A statistical study on the AGW modulations in subionospheric VLF/LF propagation data and consideration of the generation mechanism of seismo-ionospheric perturbations

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Abstract Though there have been published several papers suggesting the important role of atmospheric gravity waves (AGWs) in the generation mechanism of seismo-ionospheric perturbations, there have been no reports on the statistical study on the AGW effect in subionospheric VLF/LF data. Based on the data over nine years and for many propagation paths in and around Japan, this paper presents the first statistical result on the role of AGW. The conclusion by means of superimposed epoch analysis is that the AGW modulation (fluctuation) is rather enhanced about 10 days only for shallow (depth < 40km) earthquakes, but its significance level is just close to the conventional 2\(\sigma\) (\(\sigma\): standard deviation) level. So that, we can conceive that the AGW channel is the most dominant hypothesis for seismo-ionospheric perturbations, but an alternative channel such as chemical (+ electric field) channel is also operative either simultaneously for an EQ or may be dominant for a small number of earthquakes.

Keywords: VLF/LF subionospheric propagation, earthquakes, seismo-ionospheric perturbation, AGW modulation

1. Introduction

It is recently agreed that electromagnetic effects take place in possible association with an earthquake (EQ) (or mainly prior to an EQ) (e.g., Hayakawa and Molchanov (Ed.), 2002; Molchanov and Hayakawa, 2008 and Hayakawa (Ed.), 2009). In particular, the ionosphere is found to be very sensitive to EQs, which has been detected by means
of subionospheric VLF/LF propagation (Gokhberg et al., 1989; Gufeld et al., 1992; Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Hayakawa, 2007, 2009). The seismo-ionospheric perturbation is detected by the following two methods; (1) terminator time method (the terminator time is defined by the time when the amplitude (or phase) shows a minimum just around sunrise and sunset), or (2) nighttime fluctuation method in which we analyze (i) average nighttime amplitude, (ii) nighttime amplitude dispersion, and (iii) nighttime fluctuation. The presence or appearance of seismo-ionospheric perturbations is found by means of significant shifts in terminator times (either morning or evening) (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998) or significant changes of nighttime amplitude data such as the significant decrease in average nighttime amplitude and significant increases in dispersion and nighttime fluctuation (Shvets et al., 2002, 2004; Rozhnoi et al., 2004; Maekawa et al., 2006; Kasahara et al., 2008, 2010; Hayakawa et al., 2010).

After we have confirmed that the lower ionosphere is perturbed prior to an EQ when the EQ magnitude is strong enough (at least greater than 5.5) and EQ depth should be smaller (e.g. less than 40km), the next problem will be the generation mechanism of such seismo-ionospheric perturbations. A few hypotheses have been proposed (e.g., Molchanov and Hayakawa, 2008; Hayakawa (Ed.), 2009), but the following two are considered to be plausible at the moment. The first is called “chemical (+ electric field) channel”, and the second is “acoustic (AW) and atmospheric gravity wave (AGW) channel”. The first channel is such that radon emanation leads to the change in atmospheric conductivity, then to the change in atmospheric electric field and finally to the re-distribution of ionospheric density (Pulinets et al., 1997). Or, the direct generation of positive hole carriers in the laboratory loading experiment might be an alternative (Freund, 2009). In the second mechanism, atmospheric oscillations (such as AW and AGW) play an essential role in the lithosphere-ionosphere coupling. There have been accumulated a substantial number of facts in favor of this mechanism (though indirect), including the enhancement of AGW modulation in VLF/LF data before an EQ (Molchanov et al., 2001; Miyaki et al., 2002; Shvets et al., 2002, 2004; Rozhnoi et al., 2004, 2007; Muto et al., 2009).

So the purpose of this paper is to attempt a further statistical study on the importance of AGW modulation in subionospheric VLF/LF propagation data, because the above previous works were mainly based on the event studies or statistics during a short period. Here we present the statistical result during a much longer period and much more propagation paths than before.
2. EQs treated and VLF/LF propagation paths used in this paper

As is already described in Hayakawa (2004) and Hayakawa et al. (2004), we have established a Japanese and Pacific VLF/LF network which consists of several observing stations in and around Japan including Moshiri (abbreviated as MSR) in Hokkaido, Tateyama (Chiba)(TYM), Kochi(KCH) in Kochi prefecture, etc., and Kamchatka (KCK) in Russia. These stations are indicated in Fig. 1 as red stars. At each observation station, we observe simultaneously the signals from several VLF/LF transmitters including two Japanese transmitters (with call signs of JJY (40kHz, in Fukushima prefecture) and JJI (22.2kHz, in Miyazaki prefecture)) and a few foreign transmitters, NWC (19.8kHz, Australia), NPM (21.4kHz, Hawaii), NLK (24.8kHz, USA). The Japanese two transmitter of JJY and JJI are shown by blue diamonds in Fig. 1.

The period of data analysis is January, 2001 through December, 2009, so that the data length is a total of nine years. After the careful examination of all of the data, we have chosen the following propagation paths,

Fig. 1  Relative locations of VLF/LF transmitters and receiving stations. Two Japanese transmitters are indicated by blue diamonds (JJY and JJI), and our receiving stations are indicated by red stars (KCH (Kochi), TYM (Tateyama), MSR (Moshiri) and KCK (Kamchatka, Russia)). For each propagation path the wave sensitive area is plotted as defined by the fifth Fresnel zone (elliptic area). Finally, an EQ treated is indicated with its epicenter and depth (in color).
(1) JJY – KCH
(2) JJY – MSR
(3) JJY – KCK
(4) JJI – TYM
(5) JJI – MSR
(6) JJI – KCK

for which the data were found to be of sufficient quality for further statistical study. Fig 1 illustrates the relevant propagation paths as mentioned above and their corresponding wave sensitive areas (each defined by 5th Fresnel zone (elliptical area)). EQs with magnitude greater than 6.0, taken place within the relevant wave sensitive area are plotted in Fig 1 as a reference (we can understand the epicenter of an EQ and its depth is given in color).

It is easy for us to anticipate that AGWs are excited on the land, so that we focus on EQs taking place on the land (land EQs). Table 1 is the summary of EQ events analyzed in this paper for two different EQ depths (shallower than 40km and deeper than 40km). As the total, approximately 50 EQ events are subjected to the following superimposed epoch analyses.

<table>
<thead>
<tr>
<th></th>
<th>&lt;40km</th>
<th>&gt;40km</th>
</tr>
</thead>
<tbody>
<tr>
<td>JJY-KCH</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>JJY-MSR</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>JJY-KCK</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>JJI-TYM</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>JJI-MSR</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>JJI-KCK</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>54</strong></td>
<td><strong>45</strong></td>
</tr>
</tbody>
</table>

3. AGW modulation index and analysis results

Ionospheric perturbations have been investigated so far in terms of the following three physical parameters of amplitude in subionospheric VLF/LF data as in our previous papers (Shvets et al., 2002, 2004; Rozhnoi et al., 2004; Maekawa et al., 2006; Kasahara
et al., 2008; Hayakawa, 2009).

1. Average nighttime amplitude (called here trend)
2. Nighttime dispersion
3. Nighttime fluctuation

The detailed definitions of these parameters are found in Kasahara et al. (2010) and Hayakawa et al. (2010).

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Fig. 2  Analysis method of AGW modulation index. Top panel illustrates an example of the diurnal variation of dA(t). The bottom panel indicates the fluctuation spectrum S(f) obtained by FFT analysis for the above dA(t), and <S(f)> is the running average over ±15 days around the current day. Then, we estimate a difference dS(f)=S(f)-<S(f)>, and we focus on the parts of dS(f)>0. The range of AGW is indicated by two limiting values (T=10-100m).

Recently Muto et al. (2009) have suggested one more parameter which is called AGW modulation index. An example of estimating the modulation spectrum dS(f) is given in Fig. 2. Top panel indicates the diurnal variation of dA(t) (=A(t)-<A(t)>, where A(t) (in red) is the amplitude at a time t on a particular day, and <A(t)> (in blue) is the mean amplitude averaged over ±15 days around the current day. The nighttime part of dA(t) is subjected to FFT analysis to obtain the fluctuation spectrum S(f) (in red). <S(f)> (in blue) is the mean value of S(f) averaged again over ±15 days around the current day,
and then we estimate $dS(f) = S(f) - \langle S(f) \rangle$ (in black bars in the bottom panel). The range of AGW is indicated by two limiting values ($T$ (period) $= 10\text{min} \sim 100\text{min}$ as vertical red lines) and we pay attention only to the parts of $dS(f) > 0$ because we expect the enhancement in the spectra in the AGW range. Then we impose the standardization to the data for different propagation paths (i.e., normalization by means of the standard deviation for each path). Though the variability of VLF/LF propagation characteristics may be different from one path to another, we want to deal with different paths uniformly by means of this standardization.

As a statistical analysis method, we use the same superimposed epoch analysis as is used before in Rozhnoi et al. (2004), Mackawa et al. (2006) and Kasahara et al. (2008). In this method we stack the data with EQ day as the reference day, so that we can increase the S/N ratio in finding out any effect associated with an EQ. The superimposed epoch analysis on the AGW modulation, is presented in Fig.3, in which the red line refers to shallow (depth $\leq 40\text{km}$) EQs and blue line to deep (depth $> 40\text{km}$) EQs. The EQ on the abscissa day is the reference day of zero, and minus ($-\text{)}$ on the abscissa means that the phenomenon takes place prior to an EQ, while plus ($+\text{)}$), after the EQ. The ordinate in Fig. 3 is AGW modulation index normalized by the standard deviation.

A glance at Fig.3 indicates that the AGW index for deep EQs (in blue) remains just around zero during the whole period from -30 to 30 days of the EQ, which means that there is no activated effect in AGW modulation in the lower ionosphere in the case of deep EQs. On the other hand, the corresponding result for shallow (depth $\leq 40\text{km}$) EQs is found to be completely different from that for deep EQs when we look at the red curve in Fig.3. Undoubtedly, we can recognize a very significant activation of AGW fluctuation 12 days before the EQ. Though the significance level of this enhancement does not exceed the conventional $2\sigma$ criterion, it amounts notably to about $1.5\sigma$ level.

4. Discussion

The AGW modulation in VLF/LF subionospheric VLF/LF propagation data has been studied extensively in this paper in a statistical sense. The data during a long-enough period of nine years and also for many propagation paths have been utilized in this paper. As the result of statistical analysis of AGW modulation, we have confirmed that the activation in AGW fluctuation (or modulation) is observed prior to an EQ (about 10 days before the EQ) only for shallow EQs with depth less than 40km. But, the significance level of this precursory enhancement in AGW modulation is not exceeding $2\sigma$ level, but is notable on the order of $1.5\sigma$. Then completely no effect is seen for the
AGW modulation for deep EQs.

Here we compare this statistical result with our former works (Shvets et al., 2002, 2004; Rozhnoi et al., 2004, 2007; Muto et al., 2009; Kasahara et al., 2008). These previous works have indicated the important role of AGWs in the mechanism of seismo-ionospheric perturbations. But these papers are based on the study during relatively short periods, which have presented examples of AGW activation. Of course, a much more distinct evidence on the presence of AGW has been obtained by Horie et al. (2007) for a particular event of Sumatra EQ, but this is only one example. In this sense, the present paper has provided the first statistical treatment of AGW effects in VLF/LF propagation.

By using the above statistical result on the AGW modulation in subionospheric VLF/LF propagation data, we discuss here the generation mechanism of seismo-ionospheric perturbations. As is mentioned in Introduction, there are two plausible hypotheses; (1) chemical (+ electric field) channel and (2) atmospheric oscillation channel, but which of these mechanisms is more relevant, is quite unclear.

Fig. 3 Superimposed epoch analysis for the AGW modulation index. The abscissa indicates the day (with zero as EQ day), in which minus (−) means prior to an EQ and plus (+), after the EQ. The ordinate indicates the AGW modulation index normalized by its standard deviation. Red line refers to EQs with d ≤ 40km, while blue, deep (d > 40km) EQs.
Though as compared with the 1st hypothesis, we think that there exist a substantial number of evidences in favor of the 2nd channel. The first statistical study of AGW effect in this paper opens a window of opportunity to think of the relative importance of the 1st and 2nd channels. The activation in AGW modulation is recognized only for shallow EQs, but the significance level is not so high. Finally we may conclude that the 2nd channel based on the atmospheric oscillations seems to be dominant, but when thinking of the not so much significant correlation, we might suggest that any other possibility like 1st channel can also be involved in the generation of seismo-ionospheric perturbations. In other words, a large number of shallow EQs accompany ionospheric perturbations by means of AGW effect in the 2nd channel, but it might be considered that the 1st channel is also simultaneously working as a minor effect for an EQ or it is effectively working dominantly for a small number of EQs.

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