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On the statistical correlation between the ionospheric perturbations as detected by subionospheric VLF/LF propagation anomalies and earthquakes

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Abstract. Relatively long-period (4 years) data on different propagation paths by means of Japanese-Pacific VLF/LF network observation, are used to obtain further statistical significance on the correlation of ionospheric perturbations as revealed by VLF/LF propagation anomalies with earthquakes. Earthquakes with magnitude greater than 6.0, taken place only within the fifth Fresnel zone of each great-circle path are selected for the correlation study. It is finally found based on the superimposed epoch analysis that the nighttime trend (average amplitude) exhibits a significant decrease exceeding 2σ (σ: standard deviation) several days before the earthquake and the nighttime fluctuation exceeds the corresponding 2σ again several days before the earthquake when the earthquake depth is smaller than 30 km (shallow earthquakes). However, when we treat all earthquakes including deep earthquakes, the trend shows a significant decrease (just approaching 2σ line), and the nighttime fluctuation shows a less significant broad enhancement before the EQ.

1 Introduction

There have been recently accumulated a lot of evidence on the presence of electromagnetic phenomena associated with earthquakes (EQs) including (1) the direct electromagnetic emissions in a wide frequency range from DC/ULF to VHF, (2) the indirect effects of seismo-atmospheric and – ionospheric perturbations, etc. (e.g., Hayakawa and Molchanov, 2002; Molchanov and Hayakawa, 2008). In the first category, we can detect some precursors of EQs only when our observatory is luckily located relatively close to the EQ epicenter. This kind of measurement can be called "local measurement", so that it would take much time to accumulate a sufficient number of data. On the other hand, the second category can be called "integrated measurement", for which any EQs close to the great-circle path may exhibit significant effects on the propagation characteristics of pre-existing transmitter signals in the form of propagation anomalies.

Because of the advantageous nature of subionospheric VLF/LF propagation as an integrated measurement, it has been much easier for us to accumulate a lot of convincing data on the seismo-ionospheric perturbations as revealed in the form of subionospheric VLF/LF anomalies. There have been so many case studies on subionospheric VLF/LF propagation anomalies; e.g., Kobe EQ (Hayakawa et al., 1996), Tokachi-oki EQ (Shvets et al., 2004), Niigata-chuetsu EQ (Hayakawa et al., 2006), Indonesia-Sumatra EQ (Horie et al., 2007), etc. In addition to these case studies, statistical studies on the correlation of ionospheric perturbations with EQs are highly required. Rozhnoi et al. (2004) have actually analyzed the two years data for the wavepath from a Japanese LF transmitter, JJY to Kamchatka, Russia, and Maekawa et al. (2006) have used the 5 years data for the wave propagation from the same JJY transmitter to Kochi station. Both of these studies have indicated a statistically significant correlation between the ionospheric perturbations as detected by subionospheric VLF/LF propagation and EQs with magnitude, at least, greater than 5.5.

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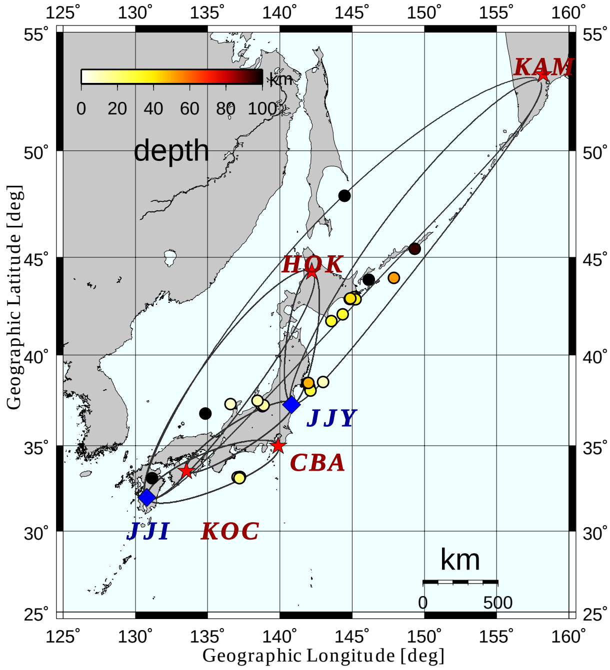

Fig. 1. The wave propagation paths used in this papers. Two Japanese transmitters (JJY and JJI) (indicated by blue diamonds) are used, and all of the combinations of transmitters and receivers (indicated by a red star) are indicated by plotting their corresponding fifth Fresnel zones (wave sensitive areas). EQ epicenters are indicated by circles, and the EQ depth is indicated in color.

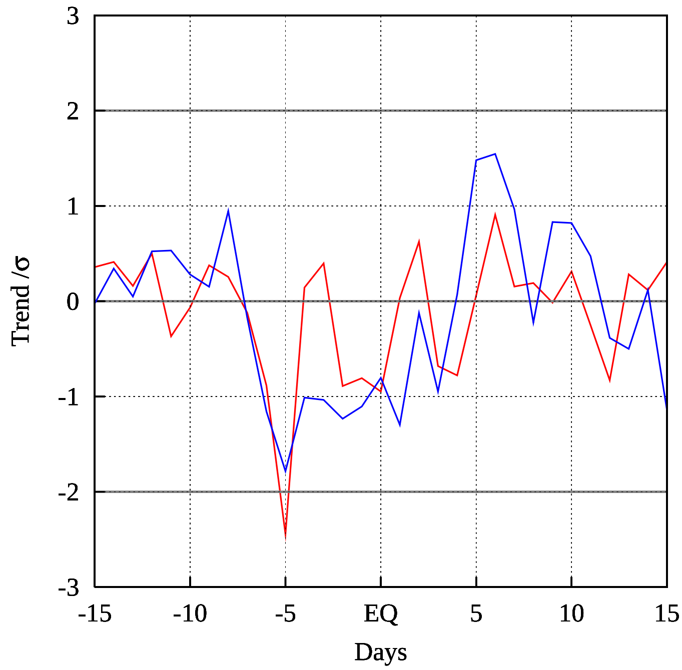

Fig. 2. Superimposed epoch analysis for trend (nighttime average amplitude). Red line refers to the EQs with depth smaller than 30 km (i.e., shallow EQs), while blue line refers to the case including all EQs (including any depths). The ordinate is normalized by the standard deviation.

The purpose of this paper is to offer an additional statistical study on the seismo-ionospheric perturbations on the basis of more VLF/LF data recently observed by means of the Japanese-Pacific VLF/LF network.

1.1 Analysis period and analysis propagation paths

The period of subionospheric VLF/LF propagation data used in this paper, is 4 years from 2004 to 2007. As is already shown in Hayakawa (2007) and Molchanov and Hayakawa (2008), we have a Japanese VLF/LF network consisting of seven observing stations within Japan and also one station in Kamchatka (Russia). The details of our VLF/LF receiving system have already been described in Maekawa et al. (2006) and Hayakawa (2007). At each station we normally observe simultaneously several VLF/LF transmitter signals (normally two Japanese transmitters (one is JJY (40 kHz, in Fukushima) and JJI (22.2 kHz, at Ebino, Kyushu)), so that we have many combinations of the transmitter and receiver. However, with taking into account the quality of the data for all propagation paths, we have chosen the following wave paths, which are illustrated in Fig. 1.

1. JJI-Kochi (abbreviated as KOC)
2. JJY-Moshiri (Hokkaido) (HOK)
3. JJY-Kamchatka (KAM)
4. JJI-Chiba (CBA)
5. JJI-Moshiri (HOK)
6. JJI-Kamchatka (KAM)

The locations of two Japanese VLF/LF transmitters are illustrated in Fig. 1 as a blue diamond, and their positions (geographical coordinates) are given by (37.3° N, 140.8° E) and (32.0° N, 130.8° E), respectively. The transmitting frequency of the JJY transmitter is 40 kHz and its transmitter power is 10 kW. Then, the frequency of the JJI transmitter is 22.2 kHz, but its transmitting power is not published. The receiving stations (with abbreviated notations) used in this paper are indicated by a red star in Fig. 1. All of these data are sampled with a time interval of 120 s (2 min), this sampling being sufficient for our seismogenic analysis. We analyze only the amplitude data for all transmitter-receiver combinations, because the phase data are not good enough.

2 EQs selected for analysis

According to our previous two papers on the statistical study on the correlation between VLF/LF anomalies and EQs (Rozhnoi et al., 2004; Maekawa et al., 2006), the correlation is significant only when EQ magnitude is, at least, 5.5. So that, we impose the following criteria on the selection of EQs for our analysis.

1. EQ magnitude is greater than 6.0.
2. The epicenter of an EQ is located within the fifth Fresnel zone of each great-circle path (see Hayakawa et al. (1996) and Molchanov and Hayakawa (2008) for the details of Fresnel zone).
3. Depth is not considered.

The second condition seems to be of essential importance in obtaining significant effect on subionospheric VLF/LF propagation. As for the point (3), we want to study the effect of EQ depths on the propagation anomaly by changing the range of EQ depth. The EQs satisfied the above criteria are all indicated in Fig. 1 as a circle, and the color of each circle indicates its depth.

3 Analysis method of subionospheric VLF/LF propagation (amplitude) data

We follow our conventional way of analysis in VLF/LF data (Rozhnoi et al., 2004; Maekawa et al., 2006; Hayakawa, 2007; Molchanov and Hayakawa, 2008), and we show the analysis procedure briefly. In order to study short-term variations (such as EQ precursors), we want to remove the long-term (e.g., seasonal) variation from the data. We make the following residue in VLF/LF amplitude,

$$dA(t) = A(t) - <A(t)> \quad (1)$$

where $A(t)$ is the amplitude at a particular time (t) on one day and $<A(t)>$ is the average of the amplitudes at the same time, t, over ± 15 days around the relevant day. Then, we pay attention to the local nighttime (UT=11:00 a.m.–07:00 p.m.; LT=08:00 p.m. to 04:00 a.m.). Two physical parameters are dealt with as in Maekawa et al. (2006); (1) trend (or average amplitude at night) and (2) nighttime fluctuation (abbreviated as N.F.). As for (1) trend, we estimate the average (mean) value of the amplitude ($dA>0$ and $dA<0$) during the whole night (LT=08:00 p.m. to 04:00 a.m.). As for (2), we take only the dA (<0) because we know that a decrease in amplitude is likely to be the seismic effect, and then we integrate (dA^2) (only when $dA<0$) over the local night as defined above. This is the definition of nighttime fluctuation (N.F.). So that, we have one datum per day.

We are going to use different propagation paths, but the VLF/LF properties are seen to be different from one path to another. Hence, we adopt the standardization to the dA data; that is, both amplitude (trend) and nighttime fluctuation are standardized (or normalized) by means of the corresponding standard deviation (σ) for each path.

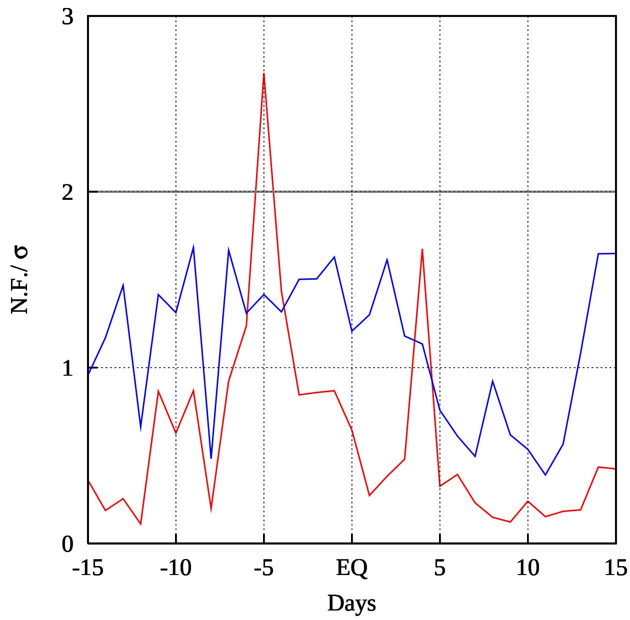

Fig. 3. The same as Fig. 2, but for the nighttime fluctuation (abbreviated as N.F.).

4 Analysis results based on superimposed epoch analysis

Then, we perform the superimposed epoch analysis, in which we superimpose the temporal evolutions of trend and nighttime fluctuation for all propagation paths with EQ day as zero. The results of superimposed epoch analysis for the trend (nighttime average amplitude) and nighttime fluctuation (N.F.) are presented in Figs. 2 and 3. In both figures, a red line refers to the case including only shallow (depth <30 km) EQs, while a blue line, corresponds to the case of EQs with any depths. The number 0 in the abscissa indicates EQ day, and – means days before an EQ and +, means the days after the EQ. The ordinate is always normalized by the corresponding standard deviations.

The number of events for the red lines in Figs. 2 and 3, is 12, while the number of events for the blue lines, 31. As is shown in Fig. 1, the total number of EQs is found to be 20. About one half of the EQs is shallow (depth < 30 km). When one EQ happened on two propagation paths, those events are treated as being independent in our analysis.

It is clear from Fig. 2 that the trend (or nighttime average amplitude) exhibits a definite depletion (decrease) about 5 days before the EQ (with including all depths), followed by a slow recovery after the EQ. However, it seems that the depletion in the trend becomes more prominent for shallow EQs with depth tentatively smaller than 30 km. While, the nighttime fluctuation (N.F.) in Fig. 3 is found to be very much dependent on EQ depth. That is, only when the EQ depth is smaller (shallow EQs), we have a very significant enhancement in the nighttime fluctuation, exceeding the 2σ criterion. Though it is advisable from the statistical point of view to adopt the criterion of 3σ. On the other hand, it seems that the nighttime fluctuation for the case of EQs with all depths is relatively enhanced before the EQ and even a few days after the EQ. In both Figs. 2 and 3 a sharp increase 5 days before the EQ is probably due to the smaller number of data set, so that we can conclude that both the trend and nighttime fluctuation would show remarkable changes several days before the EQ.

5 Conclusions

The superimposed epoch analysis based on the 4 years data, has indicated a statistically significant correlation between the lower ionospheric perturbations as detected by subionospheric VLF/LF propagation and EQs with magnitude greater than 6.0. We think that the results obtained in this paper (Figs. 2 and 3) would lend further support to our previous conclusions by Rozhnoi et al. (2004) and Maekawa et al. (2006). That is, it may be concluded from the statistical sense that the lower ionosphere is definitely disturbed due to seismic effects just around the EQ (but mainly before the EQ).

Then, though the number of events analyzed is not so large in this paper, it is seems that the EQ depth plays an important role in the generation of lower ionospheric perturbations. This has given support to our previous result by Molchanov and Hayakawa (1998), in which deep (depth >100 km) EQs had no effects onto the ionosphere. Shallow EQs seem to be much more likely in exciting the perturbation in the lower ionosphere. A few hypotheses (electric field effect, atmospheric oscillations, electromagnetic waves) have been proposed as a candidate for the lithosphere-ionosphere coupling (Hayakawa, 2007; Molchanov and Hayakawa, 2008), but it seems likely from our different data that the atmospheric gravity waves (AGWs) might be most promising (e.g., Molchanov et al., 2001) in this coupling system. Then it is not difficult for us to imagine that AGWs are excited very easily by shallow EQs.

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