. These values are significantly smaller than those for the scattered signal intensities for sprite events by about 10 dB, as compared with the findings of Hobara *et al.* (2001), but they are relatively close to those

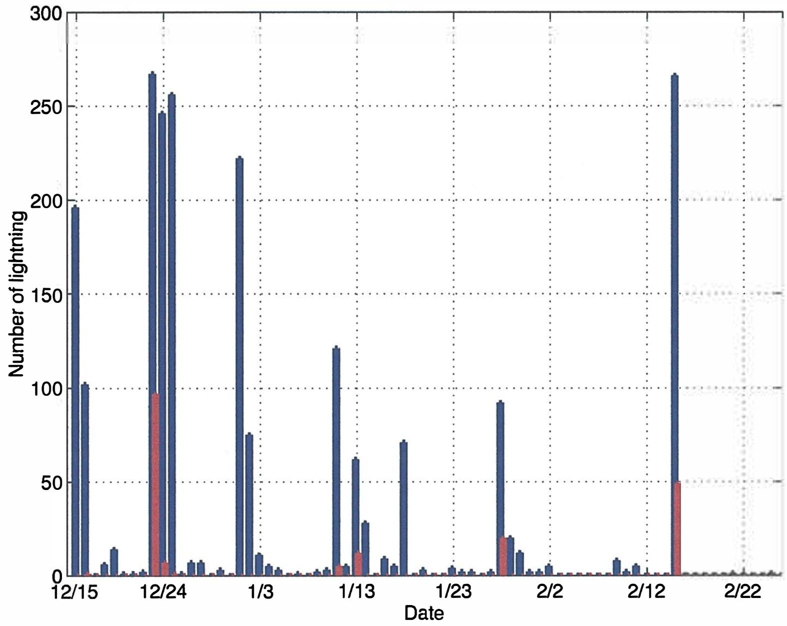

Fig. 3. *Temporal evolution of total lightning occurrence (in blue) and Trimpis activity (in red) during a three-month period (December 2000 and January, February 2001).*

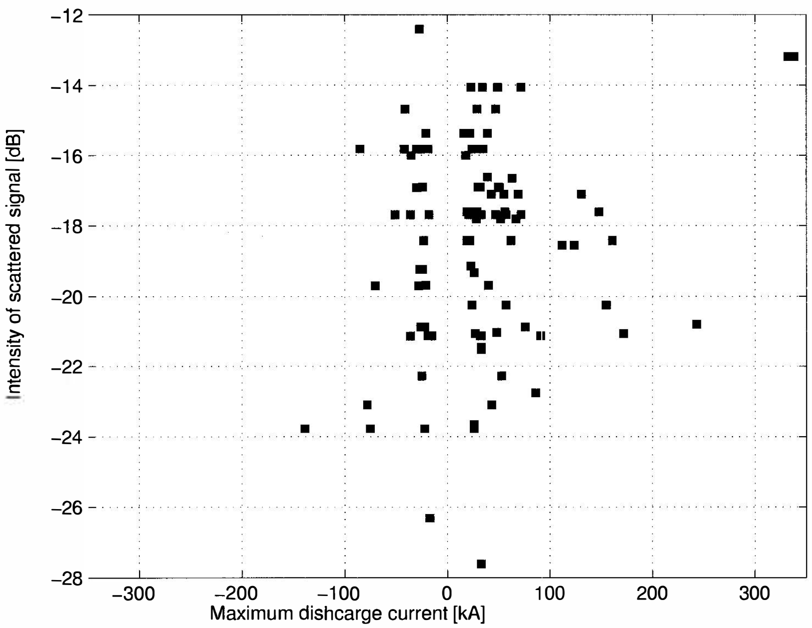

Fig. 4. *Distribution of the intensity of scattered signals (with respect to the unperturbed signal) for both polarities of causative CG discharges as a function of the maximum current value.*

for elves events (Hobara *et al*., 2001).

3.4. *Effect of the distance between the causative lightning location and the great circle path on Trimpi occurrence*

Figure 5 shows an event that occurred on December 23, 2000; each lightning causative discharge is characterized by its distance from the great circle path (GCP) and its maximum current (+ or −). The blue boxes indicate lightning discharges that did not induce Trimpis. The green circles indicate causative lightning discharges that led to Trimpis which were only observed at Moshiri, while the red diamonds indicate lightning discharges that led to Trimpis which were observed simultaneously at Moshiri and Kasugai. The abscissa indicates the maximum lightning current (+ and −CG discharge), and the ordinate indicates the distance of lightning from the GCP connecting NWC and Moshiri. As this figure shows, the lightning itself (in blue) was distributed very widely as a function of the maximum current; that is, −160 kA to +350 kA. In contrast to this wide distribution, the lightning discharges leading to a Trimpi (indicated either by green or red) were limited to a lower current (−100kA~+150 kA) range, with the exception of two lightning discharges with a highly positive current. Another important finding is that the lightning discharges leading to Trimpis were located very close to the GCP; the distance from the path was relatively small, less than

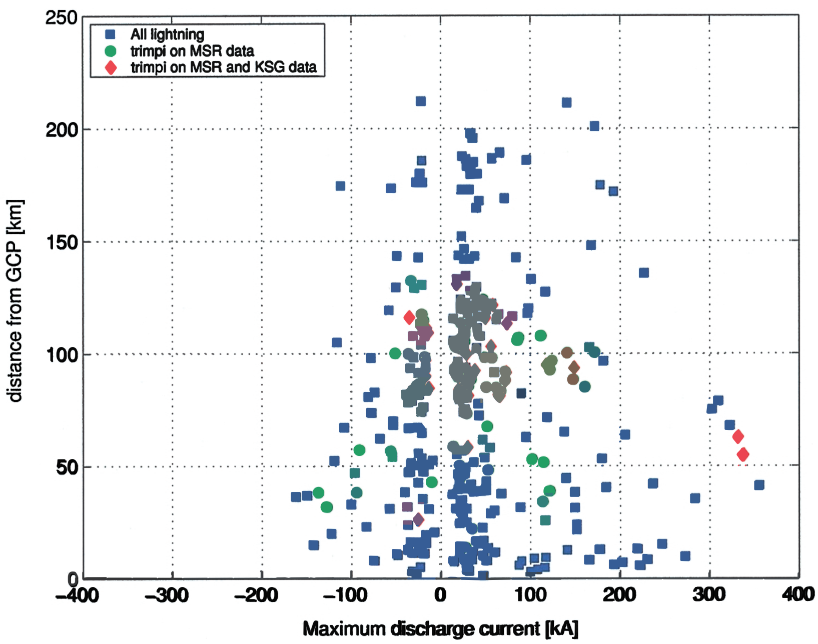

Fig. 5. Scatter plot of lightning discharge with and without Trimpis in the plane of maximum current (+ and −) versus distance from the great circle path between Moshiri and NWC. The green circles represent Trimpis that were only observed at Moshiri, and the red diamonds represent Trimpis that were observed simultaneously at Moshiri and Kasugai. The event occurred on December 23, 2000.

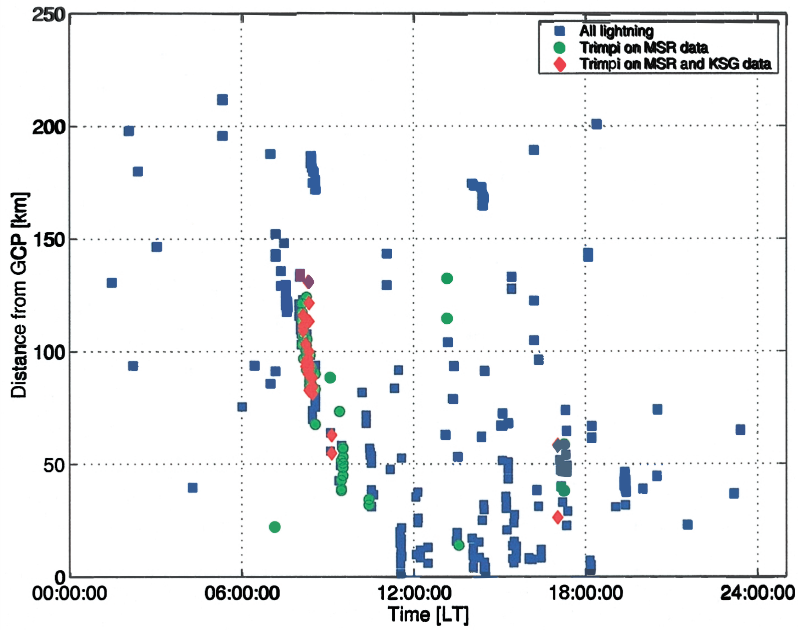

Fig. 6. Temporal evolution of lightning discharges that did not induce Trimpis (blue box) and that did induce Trimpis (green, only at Moshiri; red, observed simultaneously at Moshiri and Kasugai) on December 23, 2000.

130 km. In this event on December 23, no Trimpis occurred at distances shorter than 30–40 km, but this is simply due to the characteristics of the lightning on this day. Further analyses have indicated that Trimpis are sometimes observed at shorter distances on other days. Thus, the important findings illustrated by this figure are that the occurrence of Trimpis tends to decrease drastically with distance and that Trimpis are observable at distances of less than ~130 km from the GCP.

Figure 6 shows the temporal evolution of lightning discharges leading to Trimpis and without Trimpis on December 23, 2000. This figure suggests another important aspect of the lightning discharges that induce Trimpis. The same notation that was used in Fig. 5 is used in the figure. Between 8 h–10 h LT, lightning cluster occurred during several lightning discharges led to the occurrence of Trimpis. Lightning discharges that induce several Trimpis appear to form a group; in other words, they are clustered or self-organized. The data shown in Fig. 6 is not exceptional; this tendency was seen on two other days.

4. Summary and discussion

Winter lightning and Trimpis in the Hokuriku area of Japan were observed for a relatively long term, with particular attention to the events that occurred on three days: December 23, 2000; January 28; and February 15, 2001. Several Trimpis are observed on these days. The important findings are summarized below.

1) Several Trimpis were observed at Moshiri, but not as many were seen at Kasugai. The Trimpi lightning occurred very close to the GCP, between the NWC and Moshiri (less than 130 km), and the occurrence of Trimpis at points further than 130 km from the GCP was very rare.
2) The amplitude of the scattered signals ranged between −12 dB to −28 dB with respect to the unperturbed input signal, and was independent of the polarity.
3) Only a small number of lightning discharges include Trimpis (about 5% of causative +CG discharges and about 7% of −CG discharges). The percentages of +CG and −CG discharges that induced Trimpis were similar.
4) The maximum current of all the lightning discharges varied widely from −150 kA to +700 kA, but that of the lightning discharges that led to Trimpis was generally restricted to a narrow range of −100 kA to +150 kA.
5) Trimpis often occurred in association with a group of lightning discharges (in other words, when the lightning discharges were clustered).

The lightning discharges that induce Trimpis occur very close to the GCP, or within the first Fresnel zone. The predominance of Trimpis occurring at Moshiri rather than at Kasugai, may be indicative of a preference for forward scattering, as opposed to backscattering. Together with the information on the scattered signal, we can infer that the ionospheric perturbation is sufficiently large (compared with the VLF wavelength) and lies close to the GCP. This situation is similar to the case of classical Trimpis with a large horizontal duct size dimension (more than 100 km wide) on the GCP (as suggested by Inan *et al*., 1996; Dowden and Adams, 1993). We confirmed that no optical events (red sprites, elves etc.) were observed during our observation period. The intensities of Trimpis during our analysis period were between the range of −12 dB to −28 dB (with a mean of −18.6 dB), with respect to the unperturbed signal. This intensity range is significantly smaller than that associated with sprite events (Hobara *et al*., 2001). However, this value seems to be comparable to that of elves events (Hobara *et al*., 2001; Otsuyama and Hayakawa, 2002). Furthermore, the scattered signal intensity does not exhibit any difference between the two polarities of CG discharges. The Trimpis observed here in this paper are likely to correspond to early fast Trimpis, as defined by Inan *et al.* (1996), and to RORDs, as described by Dowden *et al.* (1994).

Next, we discuss the properties of lightning discharges leading to Trimpis, compared with the general characteristics of lightning discharges. The first necessary condition is that the lightning discharge must occur close to the GCP to trigger a Trimpi, as summarized in Point (1). What other conditions are necessary? In spite of a wide overall intensity distribution for the lightning discharges (−200 kA to +600–700 kA), the Trimpis were triggered by lightning discharge with a relatively small current (−100 kA~+150 kA), as summarized in Point (4). Hobara *et al.* (2001) have shown that elves are induced by lightning discharges with a large current (either + or −) and that they are associated with rather small ionospheric disturbances; sprites, on the other hand, are excited by a large positive charge moment at a low frequency range (Hobara *et al*., 2001). These observations suggest that sprite-induced ionization perturbations generated below the lower ionosphere (*e.g.* Dowden *et al*., 1994) are caused by a lightning discharge with enhanced energy at a lower frequency (*e.g.* ELF) (corresponding to a large charge transfer (Qds)), while elves seem to be excited by a lightning discharge with enhanced energy in the higher frequency range (VLF and higher). Furthermore, the scattered amplitude caused by elves is smaller than that caused by sprites. For winter lightning, the peak current does not appear to be proportional to its charge transfer because there is a high possibility that lightning discharges will contain a continuous current, even though the peak current is low. As preciously mentioned, the JLDN uses a combined system of IMPACT based on the time of arrival with LPATS based on goniometric direction finding (Cummins *et al*., 1998). This system was developed in the U.S. to detect continental summer lightning. When the system was installed in Japan as the JLDN, some essential problems in detecting Japanese lightning were encountered. First, the magnetic direction finding is known to be sensitive to site error; consequently, a larger measuring error was expected in Japan because Japan is composed of islands. A further problem related to using IMPACT based on the time of arrival is that the waveform for winter lightning in Japan is too complicated to find an effective peak, resulting in a large error. Ishii *et al.* (2002) reported a low detection rate (70–75%) for winter lightning using the JLDN, which may have resulted from the above-mentioned limitations inherent to the JLDN system. This system seems to reject long-lasting pulse waveforms that exceed the threshold level, a characterlistic that may be associated with continuous current lightning. The system itself is designed to detect continental summer lightning, so lightning discharges with both a large charge transfer and large peak current cannot be detected by this system because of the initial conditions used for lightning detection. However, lightning discharges with a medium peak current (around 100 kA) or higher and a small charge transfer are easily detected. Point (4) indicates that a lightning discharge with large charge transfer is likely to induce a Trimpi, but the reason for this is uncertain. Additionally, as shown in Tables 1 and 2 of Hobara *et al.* (2001), the charge transfer and ionospheric scattering of some optical events were seccessfuly estimated by ELF observation and VLF scattering, respectively, but the causative lightning currents were not detected by the JLDN. This finding might again have something to do with the detection conditions of the system and/or the above-mentioned system performance limitations (Ishii *et al*., 2002).

Using fractal analysis of radar images, Hayakawa *et al.* (2003) showed that when a sprite is observed, the causative lightning structure appears to be clustered (or self-organized). That is, the fine structure, such as the contiguity of charge among the thunder cells, is essential. This kind of analysis is likely to be related in some way to the clustering nature described in Point (5).

In conclusion, the Trimpis observed in this paper arose from electromagnetic pulses of lightning of either polarity (+ or −) and with a sufficient charge transfer. The maximum current does not appear to be a reliabe predictor of Trimpi occurrence; instead, charge transfer appears to be the most important factor in the occurrence of Trimpis. In the future, ELF observations (Nickolaenko and Hayakawa, 2002) (as performed at Moshiri (Hobara *et al*., 2001)) will be an important factor in understanding the details of winter Trimpis in the Hokuriku area.

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