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Seismo-ionospheric perturbations as observed by subionospheric VLF/LF propagation, and their generation hypothesis in terms of atmospheric gravity waves

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Abstract

The long-term observation of subionospheric VLF/LF signals has yielded that lower-ionospheric perturbations do appear prior to an earthquake (EQ), and it is believed that this VLF/LF method is the most established tool for short-term EQ prediction. However, the mechanism why and how those perturbations are generated in the lower ionosphere before an EQ, is not well understood. The purpose of this paper is to review clear signatures of seismo-ionospheric perturbations for some case studies including the 1995 Kobe EQ and the recent major 2011 Tohoku EQ. Then we review a statistical correlation between such VLF/LF perturbations and EQs. Finally, we have proposed a hypothesis of atmospheric gravity waves (AGWs) as the most promising mechanism for seismogenic ionospheric perturbations, with special reference to a lot of experimental evidence in favour of this AGW hypothesis.

1. Introduction

The recent sequence of highly destructive earthquakes (hereafter EQs) around the world, including the latest 2011 Tohoku EQ, has heightened awareness of EQs, and the inability of seismology as a discipline to derive information of increasing EQ hazards in the weeks and days before major seismic events. In order to mitigate the EQ disaster, especially human lives, it would be immensely meaningful to forecast the approach of a large EQ on a time-scale of days and weeks (this is called “short-term” EQ prediction) [e.g., Hayakawa, 2015]. The situation for this short-term EQ prediction seems to have been drastically changed in Japan during the last two decades since the Kobe EQ in 1995, because the conventional EQ prediction based on the measurement of crustal movements (so-called medium-term

EQ prediction), has been found to be not so useful for short-term EQ prediction. During the last two decades new waves of the measurements on electromagnetic effects in relation to EQ , have accumulated a substantial number of evidence that electromagnetic phenomena do take place prior to an EQ [e.g., Hayakawa and Molchanov (Eds), 2002; Pulinets and Boyarchuk, 2004; Molchanov and Hayakawa, 2008, Hayakawa (Ed), 1999, 2009a, 2012, 2013]. This is the reason why the electromagnetic effects attract a lot of attention of scientists as a promising candidate of short-term EQ prediction.

The electromagnetic method for EQ prediction can principally be classified into two categories: the first is the detection of radio emissions from the EQ hypocenter (or epicenter), and the second is to detect indirect effects of EQs taking place in the atmosphere and ionosphere by means of the pre-existing radio transmitters (we call it "radio sounding").

This paper deals with our method of VLF (3-30 kHz)/LF (30-300 kHz) sounding of seismo-ionospheric perturbations belonging to the second category. In our separate paper [Hayakawa et al., 2016] we have discussed various physical agents of the ionospheric perturbations because the lower ionosphere is sensitive to different physical parameters (not only from above (geomagnetic activity, solar effects, etc.), but also from below (meteorological phenomena)), and in this paper we pay particular attention to the perturbations in possible associations with EQs. Many specific EQs have been treated [Hayakawa, 2015], but we present the results for the 1995 Kobe EQ and the recent 2011 Tohoku EQ. Then, we review a statistical correlation between those ionospheric perturbations and EQs on the basis of our long-term observation. Finally, we present the mechanism of how the ionosphere is perturbed prior to an EQ, with special reference to a hypothesis of atmospheric gravity waves (AGWs).

2. VLF/LF sounding of the lower ionospheric perturbations

A number of nations currently operate large VLF/LF transmitters primarily for navigation, radio watches and communication with military submarines. To radiate electromagnetic waves efficiently at these lower frequencies, one needs an antenna with dimension on the order of a wavelength of the radiation, which suggests that VLF/LF transmitter antennas must be very large, typically many hundreds of meters high [Watt, 1967; Hayakawa, 2015].

Our method of VLF/LF sounding is a well-known radiophysical technique [Hayakawa, 2007, 2009b;Rozhnoi et al., 2013], in which the amplitude and phase of radio signals from navigational transmitters propagating inside the Earth-ionosphere waveguide are monitored. If the transmitter frequency and receiver distance are fixed, then the observed VLF signal parameters are mainly determined by the position of the reflection height which depends on the value and gradients of electron density near the atmosphere-ionosphere boundary. It is typically 80-85 km in daytime and is about 90 km in nighttime. These altitudes are too far for balloons and too low for satellites, making in-situ measurements extremely rare. The only possible means for probing this D/E region is VLF/LF subionospheric radio signals. The region of D/E layer is very sensitive to any kind of agents, not only from above but also from below, and also as the most important advantage of our VLF/LF method the dynamic range of lower ionospheric density change is extremely large as compared with that in the upper F region.

We here briefly mention the effects other than EQ effects. The well-known effect from the upper is solar-terrestrial effects. So, the VLF method has become a standard for recording short-time electron density variations in the lower ionosphere and upper atmosphere connected with solar flares (e.g. Roentgen flares), cosmic rays (Forbush effect), magnetic storms [Belrose and Thomas, 1968; Potemra and Rosenberg, 1973; Kikuchi, 1981; Sauer et al., 1987], and precipitation of energetic particles due to the wave (whistler)-particle interaction in the magnetosphere [Inan et al., 1985; Dowden and Adams, 1988].

The effects from below can be (i) nuclear test, and (ii) lightning-induced ionization (and /or heating) [e.g., Nickolaenko and Hayakawa, 1995; Craig and McCormik, 2006] and (iii) meteorological effects [Rozhnoi et al., 2006; Hayakawa et al., 2016]. The ionospheric perturbation due to a lightning discharge is very short-lived, just as the solar flare, precipitation effect of energetic particles from the magnetosphere. So these effects are not our interest, because these short-lived effects are not a serious interference in detecting seismo-ionospheric perturbations. Hayakawa et al., [2016] have discussed the meteorological effects such as typhoons as the more long-lasting ionospheric perturbations.

3. VLF/LF anomalies in association with EQs

The first suggestion to use this VLF/LF method in EQ research was made by Russian scientists about 20 years ago [Gokhberg et al., 1989; Gufeld et al., 1992]. Nighttime ‘‘baylike’’anomaly of the phase and amplitude from “Omega” VLF signals were detected before a number of strong EQs in the 3rd Fresnel zone for the long wave paths. Another data processing method (so-called terminator time (TT) method) was developed in Japan during an analysis of the famous 1995 Kobe EQ (M=7.1; January 17, 1995) [Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Hayakawa, 2007], which will be described in detail in the following section.

3.1 VLF ionospheric perturbation for the 1995 Kobe EQ and further results for a longer term

The most convincing evidence on the seismo-ionospheric perturbations with VLF sounding was obtained by Hayakawa et al. [1996] for the famous Kobe EQ on 17 January, 1995. Some important peculiarities in their paper are summarized as follows: (1) the propagation distance from the VLF Omega transmitter at Tsushima (geographic coordinates 34.37°N, 129.27°E) to Inubo observatory (35.42°N, 140.52°E) is relatively short (~1 Mm (1000 km) at VLF, as compared with 5-9 Mm used in previous Russian papers [Gokhberg et al., 1989; Gufeld et al., 1992], and (2) they found that the nighttime fluctuation method as used before, was not so effective for the short-propagation path, so they developed another way of analysis, so-called the terminator time (TT) method. The TT is defined as the time when the diurnal amplitude (or phase) variation exhibits a minimum around sunrise and sunset (which we call morning (t_m) and evening (t_e) TTs). We found a significant shift in TTs before the EQ; that is, t_m shifts to early hours and t_e to later hours. See the details on the Kobe results in Hayakawa et al. [1996], Molchanov et al. [1998], and Hayakawa [2007, 2009b].

A further extensive study by Molchanov and Hayakawa [1998] was based on the a large number of events during 13 years (11 events with magnitude greater than 6.0 and within the first Fresnel zone) for the same propagation path from the VLF Omega, Tsushima to Inubo, and they came to the following conclusion.

(1) As for shallow (depth smaller than 30 km) EQs, four EQs from five, exhibited the same TT anomaly as for the Kobe EQ with the same 2σ criterion.

(2) When the depth of EQs is in a medium range of 30-100 km, there were two types of anomaly events. One event exhibited the same TT anomaly as observed in Kobe EQ, while the other indicated an anomaly of different type .

(3) Deep (depth larger than 100 km) EQs (four events) did not accompany any anomaly. Two of them had an extremely large magnitude (greater than 7.0), but had no propagation anomaly.This summary might indicate a relatively high probability of the propagation anomaly (in the form of TT anomaly) on the order of 70%-80% for larger (magnitude greater than 6.0) and shallow EQs located relatively close to the great-circle path (e.g., first Fresnel zone).

Another important finding is that when we have such a TT propagation anomaly (ionospheric perturbations), a harmonic analysis on the data of the TTs exhibits an enhanced modulation with periodicities of 5 days or 9-11 days (these periods are those of planetary waves). This implies that atmospheric oscillations with those periodicities may play a significant role in the coupling from the lithosphere to the ionosphere. Recently we proposed AGWs (internal gravity waves) as the carrier because of their stronger tendency of upward propagation in the lithosphere-ionosphere coupling, with the planetary wave as the modulating signal [Hayakawa, 2009b]. Based on the study of fluctuation spectra of our observational data (on amplitude and phase), we found an enhanced occurrence of fluctuation power in the frequency range (10 min to 2 h) of AGWs, probably associated with EQs [Molchanov et al., 2001]. These findings may provide a fundamental basis for the study of lithosphere-atmosphere-ionosphere (LAI) coupling as will be discussed later.

Hayakawa et al., [1996] and Molchanov et al. , [1998] suggested to explain the change in the lower ionosphere by means of the full-wave theory of subionospheric VLF propagation over a short distance (~1Mm) for which there exist several modes of propagation (i.e. TT is the consequence of wave interference of the ground and those sky waves). On the basis of the comparison of theoretical estimations with the experimental data, we concluded that the lower ionosphere might have been lowered by a few kilometers. Here we present a comprehensive view on the importance of TT shift in the subionospheric VLF/LF diurnal variation and its use in inferring the lower ionospheric changes associated with EQs. Yoshida et al. [2008] made full use of another wave hop method (theory) to interpret the TT changes in terms of the wave interference between the ground and sky waves, and indicated how to estimate the change (normally decrease) in ionospheric height by means of the observed shift of TTs.

3.2 VLF ionospheric perturbations for the 2011 Tohoku EQ

The details of the VLF ionospheric perturbations for the recent massive 2011 Tohoku EQ, have already been published by Hayakawa et al. [2012a, 2013], so that we will describe only a few of important findings in this section.

An extremely huge EQ (with magnitude of 9.0) occurred under the sea bed in the Pacific Ocean off the Tohoku area of Japan. This EQ took place at 14:46:18 LT on March 11, 2011 with its epicenter at the geographic coordinates (36°6.2'N, 142°51.6'E) as shown in Figure 1 by a red star with its date and its depth of ~20 km. This EQ is a very typical oceanic EQ of the plate type around Japan, which is very different from the extensively-studied fault-type EQs such as the Kobe EQ [Hayakawa et al., 1996] and the Niigata-chuetsu EQ [Hayakawa et al., 2006].

We established our Japanese and Pacific network for subionospheric VLF/LF propagation just after the 1995 Kobe EQ within the framework of the former NASDA's frontier project [Hayakawa et al., 2004]. This network observation has been in continuous operation to date. The main observatories within Japan are (1) Moshiri (abbreviated as MSR) in Hokkaido, (2) Chofu (CHF) in Tokyo, (3) Kasugai (KSG) near Nagoya and, (4) Kochi (KCH) on Shikoku island, as shown by red stars in Figure 1. At each receiving station we normally detect simultaneously the signals from two Japanese transmitters with call signs of JJY (in Fukushima, 40 kHz) and JJI (in Miyazaki, Kyusyu, 22.2 kHz) as shown by diamonds and also a few foreign transmitters (i.e., NWC (North West Cape, Australia), NPM (Hawaii) and NLK (Seattle, USA)). The details of this UEC network and corresponding VLF receiving system can be found in Hayakawa et al. [2004, 2010] and Hayakawa [2009b].

This subionospheric VLF/LF network has been extended to cover a wider area of the Pacific ocean, including one station in Russia, Petropavlovsk-Kamchatsky (PTK) shown as a green dot in Figure 2 [Uyeda et al., 2002; Molchanov and Hayakawa, 2008]. Observations at PTK have been performed regularly resulting in significant scientific outputs [Rozhnoi et al., 2004, 2006, 2007, 2012a, b]. The Russian colleagues have recently established one more station, Yuzhno-Sakhalinsk (YSH shown as a green dot in Figure 2). These two stations are equipped with the same type of VLF/LF receiving system used at Japanese stations.

Figure 1 illustrates one path from JJY to MSR (and its corresponding 5th Fresnel zone as the wave sensitive area (elliptic zone)) and the three paths from NLK (Seattle, USA) to Japanese VLF/LF observatories (CHF, KSG and KCH). Furthermore, the 5th Fresnel zones for the propagation paths from NLK to CHF, KSG and KCH are plotted in thin black lines which are the wave sensitive areas for these paths and are much bigger than that for the path from JJY to MSR because of a much larger distance of NLK-CHF path than that for JJY-MSR path.

As for the analysis technique , we do not follow the TT method as initially developed for the Kobe EQ [Hayakawa et al., 1996], but apply an alternative way of "the nighttime fluctuation method" [Rozhnoi et al., 2004; Maekawa et al., 2006; Kasahara et al., 2008; Hayakawa et al., 2010]. We first read the temporal evolution of amplitude A(t) at a current time t during the local nighttime on a particular day, while $\langle A(t)\rangle$ is estimated as the average amplitude at the same time t during the period from one day to 30 days before the current day. Then, we can estimate the residue $dA(t) = A(t) - \langle A(t)\rangle$. Using this residue, we can estimate the most important parameter, "trend" as the nighttime average amplitude (mean value of dA(t) over local time). The second parameter is dispersion, which is characterized by how much the amplitude fluctuates around the average. These two parameters are independent variables.

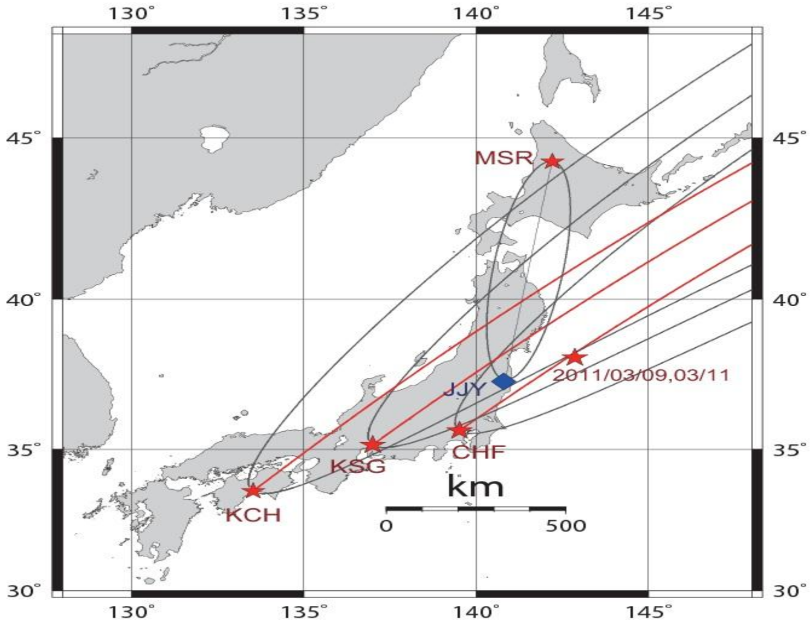

Figure 1**.** The relative locations of two Japanese VLF/LF transmitters (with call signs of JJY (Fukushima) and JJI (Miyazaki) indicated by blue diamonds) and VLF/LF receiving stations (Moshiri (MSR), Chofu (CHF), Kasugai (KSG) and Kochi (KCH) shown with red stars). The wave sensitive area defined by the Fresnel zone (elliptic zone) for the propagation path of JJY-MSR is plotted, and also that for the propagation path of NLK (Seattle, USA) - CHF is plotted. Further, the great-circle paths (in red thin lines) and the corresponding wave sensitive areas (in black thin lines) are indicated for the paths of NLK-KSG and NLK-KCH. The epicenter of the main shock is indicated with a red star with the corresponding dates.

All of these parameters are normalized by their corresponding standard deviations (σ) over the previous 30 days before the current day. Further details of this nighttime fluctuation method can be found in Rozhnoi et al. [2004], Kasahara et al. [2008] and Hayakawa et al. [2010].

As for the definition of nighttime period, we take the UT period of UT = 11 - 19 h for the propagation path from JJY to MSR because the LT in Japan = UT + 9 h. While the definition of nighttime is considerably complicated for the east-west long-distance propagation from NLK to Japanese stations (such as CHF) (distance = 7-8 Mm). By considering the sunrise and sunset both at the transmitter and receiving observatory (that is, terminator times [Hayakawa et al., 1996]) and also checking the real diurnal variations for the relevant NLK-CHF path, we have taken UT = 10 to 12 h for the nighttime for the NLK-CHF path (that is, only during this period the propagation path is completely in the dark).

Figure 2 illustrates the relative location of the Japanese VLF/LF transmitters (JJY in Fukushima and JJI in Miyazaki) and two Russian observatories, PTK and YSH. The wave sensitive areas for all combinations of transmitter-receiver, are also shown (i.e., JJY-YSH, JJY-PTK, JJI-YSH, and JJI-PTK), together with the locations of the main shock and aftershocks.

Next we have to discuss the nighttime interval for the Russian data because we use the same nighttime fluctuation method. The night in February is UT = 10:30-18:40 and UT = 11:00-16:30 for May. Correspondingly, the nighttime for March and April is within this interval; UT = 10:30-11:00 for sunset and 16:30-18:40 for sunrise. The data analysis for Russian data is exactly the same as the data analysis for Japanese data as mentioned above. The analysis period is taken from January 1 to May 22, 2011, including our target EQ on March 11.

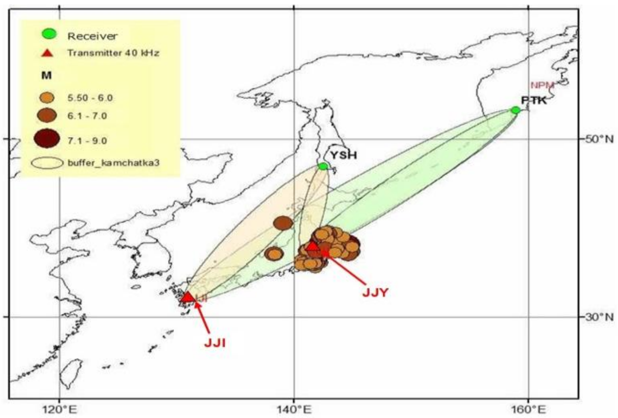

Figure 2. Relative locations of the two Japanese VLF/LF transmitters (JJY and JJI in triangles) and two observing stations (Petropavlovsk-Kamchatsky (PTK) and Yuzhno- Sakhalinsk (YSH) as small green dots). The wave sensitive areas (elliptic zones) for the propagation paths of JJY-YSH, JJY-PTK, JJI-YSH and JJI-PTK are plotted. Further, the main shocks and aftershocks are plotted, with their sizes being proportional to EQ magnitude.

Unlike the 2005 Miyagi-oki EQ [Muto et al., 2009a], the epicenter of this 3.11 EQ was found to be located considerably distant from the JJY-MSR path wave sensitive area, because this EQ occurred ~150 km away from the coast line of the Tohoku area [Hayakawa et al., 2012a]. Though not shown as a figure in this paper, we have found in our latest paper [Hayakawa et al., 2012a] based on our preliminary analysis that there is definitely no time interval from March 1 to March 9 before the EQ on the JJY-MSR path in which the trend shows a notable decrease together with the simultaneous increases in the dispersion as in the case of a tremendous number of land EQs.

Next we analyzed the propagation paths of JJY-YSH and JJI-YSH. The path of JJY-YSH is relatively close to the previous path of JJY-MSR as seen in Figure 4 because the JJY-YSH path is likely to be just an extension of the JJY-MSR path. We have analyzed the paths of JJY-YSH and JJI-YSH, but we have not found any definite significant effects (no propagation anomalies) on these paths, though not presented as figures.

Figure 3 suggests that the propagation paths from Japanese receiving stations (CHF, KSG,and

KCH) to the American transmitter NLK (at Seattle, USA) are favorably located with respect to the epicenter of this oceanic EQ and is especially so for the NLK-CHF path passing just above the EQ epicenter; the corresponding wave sensitive area for this NLK-CHF path is plotted in a thin line in Figure 1. Two other propagation paths from NLK to KSG and from NLK to KCH are also favorable for us to detect any corresponding ionospheric perturbations. In response to these theoretical expectations, Figure 3 illustrates the real temporal evolutions of propagation characteristics only for the NLK-CHF path (the most noticeable path). In the figure we have illustrated, from top to the bottom, the trend and dispersion, with these parameters being all normalized by their corresponding standard deviations (σ). We have found from this figure that the trend does not drop down to a -2σ level over the entire period, except on January 29 and an extremely significant propagation anomaly on the two days of March 5 and 6. The propagation anomaly on March 5 is characterized by a remarkable decrease in trend (exceeding -3σ or even approaching -4σ), together with the nearly simultaneous (though not on the same days) increases in the second parameter (dispersion) (approaching +2σ). The corresponding anomaly is also recognized for other paths of NLK-KSG and NLK-KCH.

Here, we try to associate other depletions in trends in Figure 3 to EQs in the relevant region. First, we comment on the anomaly of January 29 in Figure 3. Probably , in possible association with this anomaly, two EQs have occurred off the coast of Iwate (on February 3) and Fukushima (on February 10, M=5.3).

Among the three Russian propagation paths, we have found a conspicuous effect only on the propagation path from JJI to PTK (Kamchatka). Figure 4 illustrates the temporal evolution of the nighttime average amplitude (trend) (top panel). The second panel refers to the the conventional dispersion and the bottom indicates the evolution of the EQs with magnitude greater than 5.5. In the top panel, horizontal dotted lines indicate the 2σ and -2σ levels. In the middle panel of dispersion, the +2σ line is again plotted as a horizontal dotted line. Figure 4 shows that a significant and prolonged decrease in nighttime amplitude takes place during a rather long period from February 28 to March 6 on the path from JJI to PTK with a maximum depletion on March 3 and 4. The corresponding increases in dispersion are simultaneously observed during the same prolonged period with the maximum on March 3 and 4. The dates with VLF/LF propagation anomaly on the Russian path are shifted somewhat compared with that for the NLK-CHF path in Figure 3, but the anomaly on this propagation path is considered to be the same one for the previous propagation path of NLK-CHF because we know that there exists some inhomogeneity in the time and space of the ionospheric perturbation [Yamauchi et al.,

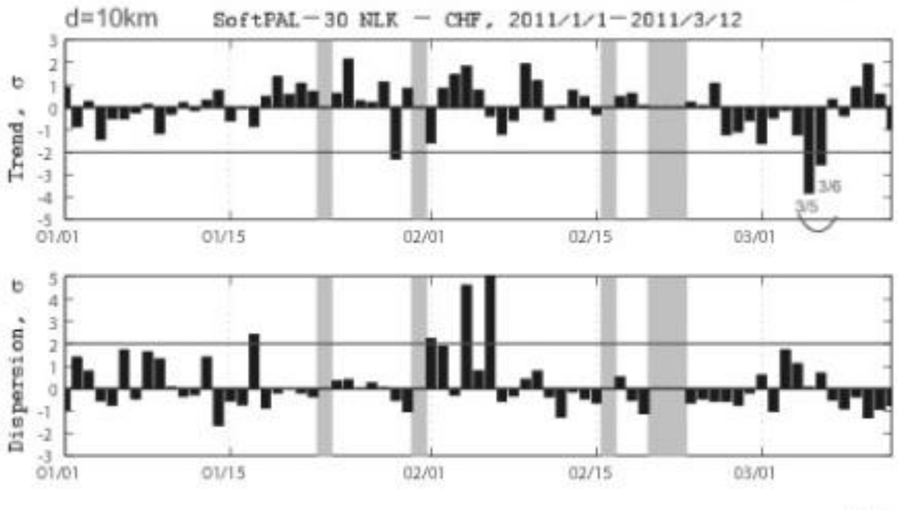

Figure 3. Temporal evolutions of the propagation characteristics for the NLK-CHF path. In the figure, the top panel refers to the average nighttime amplitude (called trend), and the bottom, to the dispersion. All of these values are normalized by their corresponding standard deviations (σ). A clear anomaly is seen on March 5 and 6. After Hayakawa et al. [2013].

2007]. Finally,we comment on the last Russian path, JJY-PTK. The wave sensitive area for this propagation path is seen from Figure 2 to be completely within the wave sensitive area of the above-mentioned JJI-PTK path with significant anomalies. Though not shown as a figure, it is found that the trend shows a significant decrease on March 4, but not exceeding -2σ, but approximately -1.5σ. Finally, an anomaly is observed for this path as well on March 4, but this nature is indicative of highly heterogeneous property of the ionospheric perturbation.

By making full use of the Japanese-Russian subionospheric VLF/LF network, the following observational facts have emerged in possible relation to the March 11, 2011 3.11 Japan EQ :

(1) No definite anomaly has been detected for the three propagation paths of JJY-MSR, JJY-YSH and JJI-YSH.

(2) On the other hand, clear and significant propagation anomalies have been observed for the two propagation paths of the NLK-Japanese stations (CHF, KSG and KCH) and JJI-PTK. The propagation anomaly for the path NLK-CHF takes place on March 5 and 6, which is characterized by a significant decrease in trend (nighttime average amplitude) well exceeding the -3σ level, together with the simultaneous increases in dispersion. While, the anomaly on the path of JJI-PTK shows a broad depletion from February 28 to March 6, with maximum depletions on on March 3 and 4, which is also characterized by a significant decrease in tend and an increase in dispersion. A small difference in dates of maximum perturbation for Japanese and Russian data, might be related with the adoption of different

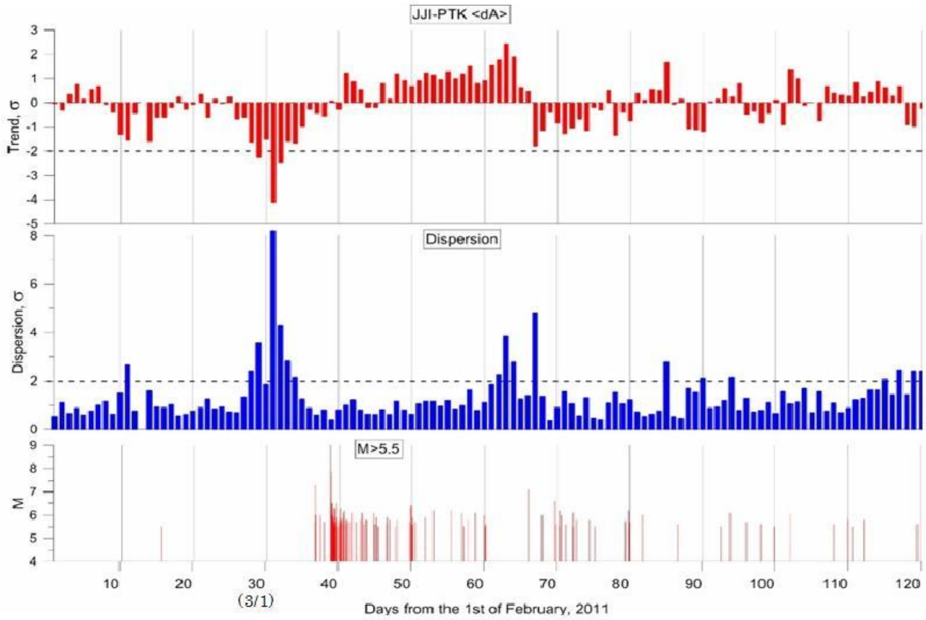

Figure 4. Temporal evolution of the propagation characteristics for the propagation path of JJI-PTK. The top panel refers to the average nighttime amplitude (corresponding to the trend in Figure 3) (horizontal broken line indicates -2σ level), and the middle panel, the dispersion (horizontal broken line, +2σ level). Again, both parameters are normalized by their standard deviations (σ). The bottom panel indicates the temporal evolution of the seismic activity.

LT intervals. So, the remarkable ionospheric perturbation is likely to be persistent, at least, for 4 days (March 3-6).

Finally, as already shown in subsection 3.1, the effect of geomagnetic activity which might influence the ionospheric perturbation because there happened a small geomagnetic storm on 1 March. So the effect of this storm has been discussed in Hayakawa et al. [2013].

3.3 Statistical correlation of VLF ionospheric perturbations with EQs

A statistical study on the correlation of VLF ionospheric perturbations with EQs has been presented by Hayakawa et al. [2010] based on the long-term observations in Japan and Kamchatka, and we review the essential points of Hayakawa et al. [2010]. We have used the data over total seven years from January 1, 2001 to December 31, 2007. Based on the previous statistical studies [Rozhnoi et al., 2004; Maekawa et al., 2006; Kasahara et al., 2008], the magnitude of 5.5 is found to be just at the border to obtain any significant correlation with 2σ criterion between the VLF/LF propagation anomalies and EQs, so that we choose the magnitude of 6.0 here as a rather severe criterion of selecting EQs. By imposing this condition, we have found 37 EQs taking place within the wave sensitive areas defined by the fifth

Fresnel zones of the great-circle paths of different propagation paths. For our analysis we divide the EQ depth into two regions: shallower or deeper than 40 km in order to find the dependence on EQ depth. 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 homogeneously treat the VLF/LF data when we analyze different propagation paths. We have proposed so-called "standardization" in the following way. That is, when taking one particular path, we deal with two physical quantities of average nighttime amplitude (trend) and *D* (dispersion) and we estimate the following normalized trend (trend*), and normalized *D* (*D**). When taking an EQ with a particular date, we estimate the trend on this day and then calculate the average <trend> over ±15 days around this date. Then, the normalized trend (trend*) is defined as (trend-<trend>)/σ_T (σ_T is standard deviation over ±15 days around the current date). The same principle is applied to the dispersion in order to obtain the normalized *D* (*D**).

By using these normalized (or standardized) trend and *D*, we make full use of a superimposed epoch analysis [e.g., Rozhnoi et al., 2004; Maekawa et al., 2006], which is of extreme importance in enhancing the signal to noise ratio by stacking the data around the EQ day as a reference day. Although we have chosen EQs with magnitude greater than 6.0, we pay more attention to the effect of EQ depth here because this point is poorly studied even though Maekawa et al. [2006] have suggested this point qualitatively.

Figures 5a and 5b are the final results on the trend* and *D** on the basis of superimposed epoch analysis. We can deduce from these figures the following summary :

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

(2) Next the nighttime dispersion (*D**) for EQ depths smaller than 40 km (in red) in Figure 5b is found to exhibit a significant increase three 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 40 km (in blue line in Figure 5b), there is no clear precursory effort before such a deep EQ.

Then we describe some other possible interference effects on VLF/LF perturbations as mentioned in subsection 3.1, and the most confounded effect might be geomagnetic storms. When obtaining Figure 5 we have paid no attention to the geomagnetic activity at all. The geomagnetic effect was extensively discussed in Hayakawa et al. [2010], so that we do not repeat it here. Finally it is reasonable to think that all of the ionospheric perturbations in Figure 5 are the consequence of EQs.

4. Discussions on the generation mechanism of seismo-ionospheric perturbations

As is extensively confirmed by means of case and statistical studies and the study on the modulation effects etc., it seems highly likely that the ionosphere is disturbed before an EQ. But it is poorly understood how the ionosphere is perturbed by the precursory seismic activity in the lithosphere. Hayakawa et al. [2004] , have already proposed a few possible hypotheses on the mechanism of coupling between the lithospheric activity and ionosphere: (1) chemical channel, (2) atmospheric oscillation (or acoustic) channel, and (3) electromagnetic channel. Figure 6 illustrates the schematic diagram of these three coupling mechanisms [Hayakawa et al., 2004]. As for the first channel, radon emanation induces the perturbation in the conductivity of the atmosphere, the change in the atmospheric electric field, then leading to the ionospheric modification through the atmospheric electric field [e.g., Pulinets and Boyarchuk, 2004; Sorokin et al., 2006].

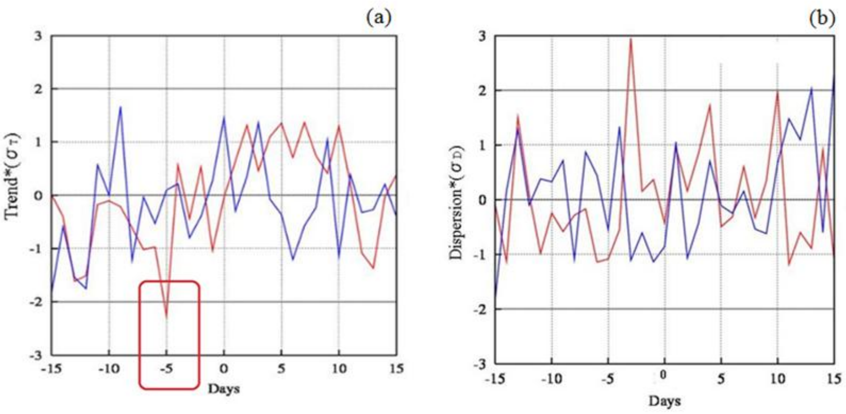

Figure 5. Superimposed epoch analysis for the normalized trend (trend*) (a), and the normalized dispersion (D) (dispersion*) (b). The red line refers to shallow EQs (depth<40 km), and the blue line refers to EQs with depth larger than 40 km. The abscissa indicates the day with respect to the EQ day (0), that is —(minus) means the day before the EQ and + (plus), the day after the EQ. After *Hayakawa et al*. [2010].

The second channel is based on the key role of atmospheric oscillations (AW (acoustic wave) or AGW (atmospheric gravity wave or internal gravity wave)) in the LAI coupling, and the perturbation in the Earth's surface (such as the injection of charged aerosols or radons into the atmosphere, changes of temperature, pressure etc.) in a seismo-active region excites the atmospheric oscillations traveling up to the ionosphere and inducing the ionospheric density perturbations in the dynamo region [Molchanov et al., 2001; Miyaki et al., 2002; Shvets et al., 2004; Korepanov et al., 2009]. The last mechanism of electromagnetic channel is that the radio emissions (in any frequency range) generated in the lithosphere propagate up to the ionosphere, and modify the ionosphere thereby heating and/or ionization. But this mechanism is found to be insufficient because of the weak intensity of lithospheric radio emissions [Molcchanov et al., 1993]. So, the 1st and 2nd mechanisms are likely plausible candidates for this coupling at the moment [Molchanov and Hayakawa, 2008]. Pulinets and Boyarchuk [2004] insisted the chemical channel as the most promising candidate for the ionospheric perturbations associated with EQs. That is, the emanation of radon is suggested as an important main player of seismo-ionospheric perturbation [Pulinets and Ouzounov, 2011], but there seems to be very few experimental (observational) evidence in support of their hypothesis. Of course, we know that there have been reports on the radon emanation itself [e.g., Molchanov and Hayakawa, 2008] as a precursor to an EQ. However, it is poorly understood whether the radon emanation might result in the ionospheric perturbation..If so, how it is realized, is not well understood. However, there have been very few papers on the correlation between the Earth's surface information (such as surface latent heat flux) and ionospheric perturbation as seen from VLF/LF subionospheric perturbation [Cervone et al., 2006]. This channel has recently been criticized by Sorokin and Hayakawa [2013] and Sorokin et al. [2015], who have further suggested an alternative mechanism based on the electromotive force (EMF) due to the injection of charged aerosols from the ground to the atmosphere. They have found that unlike the conventional chemical channel this new hypothesis enables us to explain both the experimental facts prior to an EQ: (1) no significant change of atmospheric electric field on the ground surface, and (2) significant enhancement of electric field in the ionosphere.

Though not shown in Figure 6, a new hypothesis of electrostatic channel has been put forward by Freund [2009] on the basis of discovery of positive holes charge carriers in crustal rocks, alongside electrons. Normally, these charge carriers lie dormant in the crystal structures of the constituent minerals. When deviatoric stresses are applied in the focal region of a coming EQ, they wake up, turning the stressed rock volume into a battery, from which electric currents can flow out. When the positive holes arrive at the Earth's surface, they can cause a variety of effects including ionization of air at the air-ground interface, ionospheric perturbations, etc.

As compared with the 1st chemical channel, there have been accumulated a lot of evidence on the importance of the 2nd channel (due to atmospheric oscillations) mainly by using the VLF/LF subionospheric data. Below we indicate several observational facts in support of the 2nd channel (see the details in Hayakawa et al., [2011]).

(1) Observation of AGW modulations in subionospheric VLF/LF data :

Molchanov et al., [2001] and Miyaki et al., [2002] made the first attempt to identify the AGW modulation in the subionospheric VLF/LF data during (or before) an EQ, who found that such AGW modulation is clearly enhanced before EQs. Since then, there have been accumulated a lot of further evidence on those AGW modulations in the VLF data [Shvets et al., 2004; Rozhnoi et al., 2004, 2007; Muto et al., 2009b; Kasahara et al., 2010].

Horie et al., [2007] have treated the famous Sumatra EQ of 26 December, 2004 on the propagation paths from the Australian transmitter NWC to several stations in Japan. Of course, the VLF amplitudes at Japanese stations have indicated a depression in nighttime amplitude and also an enhancement in amplitude fluctuation before an EQ as a precursor. An additional important point is that the nighttime fluctuation is composed of wave-like structures, and the wavelet and cross-correlation analyses have been performed, and they have found a significant enhancement in the fluctuation spectra in the period of 20-30 min to ~100 min (the frequency range of AGWs). The cross-correlation between two propagation paths indicates that the wave-like structures tend to propagate horizontally from the NWC-Kochi path to NWC-Chiba path with a delay of ~2h, corresponding to the propagation speed of ~ 20 m/s.

(2) A statistical study on the AGW modulation:

In addition to the above event studies, Kasahara et al., [2010] have made a statistical analysis on the correlation between the AGW modulation with EQs with magnitude greater than 6 by means of superimposed epoch analysis. Their conclusion is that there is a significant correlation between the two.

(3) Modulation of VLF/LF data by planetary waves:

As is already shown before, the harmonic analysis of TTs has indicated the presence of modulation in subionospheric VLF/LF data (amplitude, phase) with the periods of planetary waves (2, 5 days, 10-11 days or so) [Molchanov and Hayakawa, 1998], which has indicated the important role of atmospheric oscillations in the LAI coupling.

(4) VLF/LF Doppler shift observation:

We have established, as the first attempt, a new equipment of observation of Doppler-shifts of the LF transmitter signal of JJY (Fukushima, Japan) [Asai et al., 2011]. Hayakawa et al. [2012b] have found that

Doppler shifts are really observed in the frequency range of AGW and AW before an EQ when we have ionospheric perturbations. This is direct evidence of the presence of AGW (and AW) as involved in the seismo-ionospheric perturbation. Further, the observed Doppler shift enabled us to estimate the vertical velocity of AGW as ~10 m/s which is in good agreement with theoretical estimates.

(5) Ground-satellite coordination:

Korepanov et al., [2009] have studied the correlation of the ground effect with satellite observation, using meteorological disturbances, and concluded that that AGW is the main agent of LAI coupling. Following this work, Nakamura et al., [2013] have made a challenging attempt to correlate the pre-EQ effect with ionospheric perturbations as seen by VLF/LF data. The scenario is as follows. Pre-EQ effects appear on the Earth's surface, leading to the change in atmospheric pressure and exciting the atmospheric oscillations. Those atmospheric waves propagate upward and modify the dynamo region (ionospheric perturbations). The change in the dynamo region might result in the change in ULF magnetic field on the

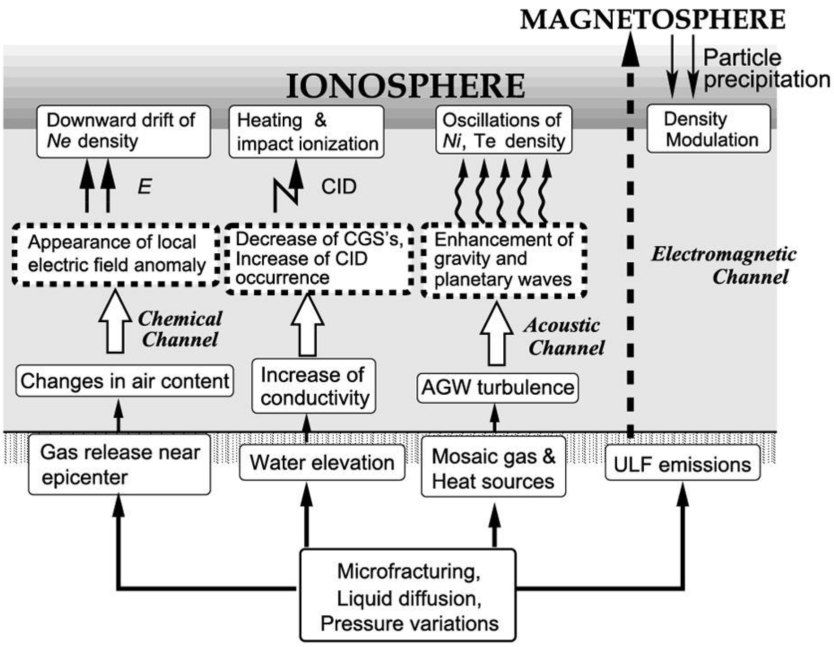

Figure 6. Schematic illustration of the lithosphere-atmosphere-ionosphere coupling and three channels, (1) chemical (+electric field) channel, (2) AW and AGW channel, and (3) electromagnetic channel. After Hayakawa et al. [2004] and Hayakawa [2009b, 2011].

ground. Three physical parameters are compared extensively with the use of wavelet analysis. They analyzed two EQ events, but we have found some significant results for one EQ. It seems that there existed a time delay of a few hours between the VLF/LF fluctuation and atmospheric pressure fluctuation and nearly no delay between the VLF fluctuation and ULF magnetic field variation for one particular EQ.

The above studies are based on the assumption that there appear some kinds of effects on the ground before an EQ, which disturb the atmosphere. This assumption has been long criticized very much as being rosy because there have been reported very few reports on those surface changes before an EQ. Fortunately recently, surface deformations before an EQ have been found with sophistical signal processing for the GPS data [Chen et al., 2011; Kamiyama et al.,2014], indicating short-term precursors even in the surface deformation. Also, ground deformations have been compared extensively with electromagnetic precursors for the 2011 Tohoku EQ in Kamiyama et al. [2014], suggesting a close correlation between the two. However, we have to guess what is happening between the focal region and ground surface.

Sun et al., [2011] have tried to understand what is happening between the ionospheric F region and the ground surface, when there is a seismo-ionospheric perturbation. With the use of information on T_n (neutral particle temperature) by SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument on board the TIMED satellite, Sun et al. [2011] have concluded the importance of seismogenic internal gravity waves in the dynamo region, giving a strong and direct evidence to the 2nd channel of LAI coupling.

Further studies both observational and theoretical, are extensively required before we come to the conclusion on which channel is more relevant. We here briefly comment on some computer simulations on the LAI coupling. A theoretical simulation of LAI coupling has been performed by Kuo et al. [2011] on the assumption of a seismogenic source in the lithosphere. Then Klimenko et al. [2012] have simulated the effects of AGWs and the penetration of vertical electric field, and have found that the simulation results with the AGW hypothesis are in better agreement than the electric effect with the actual GPS TEC data, in favor of the 2nd channel. Even though it is clear that the 2nd channel is more probable at the moment, we need to carry out further works on different channels before a definite conclusion.

5. Conclusion

The results for a few case studies including the 1995 Kobe EQ and the 2011 Tohoku EQ, have been presented, together with our statistical study based on the long-term VLF/LF data, in order to show that the perturbations in the lower ionosphere with the use of subionospheric VLF/LF propagation signals, take place prior to an EQ. Then, we have discussed how and why such lower ionospheric perturbations are formed before an EQ. Though a few hypotheses have been proposed, we support the idea of AGW as a possible agent of LAI coupling. A lot of observational evidence (either indirect or direct) has been presented including the enhancement of VLF/LF amplitude in the AGW range, Doppler-shift observational results and others in favor of the AGW hypothesis.

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