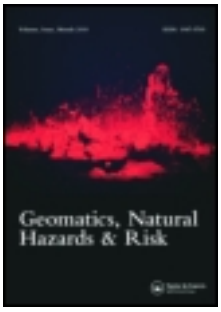

Current status of seismo-electromagnetics for short-term earthquake prediction

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Current status of seismo-electromagnetics for short-term earthquake prediction

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Short-term (timescale of hours, days and weeks) earthquake (EQ) prediction is of essential importance to mitigate EQ disasters. Short-term EQ prediction has so far been based on seismic measurements (i.e. mechanical observation of crustal movements), but it was concluded in Japan about 10 years ago that EQ prediction is impossible by means of the mechanical method. Hence, there has been an increased interest and a lot of progress in non-seismic measurement during the last decade. A new approach was developed where electromagnetic measurements provide microscopic information on the lithosphere. The present paper is intended to give a history of short-term EQ prediction, and also we hope that this paper reviews the current status of a new science field, 'seismo-electromagnetics'. We make a general review of different phenomena taking place in the lithosphere, atmosphere and the ionosphere, but we pay more attention to the subjects of our preference including lithospheric ultra low frequency (ULF) electromagnetic emissions, and seismo-ionospheric perturbations.

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1. Introduction

Earthquake (EQ) prediction is classified into the following three categories: long-term (timescale of 10 to 100 years), intermediate-term (timescale of 1 to 10 years) and short-term predictions. Both the long-term and intermediate-term EQ predictions are the subjects of seismologists, because they are mainly based on the geological studies of faults, historical records of seismicity and recent instrumental data of seismology and geodesy. Although much more difficult than the above long-term and intermediate-term predictions, short-term EQ prediction on a timescale of hours, days and weeks, is our interest and also the topic of this review.

Short-term EQ prediction is believed to be of the highest priority for social demands in seismo-active countries like Japan. Of course, we understand that the preparation for EQ disasters is more direct than the EQ prediction in order to mitigate disasters, so needless to say, structure issues are of the highest priority. However, if we could achieve EQ prediction, we could drastically reduce casualties, which would be of great potential from the standpoint of preparation for EQ

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disasters and would attract a lot of attention from the public. Also, from another scientific point of view, this short-term EQ prediction is one of the frontiers left for geophysics and is an extremely interesting challenge for scientists. We emphasize here that the following are equally important: preparation for EQ disasters, EQ prediction and quick rescue operation after an EQ.

Unfortunately short-term EQ prediction has not yet been achieved, and pessimistic views are widespread in seismological and mass media communities. Seismologists very often state categorically that EQs cannot be predicted (impossibility myth), but a lot of progress has been made in non-seismic (electromagnetic) measurements for EQ prediction during the last decade. So, in this paper, we first review the history of EQ prediction, mechanical (seismic) versus electromagnetic (non-seismic) measurements, and we want to show the fundamental difference between the two and the decisive advantages of electromagnetic effects. Then, we will show some of the recent findings in the lithosphere, in the atmosphere and finally in the ionosphere, but we pay more attention to our own findings based on our own preference and choice. Finally, the scientific goal of this study of seismo-electromagnetics is discussed; that is, lithosphere–atmosphere–ionosphere coupling. Recently Uyeda *et al*. (2009) published a review of short-term EQ prediction, so we hope this review is complementary to theirs.

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2. Seismic (mechanical) versus non-seismic (electromagnetic) measurements

Here in this section we discuss the relationship between conventional seismic measurements and a new wave of non-seismic measurements. The conventional (or traditional) method of EQ prediction, carried out by seismologists during the last five decades, was based on the mechanical measurement of crustal movements by means of seismometers etc. (or seismic measurement). We know that some huge EQs accompany a series of foreshocks as a precursor, and this kind of information was once used successfully for the useful prediction of a Chinese EQ. However, the occurrence of such foreshock activity is observed only for 20–30% of EQs, so this seismic measurement cannot be a promising EQ predictor. Based on a survey of the above seismic sequences and also on the former precursor studies in Japan, in 1998 a report was published by the Geodesy Council of the former Ministry of Education of Japan that EQ prediction is impossible. Since then, the myth of impossibility of EQ prediction has prevailed among seismologists and then in the mass media. However, the report should be modified as follows, 'EQ prediction by means of conventional seismic measurement is impossible.' Such a general conclusion by seismologists might be related to their haughty attitude that because seismologists cannot predict EQs, nobody else can do it.

Now it has been found that EQ prediction is difficult by mechanical means, we have to think of an alternative way. Amid the general pessimism, some significant new waves have been rising in short-term EQ prediction during the last decade since the disastrous Kobe EQ. Conventional seismic observation provides us with macroscopic information of the lithosphere, particularly after the occurrence of an EQ, which contributes much to the understanding of the mechanism of EQ generation, but is no contribution to EQ prediction as concluded by the Geodesy Council as mentioned above. It is likely that microscopic effects of the lithosphere would provide us with useful information for EQ prediction. An increase in pressure just around the EQ hypocentre would always accompany micro-fractures, leading to

the charge separation and generation of currents, which would be an essential source of subsequent electromagnetic effects. One of the electromagnetic effects generated are em waves, which can propagate over relatively long distances, of course depending on the wave frequency. These two factors (precursory and the long-distance propagating nature) of electromagnetic effects are decisively advantageous over the former conventional seismic measurement.

We can list a few possible reasons why such electromagnetic effects attracted an interest in relation to EQ prediction. The first is that some interesting phenomena have been observed. Ultra low frequency (ULF) electromagnetic emissions were observed for the Spitak EQ in 1988 and similar ones were also recorded for the Loma Prieta EQ in 1989. Further evidence was confirmed for the Guam EQ in 1993. Convincing evidence of the presence of seismo-ionospheric perturbations with the use of subionospheric very low frequency (VLF)/low frequency (LF) propagation was found for the Kobe EQ. The former ULF emission is a direct consequence of the lithosphere, so it is relatively easy for us to accept, but the latter has been a discovery that could not be believed at the beginning. The second reason is the projects by the former Ministry of Science and Technology of the Japanese Government entitled Coordinated EQ Frontier just after the Kobe EQ. Two institutions – RIKEN and former NASDA were asked to perform a 5-year project studying the feasibility of the use of electromagnetic effects in EQ prediction. One of the authors (MH) was responsible for the latter EQ Remote Sensing Frontier project, and we were lucky to obtain interesting findings. One additional important contribution was the generation of a consortium of the seismo-electromagnetic society, by organizing four international workshops (International Workshop on Seismo Electromagnetics, IWSE), which contributed to worldwide activities. Being stimulated by the success of Japanese frontiers, several countries (e.g. Taiwan, India, Italy, Russia, Mexico) accepted those seismo-electromagnetics as their own national projects. The third and last reason is the launch in June 2004 of a French satellite (named DEMETER) dedicated to the study of seismo-electromagnetics. This satellite observation is preferably coordinated with the ground-based observations, which would help understanding the lithosphere–atmosphere–ionosphere coupling mechanism. Finally, we can say that EQ prediction is being extensively pursued as a new and very interdisciplinary science field known as 'seismo-electromagnetics'.

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3. Seismo-electromagnetic effects

It has been recently reported that electromagnetic phenomena take place in a wide frequency range prior to an EQ (Hayakawa and Fujinawa 1994, Hayakawa 1999, Hayakawa and Molchanov 2002, Molchanov and Hayakawa 2008). Basically there are two principal methods of observation of EQ signatures. The first is the direct observation of electromagnetic emissions (natural emissions) from the lithosphere and the second is to detect indirectly the seismic effects that have taken place in a form of propagation anomaly of the pre-existing transmitter signals. The first method is based on the idea that natural emissions are radiated from the hypocentre of EQs due to some tectonic effect during their preparation phase. The problem with this 'local' measurement is that our observing station should be located very close to the EQ epicentre in order for us to detect seismogenic emissions. The second method is based on the idea that there are anomalies in the atmosphere and ionosphere due to seismicity, leading to the generation of a propagation anomaly on the pre-existing

transmitter signal characteristics. We call this type of observation 'integrated' measurement, because we can detect any EQs that are located very close to the propagation path from the transmitter to the receiver, so that it is much easier for us to accumulate the number of events for this integrated measurement.

In the following, we will discuss different electromagnetic effects occurring in the lithosphere, in the atmosphere and in the ionosphere, and finally the mechanism of lithosphere–atmosphere–ionosphere coupling. Also, please refer to a recent monograph edited by Hayakawa (2009a), in which detailed discussions are carried out. However, let us pay more attention to the subjects on the basis of our own preference.

4. Electromagnetic effects in the lithosphere

Several seismogenic phenomena have already been found over the extremely wide frequency range from direct current (DC), ULF up to VHF (or even more) originating in the lithosphere, some of which would be promising for short-term EQ prediction.

4.1 *Geoelectric and geomagnetic field anomalies in DC*

DC electric currents flowing in the surface layers of the Earth's crusts are measured as the electric potential difference between separately buried electrodes. A lot of progress has been made, and details can be found in the monograph by Varotsos (2005). Some recent findings on their results have been summarized in Uyeda *et al.* (2009).

DC magnetic field anomalies are also measured by the conventional flux-gate magnetometers, but there have been very few reports on DC magnetic field anomalies possibly associated with EQs.

4.2 *ULF emissions*

Beginning late in the 1980s seismogenic ULF (a frequency lower than several Hz) electromagnetic emissions were reported. Even though the radio emissions are generated as a pulse in the EQ hypocentre, higher frequency components cannot propagate over long distances in the lithosphere due to severe attenuation, but ULF waves can propagate up to an observation point near the Earth's surface with small attenuation.

Three reliable events have been reported for the ULF magnetic field variations prior to the EQs (1) Armenia, Spitak EQ (8 December 1988, magnitude 6.9) (Molchanov *et al.* 1992), (2) USA, California, Loma Prieta EQ (18 October 1989, magnitude 7.1) (Fraser-Smith *et al.* 1990) and (3) Guam EQ (8 August 1993, magnitude 8.0) (Hayakawa *et al.* 1996a). The epicentral distance is 129 km for (1), 7 km for (2) and 65 km for (3). The Loma Prieta EQ happened very close to the observing station, so that it is better for us to indicate the results for this EQ. Figure 1 illustrates the temporal evolution of the ULF magnetic field (horizontal component, frequency = 0.01 Hz, period = 100 s), which indicates that the magnetic field increases for about one week (5–12 days) before the EQ, followed by a quiet period and a sharp increase one day before the EQ (especially an abrupt increase 3–4 h before the EQ). Very significant changes in the ULF magnetic field were also

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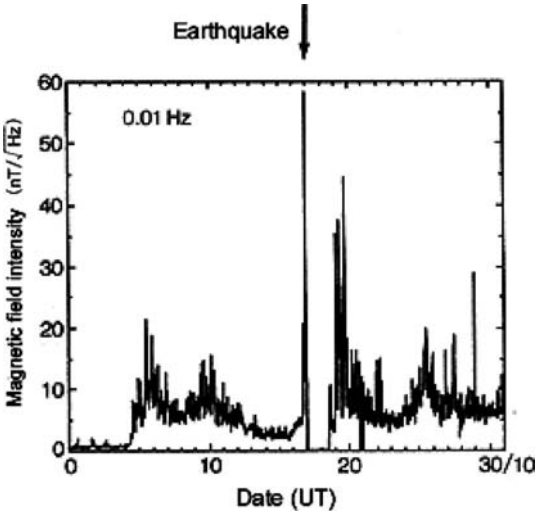

Figure 1. Temporal evolution of geomagnetic variation for the Loma Prieta earthquake (frequency = 0.01 Hz) (after Fraser-Smith *et al.* 1990). Earthquake means the date of the earthquake.

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observed for the other two EQs, which was a stimulus to the extensive research on the relationship of ULF emissions and EQs. Here we review the relationship between the two. An additional important point is that these seismogenic ULF emissions are so weak that it is of essential importance for us to develop any signal processing methods to identify those signals. We need sophisticated methods of signal processing, and we review the observational results by those methods. Please refer to some reviews by Hayakawa *et al.* (2007a), Fraser-Smith (2009) and Kopytenko *et al.* (2009).

4.2.1 Magnetic field sensors and observation system. Figure 2 shows a summary of the occurrence of EQ-related ULF activities in the form of EQ magnitude (M) versus epicentral distance (R) from a ULF magnetic station (Hattori 2004, Hayakawa *et al.* 2007). White and black circles show an EQ with and without accompanied ULF anomalies, respectively. The dashed line indicates the empirical threshold ($0.025R \leq M$ -4.5) for the appearance of anomalous ULF signals preceding large EQs. This figure demonstrates that ULF emissions could be observed about 60 km from the source region for an EQ with $M \geq 6$, and the detectable distance of ULF magnetic anomalies would be extended to about 100 km in the case of an EQ with $M \geq 7$.

It is important to predict EQs with $M \geq 6$ in a highly populated region to mitigate disasters. Therefore, we have established a network of ULF magnetometers with high sampling rates to cover the Kanto (Tokyo) area with inter-sensor distances of about 70–80 km (Hattori *et al.* 2004) as seen in figure 3. Circles in the figure indicate a distance of 70 km from each station.

4.2.2 Analysis methods of ULF magnetic field variations. In addition to the installation of highly sensitive ULF sensors as in figure 3, we have to carry out

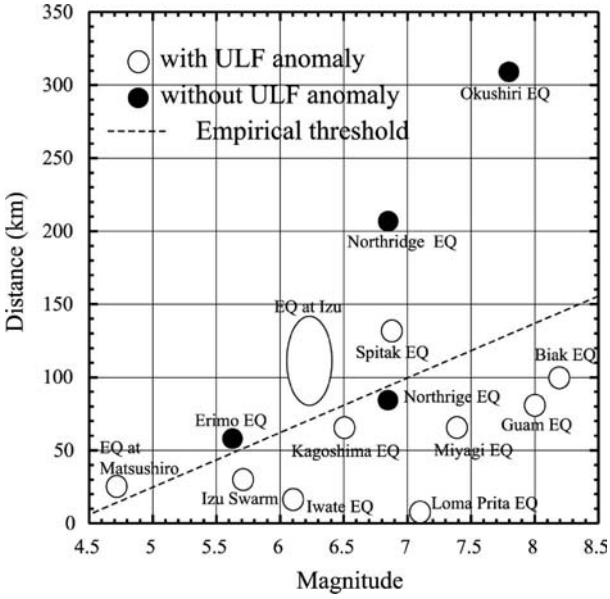

Figure 2. Summary of the seismo-ULF emissions in the form of earthquake magnitude (M) versus epicentral distance (R). A white circle means the event with ultra low frequency (ULF) anomaly, while a black circle is the event without ULF anomaly. The empirical threshold is indicated by a dotted line (0.025R = M-4.5).

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sophisticated signal processing in order to detect and identify weak seismogenic ULF emissions. We have already developed several useful signal processing techniques, some of which will be described below.

4.2.2.1 The ratio of vertical to horizontal components of the magnetic field (polarization analysis). It has been reported that it is useful to use the ratio of magnetic vertical to horizontal component S_Z/S_G ($S_G^2 = S_H^2 + S_D^2$, where H and D are two horizontal magnetic components and Z is the vertical component) to distinguish the seismogenic ULF emissions from other noises (Hayakawa *et al.* 1996a). While we expect that this ratio (S_Z/S_G) (polarization) is relatively small for the plasma waves coming from the ionosphere/magnetosphere, we expect that this ratio is considerably enhanced, $S_Z/S_G \sim 1$ or even more for seismogenic emissions. One particular event in Kyushu is presented here with the application of this polarization analysis (Hattori *et al.* 2002). There were two EQs in the northwest part of Kagoshima prefecture with M = 6.5 and M = 6.3 on 26 March and 16 May 1997, respectively. Both EQs had a depth of about 20 km. Our ULF observatory (at Tarumizu, Kagoshima) is located about 60 km away from their epicentres, and three magnetic field components were measured there with a sampling of 1s. By using the data from a year (August 1996 to September 1997) on the relationship between ULF magnetic field variation and seismic activity, we try to indicate the presence of ULF field variation in response to the crustal activity. We use only the data from the local midnight (LT = 0–4 h). By considering different spatial scales of space geomagnetic variations and local EQ effects, we examine also the magnetic field data at Ogasawara Island (Chichi-jima) 1200 km away from Tarumizu and at Darwin as the

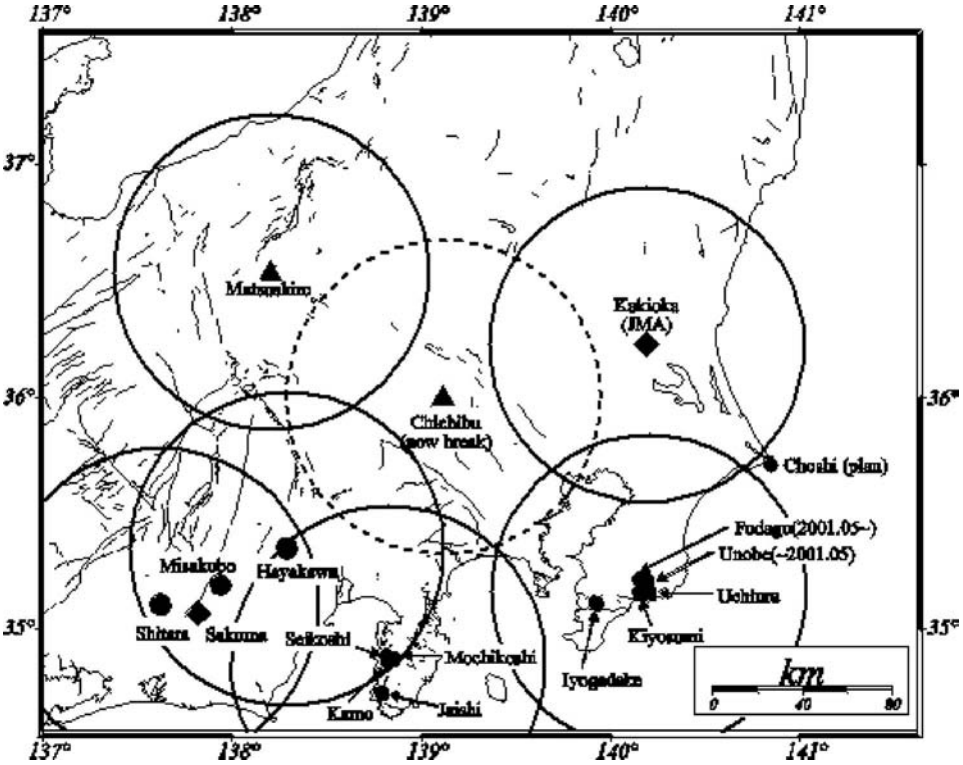

Figure 3. Network for ultra low frequency (ULF) emission observation in the Kanto (Tokyo) area. Different types of magnetometers are used (a triangle indicates an induction magnetometer and a circle, the torsion-type magnetometer. Kakioka observatory is equipped with induction magnetometers, and a box indicates the fluxgate magnetometer). The circles around each station have radii of 70 km.

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conjugate point of Tarumizu. The largest noise at ULF is geomagnetic variation in the upper atmosphere, and this is the reason why we look at the data at the conjugate point. At these stations, the same sensors (inductions) are working. During our analysis period, we have confirmed that there were no EQs within a radius of 100 km from Chichi-jima and Darwin observatories.

Figure 4(*a*) illustrates the temporal evolution of seismic activity and figure 4(*b*) shows the temporal plot of the polarization (S_Z/S_G) from 10 days before the current day at three stations. The full line refers to Tarumizu. Figure 4(*c*) refers to the geomagnetic activity (ΣKp). When we look at figure 4(*b*), the polarization at the two stations (Chichi-jima and Darwin in thin lines) is found to be stable, while we find a very significant change in the polarization at Tarumizu in a thick line. The polarization is seen to be increased from the background value of $\sim$ 1.0 to more than double prior to the first EQ. We find a decrease in polarization and, when this decrease is stabilized, the first EQ occurred. The polarization value is found to remain at this value for a while. Then, again we notice a decrease in polarization, and the second EQ occurred. In the beginning of July, the polarization value returned to the background value. Significant changes are noticed only at Tarumizu, but not at Darwin and Chichi-jima. When comparing the seismic activity around Tarumizu and

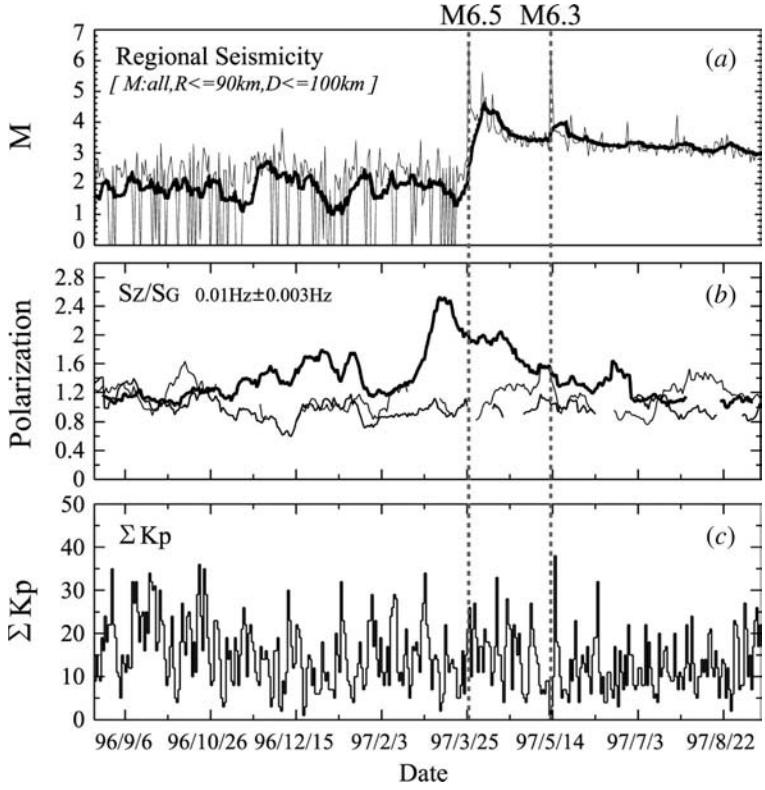

Figure 4. Polarization results at Tarumizu, Chichijima and Darwin for the ultra low frequency (ULF) emission in Kyushu in 1997. (*a*) Temporal evolution of regional seismicity, (*b*) temporal variation of polarization (S_Z/S_G, 0.01 Hz) at Chichijima and Darwin (thin lines) and at Tarumizu (thick line), and (*c*) ΣKp variation. The dates of the two earthquakes are indicated by two vertical dotted lines.

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the polarization, (1) the polarization at Tarumizu is found to be significantly enhanced prior to the EQ, and (2) the temporal variation of the polarization seems to be very parallel to that of seismic activity. This means that the polarization of the magnetic field variation is a good indicator for monitoring local seismic activity (Hattori *et al.* 2002, 2004) and the important point is that the polarization increase is taking place before the EQ. No significant correlation with geomagnetic activity is found.

4.2.2.2 Principal component analysis. We performed the array observation by using 3–4 torsion-type magnetometers both at the Izu and Boso peninsulas as shown in figure 3. We know that seismic activity at Miyake Island started in late June 2000, and the volcano eruption started there. Though the distance between our ULF observations and the EQ epicentre is about 100 km, which is marginal for the detection of seismogenic ULF emissions, we adopted principal component analysis (PCA) for the ULF data observed at several stations in the Izu peninsula (Gotoh *et al.* 2002). By using the ULF data observed at three close stations, we obtained three datasets, which enabled us to separate three possible sources.

Generally speaking, the ULF signal observed at a station is a combination of a few effects: (1) geomagnetic variation of the magnetosphere (e.g. geomagnetic storms)

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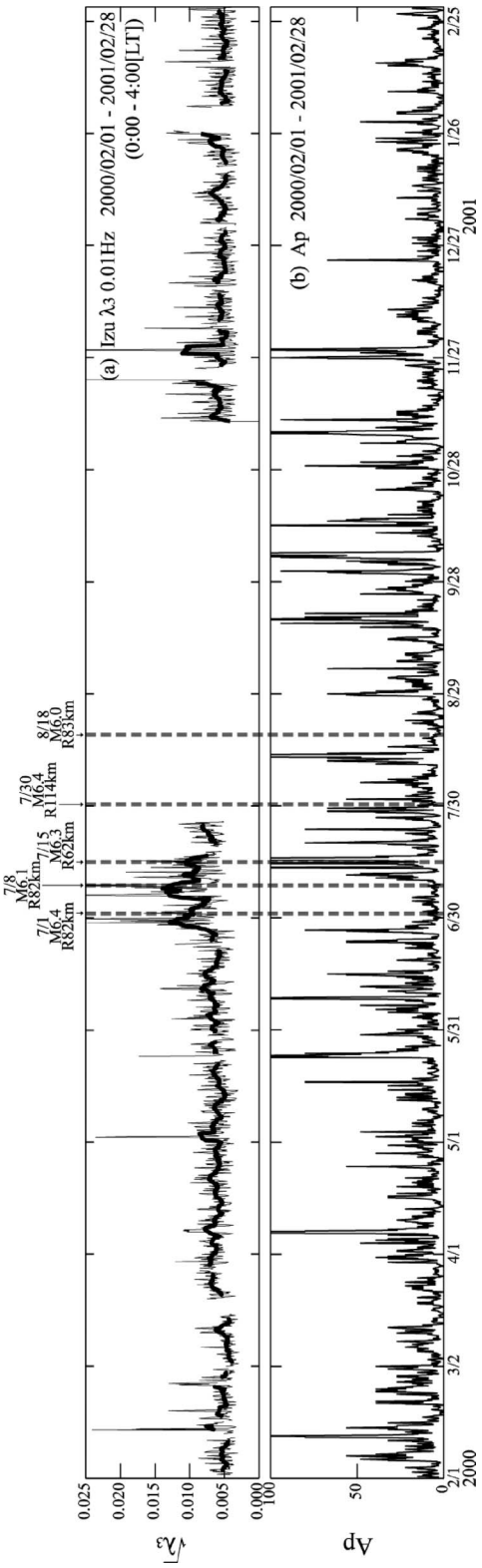

Figure 5. Principal component analysis on the ultra low frequency (ULF) emissions (frequency = 0.01 Hz) for the Izu peninsula EQ swarm in 2000. The upper panel (*a*) indicates the temporal evolution of the third principal component ($\sqrt{\lambda_3}$), and the lower panel (*b*), the geomagnetic activity (Ap).

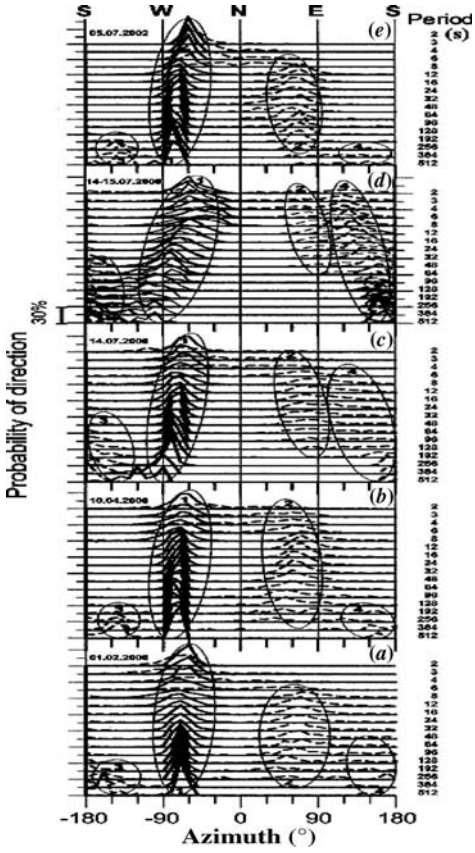

Figure 6. Temporal variation of the occurrence histogram of the direction of arrival (azimuth) of ultra low frequency (ULF) geomagnetic variations for the same Izu peninsula EQ swarm. The abscissa is the arrival azimuth (0 north, + east and - west). Time goes from the bottom (*a*) to the top (*e*); (*a*) 1 February 2000 (4 months before the swarm), (*b*) 10 April 2000 (2 months before the swarm), (*c*) 14 June 2000 (12 days before the swarm), (*d*) 14–15 July 2000 (during the swarm) and (*e*) 5 July 2002 (2 years after the swarm). There are four characteristic noise sources numbered from 1 to 4. The number 4 is the seismogenic emission of our interest.

due to the solar activity; (2) man-made noise; (3) any other effect (including seismogenic emissions). We traced the eigenvalue λ_n ($n = 1, 2, 3$) of three principal components in the frequency range from $T = 10$ s to $T = 100$ s by using the time-series data with a duration of 30 m. As a result of analysis, the first principal component (λ_1) is found to be highly correlated with the geomagneric activity (Ap). The second eigenvalue (λ_2) is found to have a period of 24 h, with a daytime maximum and a night-time minimum. This suggests that this noise is due to human activity. The upper panel of figure 5 illustrates the temporal evolution of the 3rd (or smallest) principal component (λ_3). We notice an enhancement in λ_3 from the middle of March to the middle of June (about a few months), followed by a quiet period (about one week before the first EQ) and by a sharp increase a few days before the first EQ. Similar sharp peaks are seen for subsequent EQs with magnitudes greater than 6.0. This general behaviour seems to be in close agreement with the case of Loma Prieta EQ in figure 1, which indicates that this variation is a reflection of the crustal activity in this district.

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4.2.2.3 Direction finding (magnetic field gradient method). The objective of the above two methods was to identify the presence of seismogenic ULF emissions, but we have to convince others that the detected ULF emission is much more likely to be associated with an EQ if we could locate its generation point in order to compare it with the epicentre of a future EQ. We have performed so-called direction finding for the ULF emissions for the above-mentioned Izu peninsula EQ swarm. We have used the same local array network, consisting of at least three stations in the Izu and Boso peninsulas. By measuring the gradient of horizontal and vertical components of the magnetic field at different frequencies (Kopytenko *et al.* 2002, Ismaguilov *et al.* 2002) (or periods in the ordinates of figure 6), we deduce the direction of azimuth from the normal to the observed gradient. The result by means of the Izu array is given in figure 6. In this figure, 0° indicates the north direction, + east and - west, and figure 6 illustrates the temporal evolution of the arrival directions of ULF emissions. The ordinate indicates the occurrence probability of the arrival azimuth of ULF emissions in the night-time period of 0 to 6 h. Full lines refer to the vertical component, while broken lines refer to a horizontal component.

Judging from the azimuth distributions, there are four noise sources. In the Izu array observation there generally exists a signal predominantly from the west (Suruga-Bay) (numbered 1 in figure 7) (corresponding to the Parkinson vector) in the vertical component, reflecting the geological contrast between the sea and land. For the horizontal component, there are two stationary signals. One is located in the east, which is directed to the seismo-active region in the eastern sea of the Izu peninsula (designated as 2 in figure 7). The second is the signal from the direction of Zenisu, which is designated as 3 in figure 7. The locations of the noise sources are summarized in figure 7. The time goes from figure 6(*a*) to (*e*); (*a*) 4 months before the swarm, (*b*) two months before the swarm, (*c*) 12 days before the swarm, (*d*) during

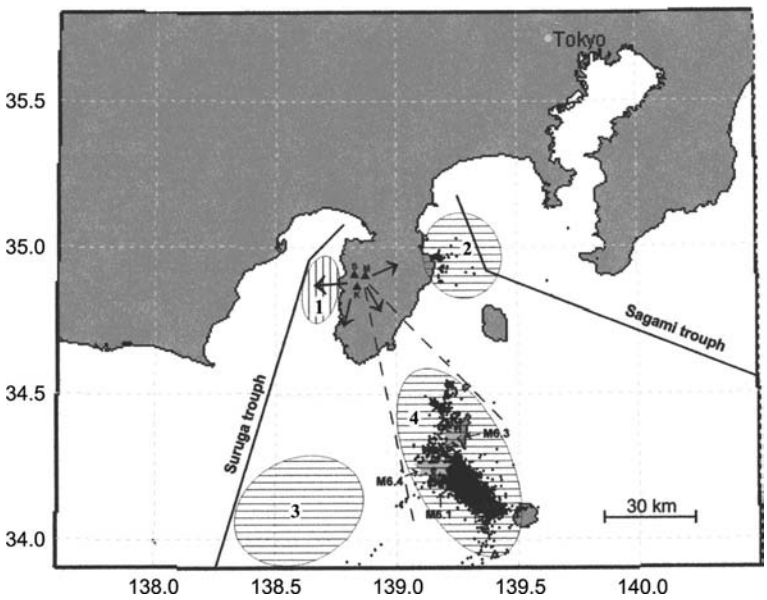

Figure 7. Ultra low frequency (ULF) direction finding results. Different azimuthal directions in figure 6 correspond to different noise sources (numbered 1–4 in figure 6).

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the swarm, and (*e*) two years after the swarm. Now we look at the noise designated as 4 in figure 6. This noise is found to be observed about 2 weeks before the EQ swarm (figure 6(c)) due to the volcano eruption of Miyake Island, and these noise emissions are found to have propagated from Miyake Island and their occurrence is most enhanced during the swarm (see figure 6(*d*)). Furthermore, we have tried to perform the direction finding for this noise numbered 4 from the Izu and Boso peninsulas. Figure 8 is the direction finding result. The azimuthal direction from each peninsula is given by the area within the two directions in broken lines. The area located by the triangulation is found to be coincident with the active area of the Izu peninsula EQ swarm. As the conclusion, the ULF emissions identified in figure 8 are highly likely to be associated with the swarm activity of Izu peninsula EQs.

4.2.2.4 Direction finding (goniometric method). The importance of direction finding is again stressed by showing another result for a recent, large Niigata Chuetsu EQ (Ohta *et al.* 2005, Hayakawa *et al.* 2006). This EQ happened at 17:56 JST on 23 October 2004, magnitude 6.8 and depth 10 km. We show the presence of ULF emissions for this EQ by using the data from other observatories at Nakatsugawa. The three components of the magnetic field (Bns, Bew, Bz) are measured at Nakatsugawa using the same induction magnetometers as at Izu and Boso peninsulas, but the important different point is that the waveform measurement is being performed in a wide frequency band. That is, the sampling frequency is 100 Hz, and figure 9 illustrates the temporal evolution of the emission intensity (Bew component) in the frequency range, $f \leq 0.1$ Hz, which shows that the signal intensity is extremely enhanced by 3 dB as compared with the monthly mean during several days from 2 to 6 October. This noise seems to be anomalous. However, we cannot conclude that this is associated with the EQ, even though it occurs a few weeks before. Then, we performed the direction finding for this noise

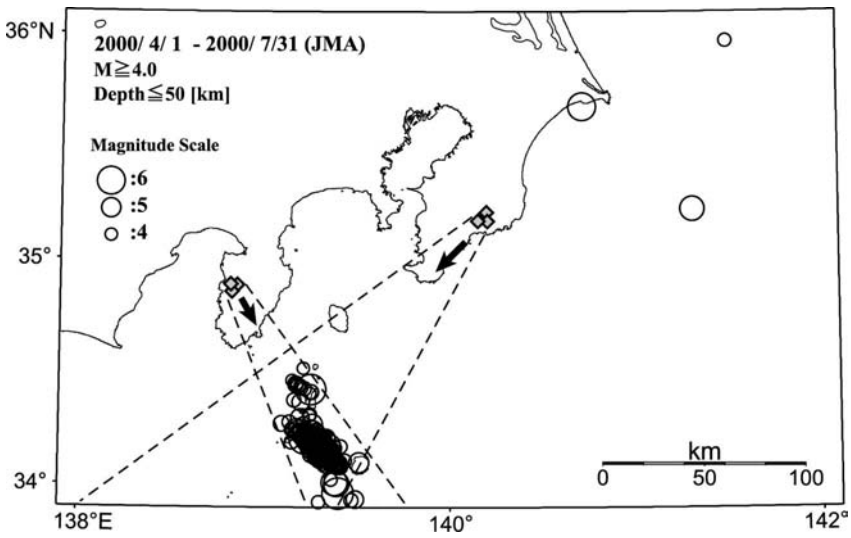

Figure 8. Triangulation of the ultra low frequency (ULF) noise source (#4 in figure 6) using the azimuths estimated from the Izu and Boso peninsula arrays.

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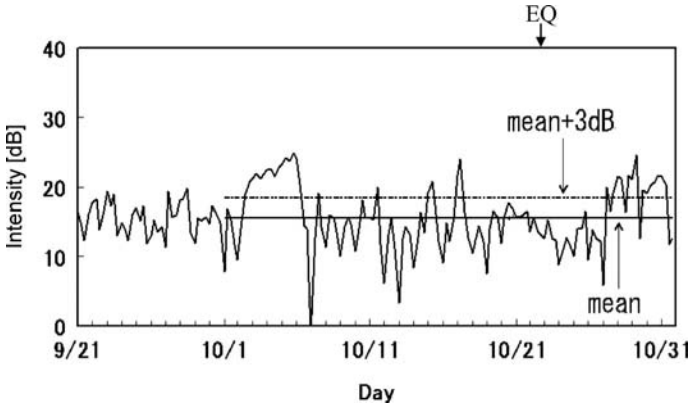

Figure 9. Temporal evolution of magnetic field intensity observed at Nakatsugawa for the Niigata Chuetsu earthquake in 2004. The frequency is less than 0.1 Hz. Strong emissions are observed from 2 to 6 October 2004. EQ indicates the earthquake time.

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using the goniometer principle by means of two horizontal magnetic field components. We estimated the arrival azimuth by taking the ratio of Bns/Bew for the emissions with anomalous amplitude during 2–6 October. The estimated azimuth (mean value) is indicated in figure 10. The azimuthal direction is 55° from the east, which is consistent with the epicentral direction. This is indicative of a higher possibility that the noise is associated with the EQ.

4.2.3 Summary of seismogenic ULF emissions and generation mechanism. A number of papers on seismogenic ULF emissions have been published since the famous EQs, Spitack, Loma Prieta, Guam, and in this section we have reviewed mainly our published results. We can summarize the characteristics of seismogenic ULF emissions based on not only our results, but also previous foreign results.

(1) There is no doubt that ULF emissions take place as a precursor to a relatively large EQ. The distance of detection (R) is 70–80 km for magnitude 6.0, and $\sim$ 100 km for magnitude 7.0. The empirical threshold of detection in figure 2 is given by 0.025 R = M -4.5.
(2) The ULF emissions for large EQs (with magnitude greater than 6.0), seem to exhibit a typical temporal evolution. Initially, we have a first peak one month to a few weeks before the EQ, followed by a quiet period and a significant increase in amplitude a few days before the EQ.
(3) The amplitude of those seismogenic ULF emissions is found to range from 0.1 nT to a few nT. However, their frequency spectra are not well understood; that is, what is the predominant frequency? Recent studies indicate the importance of the frequency of 0.01 Hz = 10 mHz (period of 100 s).
(4) The observation of ULF emission is a local measurement. So that only when our observing station happens to be very close to the EQ epicentre can we detect seismogenic emissions. Otherwise it is impossible to detect any seismogenic emission, and this is the reason why we do not have an abundant dataset as summarized in figure 2. The case of the Niigata Chuetsu EQ does

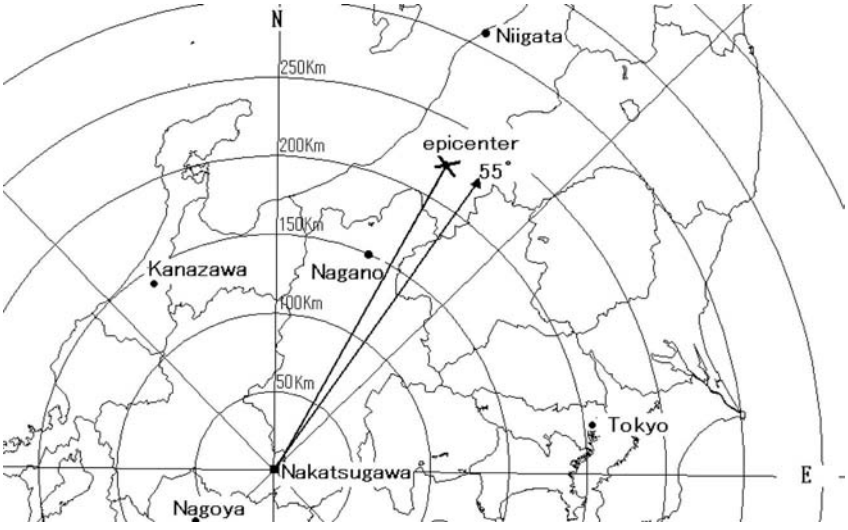

Figure 10. Goniometric direction finding of ultra low frequency ULF noises during 2–6 October 2004 as seen from Nakatsugawa. The epicentre is also indicated, for the sake of comparison.

not follow the above-mentioned threshold, so we have to think of the generation and subsequent propagation for this case.

We next review the generation mechanism of seismogenic ULF emissions. It has been proposed that the ULF emission is generated by a mechanism that requires the charge separation (as an ensemble of small antennas) due to microfracturing by the stress change in the focal region before the EQ (Molchanov and Hayakawa 1995). According to their theoretical estimate, the ULF emission can be detected within 60 km for a magnitude of 6 and 100 km for a magnitude of 7. This theoretical estimate seems to be in good agreement with the above-mentioned experimental threshold in figure 2. When the radio emission is generated at the source region, it should be wide-banded. However, the higher-frequency components decay during the propagation in the lithosphere, which results in the possible detection of ULF emissions near the Earth's surface (Molchanov *et al.* 1995). Other possible mechanisms are electro-kinetic effect (Fenoglio *et al.* 1995) or positive hole carriers (Freund 2009). We cannot say, at the moment, which one of these representative mechanisms is more probable as the generation mechanism of seismogenic ULF emissions. However, we can comment on another aspect of the preparation process of EQs. During this preparation phase, the lithosphere is known to exhibit a self-organized criticality phenomenon. That is, we expect the microfracturing in the focal region due to the stress increase, followed by the growth and coalescence of microcracks. This process is thought to be involved in the generation of ULF-emissions. This nonlinear process in the lithosphere can be tackled with the use of fractal analysis (Hayakawa *et al.* 1999, Ida *et al.* 2005, Ida and Hayakawa 2006). The results from fractal analysis are preferably taken into account in the generation mechanism of seismogenic ULF emissions.

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4.3 *Laboratory experiment on rock rupture*

Recently a lot of laboratory experiments on rock rupture and relevant charging have been performed by a group led by Freund (2009). This kind of laboratory experiment is of crucial importance in understanding the mechanism of pre-EQ DC and ULF electromagnetic emissions. Please refer to a recent review by Freund (2009), who has discovered that positive hole charge carriers exist in essentially deep crustal rocks and that they become activated by stress, alongside electrons. An attempt to explain different seismogenic effects in terms of his hypothesis of positive holes has been performed by Freund (2009).

4.4 *Geochemical parameters*

These geochemical parameters include radon, different types of ions, and so on. A few good reviews have been published suggesting the important role of geochemical observation in the study of seismo-electromagnetics by Biagi (2009) and Molchanov and Hayakawa (2008).

Satellite observations of the anomalies in geochemical quantities have been performed in the visible and infrared (IR) ranges (see the latest by Singh *et al.* (2010)), and please refer to Parrot (2009) and Pulinets (2009) for more details of those satellite measurements.

4.5 *Summary of seismo-lithospheric effects*

The lower frequency (DC and ULF) electromagnetic radiations from the lithosphere have been investigated extensively, so that a substantial number of observational facts have been accumulated. Though a few hypotheses have been proposed for the generation mechanisms of DC and/or ULF emissions, it is not fully understood which one of the mechanisms is relevant. The time is now ripe for further studies on the accumulation of more events in ULF and for an elaborate theoretical consideration. Geochemical phenomena (either measured on the ground or by satellites) are known to exist and appear prior to an EQ, but coordinated measurements along with ionospheric observations are highly necessary because they are sometimes considered to be a possible agent of seismo-ionospheric perturbations.

5. Electromagnetic effects in the atmosphere

We can classify several types of atmospheric seismogenic electromagnetic emissions as follows (Molchanov and Hayakawa 2008); (a) EQ light, (b) HF/VHF emission in a frequency range of 10–100 MHz, (c) electromagnetic radiation in the ELF/VLF/MF frequency range from hundreds of Hz to hundreds of kHz, and (d) ULF/ELF atmospheric emission in the frequency range of 3–30 Hz.

Then, another effect is the perturbation of the atmosphere in possible association with EQs. This effect has been investigated with the use of an over-horizon VHF transmitter signal (a kind of integrated measurement such as subionospheric VLF/LF propagation).

We will present the latest results of only some of the above phenomena.

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5.1 *Seismo-atmospheric electromagnetic emissions*

5.1.1 HF/VHF emission in the frequency range of 10–100 MHz. Several case studies were reported in the USA (Warwick *et al.* 1982, frequency ~18 MHz), Greece (Nomicos *et al.* 1995, frequency ~41 MHz and 53 MHz), and in Japan (Maeda and Tokimasa 1996, frequency ~22 MHz; Yamada *et al.* 2002, frequency ~50 MHz). The intensity and duration of those emission bursts reported were comparable with conventional HF radiation from the thunderstorm system because HF noise reception on board meteorological satellites is routine monitoring for lightning activity. Nevertheless, there were no attempts to produce any correlation statistics or to detect and identify natural background from the HF bursts allegedly associated with EQs.

Here we present some latest results on these seismogenic VHF radio emissions. Yonaiguchi *et al.* (2007b) made the first attempt of using fractal analysis for VHF radio noises observed at several stations in the Sendai area for a particularly large EQ, Miyagi-ken oki EQ (16 August 2005; magnitude 7.2). The use of fractal analysis has enabled them to distinguish between different noise sources (lightning, solar-terrestrial effects and seismogenic effects).

5.1.2 ULF/ELF atmospheric emission in the frequency range of 3–30 Hz. The ULF range of 0.003–30 Hz can be divided into two physically different parts: the first is a range of 0.003–3 Hz, where we meet sporadic magnetospheric emissions (magnetic pulsations), natural emissions from the ionosphere and Ionospheric Alfven Resonances (IARs) (0.3–3 Hz) with a small addition of occasional seismogenic emissions (Molchanov *et al.* 2003). While in the second part, the main input is originated in lightning pulses (atmospherics) resulting in the reception of Schumann resonances. These spectrum maxima arise due to far-distant propagation of the atmospherics (e.g. Nickolaenko and Hayakawa 2002). Based on the ULF/ELF observation in Nakatsugawa, Japan, Ohta *et al.* (2001) found an abnormal enhancement in ULF/ELF noise intensity one day before and after the famous Chi-Chi EQ in Taiwan (21 September 1999, magnitude 7.6) and their goniometric direction finding suggested that those noises are coming from the direction of the EQ epicentre. Later, Hayakawa *et al.* (2005) reported on the abnormal Schumann resonance phenomena, especially the significant effect in the fourth harmonic (frequency ~25 Hz) and this anomaly is interpreted in terms of seismo-ionospheric perturbations.

Being stimulated by the paper of Hayakawa *et al.* (2005), similar data on ULF/ELF magnetic field observations in a Russian station will be presented here (Schekotov *et al.* 2007). Local variations of the magnetic field in the ULF–ELF frequency range associated with seismicity are studied with observational data from the Karimshimo complex observatory (52.83° N latitude, 158.13° E longitude, Kamchatka, Russia). A wideband emission is found to start about 5 days before an EQ and last until 5 days after it. The seismic ULF/ELF emission in the frequency range of 4–6 Hz as compared with the seismically quiet background has an enhanced P_{hh}/P_{dd} (P_{hh} and P_{dd} are the spectral power densities of H and D components) spectral ratio and a reduced standard deviation of ellipse orientation angle and ellipticity, and it has a more linear polarization, as shown in figure 11. Parameters of this emission are studied for more than 30 individual EQs and statistically with the superposed epoch method. The reliability of the EQ predicting hypothesis is verified, and the favourable parameters for EQs together with those for ELF magnetic fields

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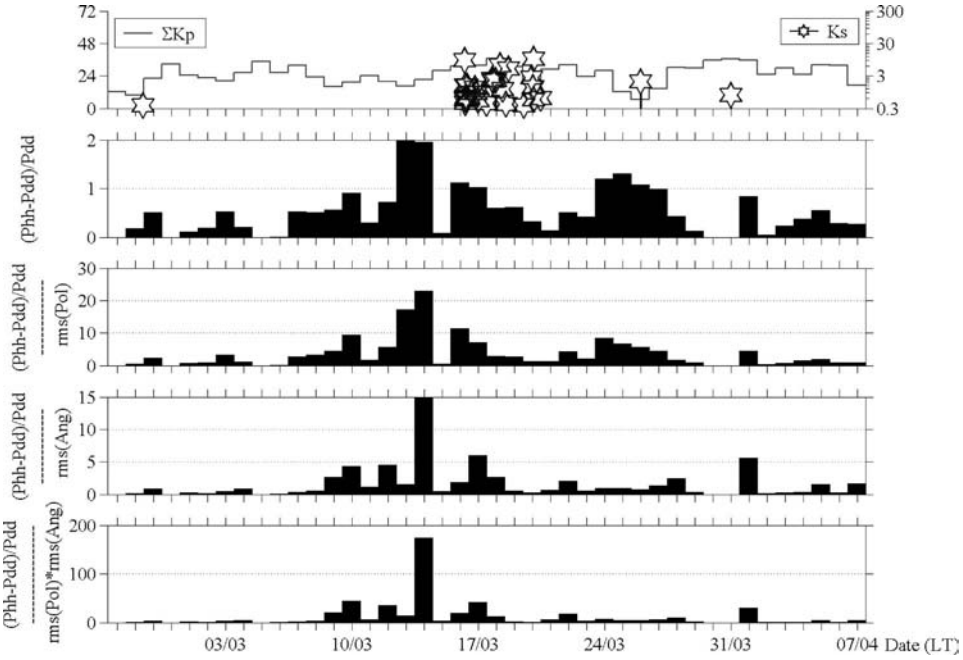

Figure 11. Observation results at Kamchatka in the frequency range (4–6 Hz) for different parameters: $<H/D> -1$ (second panel), $[<H/D> -1]/[\mathrm{rms(Pol)}]$ (third panel), $[<H/D> -1]/[\mathrm{rms(Angle)}]$ (fourth panel) and $[<H/D> -1]/[\mathrm{rms(Angle)\ rms(Angle)}]$ (bottom). Here rms (Pol) is the dispersion in polarization and rms (Angle) is the dispersion in ellipse orientation. The top panel indicates the ΣK_p index (dotted line) (the scale is given on the left) and also K_s index (so-called seismic index) (its scale is given on the right).

are selected. The following EQ parameters are favourable for this emission: depths $H < 50$ km, magnitudes $M_s > 5.5$, and epicentre distances $R < 300$ km. The changes of natural ULF/ELF emissions during the periods of enhanced seismic activity are interpreted as the result of the excitation of additional ULF/ELF emissions in the seismic zone to the east of the observatory or the redistribution of lightning discharges with their possible concentration near the active crust fault.

5.2 *Seismo-atmospheric perturbation by means of over-horizon VHF transmitter signals*

The propagation of over-horizon frequency modulation (FM) signals probably associated with impending EQs was observed by Kushida and Kushida (1998), who detected the signals from an over-horizon transmitter in central Japan several days or weeks prior to the Kobe EQ. Though we do not receive any signals from a VHF transmitter out of the line-of-sight, we sometimes receive the signals from the transmitter and we define this as being abnormal. Some correlation was found between the abnormal VHF wave propagation and the EQs, which happened in certain sensitive regions. This phenomenon was studied intensively for a number of EQs in central Japan from 1 February until 30 June 2000 by Fukumoto *et al.* (2001) by making full use of the advantage of an integrated measurement. The FM transmitter is located in Sendai, 312 km away from the receiver in Chofu, whereas the line-of-sight distance was 80 km. Though FM signals (77.1 MHz) from Sendai

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have not been detected in Chofu on normal days because it is out of the line-of-sight, over-horizon FM signals have been occasionally received in Chofu with incident angles smaller than 20°. Figure 12 illustrates one example of the detection of over-horizon signals from FM Sendai. The data were observed on 27 May 2000, as a precursor to an EQ on 3 June 2000 (with a magnitude of 6.2). The direction findings of the signal bearings have shown that there are sometimes a lot of differences with regards to the bearings of the future EQ epicentre. Fukumoto *et al.* (2001) found that the cross-correlation between the abnormal over-horizon FM signals and EQs exhibits a significant peak around 7 days before the EQ. Recently, experimental evidence for the same phenomena has been confirmed by Fujiwara *et al.* (2004). There are few papers on seismo-atmospheric perturbations on the basis of studies on over-horizon VHF signals (Kushida and Kushida 1998, Fukumoto *et al.* 2001, Fujiwara *et al.* 2004). We can summarize the important information from these earlier works as follows, which would be essential for the following theoretical considerations.

(i) Over-horizon VHF FM transmitter signals are not detected during normal conditions (Kushida and Kushida 1998, Fukumoto *et al.*, 2001), but they are received on some occasions.
(ii) Such abnormal over-horizon VHF signals are found to be received at a station out of the line-of-sight with a small incident angle (incident angle $\leq 20°$) (Fukumoto *et al.* 2001).

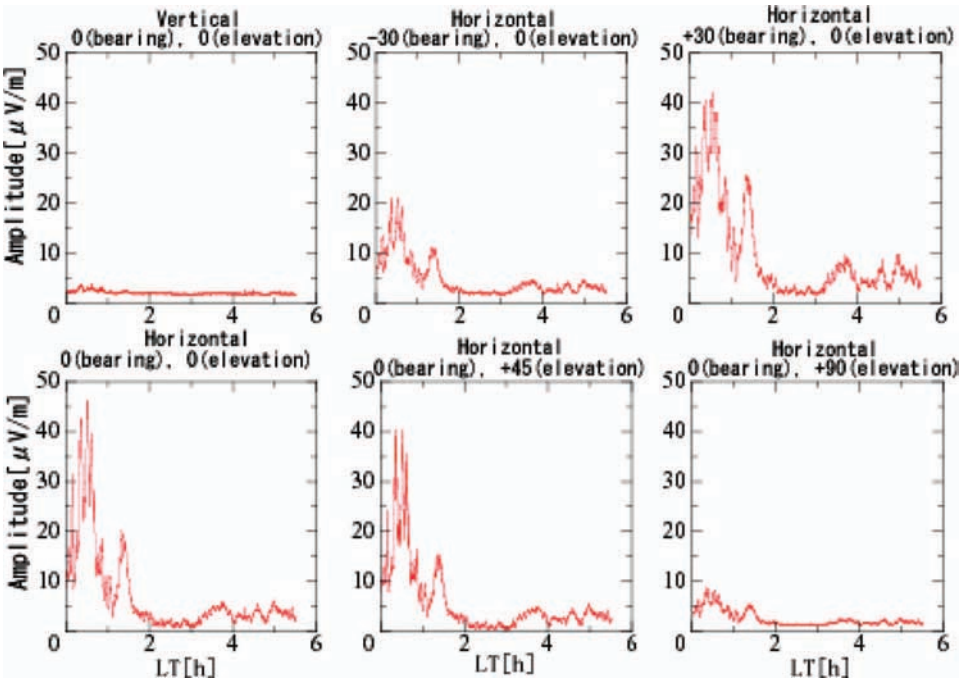

Figure 12. An example of the reception at our university of over-horizon very high frequency (VHF) signals from FM Sendai on 27 May 2000. The outputs from different antenna systems are plotted, indicating the source bearing in the atmosphere (not the ionosphere). This reception may be a precursor to an earthquake on 3 June 2000 (magnitude 6.2).

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(iii) The cross-correlation between over-horizon VHF signals and EQs indicates that such an anomaly takes place about one week before the EQ (Fukumoto *et al.* 2001, Fujiwara *et al.* 2004).

(iv) The direction finding of the bearing of an observed over-horizon signal shows that there is sometimes a lot of difference with regards to the bearing of a future EQ. Always, the region of the atmospheric perturbation seems to be close to the land area for oceanic EQs (Fukumoto *et al.* 2001).

Unlike the initial hypothesis by Kushida and Kushida (1998), Fukumoto *et al.* (2001) have found that this VHF anomaly is not attributed to the ionosphere, but to the atmospheric perturbation (point (ii)). This atmospheric perturbation tends to take place about one week before the EQ (point (iii)). Point (iv) is indicative of the suggestion that the atmospheric scatterer for an over-horizon VHF signal seems to take place close to the land (not over the sea).

Yonaiguchi *et al.* (2007a) have made the first attempt at statistical correlation between the over-horizon VHF signal (FM Sendai received at Chofu) and EQs on the basis of one complete year of data. It is found that the meteorological radio duct effect is dominant from July to September. On the other hand, when we make our analysis area narrower, just around the middle region of the great-circle path, we always have significant correlation between VHF signal characteristics (average, median intensity or variance) with seismicity in any month of the year, exceeding the confidence level.

Yasuda *et al.* (2009) developed an interferometric direction finding for over-horizon VHF signals. The azimuth distribution by means of our interferometer has enabled us to correlate any burst in the temporal evolution of electric field intensity to a certain EQ. The over-horizon VHF transmitter signals (in our case FM Sendai (77.1 MHz)) in possible association with EQs are always well above the background noise, whose azimuth is found to be relatively close to the direction of Sendai, relatively away from the EQ epicentral direction. Whereas the VHF radio noises as discussed in §5.1.1 are always simultaneously detected as an enhancement of background noise, with their azimuths being relatively close to the EQ epicentre.

Here we discuss the generation mechanism of seismo-atmospheric perturbations. Kushida and Kushida (1998) and Pilipenko *et al.* (2001) have assumed without any convincing observational results that the abnormal over-horizon VHF wave propagation is due to the back-scattering from the metre-scale plasma irregularities in the ionosphere above the seismo-active region. But, it is concluded as mentioned above that the reception of over-horizon VHF signals is obviously due to the atmospheric perturbation. Since Hayakawa *et al.* (2007b) proposed a hypothesis on the generation mechanism of seismo-atmosphere perturbation due to the pre-seismic ground temperature variation.

5.3 *Summary of seismo-atmospheric effects*

We have reviewed seismogenic radio emissions in the atmosphere in possible association with EQs, including HF/VHF radio emissions, ULF/ELF radio emissions. Generally speaking, it is likely that those radio emissions take place in possible association with EQs, but there are very few attempts at any correlation statistics and also very few attempts to separate those seismogenic emissions from

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other noises. Therefore, the generation mechanism of these seismogenic emissions is extremely poorly understood or studied at the moment.

On the contrary, the study of seismo-atmosphere perturbations as studied by over-horizon VHF signals has greatly advanced recently, which indicates that the atmosphere is definitely perturbed before an EQ. The statistical study and direction finding studies have been very useful in elucidating the characteristics of seismo-atmospheric perturbations. Also, a generation mechanism has been recently proposed on the basis of the changes in geochemical quantities related to EQs, leading to the generation of radio ducts.

In the framework of this scenario one may also suppose that the increase of humidity and mean temperature in the atmospheric near-surface layer is accompanied by a weak fall-off of the atmospheric breakdown voltage. It is interesting to note in this connection that some strange phenomena such as sheet lightning/heat-lightning, luminescence of mountain tips and fog regions were occasionally observed prior to and during strong EQs. The above assumption is in favour of this fact, although we are not sure whether these intriguing phenomena are really related to EQs. Finally, some aspects we wish to emphasize are summarized as follows:

(1) It seems that seismogenic emissions in a wide frequency from ULF/ELF to VHF are generated, possibly in association with EQs, but the presence of those emissions cannot be fully established before detailed statistical correlation studies are done.
(2) We have assumed that the tectonic activity in the fault zone could trigger a weak increase in the ground surface temperature, underground water lifting and gas emanation, which, in turn, results in some variation of the humidity in the near surface layer of the atmosphere, followed by changes in the atmospheric refractive index and possibly in the breakdown voltage.
(3) The appearance of over-horizon VHF signals and the increase in the ground surface temperature in seismo-active regions may result from the general origin that is heating the ground surface due to gradual groundwater squeezing out from the higher depths towards the Earth's surface or due to a weak greenhouse effect.
(4) All the effects treated here seem to be sporadic and case sensitive, since they depend on meteorological conditions, diurnal and seasonal variation of the air humidity, proximity of the coastline, etc. Further experiments are necessary to sort out this interesting problem in seismically active regions in order to elaborate the theoretical consideration presented in this section.

6. Electromagnetic effects in the ionosphere

We report on the electromagnetic effects taking place in the ionosphere possibly associated with EQs. Initially, we discuss the lower ionospheric effects, and then the upper ionospheric effects.

6.1 *Perturbations in the lower ionosphere*

Most of the energy radiated by VLF/LF transmitters is trapped between the ground and the lower ionosphere, forming the Earth–ionosphere waveguide. Subionospheric

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VLF/LF signals reflect from the D-region of the ionosphere, probably the least studied region of the Earth's atmosphere (Rodger and McCormick 2006). These altitudes ($\sim$ 70–90 km) are too far for balloons and too low for satellites, and the only possible method of probing this D region is VLF/LF subionospheric radio signals.

Any variations in the ionospheric D/E-region lead to changes in the propagation conditions for VLF waves propagating subionospherically, and hence changes in the observed amplitude and phase of VLF/LF transmissions are due to different kinds of perturbation sources: (1) solar flares, (2) geomagnetic storms (and the corresponding particle precipitation), (3) the direct effect of lightning (e.g. Rodger and McCormick 2006). In addition to these solar-terrestrial effects we can suggest one more effect of EQs (or seismic activity) on the lower ionosphere (Hayakawa 2007, 2009b).

The first attempt of VLF/LF radio sounding for seismo-ionospheric effects was made by Russian colleagues (Gokhberg *et al.* 1989, Gufeld *et al.* 1992), who studied the VLF propagation over a long distance from Reunion (Omega transmitter) to Omsk to detect any effect of an EQ on the Caucasia region. Then, they succeeded in finding out a significant propagation anomaly over the two long-distance paths from Reunion to Moscow and also to Omsk a few days before the famous Spitak EQ (Gufeld *et al.* 1992).

The most convincing result of the seismo-ionospheric perturbations with VLF sounding was obtained by Hayakawa *et al.* (1996b) for the famous Kobe EQ in 1995 (with a magnitude of 7.3 and a depth of 20 km). Some important peculiarities in their paper are summarized as follows: (1) the propagation distance (from Tsushima Omega to Inubo observatory) is relatively short-path at VLF ($\sim$ 1 Mm) as shown in figure 13(*a*), compared with $5\sim9$ Mm used in Russian papers (Gokhberg *et al.* 1989, Gufeld *et al.* 1992); and (2) they found that the fluctuation method used before was not so effective for the short-propagation path, so they developed another method of analysis. That is, they paid attention to the terminator times (morning and evening). They found significant shifts in the terminator times before the EQ, as shown in figure 13(*b*). The morning terminator time (t_m) shifts to the early hours, while the evening terminator time, t_e shifts to later hours. This point was statistically examined by a much longer database of ±4 months, which indicates that the shift in t_e (phase) in figure 13(*b*) is found to exceed well above twice the standard deviation (2σ) (σ, standard deviation). This means that the daytime felt by subionospheric VLF signals is elongated for a few days around the EQ, and the theoretical estimation (Hayakawa *et al.* 1996b, Molchanov *et al.* 1998, Yamauchi *et al.* 2007) suggests that the lower ionosphere is lowered before the EQ.

A later extensive study by Molchanov and Hayakawa (1998) was based on the larger events during 13 years (11 events with magnitude greater than 6.0 and within the 1st Fresnel zone) for the same propagation path from the Omega, Tsushima to Inubo, and they came to the following conclusions.

(1) As for shallow (depth smaller than 30 km) EQs, four EQs out of five exhibited the same terminator time anomaly as for the Kobe EQ (as in figure 13(*b*)) (with the same 2σ criterion).
(2) When the depth of EQs is in a medium range of 30–100 km, two events were observed. One event exhibited the same terminator time anomaly, and another indicated a different type of anomaly.

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(3) Deep (depth larger than 100 km) EQs (four events) did not show 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 the terminator time anomaly) of the order of 70 ~ 80% for larger (magnitude greater than 6.0) EQs located relatively close to the great-circle path (e.g. the 1st Fresnel zone).

Here we have to explain how the shift in terminator times (figure 13) is related to the change in VLF reflection height (Hayakawa *et al.* 1996b, Molchanov *et al.* 1998). We have so far been using propagation paths for short-distance (up to a few Mm), so twe will use the wave hop method to estimate the characteristics of subionospheric VLF/LF propagation. The VLF/ LF signal received at a receiver (R) is composed of (1) ground waves and (2) sky waves. Sky waves stand for hop signals reflecting from the ionosphere, and the total (resultant) field is expressed with the help of a phase diagram in figure 14 (Yoshida *et al.* 2008). The phase difference of 1 hop wave (we consider only the 1 hop because the 2nd hop is weaker than the 1st hop) with respect to the ground wave (φ_1 in figure 14) would play an essential role in the diurnal VLF/ LF propagation. Figure 15 illustrates an example of the computations at a particular frequency of 40 kHz (JJY frequency), and the receiving station is assumed to be KCH (Kochi) (distance of 870 km). The top panel is the diurnal variation of the VLF reflection height, and the middle panel indicates the most important information on φ_1. When φ_1 is 180°, the ground and sky waves interfere destructively, and this is the reason why we have a terminator time just around sunrise and sunset as in the bottom panel of figure 15. As is easily inferred from this figure (though not shown as a figure, see Hayakawa (2009b)), the shift in terminator time as observed in figure 13 can be reasonably explained by the lowering of the ionosphere by a few kilometres.

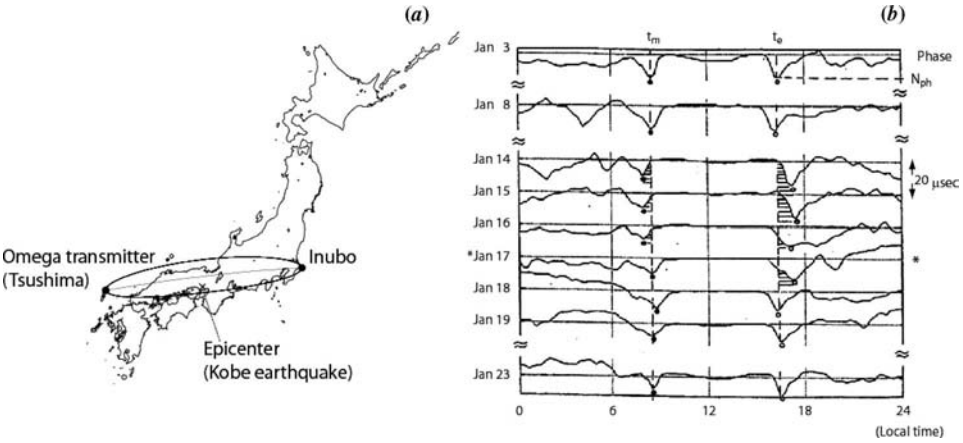

Figure 13. (*a*) Relative location of the very low frequency (VLF) transmitter (Omega, Tsushima), our observatory at Inubo and the EQ epicentre of the Kobe earthquake in 1995 (x). The first Fresnel zone is indicated. (*b*) The sequential plot of diurnal variation (phase) (nearly the same pattern as for amplitude) and we note the variation in t_m (morning terminator time) and t_e (evening terminator time). The shaded areas indicate anomalies as the shift from the monthly mean value.

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In response to the above-mentioned significant results (especially the result for Kobe EQ), the Japanese government conducted the integrated EQ frontier project, and the former National Space Development Agency of Japan (NASDA) conducted the so-called EQ Remote Sensing Frontier Project (for which the author was the principal investigator) during 1997 to 2001 (5 year project) (Hayakawa 2004, Hayakawa *et al.* 2004a,b). In this project our greatest attention was paid to the subionospheric VLF/LF propagation aimed at short-term EQ prediction. Figure 16 is the Japanese VLF/LF network established within the framework of the Frontier Project and is still working. There are seven observing stations (Moshiri (Hokkaido) (MSR), Chofu (Tokyo) (CHF), Tateyama (Chiba) (TYM), Shimizu (Shizuoka) (SMZ), Kasugai (Nagoya) (KSG), Maizuru (Kyoto) (MZR) and Kochi (KCH)), and we observe several transmitters simultaneously at each station, unlike the early VLF receiving system. The VLF/LF transmitters we now observe are (1) JJY (40 kHz, Fukushima), (2) JJI (22.2 kHz, Ebino, Kyushu), (3) NWC (19.8 kHz, Australia), (4) NPM (21.4 kHz, Hawaii) and (5) NLK (24.8 kHz, America). By using the combination of a number of observing stations and a large number of VLF/LF transmitters received, we will be able to locate the ionospheric perturbation with an accuracy of about 100 km. We make some comments on our system. Our VLF/LF receiver, named Japal, is designed to measure very slow and small changes in amplitude and phase. The magnitudes of slow phase and amplitude perturbations claimed for EQ precursors are much greater than this, so they should be detectable by our system if they exist.

Our VLF/LF system is deployed in different counties as well in response to their requests. One of our VLF/LF receivers is now working at Kamchatka in Russian with good data (Rozhnoi *et al.* 2004), and one is set in Taiwan as well (Hayakawa *et al.* 2010a). These stations, together with our Japanese dense network, form a

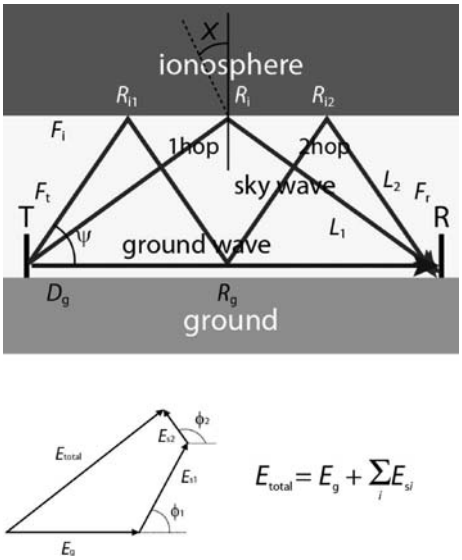

Figure 14. Very low frequency (VLF)/low frequency (LF) propagation modelling (ground and sky waves). Upper panel indicates the propagation scheme (transmitter (T), receiver (R), ground wave and sky waves), and the lower, a phasor diagram to obtain the resultant signal.

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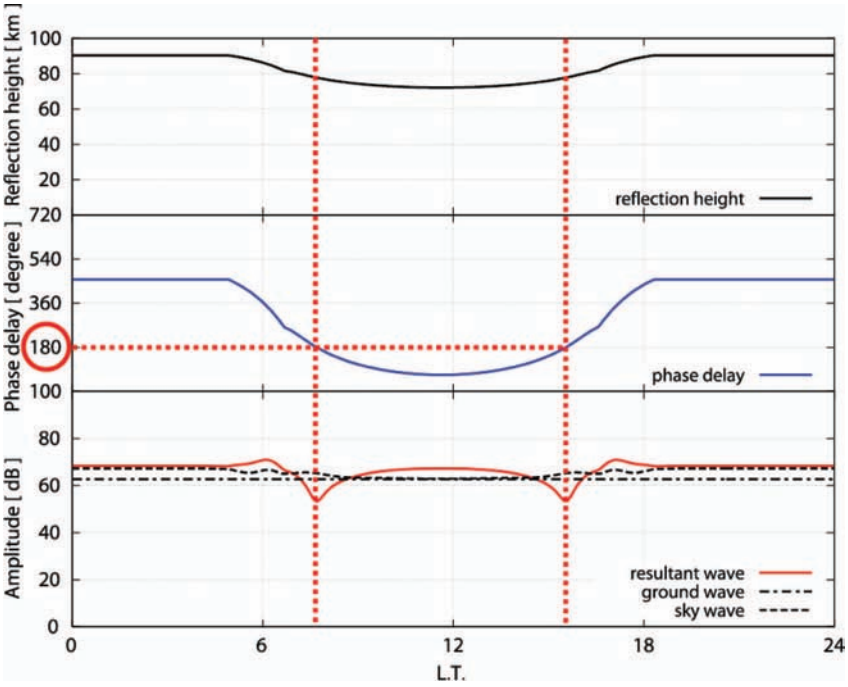

Figure 15. Diurnal variations of reflection height (top), phase difference between the ground and sky waves (middle), and the resultant wave (full line) (as a superposition of the ground and sky waves) (bottom).

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global Pacific VLF/LF network. Additionally, a few VLF/LF receivers were installed in Europe, and especially one in Italy is working well with significant results (Biagi *et al*. 2004).

By means of the above-mentioned Japanese VLF/LF network, we have been working on many case studies for large EQs: (1) Izu peninsula EQ swarm (with the largest magnitude of 6.3) in March, 1997 (with data from Tsushima, Omega to Chofu), (2) Tokai (Nagoya) area EQs (with data from NWC (Australia) to Kasugai (Nagoya) (Ohta *et al*. 2000), (3) Tokachi-oki EQ (25 September 2003, magnitude 8.3) (Shvets *et al*. 2004a, Cervone *et al*. 2006), (4) Niigata-chuetsu EQ (23 October 2004, magnitude 6.8) (Hayakawa *et al*. 2006, Yamauchi *et al*. 2007). Especially, in the case of Niigata EQ, we have made full use of our VLF/LF network observation (Yamauchi *et al*. 2007). That is, a comparison of the data on different propagation paths as a combination of several observing stations and several VLF/LF transmitter signals received, has enabled us to locate the ionospheric perturbations and to deduce their spatial scale. Also, their temporal dynamics have been inferred, together with the theoretical full-wave computations.

The terminator time method we developed for the first time, for the case of Kobe EQ, has been used so far as a standard analysis method of VLF/LF records. In addition to this terminator time method, there is another method of VLF/LF data analysis, which is called the 'night-time fluctuation method'.

Here, we present a few of our latest results by using our VLF/LF radio sounding. First, we present a result on the statistical correlation of ionospheric perturbations as

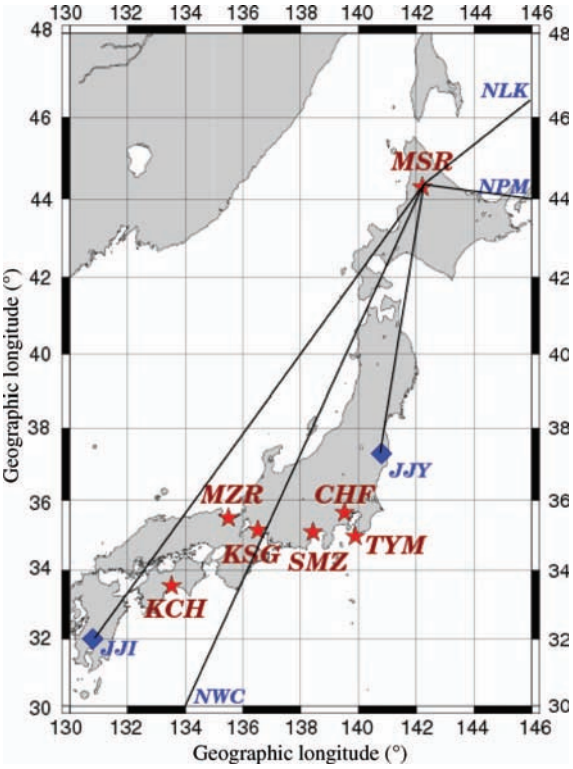

Figure 16. Very low frequency (VLF)/low frequency (LF) network in Japan. Several observing stations (Moshiri (abbreviated as MSR), Chofu (CHF), Tateyama, Chiba (TYM), Shimizu (SMZ), Kasugai (KSG), Maizuru (MZR), and Kochi (KCH)) and several VLF/LF transmitter signals detected at each station. The situation for one station (MSR) is indicated, and the receiving transmitters are two Japanese transmitters (JJY, JJI) and three foreign transmitters (NWC (Australian), NPM (Hawaii), NLK (USA)).

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detected by subionospheric VLF/LF radio sounding with the EQs (Hayakawa *et al.* 2010b). Then, we present a case study as detected in Japan for the huge Indonesia Sumatra EQ (Horie *et al.* 2007a,b).

6.1.1 Statistical study on the correlation between ionospheric perturbations and EQs. In addition to the event studies it is highly necessary to undertake any statistical study on the correlation between ionospheric disturbances and EQs based on an abundant data source. There have been very few reports on the statistical correlation between ionospheric perturbations and EQs (Shvets *et al.* 2002, 2004b, Rozhnoi *et al.* 2004). Shvets *et al.* (2004b) examined a very short-period (March–August 1997) of data for two paths (one is the Tsushima-Chofu and the other is the NWC-Chofu) and found that wave-like anomalies in the VLF Omega signal with periods of a few hours (as indicative of the importance of the atmospheric gravity wave (AGW) as suggested by Molchanov *et al.* (2001) and Miyaki *et al.* (2002)) were observed 1–3 days before or on the day of moderately strong EQs with magnitudes greater than 5.5. Then, Rozhnoi *et al.* (2004) extensively studied 2 years of data of the subionospheric LF signal along the path Japan (call sign, JJY) to Kamchatka (distance = 2300 km), and found from the statistical study that the LF signal effect is

observed only for EQs with magnitude, at least, greater than 5.5. Maekawa *et al.* (2006) and Kasahara *et al.* (2008) used a much longer dataset, but following we show our latest result (Hayakawa *et al.* 2010b) on the basis of the longest period of 7 years.

Figure 17 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. Recently we established a few more stations to elaborate our VLF/LF network: one in Kamchatka (KCK) and another in Taiwan (TWN) (Hayakawa *et al.* 2010a). 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 figure 17.

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

The transmitter frequency of the JJY transmitter is 40 kHz and its transmitter power is 10 kW. While the JJI transmitter is characterized by a frequency of 22.2 kHz, but with unknown power due to 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 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. Only the amplitude data are analysed, 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 a total of 7 years from 1 January 2001 to 31 December 2007 (to be more exact, up to 31 October 2007 only for the paths, JJY–KCK and JJI–KCK).

Based on previous statistical studies by Rozhnoi *et al.* (2004), Maekawa *et al.* (2006a) and 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 in this study as a rather severe criterion for selecting EQs. By imposing this condition, we have found 37 EQs that took place within the wave sensitive areas defined by the 5th Fresnel zones of the great-circle paths.

We tentatively divide the EQ depth by a depth of 40 km in order to find the dependence on EQ depth. As is seen from the configuration of the propagation paths in figure 17, we can imagine that some EQs are common on a few propagation paths. In the case of shallow EQs (depth < 40 km), 3 EQs are common for 3 paths and 13 EQs are common for 2 paths. Similarly, for deep EQs (depth > 40 km), 4 EQs are seen for 3 paths and 16 EQs are common on 2 paths. The total number of propagation paths that cover the EQs with depths smaller than 40 km, is 35, while the corresponding number is 38 for EQs with depths larger than 40 km. We treat the data for each propagation path as being independent events, so the total number of events is 73.

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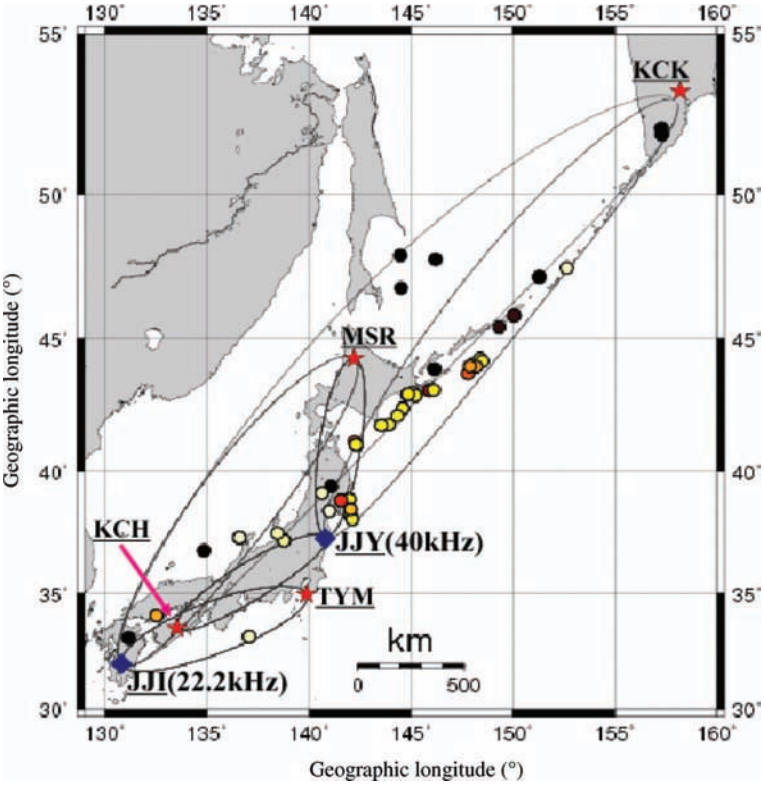

Figure 17. Relative locations of two Japanese transmitters (call signs, JJY (40 kHz, Fukushima) and JJI (22.2 kHz, Ebino, Kyushu) indicated by blue diamonds) and four observing stations (Moshiri (MSR), Kamchatka (KCK), Kochi (KCH) and Tateyama, Chiba (TYM)) in red stars. The earthquakes treated are also plotted, with their colour indicating the earthquake depth. Wave sensitive areas (defined by 5th Fresnel zone) are also plotted for all propagation paths. Available in colour online.

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 terminator time method, and then they found that the anomaly in the terminator time 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.

There have so far been proposed two specific methods of analysis of sub-ionospheric VLF/LF data. The first one is called the 'terminator time' method, in which we trace the terminator times around sunrise and sunset and try to find an anomalous shift as already seen in figure 13 in the case of the Kobe EQ (Hayakawa *et al*. 1996b). The second one is the 'night-time fluctuation' method, in which we pay particular attention to the data during the local night-time and we estimate the mean night-time amplitude, dispersion and night-time fluctuation etc. (Shvets *et al*. 2002, 2004b, Rozhnoi *et al*. 2004). This night-time fluctuation method has also been used in the following statistical studies (Maekawa *et al*. 2006a, Kasahara *et al*. 2008). Of course, we have to state that these two methods are very complimentary to each other in the subionospheric VLF/LF data analysis.

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Here we use the 2nd night-time fluctuation method, and we briefly describe the analysis method. Figure 18 illustrates the diurnal variation (amplitude) for one particular path on a particular day in UT (given in red), in which you can clearly identify the evening and morning terminator times (both defined in LT). The local night-time period is indicated in shadow. We define the difference (or residue) as follows.

$$\mathrm{d}A(t) = A(t) - < A(t) > \tag{1}$$

where $<\mathrm{A}(t)>$ is the amplitude at a time t on a current day and $<A(t)>$ is the running average at the same time t over ± 15 days (before and after the relevant day). The residue is plotted in the lower part of figure 18, and by using this kind of figure we estimate the following three physical quantities of amplitude (as in Rozhnoi *et al.* 2004, Maekawa *et al.* 2006): (1) trend (as the average of night-time 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) night-time fluctuation (NF)

$$\text{trend} = \frac{\int_{N_\mathrm{s}}^{N_\mathrm{e}} \mathrm{d}A(t)\mathrm{d}t}{N_\mathrm{e} - N_\mathrm{s}} \tag{2}$$

$$\mathrm{NF} = \int_{N_\mathrm{s}}^{N_\mathrm{e}} (\mathrm{d}A(t))^2 \mathrm{d}t \tag{3}$$

where N_s and N_e are the times of starting and ending the night-time in our analysis (we have decided $N_\mathrm{s} = 11$ h UT and $N_\mathrm{e} = 18$ UT after looking at the diurnal variations) and we know that $\mathrm{d}A(t) < 0$ is essential for our seismogenic effects (Rozhnoi *et al.* 2004, Maekawa *et al.* 2006) so that only $\mathrm{d}A(t) < 0$ is used for the estimation of NF. Our former studies (Maekawa *et al.* 2006, Kasahara *et al.* 2008) have indicated that any seismogenic effect is characterized by the almost simultaneous significant decrease in trend and significant increases in dispersion and 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. It is highly necessary to have homogeneous treatment of the VLF/LF data when we analyse 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 $<\text{trend}>$ over ± 15 days around this date. Then, the normalized trend (trend*) is defined as $(\text{trend}-<\text{trend}>)/\sigma_\mathrm{T}$ (where σ_T is the standard deviation over ± 15 days around the current date). The same principle is applied to other quantities in order to obtain the normalized D (D*) and the normalized NF (NF*).

By using these normalized (or standardized) trends, D and NF, we make full use of a superimposed epoch analysis (e.g. Maekawa *et al.* 2006, Liu *et al.* 2006), which is

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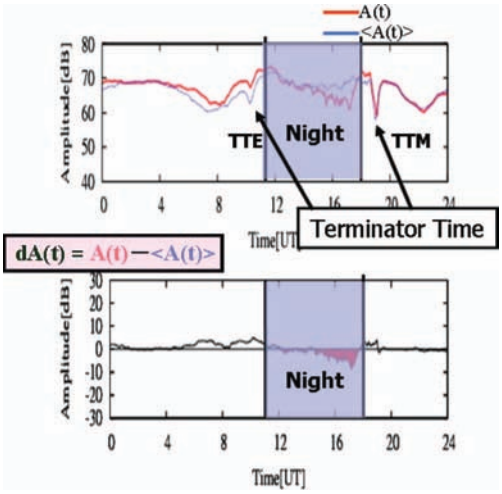

Figure 18. Explanation of analysis of very low frequency (VLF)/low frequency (LF) amplitude data. Top panel indicates the diurnal variation (in red) for a particular path on a particular day ($A(t)$) and the variation (in blue) averaged over ± 15 days of the day ($<A(t)>$). The bottom refers to the difference of $dA(t) = A\ (t)\text{-}<A\ (t)>$ (as a residue). Available in colour online.

of extreme importance in enhancing the signal-to-noise ratio by stacking the data with the EQ day as a reference day. Already we have chosen a 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 qualitatively.

Figures 19(*a*), (*b*), (*c*) are the final results on the basis of superimposed epoch analysis. Figure 19(*a*) refers to the trend*, while figure 19(*b*), the D* and figure 19(*c*), the NF*. We can deduce from these figures the following definite correlation between VLF/LF propagation anomalies (i.e. ionospheric perturbations) and large and shallow EQs.

(1) The trend (or trend* in figure 19(*a*)) 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 5 days before the EQ as a conspicuous peak. When the EQ depth becomes larger (e.g. more than 40 km in figure 19(*a*)), a similar tendency is likely to be observed in the blue line in figure 19(*a*) 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 night-time dispersion (D*) for EQ depths smaller than 40 km (in red) in figure 19(b) is found to exhibit a significant increase 3 days before the EQ (exceeding the $2\sigma_D$ criterion and even approaching the $3\sigma_D$ level). However, when the EQ depth becomes larger than 40 km (the blue line in figure 19(*b*)), there is no clear precursory effort before such a deep EQ.

(3) Figure 19(*c*), concerning the NF, is found to indicate significant enhancements only before the EQ ($5\sim6$ days before the EQ) exceeding the $2\sigma_{NF}$ criterion. No such enhancements in NF are detected for EQs with depths larger than 40 km.

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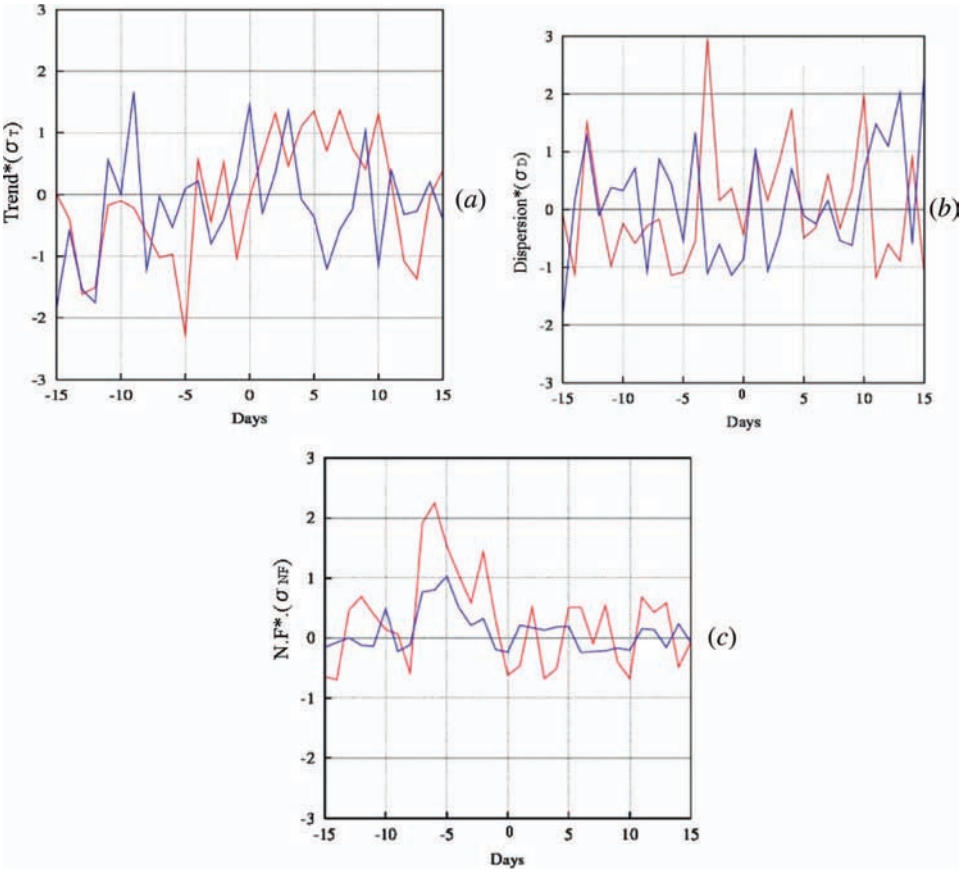

Figure 19. Superimposed epoch analysis for the normalized trend (trend*) (*a*), the normalized dispersion (D) (dispersion*) (*b*), and the normalized night-time fluctuation (NF*) (*c*). The red line refers to shallow earthquakes (depth < 40 km), and the blue line refers to an earthquake with a depth larger than 40 km. The abscissa indicates the day with respect to the earthquake day (0), – is the day before the earthquake and + is the day after the earthquake. Available in colour online.

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6.1.2 Case study of Sumatra EQ in December 2004 (ground-based VLF reception in Japan and satellite observation of VLF signals). This section is concerned with a recent case study for the Sumatra EQ by means of the VLF data on the propagation between the NWC VLF transmitter (Australia) (21.82° S, 114.15° E) to Japan (Horie *et al*. 2007a,b). Because this EQ is extremely huge, it is worthwhile studying whether this EQ has a certain effect on the lower ionosphere. If the effect exists, we would like to study the characteristics and dynamics of those perturbations.

A huge EQ happened on the west coast of the Sumatra islands on 26 December 2004. The magnitude of this EQ is 9.3 and the focal depth is 30 km. The epicentre is located at the geographic coordinates 3.31° N, 95.95° E. As shown in figure 20, the epicentre of this EQ is located as a large circle (12/26), which is found to be far away (about 2 Mm) from the great-circle paths from the NWC VLF transmitter (also shown in figure 20) and three Japanese receiving points (Chiba (abbreviated as TYM), Chofu (CHF) and Kochi (KCH)).

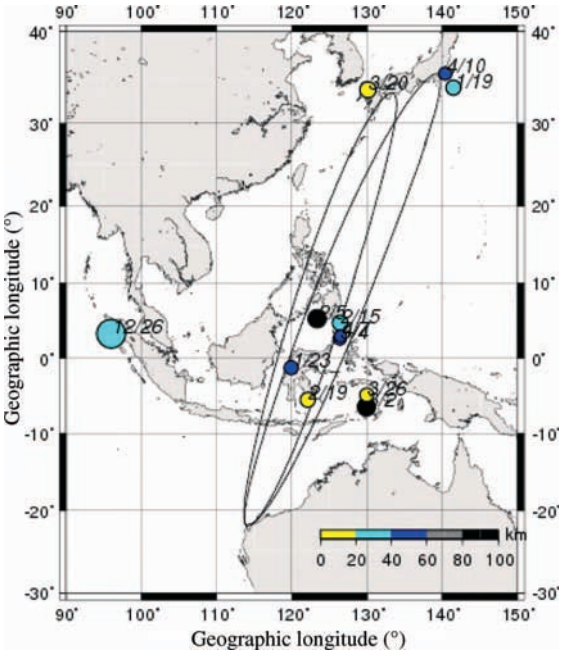

Figure 20. Propagation paths from the transmitter, NWC (in Australia) to the two receiving sites (Kochi and Chofu) in the case of the Sumatra earthquake in 2004. The fifth Fresnel zone for each propagation path is indicated. The earthquakes with magnitudes greater than 6.0 within and just close to the very low frequency (VLF) sensitive zone during years 2004 and 2005 are all indicated. The centre of each circle corresponds to the earthquake epicentre, and the size of the circle indicates the earthquake magnitude. The colour of the earthquakes during the period of November 2004 to May 2005 indicates the earthquake depth. The date of the earthquake is indicated beside the circle (i.e. 4/10 means 10 April). The Sumatra earthquake is far away from the great-circle paths, but it is indicated (12/26). Available in colour online.

We pay particular attention to the period around the Sumatra EQ; that is, the period from the middle of November 2004 to May 2005. In figure 20 we plotted only two propagation paths. During the period from the middle of November 2004 to May 2005, we have indicated the epicentres of the EQs with magnitudes greater than 6.0 and close to our propagation paths. The centre of each circle indicates the EQ epicentre, and its size is proportional to the magnitude. The colour of the circle indicates the depth with a step of 20 km.

As shown in figure 20, the propagation path is approximately in the N–S meridian plane, so that the terminator time method is not so effective for this path. Because the terminator time method is effective mainly for the E–W propagation direction (Maekawa and Hayakawa 2006), we have adopted the night-time fluctuation analysis. Figure 21 is the sequential plot of NF (defined before) of the NWC signal observed at the three observing sites (Tateyama, Chiba (TYM), Chofu (CHF) and Kochi (KCH)). It is easy to understand qualitatively that there is an increased fluctuation in the NF (defined before) at all the stations. Then, we will estimate this NF quantitatively, and we have one dataset for each day.

The fifth Fresnel zone shown in figure 20 is already found to be useful and effective as the VLF sensitive zone for EQs with magnitudes of 6.0 to 7.0 (Hayakawa *et al.* 1996b, Molchanov and Hayakawa 1998), when we think of the possible size of the

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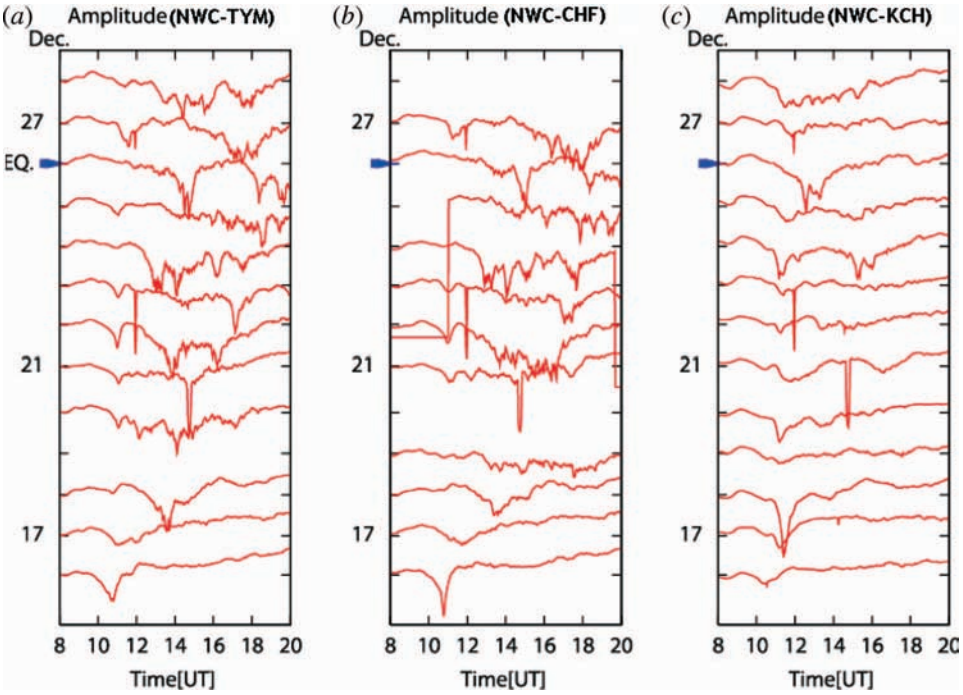

Figure 21. Sequential plot of night-time amplitude data of the NWC signal as observed at three Japanese observing stations (*a*) TYM, (*b*) CHF and (*c*) KCH. The date goes from the bottom to the top, and the earthquake date is given by EQ. Time is given in UT, so the Japanese local time (LT) is given by UT + 9 h.

seismo-ionospheric perturbations. This Sumatra EQ was extremely huge (magnitude 9.3), so we expect an extremely large area of ionospheric perturbations for this EQ. By simply using either the formula on the preparation zone size by Dobrovolsky *et al.* (1979) or the empirical formula on the size of ionospheric perturbations by Ruzhin and Depueva (1996), the radius of the preparation zone or possible ionospheric perturbations is estimated to be of the order of $7 \sim 8$ Mm. The empirical formula by Ruzhin and Depueva (1996) is mainly based on events mainly up to magnitude of 7.0 or so, so it is questionable for us to use this formula up to magnitude 9.3. However, it may be reasonable to anticipate that the VLF propagation path from the transmitter, NWC to the Japanese VLF sites is definitely influenced very much, or perturbed because the distance of the epicentre from the great-circle path is only 2 Mm.

As already shown by Horie *et al.* (2007a), the geomagnetic activity just around the Sumatra EQ (e.g. $\pm$one month around the EQ) is found to be relatively quiet except just after the middle of January 2005 when the ΣKp exceeds 40 (disturbed). For example, in December 2004, we found relatively quiet geomagnetic activity. We look at the VLF fluctuations just before the Sumatra EQ. It is very fortunate that we find a very prolonged seismically quiet period before the Sumatra EQ. Figure 22 is the extended figure for the limited time period just around the EQ time. However the temporal evolutions of the NF at three stations can now be seen (Chiba in black, Chofu in blue and Kochi in pink), together with the corresponding running value of m (mean) $+2\sigma$ (standard deviation) over ± 15 days (in the same colour). We notice

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one sharp peak on 8 December 2004 and a prolonged maximum during the period of 21 December 2004 to 2 January 2005. In the case of the fluctuation enhancement on 8 December 2004, we notice a significant enhancement at Chiba (in black) exceeding the $(m + 2\sigma)$ line. However, the fluctuation at Chofu (in blue) is not found to exceed the $(m + 2\sigma)$ line (given in the figure in pink) and also there is no enhancement at all at Kochi (in red). Taking into account these facts, we may conclude that the amplitude fluctuation takes place significantly only at Chiba, which means that this enhancement on 8 December 2004 might be the effect only for the NWC-Chiba path. Next we discuss the prolonged period of amplitude fluctuation during the period of 21 December 2004 to 2 January 2005. During this period we notice a simultaneous enhancement in fluctuations at the three observing sites (Chofu (in blue), Chiba (in black) and Kochi (in red)), which means that this prolonged fluctuation is global, and the NWC–Japan propagation path is strongly disturbed. The fluctuation at Chofu (in blue) is found to significantly exceed the $(m + 2\sigma)$ line at Chofu a few days before the EQ. Also, we recognize similar and significant enhancements in Chiba and also in Kochi. You can notice the excess of the NF over the corresponding $(m + 2\sigma)$ line both at Chofu and Kochi. Even after the main shock (magnitude 9) on 26 December 2004, several aftershocks occurred on 1–4 January 2005 with magnitudes ranging from 6.1 to 6.7. In correspondence with this high seismic activity, prolonged VLF fluctuation has been observed from 21 December 2004 to 2 January 2005.

When we look at the temporal evolutions in figure 21, we can easily identify clear wave-like structures in the data. Our visual inspection could give us an idea that clear wave-like structures exist, for example, on 16, 24 and 26 December 2004. These structures are quantitatively investigated by means of the wavelet and cross-correlation analyses. It is expected that these fine structures with wave-like properties could provide us with information on how the ionosphere is perturbed in association with EQs.

We perform the wavelet analysis with a mother wavelet of the complex Morlet to the difference $\mathrm{d}A(t)$ (Shvets *et al.* 2004a,b; Rozhnoi *et al.* 2004, Maekawa *et al.* 2006), and compute the spectral intensity of the VLF fluctuation $\mathrm{d}A$. Next we quantitatively estimate the time delay between these two stations by using the cross-correlation method. As a result of this analysis, we have found that the fluctuations in amplitude ($\mathrm{d}A(t)$) are very enhanced in the period of 20–100 min before the EQ. The further epoch analysis indicates the clear presence of time delays or wave-like structures before the EQ. The period of fluctuation is confirmed to range from 20 to 30 min to above 100 min, and the time delay at Chiba is around 2 h with respect to Kochi. There is no significant frequency dependence (dispersion) in the time delay. So the presence of such wave-like structures is likely to be a precursory signature of this EQ.

Before the EQ, we noticed an enhancement in the fluctuation spectra in the frequency range from 20 to 30 min to about 100 min. This period corresponds to that of AGW (30 to 180 min) (Grossard and Hooke 1975, Hooke 1977) and this AGW is considered to be a possible and promising candidate for lithosphere–ionosphere coupling (Molchanov *et al.* 2001, Miyaki *et al.* 2002, Shvets *et al.* 2004a,b). The wavelet at Chiba is delayed by about 2 h with respect to that at Kochi, which is indicative of its propagating nature from the epicentre towards the outside. On the assumption that the wave is propagating radially from the epicentre, we can estimate the propagation distance between NWC–KCH and NWC–TYM to be $\simeq$ 150 km. So we can estimate the wave propagation velocity of our wave-like

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fluctuation to be about 20 m s^{-1}. This value seems to be in good agreement with the theoretical estimation of AGWs (Kichengast 1996, Hooke 1968). The experimental evidence on the wave like fluctuations as a precursor to this Sumatra EQ might be considered to be evidence of the important role of AGW for lithosphere–ionosphere coupling. Further details have appeared in Horie *et al.* (2007b).

The same NWC signals have been detected on board the French satellite DEMETER (Detection of Electro-magnetic Emissions Transmitted from Earthquake Regions), which has indicated that the signal to noise ratio (the ratio of the VLF signal to the background noise) is found to be significantly depressed during one month before the EQ, and that the diameter of the ionospheric perturbation as seen on the satellite is about 5 Mm (Molchanov *et al.* 2006). This satellite finding on the presence of the ionospheric perturbation in association with the Sumatra EQ and its spatial scale is found to be further evidence for our ground-based VLF finding.

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6.2 *Perturbations in the upper ionosphere*

It is becoming more convincing that the upper ionosphere (i.e. the F region) is also perturbed prior to an EQ as for the lower ionosphere (Liu *et al.* 2006). Please refer to a recent review on this topic by Liu (2009), in which you can enjoy the case studies and statistical studies on the correlation between ionospheric perturbations and EQs.

6.3 *Satellite observation of seismo-electromagnetic effects*

The results of satellite observations of different physical parameters of the ionosphere (plasma density, particle composition, high-energy particles, electromagnetic waves etc.) have been summarized in Parrot (2009), which we advise you to consult.

6.4 *Summary of seismo-ionospheric perturbations and the lithosphere–ionospheric coupling mechanism*

Even though it seems highly likely that the ionosphere is disturbed before an EQ, it is poorly understood how the ionosphere is perturbed by the precursory seismic activity in the lithosphere. Hayakawa *et al.* (2004a,b) have already proposed a few possible hypotheses on the mechanism of coupling between lithospheric activity and the ionosphere: (1) chemical (+ electric field) channel; (2) acoustic and gravity wave channel; and (3) electromagnetic channel. As for the first channel, the geochemical quantities (such as surface temperature, radon emanation) induce the perturbation in the conductivity of the atmosphere, leading to ionospheric modification through the atmospheric electric field (e.g. Pulinets and Boyarchuk 2004, Sorokin *et al.* 2006). The second channel is based on the key role of atmospheric oscillations in the lithosphere–atmosphere–ionosphere coupling, and the perturbation in the Earth's surface (such as temperature, pressure) in a seismo-active region excites the atmospheric oscillations travelling up to the ionosphere (Molchanov *et al.* 2001, Miyaki *et al.* 2002, Shvets *et al.* 2004a,b). The last mechanism is that the radio emissions (in any frequency range) generated in the lithosphere propagate up to the ionosphere, and modify the ionosphere by heating and/or ionization. But this mechanism is found to be insufficient because of the weak intensity of lithospheric radio emissions (Molchanov *et al.* 1995). So the 1st

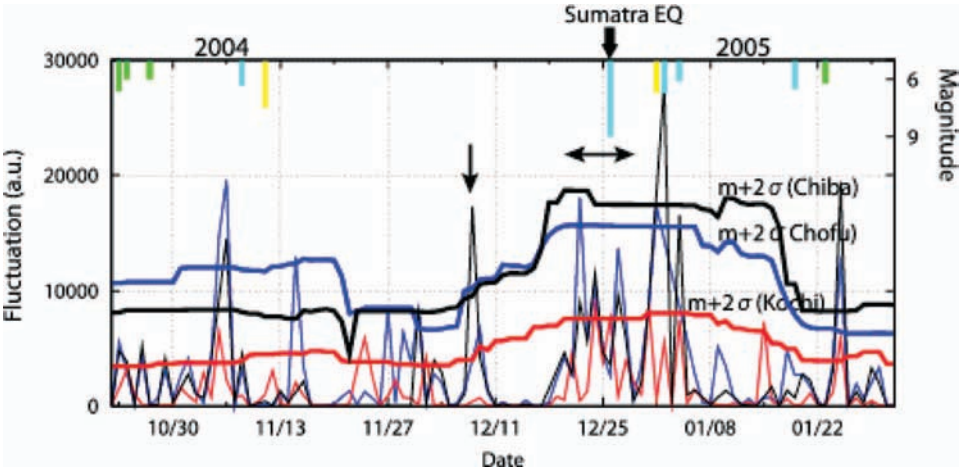

Figure 22. Temporal evolution of very low amplitude (VLF) amplitude night-time fluctuation (dA^2) at the three observing stations (Chofu (blue), Chiba (black), and Kochi (red)). The red line indicates (m (mean)+2σ (σ is the standard deviation)) at Chofu and the corresponding lines refer to Chiba and Kochi. The earthquake with a magnitude greater than 6.0 is plotted downwards, and the earthquakess during the restricted period of November 2004 to May 2005 are characterized by different colours (the colour indicates the depth). Available in colour online.

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and 2nd mechanisms are likely candidates for this coupling (Molchanov and Hayakawa 2008).

The results in §6.1 suggested the important role of AGWs in lithosphere–atmosphere–ionosphere coupling. The observational evidence is, however, not great, so we need to accumulate more facts on the generation mechanism. We can say the same thing for the 1st mechanism of the chemical channel, and the subject itself is extremely interesting and challenging. Recently, Molchanov and Hayakawa (2008), Hayakawa (2009b), Molchanov (2009) and Pulinets (2009) have discussed lithosphere–atmosphere–ionosphere coupling in detail.

7. Conclusions

The field of seismo-electromagnetics is defined by the studies of electromagnetic phenomena and effects associated with EQs for the sake of short-term EQ prediction. This review consists of some history and our latest results on a few selected topical subjects of seismo-electromagnetics including ULF emission in the lithosphere, seismo-atmospheric perturbations, seismo-ionospheric perturbations, lithosphere–atmosphere–ionosphere coupling. This new science field is very interesting, attractive and challenging, not only from a scientific point of view, but also is of potential importance as a promising candidate for short-term EQ prediction to mitigate EQ disaster in EQ-prone countries such as Japan.

We would like to mention here that former mechanical (seismic) measurements provide seismologists with the macroscopic information of an EQ in the lithosphere just after its occurrence, which would be useful for studying the EQ mechanism, but which seem to be useless for short-term EQ prediction. Our electromagnetic (non-seismic) effects are likely to be associated with microscopic effects of the lithosphere,

appearing mainly prior to an EQ. Also, those electromagnetic efforts can propagate over considerable distances in the lithosphere, though, of course, this depends on wave frequency. These two properties of precursory occurrence and long-distance propagation of electromagnetic efforts are decisively superior to conventional seismic measurement.

Although EQ prediction is not practical and a reality, we have numerous observations to understand the associated processes. Depending on the type of physical parameters (local or integrated measurements), the number of reliable events is different. The number of ULF events is still very small, so we need to increase the number of reliable events as much as possible for statistical correlation with EQs. On the other hand, the number of events of seismo-atmospheric and seismo-ionospheric perturbations is already sufficient for statistical correlations with EQs. We still have to explore the mechanism of lithosphere–atmosphere–ionosphere coupling as the final goal of seismo-electromagnetics. For this purpose, any coordinated measurements collecting different parameters reflecting the lithospheric information (i.e. ULF emissions, acoustic emissions), atmospheric information (ELF/VLF and VHF emissions, atmospheric perturbations by VHF signals etc.) and ionospheric information (D region monitoring by VLF/LF signals, ionosonde observations (f_o F2), TEC observation, satellite observation etc.), are highly necessary for the near future.

Finally we would like to ask the readers to understand that our seismo-electromagnetics is of a non-seismic nature. Although we know that the initial agent of our seismo-electromagnetics is at any rate due to the mechanical effect (not macroscopic, but microscopic) in the lithosphere, the main science fields are electromagnetics, radiophysics and engineering, geophysics, atmospheric electricity, atmospheric physics and chemistry, plasma physics, upper atmospheric physics, signal processing etc. with seismology and geology just providing us with fundamental information on the lithosphere.

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