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Characteristics of subionospheric VLF perturbations associated with winter lightning around Japan

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Abstract: VLF signature of ionospheric perturbations associated with winter lightning discharges around Japan has been investigated during 3 months observation (December 2000 through February 2001). During this period it seems that there are no optical phenomena in the Hokuriku area (Sea of Japan side) indicating that our period was not extremely active in lightning as compared with the previous winter (Y. Hobara *et al*., Geophys. Res. Lett., **28**, 935, 2001). Based on the VLF subionospheric observation at Moshiri (Hokkaido) and Maizuru (near Kyoto) for NWC (Australia) and NPM (Hawaii) transmitter signals, we have found the following results; (1) Trimpis tend to occur at least when the lightning activity is enhanced independent of the polarity, (2) Trimpis are observed when the causative lightning is located not only on the Sea of Japan side but also on the Pacific Ocean side, and (3) the occurrence of Trimpis in the Hokuriku area is more enhanced than that on the Pacific side, which is discussed with a special reference to the different meteorological conditions.

key words: Trimpis, VLF subionospheric propagation, winter lightning

1. Introduction

Recent observations on ionospheric perturbations by means of subionospheric VLF propagation have suggested that there is a new type of Trimpis (so-called early/fast Trimpi (Inan *et al*., 1996) or RORD (rapid onset and rapid decay) (Dowden *et al*., 1994)) directly related with lightning discharges in addition to the classical Trimpis due to the particle precipitation as the consequence of wave-particle interactions in the magnetosphere (see the recent reviews by Strangeways (1996), Rodger (1999), Jones (1999), Hayakawa *et al.* (2004a)). These phenomena are considered to have a certain relationship with the optical emissions in the mesosphere and the lower ionosphere (so-called sprites or elves) and there have been proposed several mechanisms to explain a variety of characteristics of early/fast Trimpis, including the ionization changes resulting 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 quasi-electrostatic (QE) field (Pasko *et al*., 1995; Inan *et al*., 1996). However, the physical mechanism responsible for creating the early/fast disturbance is still not quantitatively understood, although it is generally agreed that this phenomenon is recognized as being important to study the atmosphere-ionosphere coupling. Previous works were all based on case studies, so that a statistical study is highly required based on a large data set. Further, the most fundamental question to elucidate the physiscal mechanism is related with the study of the characteristics of lightning discharges causative to early/fast Trimpis. This paper is a further extension of our previous paper (Otsuyama *et al.*, 2003), and intends to provide a statistical study of VLF signatures of ionospheric perturbations associated with winter lightning discharges in the vicinity of Japan using a relatively long-term continuous measurment (3 months). Based on statistical study of different types of lightning occurred on the Sea of Japan side and Pacific Ocean side, we present some characteristics of lightning discharges associated with subionospheric VLF perturbations.

2. Description of the experiment and observation

The network observation of ionospheric perturbations has been established in Japan for the study of seismo-ionospheric effects, and the observation is being continued continuously at seven stations all over Japan. Four VLF/LF transmitter signals are simultaneously received at each station (see the details in Hayakawa, 2001). In order to detect slow changes in the ionospheric parameters associated with earthquakes, the JAPAL system is developed by Dowden *et al.* (1999) as an extension of Omni-pal system in which using GPS as a phase standard it enables comparison of JG2AS (40 kHz, standard wave transmitted in the Fukushima prefecture) phase measurement made days or months apart. This JAPAL system is being run with the time resolution of 20 s for the seismo-Trimpis, and is also used for the present study. We increased the time resolution up to the highest value of 50 ms during the period of December 15, 2000 to February 28, 2001 in order to have a target to the ionospheric perturbation associated with the lightning discharges. We have used the Trimpi data observed at Moshiri in Hokkaido and at Maizuru in Kyoto Prefecture with the use of NWC (f=19.8 kHz in Australia) and NPM (f=21.4 kHz in Hawaii) transmitter signals. VLF observing stations and the VLF propagation paths are illustrated in Fig. 1.

The Japanese lightning detection network (JLDN) based on the combined TOA (time of arrival)/MDF (magnetic direction finding) technology for the lightning direction finding (*e.g.* Cummins *et al.*, 1998; Ishii *et al.*, 2002) detects the lightning on and around the four main islands of Japan, and provides us with the lightning data; the absolute time, location and peak current (together with polarity) of most cloud to ground lightning discharges. We used ±1 s of the accuracy in time of lightning in the JLDN data.

At first, we have selected the data on lightning discharge that is found to take place within the 5th Fresnel zone of each propagation path. Using these lightning data, we adopted the following methods in order to judge whether it is a Trimpi effect or not. First, it is necesarry to estimate the unperturbed (direct) wave (without any scattered signal). We assumed that the amplitude and phase during 15 s before a lightning discharge are representing the unperturbed state (direct wave). We calculated the vector of the direct wave, and then estimated the scattered signal vector by applying a phasor concept to the observed signal (Dowden *et al.*, 1994). In order to identify a Trimpi, we calculated the standard deviation of scattered signal before the lightning, and when the scattered signal exceeds four times of this deviation, we consider this signal as a Trimpi. Figure 2 shows an example of

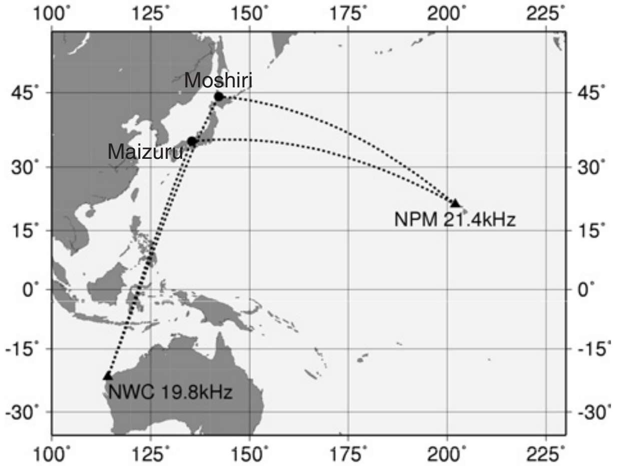

Fig. 1. Location of our two observation stations (Moshiri and Maizuru), together with the great circle paths to the VLF transmitters of NWC (Austrailia) and NPM (Hawaii).

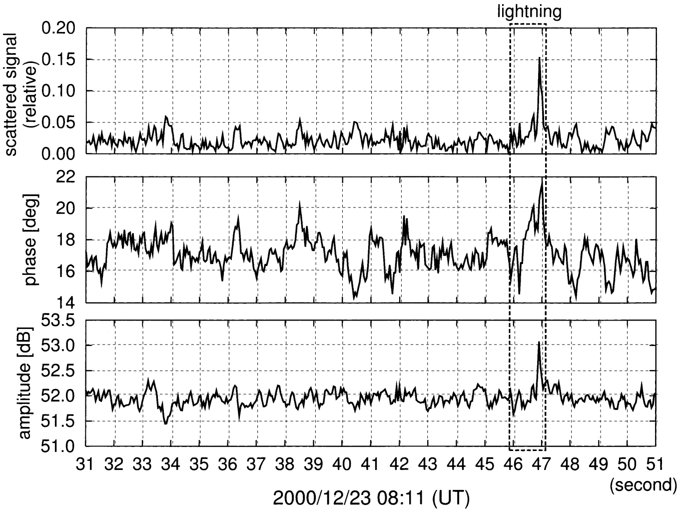

Fig. 2. A typical example o fearly/fast Trimpis observed at Moshiri: from the top to the bottom, scattered signal (relative), phase and amplitutde.

VLF data that are observed at Moshiri, and a Trimpi was observed at 0811:47 UT.

3. Analysis results

3.1. Result of optical observation

During the period of our analysis we tried to observe, in Chichibu (geographic coordinates; 35.93°N, 138.90°E), the optical phenomena such as red sprites and elves in association with winter lightning in the Hokuriku area in the winter of 2000/2001, but no optical emissions were detected. These optical measurements were not continuous because we visited the observatory at Chichibu only when we had consulted the lightning forecast from Hokuriku Electric Power Company and when it was highly likely to have the lightning activity in the Hokuriku area, we visited the optical site only several times during our observation period. So our result of no optical emission does not indicate any absolute absence of the red sprites. But, in support to our results, the Tohoku University group has also made the same observations, and their result has also indicated no optical emission in the Hokuriku area (Fukunishi and Takahashi, private communication). We have to mention that we succeeded in detecting several sprites in the Hokuriku area in the next winter of 2001/2002 with the same optical sensor (Hayakawa *et al.*, 2004b). These facts mean that the lightning activity during the period analyzed in this paper was not so intense as compared with previous winter (Hobara *et al.*, 2001).

3.2. Occurrence rate of Trimpis in relation to lightning activity

Figure 3 illustrates the temporal evolution of total lightning activity and Trimpi occurrence rate in our target area in Fig. 1 using the data observed during three months (December 2000 and January and February 2001). The bottom panel indicates the number of total lightning events and the middle one indicates the number of Trimpi occurrence. Finally the top panel illustrates the occurrence rate of Trimpis divided by the number of lightning activity. Although we can easily find two days of high activity of Trimpi occurrence rate, these days are found to have small lightning activity (January 21 and February 11, 2001). Therefore, we conclude that Trimpi occurrence rate is a few percents of lightning activity throughout the observation period.

Figure 4 illustrates the diurnal variation of total lightning activity and Trimpi occur-

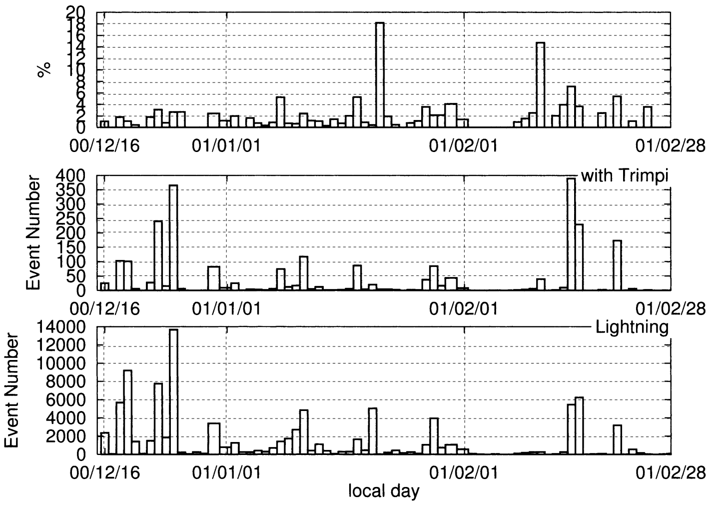

Fig. 3. Temporal evolution of total lightning occurrence (bottom), Trimpi activity (middle), and prercentage occurrence rate (top) during the three months (December 2000 to Febuary 2001).

rence rate deduced from the same data. These figures show that Trimpi occurrence rate, number of Trimpis and number of lightning events (from the top to the bottom panels). The occurrence probability of Trimpis is found to be small and also we could not find any particular dependence on the local time.

Figure 5 shows the summary of amplitude of scattered signal (with respect to the unperturbed signal) by the phasor concept (Dowden *et al.*, 1994) using the amplitude and phase information like that in Fig. 2. The polarity of the causative lightning can be seen from the polarity (+ or –) of the peak discharge current in Fig. 5. It is found from the figure

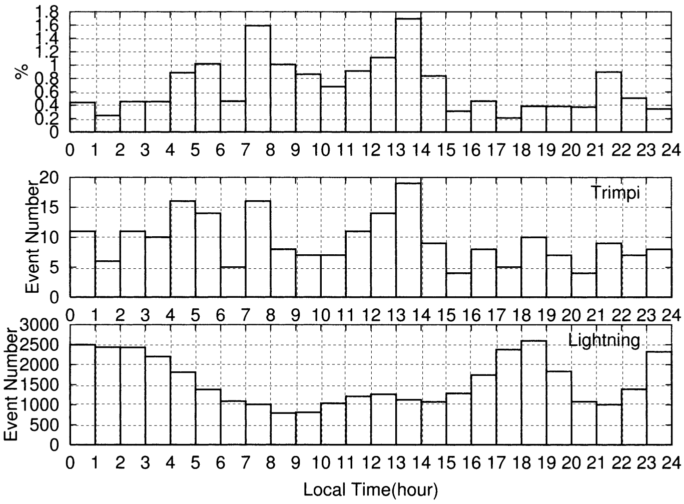

Fig. 4. Diurnal variation of lightning occurrence (bottom), Trimpi activity (middle), and percentage occurrence of Trimpi events (top).

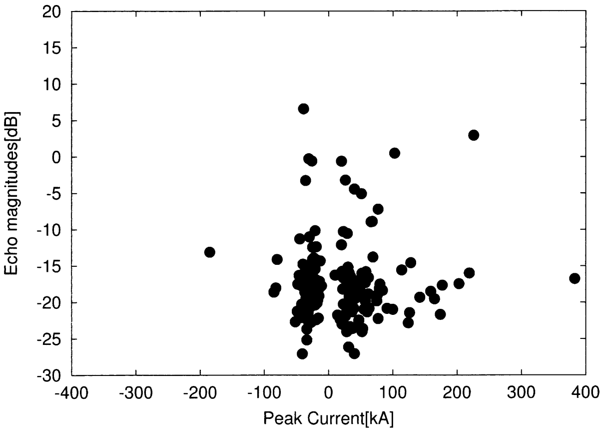

Fig. 5. Distribution of the intensity of scattered signal (with respect to the unperturbed signal) for both polarities of causative CG discharges, as a function of peak current value.

that the intensity of scattered signal ranges from –30 dB to +5 dB for both polarities of causative CG discharges and the mean value is found to be about –20 dB. No significant difference is found for the scattered signal intensity between + and – CG discharges. These intensity values are clearly found to be significantly smaller than those for sprite events by about 10 dB as compared wth Hobara *et al*. (2001), but they are relatively close to those for elves events by Hobara *et al*. (2001).

3.3. Occurrence rate of Trimpis in relation to lightning area

The winter lightning in the Sea of Japan side is famous as having peculiar characteristics; that is, (1) the positive (+) CG discharge is as numerous as –CG (Brook *et al*., 1982; Takeuti and Nakano, 1983), (2) large electric charge (Michimoto, 1993; Hayakawa *et al*., 2004b), etc. But in winter season in the vicinity of Japan a lot of lightnings occurred not only in the area of Sea of Japan, but also on Pacific Ocean side. Figure 6 shows the distributions of lightning discharges detected by JLDN with/without Trimpis in our observed area around Japan. Blue and green points correspond to events with and without Trimpis respectively. The number of lightning on the Pacific Ocean aera seems to be more enhanced than that in the Sea of Japan side. These thunderstorms are likely to possess different meteorological systems. The winter storms on the Sea of Japan side are caused by advection of Siberian air mass over the Sea of Japan, while the thunderstorms in the Pacific area are caused by cold-front. Figure 7 shows an IR (infrared) satellite image and the corresponding lightning data around Japan of typical winter season (11 January 2001). In the Sea of Japan area, we can find that there are a group of clouds associated with advection of Siberian air mass, while the Pacific Ocean side lightning seems to be associated with different type of

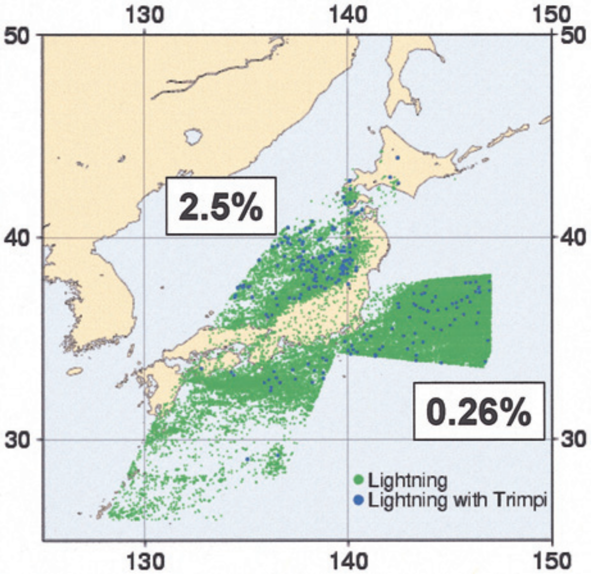

Fig. 6. The distribution of lightning discharges with/without a Trimpi event, where blue points mean that the Trimpis are observed, and the green point, not observed.

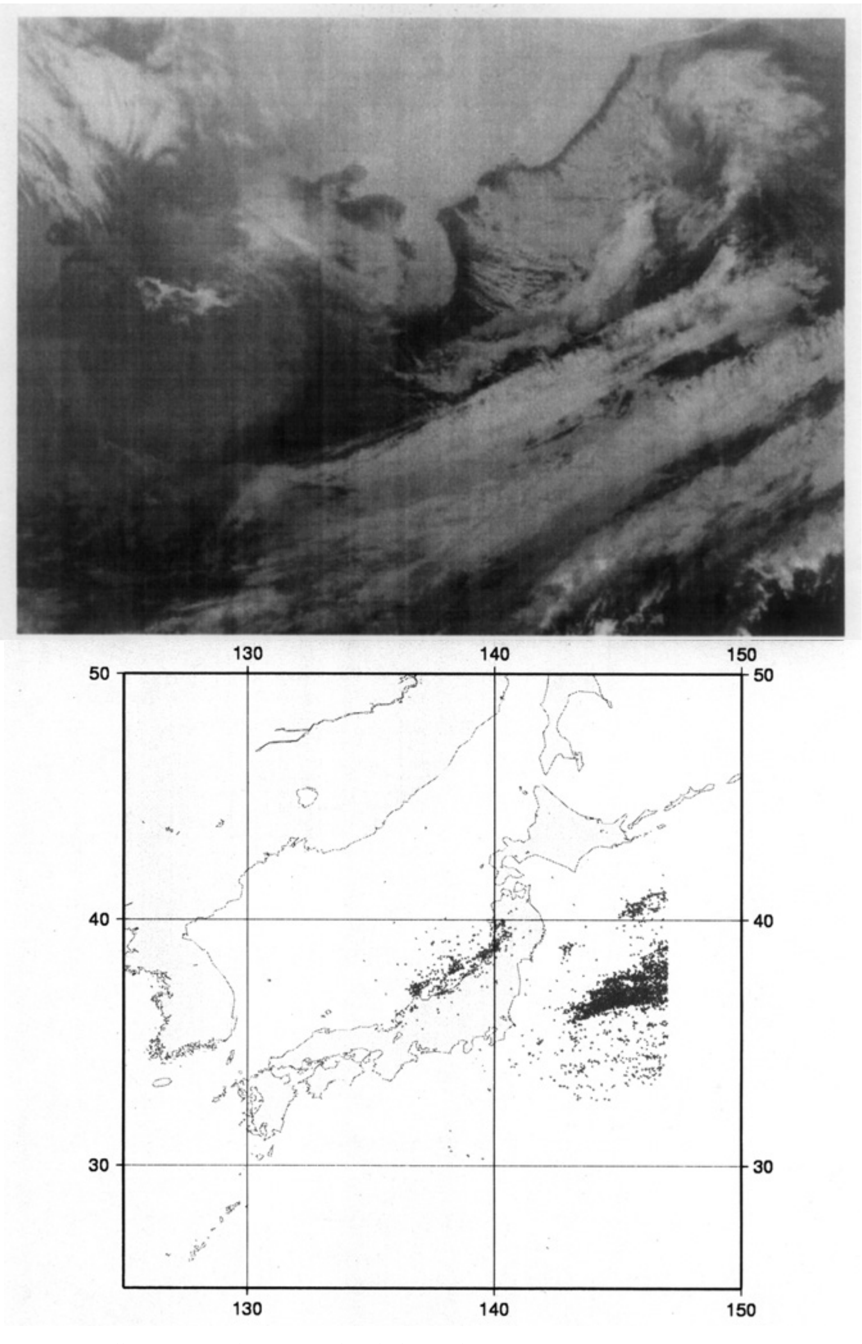

Fig. 7. An IR satellite image and corresponding lightning location map for January 11, 2001. We can see clouds due to cold air convection (Sea of Japan side) and due to cold front (Pacific side). The IR image was provided by the Kochi University, University of Tokyo, and Japan Meteorological Agency.

Table 1. Statistics of lightning activity and number of Trimpis on the Sea of Japan side and the Pacific Ocean side.

	Number of lightning	with Trimpi	Probability
Sea of Japan side	5826	141	2.5%
Pacific side	32133	85	0.26%

thunderclouds *i.e.* a cold front. In other words, the thunderstorms on the Pacific Ocean side occurred on the cold fronts or unstable area of the cold fronts. Now, we discuss the difference of Trimpis caused by these thunderstorms. Table 1 shows the result of statistical analysis of lightning activity and number of Trimpis for two regions. It is easy to see that the number of lightning in the Pacific Ocean area is about 6 times larger than in the Sea of Japan area, but the number of Trimpis is almost equal. It is therefore concluded that thunderstorms in the Sea of Japan are more likely to trigger a Trimpi.

4. Summary and discussion

We have studied the relatively long-term observation of the occurrence of winter lightning and Trimpi events around Japan. The important findings are summarized as follows.

(1) The number of lightning including Trimpis is not so large (about 2% of causative CG discharges).

(2) There is no such significant differences in the rate of lightning with Trimpi between + and – CG discharges.

(3) Trmpi is more easliy triggered on the Sea of Japan side than in the Pacific Ocean side.

Point (3) is a new finding, which deserves some more discussion with a special reference to the different meteorological conditions. A Trimpi is easily excited on the Sea of Japan. In the area of Sea of Japan, there seems to be a tendency for a greater percentage of ground flashes to lower positive charge, and positive ground flashes occasionally involve extremely large amounts of charge (Michimoto, 1993; Hayakawa *et al.*, 2004b). These thunderstorms are found over the Sea of Japan, often on or at the rear of cold fronts. They are associated with troughs or cyclones moving across the Sea of Japan when monsoon wind flows into the rear of cyclones. Hobara *et al.* (2001, 2003) have shown that an elves is induced by the lightning discharge with large current (either + and –) and that it is associated with rather small ionospheric distubances, while sprites are indicated by Hobara *et al.* (2001) to be excited by a large positive charge moment in the low frequency range. Their result suggests that a sprite-induced ionization perturbation that seems to be generated below the lower ionosphere (*e.g.* Dowden *et al.*, 1994) is due to a lightning discharge with enhanced energy at lower frequencies (*e.g.* in the range of ELF) (corresponding to a large charge transfer (Qds)), whereas an elves seems to be excited by a lightning discharge with enhanced energy in the higher frequency range (VLF and higher). Therefore, we may suggest that the thunderstorm due to advection of cold air mass over the sea is expected to lead to large charge moment lightning. Additionally, Hayakawa *et al.* (2004b) have shown on the basis of fractal analysis for the radar images that when a sprite is observed, the causative lightning structure seems to be clustered or self-organized. This kind of clustering is easily in operation in the Hokuriku winter lightning.

In conclusion, Point (2) suggests that the Trimpis observed in this paper might result from the electromagnetic pulse of a lightning discharge with either polarity (+ and –) and with a sufficient charge transfer. The peak current does not appear to be a reliable predictor of Trimpi occurrence; instead, charge moment appears to be the most important factor in the occurrence of Trimpis. So, ELF observations (Nickolaenko and Hayakawa, 2002) (as performed at Moshiri (Hobara *et al*., 2001; Hayakawa *et al*., 2004b)) yielding the charge transfer will be an important factor in understanding the details of winter Trimpis in the vicinity of Japan, which will be studied in near future.

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