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A Study on Lithosphere-Atmosphere-Ionosphere Coupling Channel for the 1995 Kobe Earthquake, by Including Ground-Based Meteorological Anomalies

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Abstract

The purpose of this paper is to investigate, first of all, extensively the spatio-temporal evolutions of meteorological anomalies (T/Hum (T: temperature, Hum: humidity (relative)) and ACP (atmospheric chemical potential) of water molecules) just one week prior to the famous 1995 Kobe (17 January, 1995) earthquake (EQ) (with magnitude of 7.3) using AMeDAS (automated meteorological data acquisition system) of JMA (Japan Meteorological Agency) ground-based open data, which have already been identified in our two series papers. We then aim to combine the detailed temporal evolution of these meteorological anomalies with earlier results on lower ionospheric perturbations observed via VLF propagation and sporadic E layer formation (together with other electromagnetic precursors), and we come to a conclusion that a diffusion-type "slow channel" in the lithosphere-atmosphere-ionosphere coupling (LAIC) exists for this Kobe EQ, with Earth's surface meteorological anomalies preceding ionospheric perturbations by 3 - 5 days, possibly related to radon exhalation. Further discussions have been performed on further details of the mechanism of this LAIC channel for the Kobe EQ.

Keywords

Lithosphere-Atmosphere-Ionosphere Coupling (LAIC), The 1995 Kobe Earthquake, T/Hum (T: Temperature, Hum: Humidity), Atmospheric Chemical Potential (ACP) of Water Molecules, VLF Precursors, Diffusion-Type Slow Channel

1. Introduction

Short-term earthquake (EQ) prediction is still a challenging subject in the field of geosciences. For the future prediction studies, we will focus on the studies of EQ precursors, because different kinds of precursors have been found to take place not only in the lithosphere, but also in the atmosphere and upper atmosphere (or ionosphere) [1]-[6]. As the most important finding during the last few decades, the ionosphere is found to be extremely sensitive to pre-EQ lithospheric activity [e.g.] [7]-[9], and it will be the main player of the short-term EQ prediction. So, we come to the attractive concept of lithosphere-atmosphere-ionosphere coupling (LAIC) [1]-[3] [10]. During the last ten years, this concept has become very popular, and there have been published in recent years many papers dedicated to the elucidation of LAIC process by means of multidisciplinary parameters not only from the ground-, but also satellite-based measurements [11]-[28]. Also, there have already been proposed a few hypotheses to account for the LAIC process [2] [3] [4] [26]; the first is the so-called chemical hypothesis, in which the emanation of radioactive radon, charged aerosols, and/or gases plays the main role, leading to the modification of atmospheric conductivity and the generation of an electric field, thereby driving the variation in ionospheric plasma density [2] [3] [26]. Additionally, air ionization in this hypothesis leads to the generation of thermal anomalies near the Earth's surface as the consequence of different physical/chemical processes [2] [26] [29], which seem to be closely related with this paper. The second is the acoustic hypothesis, in which atmospheric oscillations including atmospheric gravity waves (AGWs) and acoustic waves are excited by the precursory deformation of ground motion and/or gas emanation, or thermal irregularities, propagating upwards to the lower and upper ionosphere and leading to perturbations in the ionosphere [30]-[33]. The third is the electromagnetic hypothesis, in which electromagnetic waves generated in any frequency range (either in the lithosphere or in the atmosphere) propagate upwards into the ionosphere and magnetosphere, inducing particle precipitation into the upper atmosphere due to wave-particle interactions in the magnetosphere (e.g., [3] [4] [10]). Finally, a fourth electrostatic channel is proposed based on the laboratory experiments, in which positive holes are generated when the ground of interest is stressed by accumulated pressure [34]. These processes have been discussed individually extensively based on multidisciplinary measurements by various authors (e.g., Ouzounov *et al.* (Eds.), 2018 [35]), but none of the above hypotheses have been evidenced by any definite observational data, necessitating further studies until the process of LAIC is well understood [26]. A recent work by Hayakawa and Hobara (2024) [21] have found the simultaneous occurrence of the possible two channels (fast and slow channels), and we need much more case studies like in this paper on the observational and theoretical studies on this LAIC process.

With regards a further support to the LAIC studies, a new tool of studying the condition on the Earth's surface has been presented with the use of ground-based AMeDAS (Automated Meteorological Data Acquisition System) data by Japan Meteorological Agency (JMA) consisting of a dense network of meteorological stations for the 1995 Kobe EQ, and we have found a clear meteorological anomalies of T/Hum (T: temperature (˚) and Hum: humidity (relative) (%))and ACP (atmospheric chemical potential (in eV)) of water molecules on 10 January 1995 (just one week prior to the EQ) in the first paper of our series [36]. The present paper will deal with the more extensive investigation on spatio-temporal evolutions of those meteorological anomalies for this Kobe EQ. The spatial distributions of those two quantities have been compared with the location of fault regions, suggesting a close association with them and a support to the hypothesis of meteorological anomalies as the result of radon emanation. The temporal evolution of the anomaly indicates that the peak occurs on the night of 9/10 January, 1995, but it is persistent for the successive few days. These new findings will be compared with the earlier observations of radon concentration (both in the ground and atmosphere), and it is surprisingly encouraging that the peak of our meteorological anomalies seems to be very consistent in time with that of ground radon concentration. Then, we will re-examine the previous summary of electromagnetic anomalies for this Kobe EQ [37] [38], and combining the previous anomalies with our definite perturbations on the Earth's surface as a new precursor to the EQ, we will be able to investigate the LAIC channel for this Kobe EQ, followed by the extensive discussions of LAIC mechanism.

2. The EQ studied in This Paper, and Solar and Geomagnetic Activity

2.1. Target EQ

The target EQ of this paper is the famous 1995 Kobe EQ that happened at 5 h 46 m on January 17 (JST) 1995 at the epicenter (geographical coordinates of 34˚35.9'N, 135˚02.1'E) as shown in **Figure 1** (red star with notation of EQ) with M(magnitude) = 7.3 and with a depth of 16 km (e.g., [36]). This EQ is the second most disastrous in Japan in the past 30 years. For this EQ we discovered the first convincing evidence of ionospheric perturbations 4 days before the EQ until the day of the EQ, with subionospheric VLF propagation data from the Omega transmitter at Tsushima to the observatory at Inubo in Chiba prefecture (Hayakawa *et al.*, 1996 [37]), and also Nagao *et al.* (2002) [38] summarized various kinds of electromagnetic EQ precursors for this EQ, which will be re-examined extensively later.

2.2. Solar-Terrestrial Environment

Figure 2 illustrates the temporal evolutions of geomagnetic activity (Dst and Kp index) and solar radiation flux at the wavelength of 10.7 cm (f10.7) during the whole period of 1 May, 1994 through 31 May, 1995 (over one year) including the day of the EQ. As already discussed in [36], the solar terrestrial conditions during the short-term EQ prediction span of one month before and two weeks after the EQ, were very quiet.

3. Data and Analysis Methods

3.1. Spatial Distributions of Meteorological Anomalies

We have found in our first companion paper [36] that two meteorological

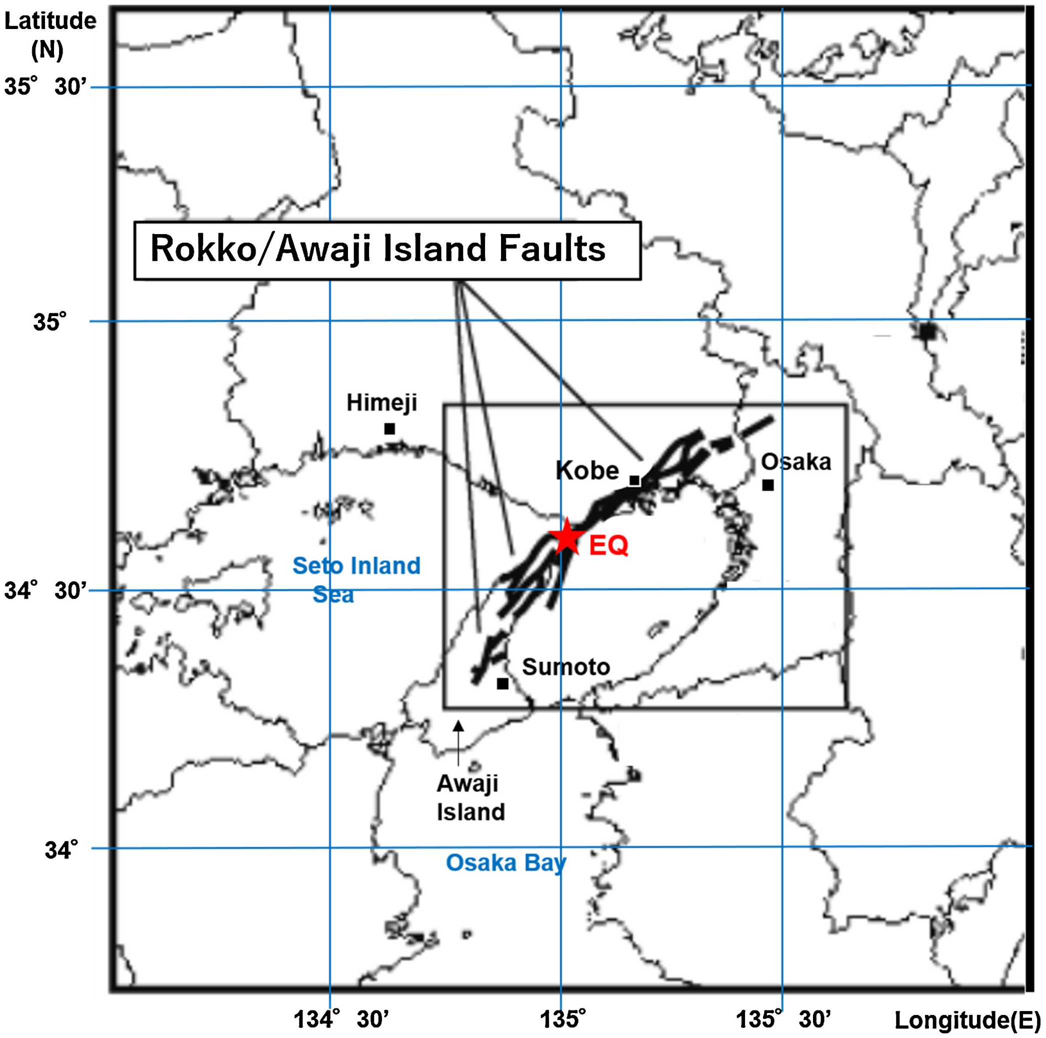

Figure 1. Location of the epicenter of the 1995 Kobe EQ (indicating by a red star), together with a few AMeDAS stations (by black boxes) close to the EQ epicenter. Also, the fault regions (Rokko/Awaji island faults) possibly related with the EQ are plotted by thick lines.

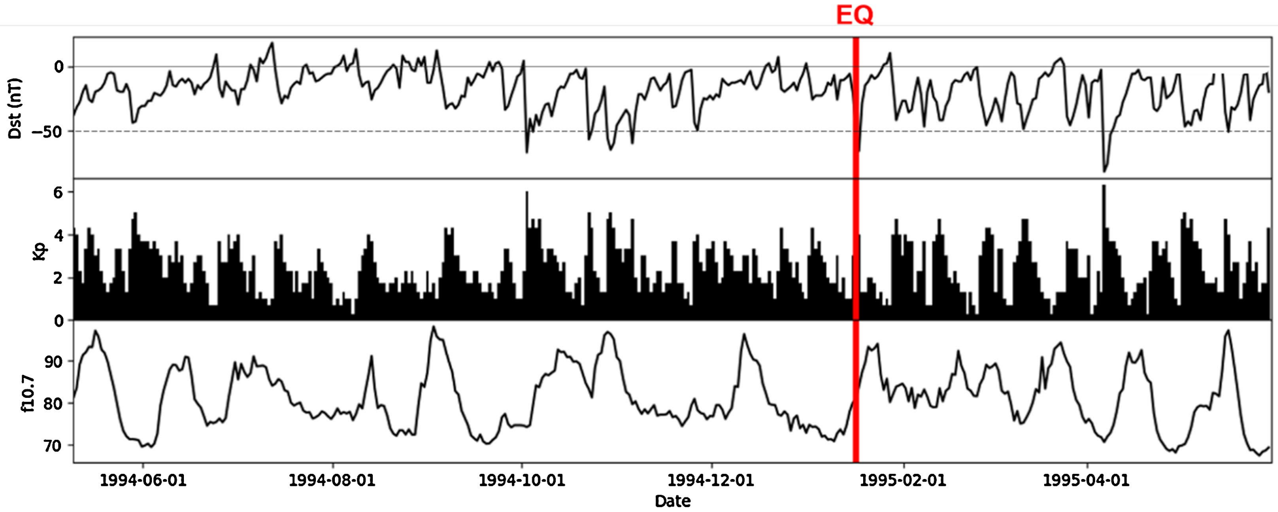

Figure 2. Temporal evolutions of solar-terrestrial conditions. From the top, two geomagnetic indexes, Dst index, Kp index, and solar radiation flux at the wavelength of 10.7 cam (f10.7).

quantities of (1) T/Hum (T: temperature (˚) and Hum: humidity (relative) (%)), and (2) ACP (Atmospheric chemical potential) of water molecules have exhibited a remarkable anomaly on 10 January, 1995; just one week before the EQ. Now, data from about 40 AMeDAS stations in the western Japan are utilized to obtain the spatial distributions of anomalies for both quantities as contour maps in **Figure 3** as already presented in [36]. **Figure 3(a)** refers to T/Hum, while **Figure 3(b)** refers to ACP. The numerical values in the contour maps indicate the deviation from the mean value normalized by the standard deviation (σ) as in [36]; for example,

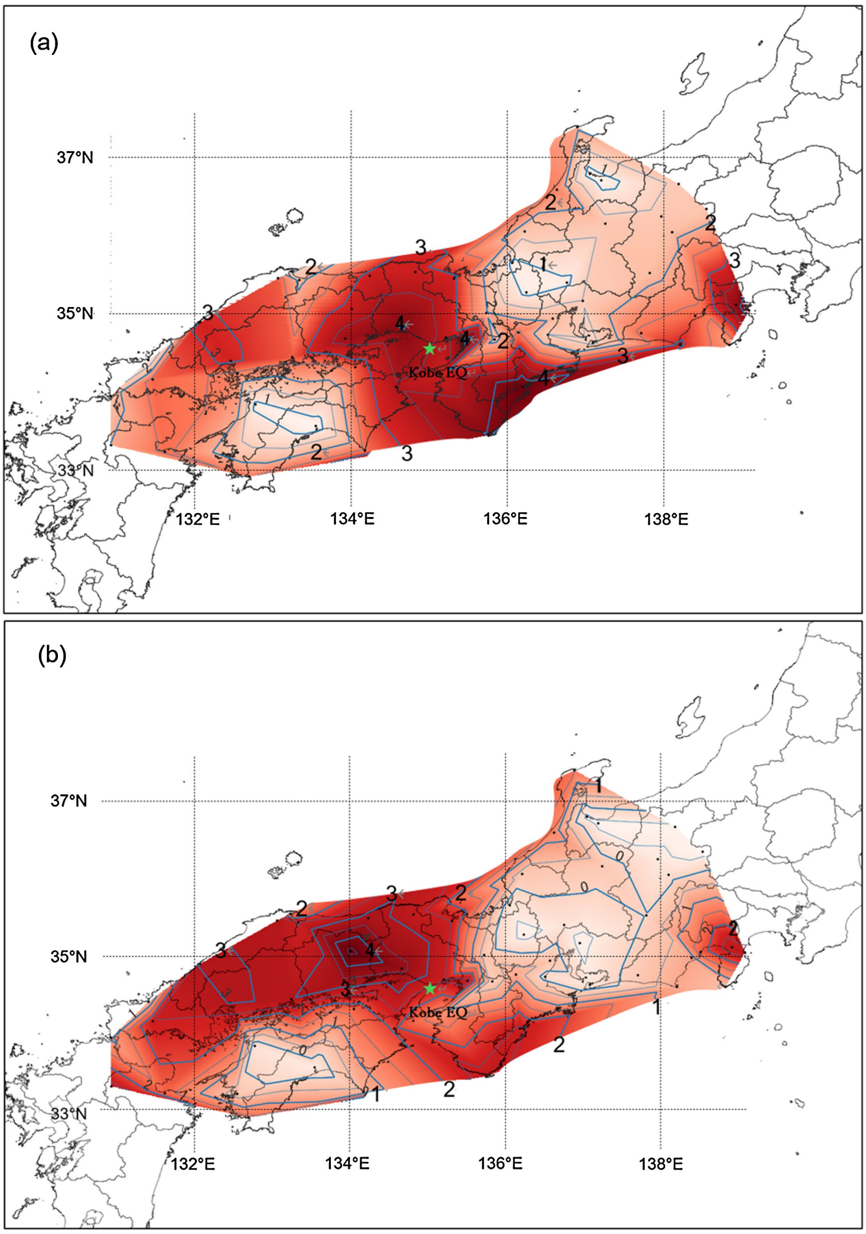

Figure 3. Spatial distributions of meteorological anomalies, (a) T/Hum and (b) ACP of water molecules on 10 January, 1995, as based on the data from about 40 AMeDAS stations in western Japan. The numerical values of 3, 2 etc. indicate the anomaly level normalized by the standard deviation (σ); For example, 3 refers to 3σ.

2 in the figures means 2σ, and 3 means 3σ. First, let us look at **Figure 3(a)**, and pay attention to the contour of 3. It indicates that the high-level anomaly of 3 σ covers well the EQ epicenter, and the 4σ area is found to be located just west of the EQ epicenter and near Osaka as well. On the other hand, we have a slightly different behavior for ACP in **Figure 3(b)**. Because high-level anomaly in **Figure 3(b)** is located a little bit west of the EQ epicenter. A common characteristic from these two plots is that the most active area seems to be located west of the EQ epicenter, but the whole area of perturbation is extended about 100 km from the EQ epicenter. Also, the western Shikoku Island area is extremely least perturbed. How about comparing these maps with the fault regions? Firstly, the area of perturbed meteorological anomalies is found to be quite similar to that of seismicity map of the EQ, which may suggest a link to the fault regions. The region of high-level anomaly in the figures, especially west of the EQ epicenter is likely to be associated with the Yamazaki fault zone. Also, the high-level anomaly located at Osaka in **Figure 3(a)** might be related with the E-W oriented strike-slip active fault region (such as the Arima-Takatsuki fault zone).

Here we comment on our previous satellite monitoring by Tronin *et al.* (2002) [39], who, based on NOAA infra-red data, found thermal anomalies related to one of the main faults in western Japan (Median Tectonic Line) on 8 January. This satellite finding is in good agreement with our ground-based results of **Figure 3**.

3.2. Temporal Evolutions of Meteorological Anomalies

Next, we will study the detailed temporal evolutions of such meteorological anomalies. In our first paper [36] we have paid attention to the midnight hours (LT = 01 h) in the analysis, but here, we will investigate the detailed temporal evolutions of those quantities only for a particular month of January, 1995. Being a little bit different from the analysis method in [36], we have used the mean and standard deviation (σ) only in this month of January, 1995, and those values are estimated at each hour (LT or JST). **Figure 4** is the results of such analyses for T/Hum (a) and ACP (b) with the value on the abscissa being the detrended daily value normalized with the standard deviation. Further, we have to mention that when the detrended value is negative, or when the daily value is less than the mean value, its value is not plotted in both figures. First, we look at **Figure 4(a)** (T/Hum), in which we can notice a single peak exceeding 3σ over the midnight from the night on 9 January till the night on 10 January, so the duration of this anomaly is several hours. Next, we will look at **Figure 4(b)** for ACP. As is already indicated in [36], we have found that this ACP is a very stable indicator of meteorological anomalies. Exactly being the same as in **Figure 4(a)**, we have noticed a conspicuous peak on 10 January (*i.e.* from the night on 9 January to the early morning on 10 January), with the peak value exceeding 3σ. Further, we can find subsequent activities for a few successive days; the midnights over 10/11 January (just 2σ level), and 11/12, January (less than 2σ level), and also daytime hours on 12 (LT = 12 to 18 h) and 13 (12 - 18 h) January, 1995 (only the latter being above 2σ level). These variations during these few days are considered as constituting a group of continuing activity.

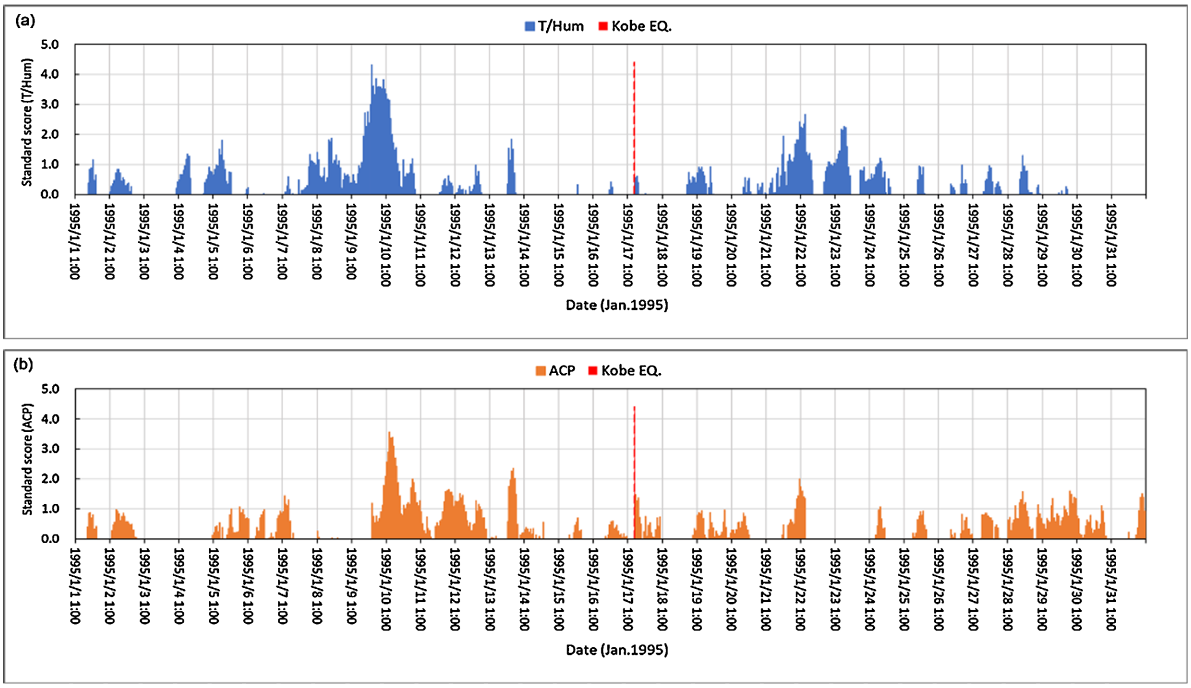

Figure 4. Temporal evolutions of two meteorological parameters, (a) T/Hum and (b) ACP at a particular station of Kobe, closest to the EQ epicenter. The ordinate indicates the anomaly level normalized by the standard deviation. Time on the abscissa indicates LT (local time, or JST).

So, we can speculate that these meteorological anomalies as the result of exhalation of radon and/or charged aerosols from the lithosphere to the atmosphere are taking place during a few successive days after 10 January.

Here we make a comment on the possible relationship of our meteorological anomaly with the traditional hypothesis of radon emanation during the EQ preparation phase in the vicinity of fault regions. The convincing evidence on the increase in radon in the ground and atmosphere has been obtained by Igarashi *et al.* [40] as observed in a well in the aftershock region, about 30 km northeast of the EQ epicenter, and Yasuoka *et al.* [41] [42] at Kobe (approximately 27 km northeast of the EQ epicenter), respectively. The radon concentration both in the ground and atmosphere began to increase from November, 1994 until the time of the EQ, and Igarashi *et al.* [40] have found a remarkable peak in ground radon concentration of more than 10 times that at the beginning of their observation on 8 January (9 days) prior to the EQ before starting to decrease. This temporal evolution seems to be very consistent with our meteorological anomaly on 10 January but starting late evening of the previous day of 9 January, and this temporal coincidence might be a strong support to the hypothesis of possible relation of our meteorological anomaly to the exhalation of radon and/or charged aerosols, leading to the subsequent air ionization and related physical/chemical processes, which might result in the meteorological anomalies.

3.3. Earlier Electromagnetic Precursors to the Kobe EQ

Nagao *et al.* (2002) [38] have summarized different electromagnetic phenomena for this Kobe EQ, but when they wrote the paper, the concept of LAIC was not so popular even though the concept itself was already proposed. This concept has been extensively discussed during the last five years or so [11]-[28], so we will discuss the wave phenomena reported so far in the context of LAIC process, together with our new knowledge of LAIC studies. We will start to discuss or re-examine the previous report [38] from the lowest part (or region) of LAIC up to the upper ionosphere for this Kobe EQ, and the summary of anomalies or precursors are plotted in **Figure 5** for our LAIC study.

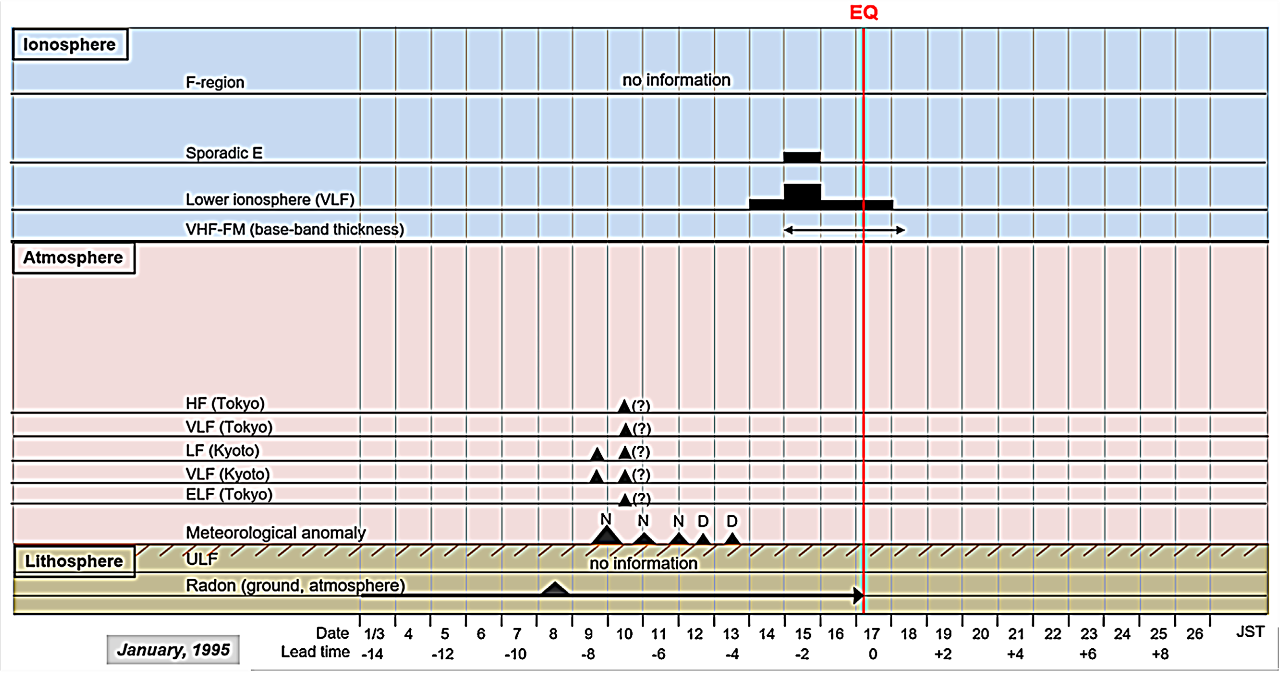

Figure 5. Summary plot of various precursors to the EQ. In the lithosphere, there is no ULF emission information, but we have indicated the presence of radon in the ground (and also in the lowest atmosphere). On the Earth's surface our meteorological anomaly is plotted with its height indicating the anomaly level. N and D mean the night and day anomaly. In the lower atmosphere there have been plotted some anomalies of electromagnetic emissions in VLF/LF, VHF and ELF, but they are all very questionable (so with question marks). The most conspicuous anomaly is the VLF propagation anomaly, suggesting the perturbation in the lower ionosphere with a duration of a few days. Probably in association with this lower ionospheric perturbation, we observed the anomaly in VHF-FM waves (as baseline thickness) and sporadic E. Further up to the F region, there is unfortunately no information of the anomalies there. It seems that the perturbations on the Earth's surface have been mapped up to the lower ionosphere, indicating the presence of slow channel.

(1) Lithospheric effect

Lithospheric effects can be studied either by SES (seismic electric signal, or DC earth current) (e.g., Varotsos (2015) [43]) or ULF electromagnetic emissions (e.g. Hayakawa *et al.* (2023) [44]), but the observations of these two phenomena were not carried out in this area. So, no information on lithospheric pre-EQ conditions is available.

(2) Earth's surface anomaly

This paper has provided a new addition to the summary by Nagao *et al.* (2002) [38]; we have just presented our first result to use the ground-based meteorological data from a dense Japanese AMeDAS network to identify significant meteorological anomalies, and we have found in this paper that a significant meteorological anomaly appeared on 10 January (or to be more exact, midnight over 9/10) (as indicated by the highest triangle in **Figure 5**), 1995 by using the two quantities of T/Hum (T: surface temperature, and Hum is relative humidity) and ACP (Atmospheric chemical potential) of water molecules. Clear anomalies in both quantities on this particular day (midnight of 9/10 January, 1995) are a definite precursor to the EQ, because those anomalies are mainly concentrated just around the EQ epicenter (Hayakawa *et al.* (2025) [36]) suggesting a close relation to the fault regions. A few successive days seem to be perturbed, *i.e.* 11 to 13 January, 1995. These anomalies are likely to be linked with the exhalation of radon and charged aerosols from the lithosphere into the atmosphere before an EQ probably due to the microfracturing taking place in and around the EQ hypocenter. This temporal evolution of our meteorological anomaly is found to be in consistence with that of radon exhalation in the ground and atmosphere [40]-[42].

(3) Lower atmosphere

Perturbations in the lower atmosphere or troposphere can be monitored by means of electromagnetic emissions in various frequency ranges from ELF (extremely low frequency), VLF (very low frequency), LF (low frequency), and HF (high frequency). In the summary by Nagao *et al.* [38], we describe the observational results close to the EQ epicenter: Oike and Yamada [45], and Yamada and Oike (1999) [46] described that the pulsive noises at VLF and LF as detected by a terrestrial antenna have been observed at Uji (about 80 km from the EQ epicenter) on 9 and 10 January at LF and 10 January at VLF, and they concluded based on a comparison with the lightning data from different electric power companies that these VLF/LF pulsive noises are highly likely to be due to conventional lightning discharges in the Hokuriku area in winter, but neither direct radiation from the fractured rocks nor the radiation from lightning induced by the EQ. There is another report by Hata *et al.* [47] [48] on ELF, but at a farther station of Usami in Tokyo area, and the ELF noise was detected on 10 January, 1995. However, the origin of their ELF noises is quite uncertain. In the far region from the EQ epicenter, Fujinawa and Takahashi [49] and Fujinawa *et al.* (1999) [50] detected VLF pulses using the borehole antennas of a Tokyo area network, and similarly Enomoto *et al.* [51] and Tsutsumi *et al.* [52] detected HF pulses on 10 January at Tsukuba in the Tokyo area again with a borehole antenna. But unfortunately, these authors have not compared with the lightning data by electric power companies, so it is very questionable whether those noises are really seismogenic or not.

We have checked extensively the meteorological maps on both days of 9 and 10 January, and have found that the Pacific Ocean side of western Japan (such as western Japan (from Osaka, Kobe, Himeji, …, Okayama), Shikoku Island area, and Kii peninsula area) was very fine on both days, being indicative of no possibility of rain and lightning.

(4) Upper atmosphere

As is indicated by Hayakawa and Hobara (2024) [21], the information in this region is of essential importance in elucidating the process or channel of LAIC, but it is very unfortunate that there is no data in this intermediate region.

(5) Lower ionosphere

This Kobe EQ is the first example of the very convincing evidence of clear ionospheric perturbations by Hayakawa *et al.* (1966) [37] and Molchanov and Hayakawa (1998) [53], because we understand that the monitoring of subionospheric VLF/LF signals enabled us to monitor the electron density variation in the lower ionosphere before this EQ. These authors have used the VLF propagation data observed at Inubo in Chiba Prefecture of the signals from the Omega VLF transmitter located in Tsushima, in which they have presented a new analysis method called "terminator time" of daily VLF amplitude and phase variations. These terminator times are defined as minima in daily variations (amplitude and phase) in the morning and evening. Significant shifts in these morning and evening terminator times have been observed starting 3 days before the EQ until the very day of the EQ, and disappeared completely on the next days. This is the first convincing evidence of seismogenic lower ionospheric perturbations, and this variation was interpreted in terms of VLF mode theory by lowering the lower reflection height by a few km.

(6) Over-the-horizon FM VHF signal reception

As is mentioned in Nagao *et al.* [38], ionospheric monitoring to receive FM radio waves from stations beyond the line of sight is a standard method to detect meteorites; meteorites penetrating into the lower ionosphere generate strongly ionized plasma tubes that make distant FM signals audible [54] [55]. Pilipenko *et al.* [56] have suggested that the over-the-horizon VHF signal reception in terms of the scattering by the seismogenic lower ionospheric perturbations. However, later interpretations have suggested the origin of such seismogenic over-the-horizon VHF reception in terms of lower atmospheric perturbations such as the formation of seismogenic radio ducts based on the changes of geochemical quantities associated with EQs (Hayakawa *et al.*, (2007) [57]), so this phenomenon is regarded as a seismo-atmospheric effect. Kushida and Kushida [54] [55] found the anomalous phenomenon in terms of the "baseline thickness" starting a few days before the EQ and even after the EQ. This temporal variation seems to be quite similar to that of VLF propagation anomaly by Hayakawa *et al.* [37]. The reception of over-the-horizon VHF signals is definitely a seismo-atmospheric perturbation, but the thickness of baseline thickness seems to be due to the fluctuation of lower ionospheric perturbations, which might lead to the similar temporal variation.

(7) Lower ionospheric perturbation: sporadic E layer

Ondoh and Hayakawa [58] and Ondoh [59] [60] observed sporadic E layers before this EQ, only on 15 January, 1995, which seems to be a very obvious finding as in [61]. This presence might be closely related with the lower ionospheric perturbations as detected by subionospheric VLF propagation [37].

(8) Upper ionosphere: F region

There is, unfortunately, no ionosonde station in the area of the Kobe EQ, so no information is available on the electron density changes of the F region of the ionosphere.

4. Results: LAIC for the Kobe EQ

Figure 5 is the summary of electromagnetic precursors summarized in Nagao *et al.* (2002) [38], together with our latest results on meteorological anomalies presented in our first paper [36] and in the present paper, and also the results on ground radon concentration [40]-[42]. We have to pay our greatest attention to the reliability of each possible precursor. Though there is no information on the lithospheric activity, we have added the previous temporal evolution of the ground radon concentration [40]-[42] which indicated an enormous peak on 8 January (9 days before the EQ) and furthermore we have presented very convincing evidence on the meteorological anomalies on the Earth's surface indicative of radon emanation from the lithosphere into the lower atmosphere on the midnight of 9/10 January (strongest anomaly) followed by a few successive midnights (10/11 and 11/12 January) (midnight) and 12, 13 January (daytime) with the very similar temporal evolutions of both meteorological and radon exhalation phenomena. On these days we can expect an enhanced activity of microfracturing in and around the EQ hypocenter, leading to various pre-EQ effects. That is, the crustal release of this EQ must have caused significant surface deformation and ruptures, so the continuous accumulation of subsurface stresses leads to the release of surface gases along the faults (such as water vapor, radon, methane etc.) prior to the destructive EQs [62]-[65].

In [38] there have been presented the occurrence of lightning discharges on 9 and 10 January, but the authors of these phenomena at VLF/LF observed at Kyoto have concluded that these are not likely to be seismogenic, but just the winter lightning in the Hokuriku area (Japan Sea side). VHF noises have also been observed at Tokyo, which are likely to be again due to the conventional atmospheric lightning. However, Hayakawa and Nickolaenko (2024) [66] have recently suggested the modification of conventional lightning due to the radon emanation, leading to the change in spectral characteristics and the increase in IC (intra- and inter-cloud) discharges. However, it seems very difficult for us to distinguish between the conventional lightning and seismogenic lightning. Further, Hayakawa *et al.* [67] have suggested the generation of seismogenic lightning discharges to explain the seismogenic lightning found by colleagues in Taiwan [68] [69], but we need further extensive works to identify these seismogenic lightning discharges. Very recently Baron *et al.* (2022) [70] have made an attempt to differentiate between artificial and natural sources of electromagnetic noise at a seismogenic fault. Based on the measurement of electromagnetic noises from ULF/ELF to VLF/LF at a seismogenic fault site and its comparison with the conventional lightning observation, they have found that a majority of the intense broadband impulses show a strong correlation with lightning activity across much of Central Europe and the Eastern Mediterranean, while the lower amplitude broadband impulses appear to be associated with local rock strain in and around the fault site. Then, the most reliable effect in [38] is the perturbation in the lower ionosphere as detected by subionospheric propagation from a VLF Omega transmitter located at Tsushima in Kyushu to the observing station of Inubo, Chiba, which persisted from 3 days before the EQ till the day of EQ [37] as indicated in **Figure 5**. The height of perturbation indicates its degree, and the highest day is the most perturbed day. Further, on the day when the lower ionosphere is perturbed most severely, Ondoh and Hayakawa [58] found the appearance of sporadic E layers, as also studied by several authors (e.g., [61]).

It is clear from **Figure 5** that the Earth' surface anomalies; *i.e.* meteorological anomalies indicative of the exhalation of radon from the lithosphere to the lowest atmosphere, exhibit the same duration of a few days as the above-mentioned lower ionospheric perturbation, and it looks that the ground and ionospheric perturbations are just shifted by a few (3 - 5) days, so this constitutes a slow channel of diffusion type as characterized in the paper by Hayakawa and Hobara (2024) [21]. Unfortunately, the information in the important intermediate region between the Earth's surface and lower ionosphere is missing for the profound study of the casual relationship between the lithosphere and ionosphere [21] [71].

5. Discussion

We first comment on the possible relationship of our meteorological anomaly with the traditional hypothesis of radon emanation. The convincing evidence on the increase of radon concentrations in the ground and atmosphere has been presented in [40]-[42]. The radon concentrations began to increase from November, 1994 until the time of the EQ. Igarashi *et al.* [40] have found a remarkable peak in ground radon concentration of more than 10 times that at the beginning of their observation on 8 January (9 days) prior to the EQ before starting to decrease. Also, [40]-[42] may indicate a peak in atmospheric radon concentration a few days before the EQ. These temporal evolutions seem to be very consistent with our meteorological anomaly on the midnight of 9/10 January, which might be a strong support to the hypothesis of possible relation of our meteorological anomaly to the exhalation of radon and/or charged aerosols.

The release of surface gases might lead to local atmospheric electric field anomalies, and the abnormal electric field acting on the ionosphere [2] [5] [6]. On the other hand, the abnormal heat source in the seismogenic region might generate AGW disturbances in the atmosphere and then cause the enhancement of internal gravity and planetary waves. The propagation of such signals to the ionosphere would cause abnormal oscillations of ionospheric temperature, density and other parameters [1] [2] [3] [5] [6] [10]. The propagation of such signals to the ionosphere would cause abnormal oscillation of ionospheric temperature, density and other parameters [2]-[6]. All the abnormal changes in the atmosphere were superimposed on the ionosphere under specific conditions, and resulted in the abnormal disturbances of ionospheric plasma, which were observed by SWARM and CSES satellites. These multi-sphere coupling anomalies have been widely reported for the major EQs, such as Gorkha-Nepal M7.8 and M7.3 EQs on 25 April and 12 May 2015 [14], Central Italy seismic sequence during 2016-2017 [72], Indonesia Mw7.5 EQ on 28 September 2018 [73], Wenchuan Ms8.0 EQ on 12 May 2008 [74], Fukushima off-shore M7.2 EQ [17], Turkey EQs on 6 February, 2023 [27], etc. These findings further confirmed the presence of LAIC mechanism ([2] [10] [71]-[77]), which provided the physico/chemical connection between pre-seismic multi-sphere anomalies and crustal tectonic activities. The whole seismogenic process of the major EQs is more likely to evolve in stages, and the activation of multi-sphere geophysical and chemical system indicates the upcoming main shock. The multi-sphere anomaly coupling needs to be further improved in order to conform to the complexity of actual crustal tectonic environment.

Compared with surface-based observing stations, we point out the importance of satellite observations. Satellite remote sensing technology has the advantages of wide global coverage, good timeliness and low cost, which is an ideal tool for studying various possible seismic anomalies on the global scale. In the future, based on multi-source satellite data, the substance migration, energy transfer and information conversion during the whole seismogenic process should be further studied to maximize the benefits of satellite remote sensing observations in seismic anomaly identification, and better promote the development of multi-sphere anomaly coupling mechanism. Furthermore, combining multi-source satellite observations and artificial intelligence analysis technology [e.g.] [36] [78]-[81] to establish an integrated system for data processing, anomaly analysis, and anomaly identification can greatly improve the accuracy of seismic monitoring and analysis, and effectively recognize the pre-seismic multi-sphere anomalies, which will help us to continuously track and predict the occurrence of the major EQs and aftershocks.

By concluding the present paper, **Figure 5** indicates definitely that the LAIC is not a fast channel as defined in [21] such that the ionospheric perturbation takes place simultaneously on the same day with Earth's surface perturbation as in several EQ events, e.g. the 2015 M7.8 and M7.3 Gorkha-Nepal EQs [82], the 2023 Mw7.8 Turkey EQ [14] etc., but we can identify the slow channel as suggested in the paper [21], which is just like of diffusion type. That is, the Earth's surface perturbations are persistent for a few days, and correspondingly the lower ionospheric perturbations are also existing from 3 days before the EQ until the day of the EQ. It looks as if the effects on the Earth's surface were mapped up to the lower ionosphere with a delay of about 3 - 5 days. Recent studies on EQ precursors based on satellite data have paid attention to the medium- (starting 3 - 4 months before the EQ) and short-term periods [11] [12] [19] [20] [23]-[25] [72]-[74] with respect to the evolution of the cumulative Benioff strain release in the lithosphere, and have shown, on the basis of the observation for different EQ events, that the number of anomalies begins to drastically increase a few weeks before the EQ, these being short-term EQ precursors. Our precursors for the 1995 Kobe EQ were concentrated in a period of one week before the EQ, and a joint analysis of ground surface information and the lower ionosphere perturbation will be a fundamental basis for future short-term EQ prediction [21] [74]. Such a slow channel as in this paper has been identified for several EQ events (such as the 2022 Samos EQ [16], the 2021 February Fukushima EQ [17] etc.). This diffusion type channel seems to remind us of a possibility of AGW effect, such as the excitation of AGWs on the Earth's surface and subsequent propagation up to the ionosphere. The travel time from Earth's surface to the lower E region is found to range from about half-hour (minimum) to more than ten hours (anyway one day or so), so the actual delay time of a few days as observed, seems to be much larger than the travel time of AGWs [32] [33] [83]. Hence, we have to conclude that a much more complicated mechanisms involving the planetary waves with a smaller vertical propagation velocity [32] [33] [75] [83] might be involved in the actual process, and we need further considerations.

6. Conclusions

Here we will summarize the conclusions from the present work as follows.

1) The conspicuous meteorological anomalies (T/Hum and ACP) on 10 January, 1995 (as detected in [36]) have been extensively investigated, with special attention to their detailed spatial distributions of anomaly and detailed temporal evolutions for better understanding of the meteorological anomalies.

2) A dense network of AMeDAS enabled us to construct the spatial distributions of T/Hum and ACP of water molecules. Though there is a small difference between the contour maps of T/Hum and ACP, it is found that those contour maps are quite similar to each other, and the high-values of anomalies are found to overlap with the locations of well-known fault regions. Then, the detailed temporal evolutions, especially ACP plot, indicate that we observe a remarkable peak on the night of 9/10 January, 1995 (8 and 7 days before the EQ) and subsequent activities for the few successive days, which is furthermore found to be very consistent with the temporal evolution of radon concentrations by previous measurements [40]-[42]. This suggests a close relationship between the radon effect and our meteorological anomalies.

3) By adding our new input of our meteorological anomalies to the previous summary by Nagao *et al.* [38] on EQ precursors to the Kobe EQ, we have re-examined the previous electromagnetic precursors to study the LAIC mechanism. Then, electromagnetic emissions on 9 and 10 January are regarded to be conventional lightning taking place in the Hokuriku area, and they were not seismogenic. Definite precursors might be only lower ionospheric perturbations (and the presence of sporadic E layers) and our meteorological anomalies, and a combined analysis of these two effects, enables us to conclude that the ionospheric perturbation might be a result of Earth's surface perturbation, forming a slow channel

as in [21] of diffusion type with delay time of a few (3 - 5) days. However, the detailed mechanism of this time delay needs further studies.

4) A joint use of our VLF/ELF propagation anomaly measurement with meteorological anomaly analysis based on Japanese AMeDAS open data, as presented in this paper, is hoped to be an excellent example for short-term EQ prediction, and it might be a fundamental basis for the future short-term EQ prediction. Of course, the addition of satellite observational data will be of further significant importance in the EQ prediction.

Acknowledgements

The AMeDAS data are available from the site of https://www.data.jma.go.jp/risk/obsdl/index.php (accessed on 1 April 2023) and the data of geomagnetic and solar activities can be downloaded from the OMNIWEB (https://omniweb.gsfc.nasa.gov/form/dx1.html, accessed on 1 April 2024).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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