A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes

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Abstract

The subionospheric VLF/LF propagation is extensively used to investigate the lower ionospheric perturbation in possible association with earthquakes. An extensive period of data over seven years from January 2001 to December 2007 and a combination of different propagation paths in and around Japan are used to examine the statistical correlation between the VLF/LF propagation anomaly (average nighttime amplitude, dispersion and nighttime fluctuation) and earthquakes with magnitude greater than 6.0. It is then found that the propagation anomaly exceeding the 2σ (standard deviation) criterion indicating the presence of ionospheric perturbation is significantly correlated with earthquakes with shallow depth (<40km). Finally some comments on the mechanism of seismo-ionospheric perturbations are discussed.

1. Introduction

There had been published in 1980s some reports that anomalous electromagnetic effects took place around an earthquake (EQ), but it is only recently that systematic studies have been performed in the field of seismo-electromagnetics. Especially after the famous and disastrous Kobe EQ there have been accumulated a lot of convincing evidence on the presence of electromagnetic phenomena associated with EQs (e.g., Molchanov and Hayakawa, 2008). This paper deals with the statistical study on the correlation of VLF/LF subionospheric propagation anomalies (ionospheric perturbations) with EQs on the basis of long-term data.

2. Subionospheric VLF/LF propagation method

A very convincing evidence on ionospheric perturbations was then obtained by Hayakawa et al. (1996) for the famous Kobe EQ (January 17, 1995) by means of shifts in terminator times (TTs) in the VLF data (TT is defined as the time when the amplitude (or phase) shows a minimum either around sunrise or sunset). So, it is found with the use of subionospheric VLF/LF propagation that the lower ionosphere is extremely sensitive to an EQ. Being encouraged with these results, we have established a Japanese VLF/LF network within the framework of NASDA's EQ Remote Sensing Frontier Project, and also European groups are going to organize the similar VLF/LF observation network in Europe (Rozhnoi et al., 2009). There have been published a lot of subionospheric VLF/LF works on this subject by means of (i) case studies (studies for any specific and huge EQs including relatively recent EQs such as Niigata-chuetsu EQ, Sumatra EQ and so on) and (ii) statistical studies on the correlation between VLF/LF propagation anomalies (that is, perturbation in the lower ionosphere) and EQs (Shvets et al., 2004; Rozhnoi et al., 2004; Maekawa et al., 2006; Kasahara et al., 2008).

The purpose of this paper is to substantiate our former statistical studies by Rozhnoi et al. (2004), Maekawa et al. (2006) and Kasahara et al. (2008). The purpose of the present paper is to offer a substantial statistical study on the correlation between VLF/LF propagation anomalies and EQs on the basis of a much longer period of analysis and of much more propagation paths, and finally we discuss the lithosphere-atmosphere-ionosphere coupling mechanism to interpret how and why seismo-ionospheric perturbations are generated.

3. Analysis periods and EQs treated

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3.1 Japanese-Pacific VLF/LF network

The Japanese VLF/LF network consist of several receiving stations. The present receiving stations are Moshiri (abbreviated as MSR) in Hokkaido, Chofu (CHF) in Tokyo, Tateyama (TYM) in Chiba prefecture, Kasugai (KSG) near Nagoya and Kochi (KCH) in Kochi prefecture. We adopt a Japal system at each station, which enables us to receive simultaneously several VLF/LF transmitter signals; two Japanese transmitters (call signs, JJY (40kHz, in Fukushima; geographic coordinates: 37.3° N, 140.8° E) and JJI (22.4kHz, Ebino, Kyushu; 32.0° N, 130.8° E)) and a few foreign transmitters including NWC (Australia, 19.8kHz), NPM (Hawaii, 21.4kHz) and NLK (USA, 24.8kHz). Fig.1 illustrates the positions of our VLF receiving stations of MSR, TYM and KCH with red stars, and also the positions of two Japanese transmitters (JJY and JJI) as blue diamonds. Molchanov and Hayakawa (2008) and Hayakawa (2009). So that, many propagation paths will be available by combinations of selecting different transmitters and receivers. However, after checking the quality of the data for all possible propagation paths, we have chosen only the following wave paths with sufficient data quality for analysis, whose wave sensitive areas are illustrated as elliptic regions in Fig.1.

1. JJY(40kHz)-KCH
2. JJY(40kHz)-MSR
3. JJY(40kHz)-KCK
4. JJI(22.2kHz)-TYM
5. JJI(22.2kHz)-MSR
6. JJI(22.2kHz)-KCK

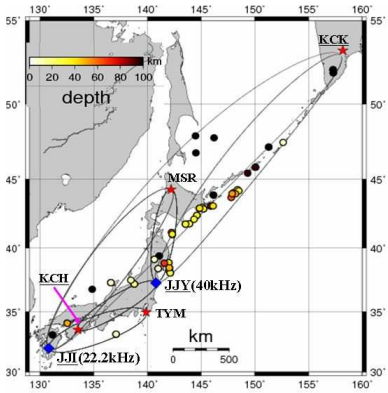

Fig. 1 The relative locations of two Japanese transmitters (call signs, JJY(40kHz, Fukushima) and JJI (22.2kHz, Ebino, Kyushu) indicated by blue diamonds) and four observing stations (Moshiri(MSR), Kamchatka (KCK), Kochi (KCH) and Tateyama, Chiba (TYM)) in red stars. EQs treated are also plotted, with their color indicating the EQ depth. Wave sensitive areas (defined by 5th Fresnel zone) are also plotted for all propagation paths.

The transmitter frequency of the JJY transmitter (belonging to National Institute of Information and Communications Technology) is 40 kHz and its transmitter power is 10kW. While, the JJI transmitter (belonging to Japanese Navy) is characterized by the frequency of 22.2 kHz, but with unknown power due to the military use. The wave sensitive area for each propagation path is defined by the 5th Fresnel zone of the great-circle path as is adopted in the previous works (Maekawa et al., 2006; Kasahara et al., 2008). All of the data received at all the receiving stations are sampled with a time interval of 120 s (2min). Only the amplitude data are analyzed in this paper, because the phase data are sometimes not good enough for analysis.

The period of analysis is considerably extended as compared with the longest period of 4 years in Kasahara et al. (2008). That is, we have used the data over total 7 years from January 1, 2001 to December 31, 2007 (to be more exact, up to October 31, 2007 only for the paths, JJY-KCK and JJI-KCK). It seems that this would be the longest analysis period so far in the field of seismo-electromagnetic studies.

3.2 EQs treated

We tentatively divide the EQ depth by a depth of 40km in order to find the dependence on EQ depth. As is seen from the configuration of the propagation paths in Fig.1, we can imagine that some EQs are common on a few propagation paths. In the case of shallow EQs (depth<40km), 3 EQs are common for 3 paths and 13 EQs are common for 2 paths. Similarly, for deep EQ (depth>40km), 4 EQs are seen for 3 paths and 16 EQs are common on 2 paths. So that, the total number of propagation paths which cover the EQs with depth smaller than

40km, is 35, while the corresponding number is 38 for EQs with depth larger than 40km. We treat the data for each propagation path being independent events.

This independent treatment seems to be validated by our previous work. That is, Yamauchi et al. (2007) have examined a few propagation paths for a particular and large EQ named the 2004 Mid-Niigata EQ by means of the TT method, and then they have found that the anomaly in TT does not happen always on the same day. This might suggest that the seismo-ionospheric perturbation is very inhomogeneous both in space and in time, leading to the effect of very dissimilar variations on different propagation paths even for the same EQ.

4 VLF/LF analysis method

Here we use the 2nd nighttime fluctuation method (the details are given in Kasahara et al. (2008) and Hayakawa et al. (2010)). We estimate the following three physical quantities of amplitude; (1) trend (as the average of nighttime amplitude), (2) dispersion (D) (in the following we use its square root, i.e.. standard deviation, but we use the terminology of dispersion in order to avoid the confusion that the standard deviation for each quantity is used very often in this paper), (3) nighttime fluctuation (NF).

Next we have to mention how to treat the data on different propagation paths, because the variability in VLF/LF amplitude data is very different from one path to another. So that, it is highly required to have a homogeneous treatment of the VLF/LF data when we analyze different propagation paths. We have proposed the use of so-called "standardization" in the following way. That is, when we take one particular path, we deal with three physical quantities of amplitude, trend, D and NF and we estimate the following normalized trend (trend*), normalized D (D*), and normalized NF (NF*). When we take an EQ with a particular date, we estimate the trend on this day and we then calculate the average <trend> over $\pm$ 15 days around this date. Then, the normalized trend (trend*) is defined as (trend-<trend>)/ σ_T (σ_T , standard deviation over $\pm$ 15 days around the current date). The same principle is applied to other quantities in order to obtain the normalized D (D*) and normalized NF (NF*).

By using these normalized (or standardized) trend, D and NF, we make full use of a superimposed epoch analysis (e.g. , Maekawa et al., 2006), which is of extreme importance in enhancing the signal to noise ratio by stacking the data with EQ day as a reference day. Already we have chosen the magnitude greater than 6.0, but we pay more attention to the effect of EQ depth in this paper because this point is poorly studied even though Maekawa et al.(2006) have suggested this point qualiatively.

Figs. 2(a), 2(b) and 2(c) are the final results on the basis of superimposed epoch analysis. Fig. 2(a) refers to the trend*, while Fig. 2(b), the D* and Fig. 2(c), the NF*. We can deduce from these figures the following summary.

(1) The trend (or trend* in Fig. 2(a)) is found to show a significant decrease (exceeding the 2 σ_T criterion) before the shallow EQ (with depth <40km) (in red). This anomaly takes place 5 days before the EQ as a conspicuous peak. When the EQ depth becomes larger (like more than 40km in Fig. 2(a)), the similar tendency is likely to be observed in blue line in Fig. 2(a) in such a way that the trend approaches the 2 σ_T criterion 12 days before the EQ (but not exceeding the 2 σ_T criterion).

(2) Next the nighttime dispersion (D*) for EQ depths smaller than 40km (in red) in Fig. 2(b) is found to exhibit a significant increase 3 days before the EQ (exceeding the $2\sigma_D$ criterion and even approaching $3\sigma_D$ level). However, when the EQ depth becomes larger than 40km (in blue line in Fig. 2(b)), there is no clear precursory effort before such a deep EQ.

(3) Fig. 2(c) concerning the NF is found to indicate significant enhancements only before the EQ (5~6 days before the EQ) with exceeding the 2 σ_{NF} criterion. No such enhancements in NF are detected for EQs with depth larger than 40km.

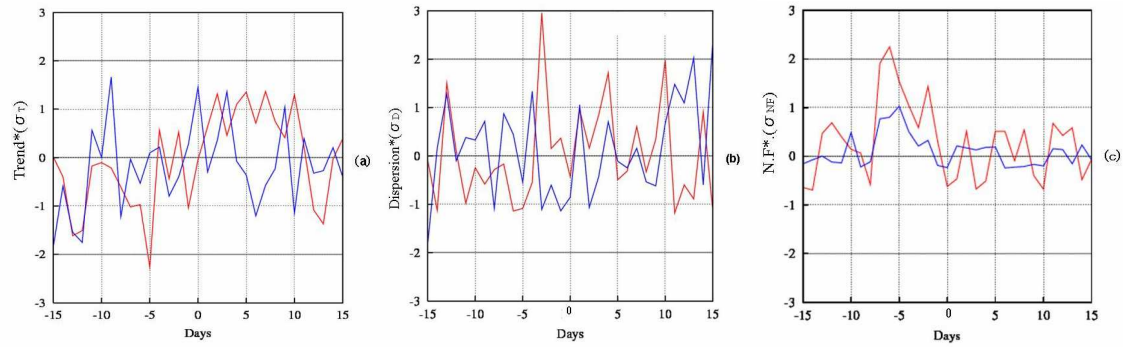

Fig. 2 Superimposed epoch analysis for the normalized trend (trend*) (a), the normalized dispersion (D)

(dispersion*), and the normalized NF (NF*) (c). The red line refers to shallow EQs (depth <40km), and the blue line refers to an EQ with depth larger than 40km. The abscissa indicates the day with respect to the EQ day (0) : – (minus) means the day before the EQ and + (plus), the day after the EQ.

5. Discussion and conclusion

We have been observing subionospheric VLF/LF signals for the last ten years or so by means of our Japanese VLF/LF network (Hayakawa, 2009; Molchanov and Hayakawa, 2008), so that we are ready to perform an extensive statistical analysis on the correlation of lower ionospheric perturbations as detected by subionospheric VLF/LF propagation and the parameters of EQs (magnitude, depth etc.) on the basis of a much longer data set and much more propagation paths than our own previous works by Rozhnoi et al.(2004), Maekawa et al.(2006a) and Kasahara et al.(2008). Then, we have used the data over seven years, and we have found the following findings from our present study.

(1) The mean nighttime amplitude (or trend) is found to decrease significantly before an EQ with magnitude greater 6.0, with shallower depth (less than 40km) and with EQ epicenter being located within the wave sensitive area.
(2) The dispersion (D) in nighttime amplitude is also found to be enhanced before the EQ with the same conditions as above.
(3) The NF defined in this paper is also found to increase before the EQ with the same condition as above

Detailed discussion on the correlation of ionospheric disturbances with magnetic activity is discussed. Finally, we discuss the generation mechanism of those seismo-ionospheric perturbations.

6. Acknowledgments

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