Earthquake Precursor Studies in Japan

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ABSTRACT

The purpose of this chapter is to review earthquake precursor studies in Japan. Among the long-, medium-, and short-term earthquake predictions that result from the study of precursors, the most meaningful are the short-term predictions because of their immediate effect on human lives. Very few investigations of earthquake precursors in Japan were undertaken before the 1995 Kobe M 6.9 earthquake, but extensive studies started after that event. The most important finding during the past two decades is that many of earthquake precursors are electromagnetic rather than seismological. Two Japanese frontier projects during the years of 1996–2001, in particular, have contributed very much to the progress of seismo-electromagnetics. Electromagnetic phenomena in possible association with earthquakes have been reviewed here with special reference to those achievements made during and after the frontier projects. Stimulated by the success of these Japanese frontier projects, national precursor studies projects devoted to earthquake prediction have been developed in different countries. In addition, several precursors are described (not only electromagnetic, but also of ground movements) that were associated with the M 9 Tōhoku mega-earthquake of 2011. Future directions of earthquake precursor studies and short-term earthquake prediction are considered, and conclusions are presented.

2.1. INTRODUCTION

In the context of earthquake prediction, people use the same terminology in totally different ways, and this results in confusion. Earthquake prediction can be classified into the following three types depending on the timescale considered [e.g., *Uyeda*, 2013; *Hayakawa*, 2015]: long-, medium-, and short-term prediction. Long-term prediction involves a timescale of hundreds to thousands years, which can be studied on the basis of plate tectonics, activity of earthquakes, anecdotal records, fault records, archeological survey, etc. Medium-term prediction involves a few decades to a few years, and uses databases of seismicity and crustal movements. Using an earthquake catalog it is possible to evaluate the long- and medium-term occurrence probability of a large earthquake in a certain area during a prescribed period. Long- and medium-term predictions, however, are mere statistical forecasts, and should not be considered as real predictions.

Only short-term earthquake prediction based on reliable earthquake precursors is of real value, but it must specify three important parameters of an impending earthquake: the time (when), the position or epicenter (where), and the prospective magnitude (how big—a few days to 1 week before an earthquake). Although success is very difficult to achieve, short-term earthquake prediction is the only useful and meaningful form for protecting human lives and social infrastructures. The purpose of this chapter is to review earthquake precursor studies initiated after the 1995 Kobe M 6.9 earthquake, then to emphasize the importance of electromagnetic phenomena in short-term earthquake prediction, and finally to present future directions of earthquake prediction study in Japan.

Before presenting earthquake precursor studies in Japan, it is necessary to briefly consider the history of general earthquake prediction in the field of seismology in Japan. The essential points that emerge from previous

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reviews on earthquake prediction in Japan [*Rikitake*, 2001a,b; *Uyeda*, 2012, 2013, 2015] are mentioned briefly. A national earthquake prediction project in the field of seismology started in 1965 and has continued to the present through consecutive 5-year plans. Unfortunately the approach involved in this project does not include short-term earthquake prediction. The general situation of this project for earthquake prediction has remained nearly the same, even after the 1995 Kobe earthquake and the 2011 Tōhoku M 9 mega-earthquake. Consequently precursor studies for earthquake prediction in Japan have been carried out extensively only after the 1995 Kobe earthquake, and we are very grateful to have been funded by the government during the years of 1996–2001 in the form of frontier projects (the only such governmental funding to date).

2.2. EARTHQUAKE PRECURSOR STUDIES IN JAPAN

2.2.1. General Description of Precursors

The purpose of this chapter focuses on earthquake precursor research by Japanese colleagues, and where necessary on important contributions by workers in other countries. Specifically, the following account is based mainly on my recent book [*Hayakawa*, 2015].

It goes without saying that short-term prediction absolutely requires study of earthquake precursors. There have been reports of many kinds of earthquake precursors, from ancient Greek times to the present [e.g., *Rikitake*, 2001a; *Molchanov and Hayakawa*, 2008; *Uyeda et al.*, 2008; *Hayakawa and Hobara*, 2010]. Earthquake precursor data can include geodetic signals such as tilt, Global Positioning System (GPS) data, hydrological data such as level, temperature, and chemistry of groundwater, electromagnetic fluctuations in various frequencies, emission of radon and other ionized gases, and anomalous animal behavior [*Rikitake*, 2001a]. Seismological events such as foreshocks and preseismic quiescence also can form precursor data. However, a majority of the reported earthquake precursor data found during the past few decades have been proven to be nonseismological, and such nonseismological (mainly electromagnetic) measurements were mainly undertaken after the 1995 Kobe earthquake [*Hayakawa*,1999, 2009, 2012, 2013; *Hayakawa and Molchanov*, 2002; *Pulinets and Boyarchuk*, 2004; *Molchanov and Hayakawa*, 2008]. As previously mentioned, however, these data were never treated seriously by the long-running Japanese seismological earthquake prediction project.

Figure 2.1 is a conceptual picture of different seismo-electromagnetic phenomena measured by different radiofrequency techniques, and Figure 2.2 summarizes a history of worldwide seismo-electromagnetic studies considered to be significant. The first two observational items in Figure 2.2 refer to the lithospheric effect, or direct effect of the lithospheric pre-earthquake phenomena. The third item is a seismo-atmospheric effect, and the last three items refer to the ionospheric effect. The first geoelectric current measurement has the longest history, including recent achievements of the Greek VAN method (named after its originators P. Varotsos, K. Alexopoulos, and K. Nomicos)[*Varotsos*, 2005]. The second, the study of ULF (ultra-low frequency: < 1 Hz) electromagnetic emissions started with the Spitak M 6.9 [*Kopytenko et al.*, 1990; *Molchanov et al.*, 1992] and Loma Prieta M 7.1 [*Fraser-Smith et al.*, 1990] earthquakes, and is of extreme importance in short-term earthquake prediction studies. Seismo-atmospheric perturbation, the third item in Figure 2.2, was discovered associated with the 1995 Kobe earthquake [*Kushida and Kushida*, 2002]. The last item of ionospheric perturbation has a relatively short history. Since the convincing evidence of ionospheric perturbation associated with the 1995 Kobe earthquake was found using subionospheric very-low-frequency (VLF 3–30 kHz) propagation [*Hayakawa et al.*, 1996a], there has been widespread use of VLF–LF (30–300 kHz) networks all over the world, including Europe, India, Russia, and South America. Stimulated by the discovery of ionospheric perturbations associated with the Kobe earthquake, many scientists devoted attention to the upper ionosphere (such as the F region) [*Pulinets and Boyarchuk*, 2004], because VLF–LF waves can monitor specifically the lowest part of the ionosphere. Statistical correlations have recently been established between the ionospheric perturbations (both in the lower and upper ionosphere) and earthquakes [*Liu*, 2009; *Hayakawa et al.*, 2010], which provide the potential to attempt to forecast any earthquake as a practical goal. The French satellite DEMETER (detection of electromagnetic emissions transmitted from earthquake regions), dedicated to the study of seismo-electromagnetics, was launched in 2004, and much scientific success has been achieved in the study of how the ionosphere is disturbed due to the lithospheric pre-earthquake effect [*Parrot*, 2012, 2013].

2.2.2. Japanese Research Activity

One more important point related to Figure 2.2 is that, as noted earlier, the seismo-electromagnetic group in Japan were funded only once just after the 1995 Kobe earthquake, and this is considered to be the commencement of extensive precursor studies in Japan [*Nagao et al.*, 2002]. Two institutions were asked to carry out a feasibility study of electromagnetic effects for short-term earthquake prediction over 5 years (1996–2001) in the framework of Earthquake Integrated Frontier by the former Science and Technology Agency (now MEXT

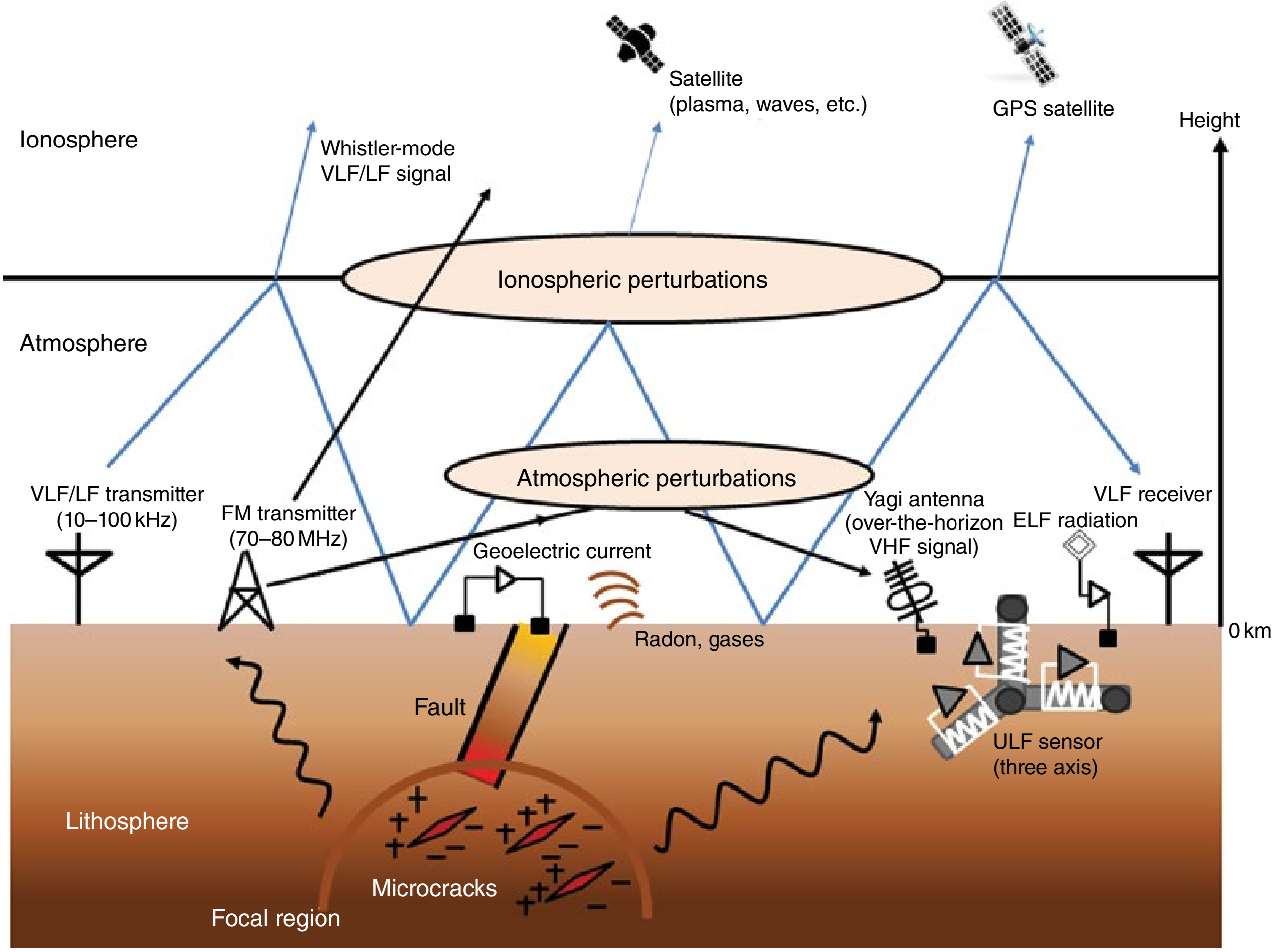

Figure 2.1 Conceptional general view of electomagnetic phenomena in possible association with earthquakes and different radiofrequency techniques to measure those electromagnetic effects.

(Ministry of Education, Culture, Sports, Science and Technology)): (a) RIKEN (Institute of Physical and Chemical Research) and (b) former NASDA (National Space Development Agency of Japan, presently JAXA). S. Uyeda led the RIKEN frontier project while the author led the NASDA frontier project.

The RIKEN group devoted their interests to installing VAN geoelectric measurement stations as in Greece, and finally about 40 stations were established all over Japan. They found geoelectric changes before four out of five $M > 5$ earthquakes [*Uyeda et al.*, 2004]. However, another important conclusion was that the presence of DC electric trains in Japan made it nearly impossible to observe the VAN geoelectric precursors in Japan, which has led them to abandon many geoelectric potential measurement stations and to concentrate their efforts where there are no DC trains. An outstanding finding was that they detected very significant precursors of DC and ULF electric and magnetic radiation before the volcano-seismic activity in 2000 in the Izu island region [*Uyeda et al.*, 2002a]. In addition, 19 anomalous changes in the telluric current were identified during the monitoring conducted on Kozu-shima Island about 170 km south of Tokyo from 14 May 1997 to 25 June 2000. *Orihara et al.* [2012] showed by rigorous statistics that correlation with nearby earthquakes was clearly beyond chance. Also in the Izu island region, anomalous changes in the ULF range (0.01 Hz), starting from a few months before the 2000 major volcano-seismic swarm activity, were observed in both geoelectric and geomagnetic fields. The changes culminated immediately before nearby M 6 earthquakes [*Uyeda et al.*, 2004]. Since then, Japanese colleagues have paid a lot of attention to ULF electromagnetic radiation before an earthquake [*Molchanov and Hayakawa*, 2008]. *Hayakawa et al.* [1996b] reported the third event of seismogenic ULF radiation prior to the 1993 Guam M 7.8 earthquake, a feature also reported by *Fraser-Smith et al.* [1990] and *Kopytenko et al.* [1990] for the earlier Spitak M 6.8 and Loma Prieta M 6.9 earthquakes. In the collaboration of the RIKEN and NASDA Frontier

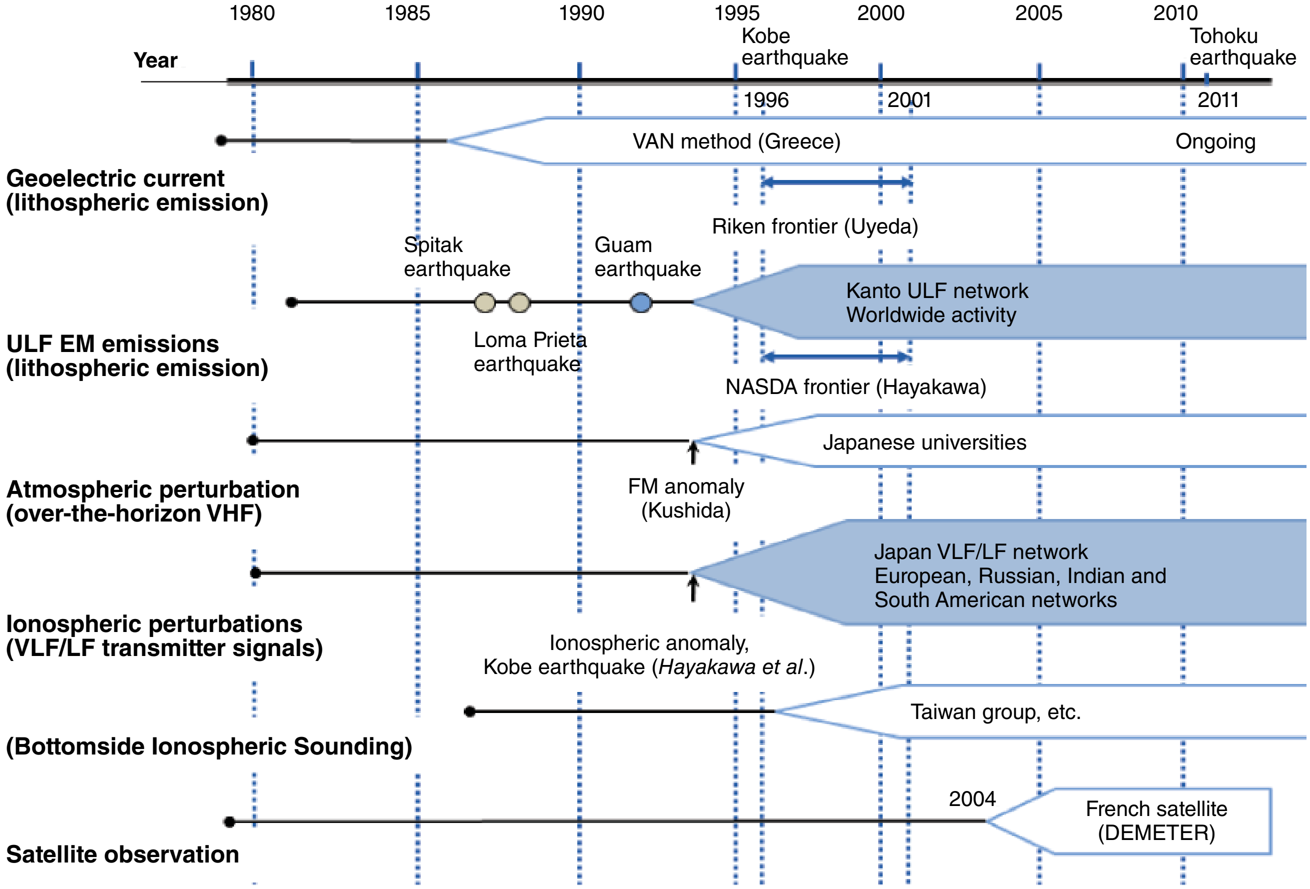

Figure 2.2 History of seismo-electromagnetic studies (including lithospheric and atmospheric effects, and the ionospheric signature.

Projects, a network to observe seismogenic ULF electromagnetic emissions was established in the Tokyo area, comprising a few stations in both Izu and Boso (Chiba) peninsulas as well as others in other areas, and this ULF network was successfully operated for about 10 years [*Molchanov and Hayakawa*, 2008; *Hattori*, 2013]. New signal processing techniques to detect ULF radiation have been developed; for example, for the first time fractal analysis was applied to the 1993 Guam earthquake by *Hayakawa et al.* [1999], subsequently followed by many such studies around the world. Recently, *Hattori* [2013] found statistically on the basis of 10-year data in Tokyo that the probability of occurrence of ULF emissions is higher before rather than after the earthquake.

In the meantime the NASDA Frontier Project team expanded the observation region as much as possible in order to complement its own interests [*Hayakawa et al.*, 2004]. Not only were ULF electromagnetic emissions from the lithosphere targeted in collaboration with the RIKEN team, but the NASDA team also targeted atmospheric and ionospheric signatures of earthquakes by making full use of ground- and satellite-based observations. As for seismo-atmospheric effects, *Fukumoto et al.* [2001] studied the characteristics of over-the-horizon VHF (very high frequency 30–300 MHz) transmitter signals as found by *Kushida and Kushida* [2002]. Although they found that the over-the-horizon VHF signals really were observed prior to an earthquake, their direction-finding results suggested that the reception of those signals is not due to ionospheric reflection, as suggested by *Kushida and Kushida* [2002], but due to atmospheric perturbation. *Fujiwara et al.* [2004] made a statistical study of VHF atmospheric effects as well. *Yasuda et al.* [2009] further extended this VHF study by developing a new interferometric direction finder. This new direction finding enabled them to distinguish between natural VHF seismogenic noises and over-the-horizon VHF signals. Based on those observed characteristics, *Hayakawa et al.* [2007] have proposed a mechanism to explain the seismo-atmospheric perturbation due to an increase in surface temperature, groundwater lifting, and gas emanation, leading to a change in atmospheric refraction index. Moriya and his colleagues established an extensive network for the over-the-horizon VHF signals at many stations in Hokkaido, and *Moriya et al.* [2010] have made a statistical study based on the long-term data on the over-the-horizon VHF signals and found a close correlation of VHF signals with earthquakes. A further seismo-atmospheric effect, ELF (extremely low frequency: 1–10 Hz) pulsive radiation prior to earthquakes, has been detected based on long-term observations in Kamchatka [*Schekotov et al.*, 2007]. Thus the polarization of ELF radiation is suggested as a new parameter among the seismogenic precursor activity. This parameter and the corresponding direction finding have been used to detect such seismogenic ELF radiation before an earthquake [*Hayakawa et al.*, 2012; *Schekotov et al.*, 2013a].

Use of satellites has been one of the most important aspects of the NASDA, aiming to make it possible to monitor features of the Earth's surface, such as the near-surface temperature variation, soil moisture variations, etc., prior to earthquakes. The advanced very high resolution radiometer (AVHRR) onboard the National Oceanic and Atmospheric Administration (NOAA) satellite has provided thermal images of the abnormal enhancement of the outgoing infrared radiation above seismo-active regions in central Asia, China, and Japan [*Tronin et al.*, 2002].

Detecting ionospheric perturbation was the primary concern of the NASDA Frontier Project, during which a network of observing VLF–LF transmitter signals was established (the so-called UEC (University of Electro-Communications) network), comprising seven stations in Japan. Signals from two Japanese transmitters (with call signs of JJY (40 kHz, Fukushima) and JJI (22.2 kHz, Miyazaki) and three transmitters in other countries (NWC (19.8 kHz, Australia), NPM (21.4 kHz, Hawaii) and NLK (24.8 kHz, Jim Creek, Washington State)) are simultaneously received at each station. This VLF–LF network has contributed much to case studies of different large earthquakes occurring in Japan and around the world: 2003 Tokachi-oki *M* 8.3earthquake [*Shvets et al.*, 2004], 2004 Mid-Niigata prefecture *M* 6.8 earthquake [*Hayakawa et al.*, 2006], 2004 Sumatra *M* 9.1 earthquake [*Horie et al.*, 2007], 2007 Niigata Chuetsu-oki *M* 6.6 earthquake [*Hayakawa et al.*, 2008], 2009 L'Aquila *M* 6.9 earthquake [*Rozhnoi et al.*, 2009], and 2010 Haiti *M* 7 earthquake [*Hayakawa et al.*, 2011a]. Statistical studies also utilized this network to examine the close correlation of the subionospheric signal anomaly (ionospheric perturbation) with shallow earthquakes [*Rozhnoi et al.*, 2004; *Maekawa et al.*, 2006; *Hayakawa et al.*, 2010].

Another discovery was made by *Schekotov et al.* [2006] following analysis of a few years of data in Kamchatka, which revealed depression of the ULF magnetic field (horizontal component) before an earthquake as a result of the lower ionospheric perturbation. That is, this new type of anomaly is attributed to the enhanced absorption in the lower ionosphere of conventional ULF emissions of magnetospheric origin, and thus is likely to be the same effect as the VLF–LF ionospheric perturbation.

Lastly, satellite observations of seismogenic phenomena are considered. Initially full use was made of the data observed by the intercosmos (IK)-24 satellite. *Molchanov et al.* [1993] detected ELF–VLF noise anomalies before earthquakes. Furthermore, data on the ionospheric plasma observed by the same satellite was used to study the possible influence of seismicity by gravity waves on the equatorial ionospheric anomaly [*Molchanov et al.*, 2002a,b]. The present author had been involved in the initial planning of the French satellite DEMETER, which was launched in 2004. The satellite data were kindly provided to other interested scientists. *Molchanov et al.* [2006] used the VLF wide-band data to detect the whistler-mode signals from any VLF–LF transmitters, and found that the signal intensity decreased significantly above the epicenter of several earthquakes, including the 2004 Sumatra earthquake, which was consistent with NASDA's ground-based VLF observation. *Muto et al.* [2008] confirmed the conclusion of *Molchanov et al.* [2006]. Studies using satellite data have continued. *Rozhnoi et al.* [2012] studied the spectral broadening of VLF transmitter signals in order to examine seismo-ionospheric irregularities, and *Rozhnoi et al.* [2015] have since compared the satellite VLF data with the corresponding ground-based VLF data to study the seismo-ionospheric response.

2.2.3. Precursors for the 2011 Tōhoku Earthquake

Although most were recognized only retrospectively, there were in fact precursors to the 2011 Tōhoku earthquake. Several reports have now been published on these precursors, mainly by Japanese colleagues, and are listed below.

1. Seismicity: *Nagao et al.* [2014] demonstrated that seismic activation started in about mid-2009 and culminated at the main shock.
2. Electromagnetic phenomena:
    (a) Lithospheric effects. *Kopytenko et al.* [2012] investigated the magnetic field variations at three observatories (Esashi, Mizusawa, and Kakioka) over the 11-year period of 1 January 1 2000 through 31 January 2011. They found a medium-term anomaly beginning around 3 years before the earthquake, and also a short-term precursor in the frequency range of 0.033–0.01 Hz was observed starting from 22 February 2011. Another type of anomalous daily variation of ULF magnetic data was observed approximately 2 months prior to the main shock [*Xu et al.*, 2013]. Unfortunately, these conventional analysis results seemed to require further study, because the anomaly in geomagnetic and ULF radiations is not so intense. After taking these into account,

Hayakawa et al. [2015] performed a critical, so-called natural time, analysis of the ULF data for the 2011 Tōhoku earthquake, and found that the horizontal magnetic field component ($f = 0.03$–0.05 Hz) fulfilled all criticality conditions for 3–5 March 2011, a few days before the shock, which is likely to be a short-term precursor.

(b) Atmospheric effects. *Ohta et al.* [2013] observed ELF atmospheric radiation on the basis of measurements at three stations in the Nagoya area: Nakatsugawa (Gifu prefecture), Shinojima (in Mikawa Bay), and Izu. It was found that ELF pulsive radiation in the frequency range from 1 to 10 Hz was reliably recorded on 6 March as a precursor to the earthquake. Further confirmation on its seismic origin was provided by the observational fact that the azimuths of the radiation source from all observatories coincided approximately with the region of the forthcoming earthquake.

Schekotov and Hayakawa [2015] extensively investigated the 5-year ULF data at Kakioka around the 2011 Tōhoku earthquake. The sequence of spectra obtained was compared with the evolution of seismicity, which resulted in detection of radiation in the vertical component. The ULF radiation data exhibit seasonal variations with a winter maxima, but can be observed to increase when approaching the moment of the earthquake and to decrease after that. As this radiation seems to be correlated with atmospheric parameters, the authors considered that it could not be caused by a subsurface source, but rather a possible source could be atmospheric discharges.

(c) Ionospheric signatures. *Hayakawa et al.* [2012, 2013a,b] studied the data obtained from their VLF–LF observation network and found a very convincing short-term precursor to the 2011 Tōhoku earthquake. A remarkable anomaly characterized by a decrease in the nighttime amplitude and an enhancement in amplitude fluctuation was detected on 5 and 6 March along the propagation from the NLK (Jim Creek, USA) transmitter to Chofu (together with similar signatures at other stations of Kochi and Kasugai (Nagoya)). The corresponding anomaly was also detected in observations in Russia.

Schekotov et al. [2013a,b] and *Hayakawa et al.* [2013b] studied the depression of ULF ($f = 0.03$–0.05 Hz) horizontal magnetic field variations of magnetospheric origin at various distances (300–1300 km) from the earthquake epicenter. They found a remarkable depression on 6 March at Kakioka (closest to the earthquake epicenter). *Schekotov et al.* [2013a] statistically correlated this kind of depression with seismicity.

The above two phenomena, subionospheric VLF anomaly and ULF field depression, can be consistently explained by a single cause, perturbation in the lower ionosphere [*Hayakawa et al.*, 2013b]. Another issue of current debate is the imminent variation of ionospheric contents (about 40 h) before this earthquake [*Heki*, 2011; *Kamogawa and Kakinami*, 2013], but further study is needed.

3. Land movements. Another highly promising development is the detection of preseismic land movements using GPS data [e.g., *Chen et al.*, 2013]. *Kamiyama et al.* [2014] investigated GPS data on land movements extensively for a period of about 10 years before the 2011 Tōhoku earthquake, trying to detect medium- and short-term as well as imminent preseismic precursors. They found a latitudinal trend toward the south whereby variation in land movement stopped around 6 months before the earthquake, showing a flat trend thereafter. The westward longitudinal trend in land movement changes also ceased about 2 months before the earthquake. So, some preseismic movements of the crust might have occurred several months before the earthquake. However, the clearest anomaly in crustal movements detected by *Kamiyama et al.* [2014] is the short-term precursor before the earthquake. The longitudinal movement change exhibited a sharp increase over 6–10 March, and stayed flat, in readiness to rebound following the activity of 3–6 March. As mentioned previously, 3–6 March has been reported to be full of electromagnetic signatures. In this sense, it is of crucial importance to combine the seismic (land movement) information with electromagnetic signatures for further understanding of the mechanism of seismo-electromagnetic phenomena.

2.3. FUTURE DIRECTION OF EARTHQUAKE PREDICTION

As of 2015, the main organizations of the earthquake prediction program, including the Seismological Society of Japan and the MEXT Headquarters for Earthquake Research Promotion, maintain an official position that they neither can or want to make any short-term prediction. Over the past two decades, however, significant new directions in precursor research have prevailed concerning short-term earthquake prediction, with the most typical example being electromagnetic phenomena in possible association with earthquakes. Extensive progress has been achieved in this new scientific field since the 1995 Kobe earthquake, as mentioned previously. The task of short-term earthquake prediction is therefore no longer the preserve of seismologists but can transferred to other researchers with different skill sets who are eager and capable of undertaking this task. It is crucial in this context to understand that short-term earthquake prediction will only be possible by conducting thorough scientific research into precursor phenomena. Taking into account both the long-held resistance of the seismological research community and the enormous progress of seismo-electromagnetics, in 2014 the "Earthquake Prediction Society of Japan" was established, in which the focus is on scientific studies of any type of precursor phenomena, including mechanical (seismic), electromagnetic, and macroscopic approaches.

There are many challenges ahead, but I do feel very optimistic about the future of earthquake prediction. First it will be necessary to address the technical problems listed below.

1. Long-term continuous observations. There are numerous electromagnetic precursors detectable using radiofrequency techniques, but the most important task is to carry out long-term (at least 5 years, but preferably 10 years or so) observations in order to establish a clear statistical correlation between any precursor and earthquakes. The most serious problem in continuous observations is the presence of data gaps owing to malfunction of equipment, so special care has to be paid to the importance of continuous observations of any observational item. It is only from long-term continuous observations, however, that a high probability exists for discovering a new phenomenon in seismogenic studies. Anomalies in Schumann resonances (SR) were a new discovery made by *Hayakawa et al.* [2005], but subsequently an additional discovery was made, also in the ELF band, i.e., unusual SR-like line emissions observed in possible association with earthquakes [*Ohta et al.*, 2009; *Hayakawa et al.*, 2011b], which can be interpreted in terms of excitation of gyrotropic waves in a thin layer of the lower ionosphere [*Sorokin and Hayakawa*, 2014]. Lastly, it is important to note the observation of acoustic emissions [*Gorbatikov et al.*, 2002] as a prominent earthquake precursor.

2. Development of highly sensitive equipment. In any frequency range, as discussed in this chapter, detectors for seismogenic electromagnetic signatures are the first step towards distinguishing seismogenic effects with smaller intensity from other interference noise. Initially, therefore, it is necessary in any frequency band to develop highly sensitive detectors. For example, a new DC geopotential detector free from the problem of contact potential with the ground, a new type of ULF sensor (with a different protocol), various kinds of direction-finding systems in ULF [*Kopytenko et al.*, 2002], ELF–VLF, VHF, and VLF–LF Doppler-shift observations [*Asai et al.*, 2011], and a VHF interferometer direction finder [*Yasuda et al.*, 2009]. Development of such sensitive receivers will surely provide new findings and discoveries of seismogenic effects. Another important direction of development is to reduce the cost of high performance equipment. For example, to establish a dense VLF network all over Japan would require 20–30 (at least) VLF receivers, which would be achievable if the unit price could be reduced.

3. Signal processing techniques. As for new measurement techniques, developing new signal processing techniques for long-term big data is an essential requirement. In the fields of DC/ULF and VLF–LF it is obvious how important new signal processing techniques were in the study of earthquake prediction. Much progress has since been achieved in the vital field of signal processing techniques, including wavelet analysis [*Alperovich et al.*, 2001], principal component analysis (independent component analysis) [*Gotoh et al.*, 2002], and fractal analysis [e.g., *Hayakawa and Ida*, 2008] to study nonlinear processes in the lithosphere and various kinds of direction-finding determination. *Varotsos* [2005] proposed a new conceptual analysis method (similar, in principle, to fractal analysis), a natural time method, in order to specify the date of an impending earthquake with a sufficient accuracy. In the future it will be necessary to consider how important this kind of critical analysis is, in further confirming the result by conventional statistical analysis or identifying any precursor imbedded in the noisy data [*Hayakawa et al.*, 2015]. Further development of new signal processing methods is a necessity.

4. Ability of private companies to release earthquake prediction information. In addition to the above progress in new directions for tackling technical problems, there are promising signs in these endeavors arising from the private sector. Short-term earthquake prediction should not be regarded as the sole domain of national projects or national governments. A few private ventures working on earthquake prediction with the help of scientists have been established, and there are local authorities in high earthquake/tsunami risk areas also involved in this research.

In addition to the above technical problems of data collection and analysis, a final goal of seismo-electromagnetic study is to develop better understanding of the physical mechanisms of different kinds of seismogenic effects (seismogenic emissions, seismo-atmospheric and seismo-ionospheric perturbations, and plasma and electromagnetic signatures in the ionosphere). It is obvious that elucidation of those physical mechanisms will also help much in the improvement of earthquake prediction. There are difficult but challenging problems to be solved in the determination of physical mechanisms, which can be summarized as listed below.

1. Extensive coordination of numerous observations. Seismo-electromagnetic phenomena are known to take place in an extremely wide range of regions, not only in the lithosphere, but also in the atmosphere and ionosphere. The most difficult, but challenging, topic for seismo-electromagnetics (earthquake predictability) is the mechanism of why and how the ionosphere is perturbed prior to an earthquake (i.e., LAIC—lithosphere–atmosphere–ionosphere coupling) is extremely difficult

to comprehend. One possible way for coordinating the various observational items is to establish a field test site (such as Kamchatka as a part of the collaboration between Russians and Japanese [*Gladychev et al.*, 2001; *Uyeda et al.*, 2002b]). The primary requirement for such a test field site is that it must be located at a place free from anthropogenic interference noise. The second requirement is to observe simultaneously as many electromagnetic phenomena in a wide frequency band as possible, as in Figure 2.2, in order to achieve extensive coordination of observational data, which will enable us to observationally verify any particular hypothesis. A few hypotheses for the LAIC [*Surkov and Hayakawa*, 2014; *Sorokin et al.*, 2015] have been proposed previously, including: (a) electrostatic channel [*Freund*, 2009], in which positive hole charge carriers in crustal rocks play the crucial role; (b) chemical channel [*Pulinets and Ouzounov*, 2011], in which radon emanating from the ground is the main player; and (c) atmospheric oscillation channel [*Hayakawa et al.*, 2004; *Molchanov and Hayakawa*, 2008; *Korepanov et al.*, 2009], in which the perturbation in the pre-earthquake Earth surface (such as land motion, temperature and pressure changes, or emanation of ionized gas, etc.) excites the atmospheric oscillations traveling up to the ionosphere. Those who are interested in more details on these LAIC mechanisms should consult the recent monograph by *Sorokin et al.* [2015]. A new direction is the fusion of electromagnetic precursor data with mechanical data such as seismicity and land movements measured by GPS (as done in *Kamiyama et al.* [2014]), because the main agent of LAIC is definitely located in the lithosphere.

2. Detailed study on the mechanisms of generation of seismogenic emissions and also on the physical mechanism of LAIC. Generation mechanisms of electromagnetic emissions in a wide frequency range (from DC/ULF to VHF or even higher) and also mechanisms of how and why both the atmosphere and ionosphere are perturbed by a pre-earthquake fracture effect, are poorly understood at the moment, even though various hypotheses have been proposed for each item of the seismogenic effects [e.g., *Hayakawa*, 2009, 2012, 2013; *Hayakawa and Molchanov*, 2002; *Pulinets and Boyarchuk*, 2004; *Molchanov and Hayakawa*, 2008; *Surkov and Hayakawa*, 2014]. Elucidation on which hypothesis is more plausible or acceptable will be possible with the help of improved radiofrequency techniques and multidisciplinary coordination of different kinds of seismogenic phenomena, together with elaboration of theoretical considerations. The final point to be considered here is the necessity of satellite observations, since it is obvious how effective satellite results are for the scientific study of LAIC [*Parrot*, 2012, 2013]. In near future, Japan has a strong desire to launch its own satellite dedicated to earthquake prediction study (like the French DEMETER satellite [*Parrot*, 2012, 2013]).

2.4. CONCLUSION

The important conclusions derived from this review can be summarized as follows.

1. Enormous progress in the studies of earthquake precursors has been achieved in Japan (and also in other countries) during the past two decades since the 1995 Kobe earthquake, and it has been found that many of earthquake precursors are not seismological, but mainly electromagnetic. Several electromagnetic precursors have been identified, and some have been demonstrated to statistically correlate with earthquakes, including ionospheric perturbations not only in the lower part but also in the upper F region. Those electromagnetic phenomena are likely to be of essential importance in short-term earthquake prediction.

2. Short-term earthquake prediction has essentially two aspects. One is purely the academic science (or obtaining the statistical correlation of any precursor with earthquakes on the basis of long-term observation and elucidation of the associated mechanisms of those precursors), and the other is the actual attempt of earthquake forecast with the use of such precursors. It is strongly recommended here that both directions should be pursued in future, especially in Japan, where private sectors are very active in this research field.

3. Once a statistical correlation of any earthquake precursor with earthquakes has been established, the most important next step is to elucidate the generation mechanism of each earthquake precursor. Then, the main goal of scientific research should be to understand much better the mechanism of LAIC. This woul be possible only with the coordinated measurements of multiple parameters, including the lithospheric, atmospheric and ionospheric. The simultaneous use of data on crustal movements is also required.

4. As earthquake precursor studies will not be supported by the government in Japan, at least in the coming few years, the important role of private sectors in the actual earthquake prediction/forecast should be emphasized. In their earthquake forecast, the most required outcome will be an increase in its accuracy, which should rely on the above-mentioned adoption of multiparameter and multidisciplinary observations.

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REFERENCES

Asai, S., Yamamoto, S., Kasahara, Y., Hobara, Y., Inaba, T., and Hayakawa, M. (2011), Measurement of Doppler shifts of short-distance subionospheric LF transmitter signals and seismic effects, *J. Geophys. Res.*, doi:10.1029/2010JA016055.

Alperovich, L., Zheludev, V., and Hayakawa, M. (2001), Application of a wavelet technique for the detection of earthquake signatures in the geomagnetic field, *Nat. Hazards Earth System Sci.*, *1*, 75–81.

Chen, C.H., Wen, S., Liu, J.Y., Hattori, K., Han, P., Hobara, Y., Wang, C. H., Yeh, T. K., and Yen. H. Y. (2013), Surface displacements in Japan before the 11 March 2011 *M*.9.0 Tōhoku-Oki earthquake, *J. Asian Earth Sci.*, *80*, 165–171.

Fraser-Smith, A. C., Bernardi, A., McGill, P. R., Ladd, M. E., Helliwell, R. A., and Villard Jr., O. G. (1990), Low frequency magnetic field measurements near the epicenter of the Loma-Prieta earthquake, *Geopys. Res. Lett.*, *17*, 1465–1468.

Freund, F. (2009), Stress-activated positive hole charge carriers in rocks and the generation of pre-earthquake signal, in M. Hayakawa (ed.), *Electromagnetic Phenomena Associated with Earthquakes*, pp. 41–96, Transworld Research Network, Trivandrum, India.

Fujiwara, H., Kamogawa, M., Ikeda, M., Liu, J. Y., Sakata, H., Chen, Y. I., Ofuruton, H., Muramatsu, S., Chuo, Y. J., and Ohtsuki. Y. H. (2004), Atmospheric anomalies observed during earthquake occurrences, *Geophys. Res. Lett.*, *31*, L17110.

Fukumoto, Y., Hayakawa, M., and Yasuda, H. (2001), Investigation of over-horizon VHF radio signals associated with earthquakes, *Nat. Hazards Earth System Sci.*, *1*, 107–112.

Gladychev, V., Baransky, L., Schekotov, A., Fedorov, E., Pokhotelov, O., Andreevsky, S., Rozhnoi, A., Khabazin, Y., Belyaev, G., Gorbatikov, A., Gordeev, E., Chebrov, V., Sinitsin, V., Lutikov, A., Yunga, S., Kosarev, G., Surkov, V., Molchanov, O., Hayakawa, M., Uyeda, S., Nagao, T., Hattori, K., and Noda. Y. (2001), Study of electromagnetic emissions associated with seismic activity in Kamchatka region, *Nat. Hazards Earth System Sci.*, *1*, 127–136.

Gorbatikov, A. V., Molchanov, O. A., Hayakawa, M., Uyeda, S., Hattori, K., Nagao, T., Tanaka, H., Nikolaev, A. V., and Maltsev. P. (2002), Acoustic emission possibly related to earthquakes, observed at Matsushiro, Japan and its implications, in M. Hayakawa and O. A. Molchanov (eds), *Seismo Electromagnetics (Lithosphere–Atmosphere–Ionosphere Coupling)*, pp. 1–10, Terra Scientific Publishing, Tokyo.

Gotoh, K., Akinaga, Y., Hayakawa, M., and Hattori, K. (2002), Principal component analysis of ULF geomagnetic data for Izu islands earthquakes in July 2000, *J. Atmos. Electr.*, *22*(1), 1–12.

Hattori, K. (2013), ULF geomagnetic changes associated with major earthquakes, in M. Hayakawa (ed.), *Earthquake Prediction Studies: Seismo Electromagnetics*, pp. 129–152, Terra Scientific Publishing, Tokyo.

Hayakawa, M. (ed.) (1999), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes*, Terra Scientific Publishing, Tokyo, 996 pp.

Hayakawa, M. (ed.) (2009), *Electromagnetic Phenomena Associated with Earthquakes*, Transworld Research Network, Trivandrum, India, 279 pp.

Hayakawa, M. (ed.) (2012), *The Frontier of Earthquake Prediction Studies*, Nihon-Senmontosho-Shuppan, Tokyo, 794 pp.

Hayakawa, M. (ed.) (2013), *Earthquake Prediction Studies: Seismo Electromagnetics*, Terra Scientific Publishing, Tokyo, 168 pp.

Hayakawa, M. (2015), *Earthquake Prediction with Radio Techniques*, John Wiley & Sons, Singapore, 294 pp.

Hayakawa, M. and Molchanov, O. A. (eds) (2002), *Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling*, Terra Scientific Publishing, Tokyo, 477 pp.

Hayakawa, M., and Ida, Y. (2008), Fractal (mono- and multi-) analysis for the ULF data during the 1993 Guam earthquake for the study of prefracture criticality, *Curr. Dev. Theory Appl. Wavelets*, *2*(2), 159–174.

Hayakawa, M. and Hobara, Y. (2010), Current status of seismo-electromagnetics for short-term earthquake prediction, *Geomatics, Nat. Hazards Risk*, *1*(2), 115–155.

Hayakawa, M., Molchanov, O. A., Ondoh, T., and Kawai, E. (1996a), The precursory signature effect of the Kobe earthquake on VLF subionospheric signals, *J. Comm. Res. Lab.*, *43*, 169–180.

Hayakawa, M., Kawate, R., Molchanov, O. A., and Yumoto, K. (1996b), Results of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993, *Geophys. Res. Lett.*, *23*, 241–244.

Hayakawa, M., Itoh, T., and Smirnova, N. (1999), Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8, 1993, *Geophys. Res. Lett.*, *26*(18), 2797–2800.

Hayakawa, M., Molchanov, O. A., and NASDA/UEC Team (2004), Summary report of NASDA's earthquake remote sensing frontier project, *Phys. Chem. Earth*, *29*, 617–625.

Hayakawa, M., Ohta, K., Nickolaenko, A. P., and Ando, Y. (2005), Anomalous effect in Schumann resonance phenomena observed in Japan, possibly associated with the Chi-chi earthquake in Taiwan, *Ann. Geophysicae*, *23*, 1335–1346.

Hayakawa, M., Ohta, K., Maekawa, S., Yamauchi, T. Ida, Y., Gotoh, T., Yonaiguchi, N., Sasaki, H., and Nakamura, T. (2006), Electromagnetic precursors to the 2004 Mid Niigata Prefecture earthquake, *Phys. Chem. Earth*, *31*, 356–364.

Hayakawa, M., Surkov, V. V., Fukumoto, Y., and Yonaiguchi, N. (2007), Characteristics of VHF over-horizon signals possibly related to impending earthquakes and a mechanism of seismo-atmospheric perturbations, *J. Atmos. Solar-Terr. Phys.*, *69*, 1057–1062.

Hayakawa, M., Horie, T., Yoshida, M., Kasahara, Y., Muto, F., Ohta, K., and Nakamura, T. (2008), On the ionospheric perturbation associated with the 2007 Niigata Chuetsu-oki earthquake, as seen from subionospheric VLF/LF network observations, *Nat. Hazards Earth System Sci.*, *8*, 573–576.

Hayakawa, M., Kasahara, Y., Nakamura, T., Muto, F., Horie, T., Maekawa, S., Hobara, Y., Rozhnoi, A. A., Solivieva, M., and Molchanov, O. A. (2010), A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes, *J. Geophys. Res.*, *115*, A09305.

Hayakawa, M., Raulin, J. P., Kasahara, Y., Bertoni, F. C. P., Hobara, Y., and Guevara-Day, W. (2011a), Ionospheric perturbations in possible association with the 2010 Haiti earthquake, as based on medium-distance subionospheric VLF propagation data, *Nat. Hazards Earth System Sci.*, *11*, 513–518.

Hayakawa, M., Y. Hobara, K. Ohta, J. Izutsu, A. P. Nickolaenko, and V. M. Sorokin (2011b), Seismogenic effects in the ELF Schumann resonance band, *IEEJ Trans. Fund. Mater.*, *131*(9), 684–690.

Hayakawa, M., Hobara, Y., Yasuda, Y., Yamaguchi, H., Ohta, K., Izutsu, J., and Nakamura, T. (2012), Possible precursor to the March 11, 2011, Japan earthquake: Ionospheric perturbations as seen by subionospheric very low frequency/low frequency propagation, *Ann. Geophys.*, *55*(1), 95–99.

Hayakawa, M., Hobara, Y., Rozhnoi, A., Solovieva, M., Ohta, K., Izutsu, J., Nakamura, T., and Kasahara Y. (2013a), The ionospheric precursor to the 2011 March 11 earthquake based upon observations obtained from the Japan-Pacific subionospheric VLF/LF network, *Terr. Atmos. Ocean. Sci.*, *24*(3), 393–408, doi: 10.3319/TAO.2012.12.14.01 (AA).

Hayakawa, M., Rozhnoi, A., Solovieva, M., Hobara, Y., Ohta, K., Schekotov, A., and Fedorov, E. (2013b), The lower ionospheric perturbation as a precursor to the 11 March 2011 Japan earthquake, *Geomatics, Nat. Hazards Risk*, *4*(3), 275–287, doi:org/10.1080/19475705.2012.751938.

Hayakawa, M., Schekotov, A., Potirakis, S., and Eftaxias, K. (2015), Criticality features in ULF magnetic fields prior to the 2011 Tōhoku earthquake, *Proc. Japan Acad. Ser. B*, *91*, 25–30, doi: 10.2183/pjab.91.25.

Heki, K. (2011), Ionospheric electron enhancement preceding the 2011 Tōhoku-Oki earthquake, *Geophys. Res. Lett.*, *38*, L17312.

Horie, T., Yamauchi, T. Yoshida, M., and Hayakawa, M. (2007), The wave-like structures of ionospheric perturbation associated with Sumatra earthquake of 26 December 2004, as revealed from VLF observation in Japan of NWC signals, *J. Atmos. Solar-Terr. Phys.*, *69*, 1021–1028.

Kamiyama, M., Sugito, M., Kuse, M., Chekotov, A., and Hayakawa, M. (2014), On the precursors to the 2011 Tōhoku earthquake: crustal movements and electromagnetic signatures, *Geomatics, Nat. Hazards Risk*, doi:10.1080/19475705.2014.937773.

Kamogawa, M. and Kakinami, Y. (2013), Is an ionospheric electron enhancement preceding the 2011 Tōhoku-Oki earthquake a precursor?, *J. Geophys. Res. Space Phys.*, *118*, 1751–1754.

Kopytenko, Yu. A., Matiashvili, T. G., Voronov, P. M., Kopytenko, E. A., and Molchanov, O. A. (1990), *Discovering of ultra-low-frequency emissions connected with Spitak earthquake and its aftershock activity with the data of geomagnetic pulsations observations at Dusheti and Vardzija*, IZMIRAN, Moscow, Preprint N3 (888), 27 pp.

Kopytenko, Yu. A., Ismaguilov, V. S., Hattori, K., Voronov, P. M., Hayakawa, M., Molchanov, O. A., Kopytenko, E. A., and Zaitev, D. B. (2002), Monitoring of the ULF electromagnetic disturbances at the station network before EQ in seismic zones of Izu and Chiba peninsulas (Japan), in M. Hayakawa and O. A. Molchanov (eds), *Seismo Electromagnetics (Lithosphere–Atmosphere–Ionosphere Coupling)*, pp. 11–18, Terra Scientific Publishing, Tokyo.

Kopytenko, Yu. A., Ismaguilov, V. S., Hattori, K., and Hayakawa, M. (2012), Anomaly disturbances of the magnetic fields before the strong earthquake in Japan on March 11, 2011, *Ann. Geophys.*, *55*(1), 101–107, doi: 10.4401/ag-5260.

Korepanov, V., Hayakawa, M., Yampolski, Y., and Lizunov, G. (2009), AGW as a seismo-ionospheric coupling responsible agent, *Phys. Chem. Earth*, *34*, 485–495.

Kushida, Y. and Kushida, R. (2002), Possibility of earthquake forecast by radio observations in the VHF band, *J. Atmos. Electr.*, *22*, 239–255.

Liu, J. Y. (2009), Earthquake precursors observed in the ionospheric F-region, in M. Hayakawa (ed.), *Electromagnetic Phenomena Associated with Earthquakes*, pp. 187–204. Transworld Research Network, Trivandrum, India.

Maekawa, S., Horie, T., Yamauchi, T., Sawaya, M., Ishikawa, M., Hayakawa, M., and Sasaki, H. (2006), A statistical study on the effect of earthquakes on the ionosphere, based on the subionospheric LF propagation data in Japan, *Ann. Geophysicae*, *24*, 2219–2225.

Molchanov, O. A. and Hayakawa, M. (2008), *Seismo Electromagnetics and Related Phenomena: History and Latest Results*, Terra Scientific Publishing, Tokyo, 189 pp.

Molchanov, O. A., Kopytenko, Yu. A., Voronov, P. M., Kopytenko, E. A., Matiashvili, T. G., Fraser-Smith, A. C., and Bernardi, A. (1992), Results of ULF magnetic field measurements near the epicenters of the Spitak ($Ms = 6.9$) and Loma Prieta ($Ms = 7.1$) earthquakes: comparative analysis, *Geophys. Res. Lett.*, *19*, 1495–1498.

Molchanov, O. A., Mazhaeva, O. A., Goliavin, A. N., and Hayakawa, M. (1993), Observations by the Intercosmos-24 satellite of ELF-VLF electromagnetic emissions associated with earthquakes, *Ann. Geophysicae*, *11*, 431–440.

Molchanov, O. A., Hayakawa, M., Afonin, V. V., Akentieva, O. A., and Mareev, E. A. (2002a), Possible influence of seismicity by gravity waves on ionospheric equatrial anomaly from data of IK-24 satellite 1. Search for idea of seismo-ionosphere coupling, in M. Hayakawa and O. A. Molchanov (eds), *Seismo Electromagnetics (Lithosphere–Atmosphere–Ionosphere Coupling)*, pp. 275–285, Terra Scientific Publishing, Tokyo.

Molchanov, O. A., Hayakawa, M., Afonin, V. V., Akentieva, O. A., Mareev, E. A., and Trakhtengerts, V. Yu. (2002b), Possible influence of seismicity by gravity waves on ionospheric equatrial anomaly from data of IK-24 satellite 2. Equatorial anomaly and small-scale ionospheric turbulence, in M. Hayakawa and O. A. Molchanov (eds), *Seismo Electromagnetics (Lithosphere–Atmosphere–Ionosphere Coupling)*, pp. 287–296, Terra Scientific Publishing, Tokyo.

Molchanov, O. A., Rozhnoi, A., Solovieva, M., Akentieva, O., Berthelier, J. J., Parrot, M., Lefeuvre, F., Biagi, P. F., Castellana, L., and Hayakawa, M. (2006), Global diagnostics of the ionospheric perturbations related to the seismic activity using the VLF radio signals collected on the DEMETER satellite, *Nat. Hazards Earth System Sci.*, *6*, 745–753.

Moriya, T., Mogi, T., and Takada, M. (2010), Anomalous pre-seismic transmission of VHF-band radio waves resulting from large earthquakes, and its statistical relationship to magnitude of impending earthquakes, *Geophys. J. Int.*, *180*, 858–870.

Muto, F., Yoshida, M., Horie, T., Hayakawa, M., Parrot, M., and Molchanov, O. A. (2008), Detection of ionospheric perturbations associated with Japanese earthquakes on the basis of reception of LF transmitter signals on the satellite DEMETER, *Nat. Hazards Earth System Sci.*, *8*, 135–141.

Nagao, T., Enomoto, Y., Fujinawa, Y., Hata, M., Hayakawa, M., Huang, Q., Izutsu, J., Kushida, Y., Maeda, K., Oike, K., Uyeda, S., and Yoshino, T. (2002), Electromagnetic anomalies associated with 1995 Kobe earthquake, *J. Geodyn.*, *33*, 477–487.

Nagao, T., Orihara, Y., and Kamogawa, M. (2014), Precursory phenomena possibly related to the 2011 *M*9.0 off the Pacific coast of Tōhoku earthquake, *J. Disaster Res.*, *9*, 303–310.

Ohta, K., Izutsu, J., and Hayakawa, M. (2009), Anomalous excitation of Schumann resonances and additional anomalous resonances before the 2004 Mid-Niigata prefecture earthquake and the 2007 Noto Hantou earthquake, *Phys. Chem. Earth*, *34*(6 & 7), 441–448.

Ohta, K., Izutsu, J., Chekotov, A., and Hayakawa, M. (2013), The ULF/ELF electromagnetic radiation before the 11 March 2011 Japanese earthquake, *Radio Sci.*, *48*, 589–596, doi:10.1002/ rds.20064.

Orihara, T., Kamogawa, M., Nagao, T., and Uyeda, S. (2012), Pre-seismic anomalous telluric current signals observed in Kozu-shima Island, Japan, *Proc. Nat. Acad. Sci. USA*, *109*, 19125–19128.

Parrot, M. (2012), Satellite observation of ionospheric disturbance before large earthquakes, in M. Hayakawa (ed.), *The Frontier of Earthquake Prediction Studies*, pp. 738–764, Nihon-Senmontosho-Shuppan, Tokyo.

Parrot, M. (2013), Satellite observation of ionospheric perturbations related to seismic activity, in M. Hayakawa (ed.), *Earthquake Prediction Studies: Seismo Electromagnetics*, pp. 1–16, Terra Scientific Publishing, Tokyo.

Pulinets, S. A. and Boyarchuk, K. (2004), *Ionospheric Precursors of Earthquakes*, Springer, Berlin, 315 pp.

Pulinets, S. and Ouzounov, D. (2011), Lithosphere–atmosphere–ionosphere coupling (LAIC) model—a unified concept for earthquake precursors validation, *J. Asian Earth Sci.*, *41*(4–5), 371–382.

Rikitake, T. (2001a), *Predictions and Precursors of Major Earthquakes: The Science of Macroscopic Anomalous Phenomena*, Terra Scientific Publishing Company, Tokyo, 198 pp.

Rikitake, T. (2001b), *Earthquake Prediction: Achievements and Future*, Nihon-Senmontosho-Shuppan, Tokyo, 617 pp. (In Japanese.)

Rozhnoi, A., Solovieva, M. S., Molchanov, O. A., and Hayakawa, M. (2004), Middle latitude LF (40 kHz) phase variations associated with earthquakes for quiet and disturbed geomagnetic conditions, *Phys. Chem. Earth*, *29*, 589–598.

Rozhnoi, A., Solovieva, M., Molchanov, O., et al. (2009), Anomalies in VLF radio signals prior to the Abrusso earthquake($M = 6.3$) on 6 April 2009, *Nat. Hazards Earth System Sci.*, *9*, 1727–1732.

Rozhnoi, A., Solovieva, M., Biagi, P. F., Schwingenschuh, K., and Hayakawa, M. (2012), Low frequency signal spectrum analysis for strong earthquakes, *Ann. Geophys.*, *55*(1), 181–186, doi: 10.4401/ag-5076.

Rozhnoi, A., Solovieva, M., Parrot, M., et al. (2015), VLF/LF signal studies of the ionospheric response to strong seismic activity in the far Eastern region combining the DEMETER and ground-based observations, *Phys. Chem. Earth*, Parts A/B/C, https://doi.org/10.1016/j.pce.2015.02.005.

Schekotov, A. and Hayakawa, M. (2015), Seismo-meteo-electromagnetic phenomena observed during a 5-year interval around the 2011 Tōhoku earthquake, *Phys. Chem. Earth*, Parts A/B/C, doi:10.106/j.pce.2015.01.010.

Schekotov, A., Molchanov, O., Hattori, K., Fedorov, E., Gladyshev, V. A., Belyaev, G. G., Chebrov, V., Sinitsin, V., Gordeev, E., and Hayakawa, M. (2006), Seismo-ionospheric depression of the ULF geomagnetic fluctuations at Kamchatka and Japan, *Phys. Chem. Earth*, *31*, 313–318.

Schekotov, A. Y., Molchanov, O. A., Hayakawa, M., Fedorov, E. N., Chebrov, V. N., Sinitsin, V. I., Gordeev, E. E., Belyaev, G. G., and Yagova, N. V. (2007), ULF/ELF magnetic field variations from atmosphere induced by seismicity, *Radio Sci.*, *42*, RS6S90, doi:10.1029/2005RS003441.

Schekotov, A., Fedorov, E., Molchanov, O. A., and Hayakawa, M. (2013a), Low frequency electromagnetic precursors as a prospect for earthquake prediction, in M. Hayakawa (ed.), *Earthquake Prediction Studies: Seismo Electromagnetics*, pp. 81–99, Terra Scientific Publishing, Tokyo.

Schekotov, A., Fedorov, E., Hobara, Y., and Hayakawa, M. (2013b), ULF magnetic field depression as a possible precursor to the 2011/3.11 Japan earthquake, *J. Atmos. Electr.*, *33*(1), 41–51.

Shvets, A. V., Hayakawa, M., and Maekawa, S. (2004), Results of subionospheric radio LF monitoring prior to the Tokachi ($M = 8$, Hokkaido, 25 September 2003) earthquake, *Nat. Hazards Earth System Sci.*, *4*, 647–653.

Sorokin, V. and Hayakawa, M. (2014), Plasma and electromagnetic effects caused by the seismic-related disturbances of electric current in the global circuit, *Mod. Appl. Sci.*, *8*(4), 61–83.

Sorokin, V., Chumyrev, V., and Hayakawa, M. (2015), *Electrodynamic Coupling of Lithosphere-Atmosphere-Ionosphere of the Earth*, Nova Publishers, New York, 355 pp.

Surkov, V. and Hayakawa, M. (2014), *Ultra and Extremely Low Frequency Electromagnetic Field*, Springer, Tokyo, 486 pp.

Tronin, A. A., Hayakawa, M., and Molchanov, O. A. (2002), Thermal IR satellite data application for earthquake research in Japan and China, *J. Geodyn.*, *33*, 477–487.

Uyeda, S. (2012), Earthquake prediction in Japan, in M. Hayakawa (ed.), *The Frontier of Earthquake Prediction Studies*, pp. 3–13, Nihon-Senmontosho-Shuppan, Tokyo. (In Japanese.)

Uyeda, S. (2013), On earthquake prediction in Japan, *Proc. Japan Acad. Ser. B*, *89*, 391–400.

Uyeda, S. (2015), Current affairs in earthquake prediction in Japan, *J. Asian Earth Sci.*, https://doi.org/10.1016/j/jseas.2015.07.006

Uyeda, S., Hayakawa, M., Nagao, T., Molchanov, O., Hattori, K., Orihara, Y., Gotoh, K., Akinaga, Y.,and Tanaka, H. (2002a), Electric and magnetic phenomena observed before the volcano-seismic activity 2000 in the Izu island region, Japan, *Proc. Nat. Acad. Sci. USA*, *99*(11), 7352–7355.

Uyeda, S., Nagao, T. Hattori, K., Noda, Y., Hayakawa, M., Miyaki, K., Molchanov, O., Gladychev, V., Baransky, L., Schekotov, A., Belyaev, G., Fedorov, E., Pokhotelov, O., Andreevsky, S., Rozhnoi, A., Khabazin, Y., Gorbatikov, A., Gordeev, E., Chebrov, V., Lutikov, A., Yunga, S., Kosarev, G., and Surkov, V. (2002b), Russian–Japanese complex geophysical observatory in Kamchatka for monitoring of phenomena connected with seismic activity, in M. Hayakawa and O. A. Molchanov (eds), *Seismo Electromagnetics (Lithosphere–Atmosphere–Ionosphere Coupling)*, pp. 413–419, Terra Scientific Publishing, Tokyo.

Uyeda, S., Nagao, T., and Tanaka, H. (2004), A report from the RIKEN International Frontier Research Project on Earthquakes (IFREQ). *Terr. Atmos. Ocean. Sci.*, *15*, 269–310.

Uyeda, S., Nagao, T., and Kamogawa, M. (2008), Short-term earthquake prediction: Current status of seismo-electromagnetics, *Tectonophysics*, *470*, 205–213.

Varotsos, P. (2005), *The Physics of Seismic Electric Signals*, Terra Scientific Publishing, Tokyo, 338 pp.

Xu, G., Han, P., Huang, Q., Hattori, K., Febriani, F., and Yamaguchi, H. (2013), Anomalous behavior of geomagnetic diurnal variations prior to the 2011 off the Pacific coast of Tōhoku earthquake (*Mw*9.0), *J. Asian Earth Sci.*, *77*, 59–65.

Yasuda, Y., Ida, Y. Goto, T., and Hayakawa, M. (2009), Interferometric direction finding of over-horizon VHF transmitter signals and natural VHF radio emissions possibly associated with earthquakes, *Radio Sci.*, *44*, RS2009, doi:10.1029/2008RS003884.