Possible mechanism of the over-horizon reception of FM radio waves during earthquake preparation period

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Abstract: Kushida noticed anomalous over-horizon reception of FM radio waves (~80 MHz) before earthquakes when epicenters were in a certain sensitive region. The suggested method of earthquake prediction recognizes precursors in supposedly back-scattered waves from the ionosphere several days or few weeks before the seismic events. We try to clarify the possible underlying physical mechanism for this method within the framework of existing notions on the lithosphere-atmosphere-ionosphere coupling. Gravity waves in the atmosphere are speculated to be generated by quasi-periodic movements of tectonic blocks or yield of gases along faults. Conversion of large-scale gravity waves above a seismically active region into ionospheric disturbances involves formation of sporadic E-layer. The sporadic E-layer in turn may be regarded as a free energy source of generation of small-scale (a few meters) ionospheric plasma irregularities, presumably due to the modified gradient-drift plasma instability. These meter-range irregularities could be the reason for the back-scattered VHF radio waves. Some experimental tests for verification of this hypothesis are suggested.

Key words: Seismo-ionospheric coupling; earthquake prediction; ionospheric irregularities.

Introduction. There are ever mounting number of indications on possible coupling between ionospheric anomalies and earthquakes (EQ). Seemingly seismo-related disturbances have been reported at all levels of the ionosphere:

- in D-layer (~90 km) by monitoring of VLF radio wave propagation^{1),2)};
- in E-region (~110 km) with ionospheric vertical radio sounding^{3),4)} and airglow observations⁵⁾;
- in F-region (~270 km) with ionospheric radio sounding^{6),7)};
- in the upper ionosphere (~1000 km) by satellites.⁸⁾

The reported links between seismicity and ionospheric anomalies of different nature resulted in speculations on the possible physical mechanisms of affecting the ionosphere from below, which might be related to the lithosphere-atmosphere-ionosphere (LAI) coupling. The suggested mechanisms can be categorized into three groups: 1) electromagnetic coupling, 2) chemical coupling, and 3) acoustic coupling. None of these cou-

pling mechanisms has been reliably confirmed (or denied) so far, so that they are still hypothetical.

New evidence of seismo-ionospheric coupling.

Kushida effect. Monitoring VHF radio waves (~80 MHz) at Yatsugatake South Base Observatory (central Japan) Kushida and Kushida unexpectedly discovered "precursory anomalies" of FM radio waves from over-horizon stations apparently back-scattered at the ionosphere above specific sensitive regions several days or few weeks before seismic events.⁹⁾ In their observation, each FM receiver is tuned slightly offset to the frequency of an over-horizon station, so that it is sensitive to weak input signals due to the characteristics of the used center-tuning meter. Anomalous signals are distinct from typical meteor radio echoes or aircraft reflections, and thus can be unambiguously identified. According to the Kushidas, the observed anomalies can be categorized into several types: i.e., in their nomenclature, (a) Charge-Discharge (CD) anomaly – deviation of pen-recorder baseline with duration 1-10 min; (b) Baseline Thickness (BT) anomaly – increase or extraordinary fluctuations of baseline thickness, which last several days. Other anomalies are basically combinations of these two.

The Kushidas empirically found the correlation

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between their VHF anomalies of unknown origin and EQs, and developed a forecasting method. In particular, strong BT anomaly was observed almost simultaneously with the occurrence of the “ionospheric terminator effect” detected with VLF radio-path monitoring²⁾ before the 1995 Kobe EQ. The results of Kushida’s forecast were objectively evaluated and it was reported that the rate of successful predictions was above pure chances.¹⁰⁾

Thus, the Kushida’s observations provide an additional indication that there may be a causal relationship between disturbances in the ionosphere and lithospheric processes. Here we discuss the possible physical mechanism of the Kushida effect within the framework of the existing notions on LAI coupling.

Electromagnetic coupling. The seismo-related DC disturbances of atmospheric electric field, reported so far, have been regarded as a result of the LAI coupling.¹¹⁾⁻¹³⁾ The ionospheric plasma is very sensitive to external electric field, so that even relatively weak (~ 1 mV/m) steady field, that may appear during EQ preparation, would cause variations of bulk ionospheric parameters. Originally, the Kushidas⁹⁾ also suggested that an appearance of seismo-related electric charges on the ground surface may cause the ionospheric anomalies.

Evaluation on the penetration of DC electric field through the atmosphere showed that the vertical electric field E_z in the atmosphere with exponentially growing conductivity with altitude, with a scale H_o , i.e., $\sigma(z) = \sigma_0 \exp(z/H_o)$, decreases exponentially with height. In order to produce a disturbance of electric field in the lower ionosphere comparable with the background electric field in the ionosphere (about a few mV/m), a near-ground large-scale disturbance E_z exceeding the typical value of atmospheric fair weather potential gradient ($\sim 10^2$ V/m) by orders of magnitude is required.¹³⁾ To our knowledge, the hypothesis on the excitation of large-scale electric fields with such intensities near the Earth’s surface in the seismic preparation zone has not found convincing observational evidence. AC electric variations might penetrate into the ionosphere more effectively as compared with DC electric field, because for AC field the lower part of the atmosphere behaves as an insulator, and not as a conductor.¹⁴⁾

The propagation of lithospheric electromagnetic field emissions from the interior of the Earth to its surface and then to the ionosphere was examined in detail.¹⁵⁾ It was shown that an underground low frequency source with a reasonable magnitude could explain the electromagnetic anomalies sometimes

observed at the ground level, but it fails to produce any noticeable electric field at ionospheric heights.

Chemical coupling. Emanation of radioactive gases from seismic faults would increase the conductivity of near-surface atmospheric layer.¹⁶⁾ Because the bulk resistance of the atmospheric gap between the ground and ionosphere is mainly determined by the lowest 5-10 km, this effect may produce a redistribution of current in global atmospheric circuit and cause a distortions in the plasma structure of the lower ionosphere.¹⁷⁾ However, according to the current notions of atmospheric electricity, the vertical scale of radioactive gas distribution is considered to be rather small, about 100 m, which cannot substantially modify the bulk resistance of the atmospheric gap. Thus, this mechanism is very questionable.

Dynamic coupling. Waves in the atmosphere comprise acoustic branch, which corresponds to waves with periods less than a few minutes, and internal gravity wave (IGW) branch, which corresponds to disturbances with periods longer than ~ 5 min. In the mechanism of LAI coupling through atmospheric waves, in contrast to electric coupling mechanism, the atmosphere acts as a natural amplifier for upward propagating acoustic and gravity waves.¹⁸⁾ The effective gain at the E-layer in the atmosphere with exponentially decreasing density with altitude, $\rho(z) = \rho_0 \exp(-z/H)$ (H is the vertical scale of neutral atmosphere), may reach $\sim \exp(z/2H) \approx 10^3$ - 10^4 . As a result, the conditions for the detection of weak, but large-scale, atmospheric oscillations excited by near-ground sources are more favorable in the upper atmosphere.

The ionospheric response to acoustic waves generated by surface seismic waves propagating from epicenter is a well-established effect.^{19),20)} However, the same mechanism can hardly be applied to interpret the pre-seismic ionospheric disturbances. The required oscillations of the ground in the acoustic frequency range preceding EQs would have been most likely detected by modern seismometers.

Alternatively, it was suggested that IGW can be responsible for ionospheric disturbances occurring before seismic shocks.²¹⁾⁻²³⁾ The possible mechanisms of the excitation of IGW in seismo-active regions may comprise: 1) Long-period oscillations of the Earth; 2) Non-steady heating of near-surface atmospheric layer due to local green-house effect caused by lithospheric gas input into the near-surface atmosphere; and 3) Quasi-periodic mass yield of lithospheric gases.

The idea to anticipate the excitation of IGW in seismo-active regions was prompted by the experiments on

the detection of the Earth's long-period oscillations.²⁴⁾ In these experiments, the long-period ground oscillations, named seismo-gravitational oscillations, with periods from tens of minutes to a few hours, were discovered with specially designed long-period seismometers. The oscillations were observed nearly permanently, even in aseismic regions, and their amplitude was reported to increase noticeably before large EQs over the globe. Moreover, peaks in the spectra of the atmospheric pressure variations corresponding to vertical displacements of the ground were revealed.^{24),25)} These oscillations are probably the result of oscillations of a tectonic block, and presumably are most prominent in seismo-active regions. Near-ground variations of air pressure, serving as an excitation mechanism of IGW, are weak near the ground. However, owing to the amplification of the large-scale disturbance at the altitude of E-layer, these IGW may contribute to the LAI coupling.

Another possibility of IGW excitation before seismic events follows from the results of satellite observations of the surface infra-red radiation above Middle Asia. The analysis of night-time thermal images revealed the existence of non-stationary anomalies of the heat flux, collocated with large-scale geological structures.²⁶⁾ The temperature contrast between anomalous regions and the background reached 3-4 K. A suggested reason of the anomalies is a local "greenhouse effect" of lithospheric gases (CO_2 , CH_4 , etc.) above active faults. The yield of natural carbon gases was reported to become especially large, about an order of magnitude, during the periods of tectonic EQ preparation.²⁷⁾ The CO_2 concentration for producing an additional temperature $\Delta T \sim 3$ K was estimated to be twice the ordinary concentration. Moreover, there are reports on periodic variations, from 2 hours to one day, of the output gas concentration.²⁷⁾ The quasi-periodic variations of the heat source could be a possible driver of IGW.²⁸⁾

The crust degassing process would also produce variation of mass flux of lithospheric gases. This factor may be another driver (mass source) of IGW. The relevant solution of the equations of gas-dynamics system shows that the energy flux into the ionosphere of IGW generated by lithospheric gas yield might be quite substantial.²⁹⁾

In general, the efficiency of the two latter mechanisms of IGW generation by heat and mass sources is estimated to be higher than that by seismo-gravitational oscillations.

Ionospheric anomaly generation by IGW.

The most promising mechanism of the LAI coupling, and

physical basis of Kushida effect in particular, in our opinion, is related to the IGW generation in a seismically active region. The proposed scenario is shown schematically in Fig. 1. The large-scale IGWs generated in seismically active region, possibly by one of the three mechanisms discussed above, are assumed to be the main factor for the stimulation of ionospheric disturbances, more specifically, a sporadic Es-layer. This Es-layer in turn may be regarded as a free energy source for generation of small-scale (meters) ionospheric irregularities due to micro-instabilities of the ionospheric plasma. These meter-range irregularities could be the reason for the back-scattering of 80 MHz radio waves. In the following, we consider this scenario in more details.

IGW-induced sporadic E-layer. During the night-time, the plasma density of the regular E-layer is rather low. Sometimes irregular formations, called sporadic E-layers can be observed. Sporadic E-layers represent high-density plasma clouds of metallic ions having small vertical (from a few hundred meters up to a few kilometers) and large horizontal (from a few kilometers up to 100 kilometers) dimensions. Sometimes these layers exhibit a fine structure in horizontal and vertical directions. The Es-layer formation is often attributed to the plasma accumulation under the action of wind with horizontal velocity shear.^{30),31)}

Here we present a simplified explanation of Es-layer formation due to wind velocity U shear produced by an IGW. Fig. 2 schematically shows the vertical profile $U(z)$ and the motion of plasma in the vertical plane at the altitude of the E-region where ions are unmagnetized (i.e., ion-neutral collision frequency exceeds the ion gyrofrequency, $\nu_{in} > \Omega_i$). Here the ions are dragged by the neutral particle motion (wind), but also experience the Lorentz force, which deflects them from the wind velocity direction. In the geomagnetic field with the horizontal component $B_y = -B_0 \cos I$ (I is the dip angle), ions are forced to move vertically and converge inward to the altitude of zero wind velocity. The strongly magnetized electrons ($\nu_{en} \ll \Omega_e$) are unaffected by the neutral wind and move along the magnetic field lines to neutralize the space charge set up by the ion motion. Thus, under the E-layer conditions, the horizontal motion of the neutral particles produced by IGW forces the ions to move vertically and results in plasma accumulation into narrow sporadic E-layers inside the wind shear area.

Following the usual wind shear theory,³⁰⁾ the redistribution of plasma density for a simple case of ion convergence in a sinusoidal neutral particle velocity disturbance, $U_x = -U_0 \sin(2\pi z/\lambda)$, can be estimated as follows:

Fig. 1. Schematic figure of the possible mechanism of the back-scattering of VHF radio waves by meter-scale irregularities excited in sporadic E-layer. Firstly, IGW is supposed to be excited by three possible mechanisms (seismo-gravitational oscillations, periodic heating and non-steady gas yield). Secondly, sporadic E-layer is formed by IGW, and finally meter-scale irregularities are excited due to instabilities of plasma.

$$N(z) = N_0 \sqrt{2\pi\delta} \exp \delta [\cos(2\pi z / \lambda) - 1] \quad [1]$$

where N_0 is the background density, λ and U_0 are the vertical wavelength of the IGW and the characteristic wind speed. The term δ in eq. [1] denotes the ratio between the time scale of the wind shear plasma convergence process, $\tau_w \approx 1/(kU_0\beta_1 \cos I)$, and the diffusion of a plasma structure with wave number vector k , $\tau_D = 1/(k^2 D_a)$, that is

$$\delta = \frac{\tau_D}{\tau_w} = \frac{U_0 \beta_1 \cos I}{2\pi D_a},$$

where $\beta_1 = \Omega_i / v_i$ and $D_a = (T_i + T_e)/m_i v_i$ is the diffusion coefficient, T_i and T_e are ion and electron temperatures. Using eq. [1], one can estimate the rate of plasma accumulation under the action of the vertical wind shear of the IGW. The plasma density maxima $N_{\max} = N_0 \sqrt{2\pi\delta}$, localized near $z = 0, \lambda, 2\lambda, \dots$, become noticeable when $\delta \gg 1$. At night-time, E-region plasma density is low, 10^3 cm^{-3} , so the wind shear factor $\sqrt{2\pi\delta}$ has to be large enough, $\sim 10^2$, to form a dense layer with $N \geq 10^5 \text{ cm}^{-3}$. The magnitudes of this factor sufficient for the production of a rather strong Es-layer may be achieved for typical values: $\beta_1 \leq 1$, $D_a \approx 10^2 \text{ m}^2/\text{s}$, $D_a \approx 10^2 \text{ m}^2/\text{s}$, and $\lambda \approx 10 \text{ km}$.

A region of dense plasma could be formed by IGW within $\tau_w \leq 10^3 \text{ s}$, which is a fraction of the typical period

Fig. 2. Schematic figure of plasma accumulation (the generation of sporadic E-layer) by the wind shear. The wind shear drags ions to $-x$ ($+x$) direction in the region of $z > 0$ ($z < 0$). An external magnetic field (one component of geomagnetic field) is assumed to be $\mathbf{B} = -B_0 \cos \mathbf{e}_y$, where $\mathbf{e}_y$ is the unit vector in the y direction. Then, positive ions are deflected by Lorentz force, and they are accumulated on the plane of $z = 0$.

of the IGW. Under the considered mechanism, formation of stable sporadic layer would be possible if there were sufficient number of metallic ions in the ionosphere. If not, because of the relatively quick recombination of the usual ions, only a short-lived ($\sim$ a few minutes) sporadic layer can be produced.

Coherent back-scattering of VHF radio signals from ionospheric irregularities may occur only when the spatial scale of plasma irregularity is half the radio wave length (Bragg condition). Thus, to provide the possibility of over-horizon VHF propagation, further evolution of the IGW-induced sporadic E-layer should produce meter-size irregularities.

Sporadic E-layer as a source of small-scale plasma irregularities. The E-region plasma with steep density gradients can become unstable to the “two stream” and “gradient drift” instabilities.³³⁾ $\mathbf{V}_d = \mathbf{E} \times \mathbf{B}/B^2$ caused by the presence of ambient electric field $\mathbf{E}$ across the geomagnetic field is large, so the ion’s inertial force exceeds the pressure gradient force, which tries to smooth out the density perturbations through diffusion (Fig. 3). This instability, which is dominant at short wavelengths, has a threshold velocity $\mathbf{k} \cdot \mathbf{V}_d > k C_s (1 + \phi)$, $\phi = v_{in} v_{en} / \Omega_i \Omega_e$. On the other hand, the gradient drift instability occurs when plasma density enhancements (depletions) are convected parallel (anti-parallel) to the direction of the background electron density gradient with perturbed drift velocity, $\delta \mathbf{V} =$

Fig. 3. Schematic figure of meter-scale irregularities of plasma in sporadic E-layer. The meter-scale irregularities are generated by two kinds of the instabilities of plasma, i.e., two-stream and gradient drift instabilities.

$\delta \mathbf{E} \times \mathbf{B} / B^2$, when $\mathbf{E} \cdot \nabla N_0 > 0$ is positive.³²⁾ This instability is usually dominant at the long wavelength (larger than a few tens of meters). These two instabilities are thought to be the main reasons for the generation of small-scale irregularities in the E-region. For the two-stream instability to be excited, a rather strong ambient electric field ($E > 10\text{--}15\text{ mV/m}$ at mid-latitudes) is necessary. The required large electric fields could be generated due to local polarization process inside a spatially confined night-time Es-layer.³⁴⁾

If the polarization electric field is not large enough for the two-stream instability, the effect of both two-stream and gradient drift processes can be combined. Thus, plasma irregularities with wavelength of a few meters could be produced. The dispersion relation from the linear fluid theory,³³⁾ for small-scale (wavelengths ranging from a meter to a few meters) plasma disturbances perpendicular to $\mathbf{B}$ is

$$\omega_k = \frac{\mathbf{k} \cdot \mathbf{V}_d}{1 + \phi}, \quad \gamma_k = \frac{\phi}{1 + \phi} \left(\frac{\omega_k^2 - k^2 C_s^2}{\nu_i} + \frac{\Omega_e \omega_k}{\nu_e (\mathbf{k} \cdot \mathbf{L}_\perp)} \right) - 2\alpha N_e \quad [2]$$

where ω_k is the frequency and γ_k the growth rate of the harmonic with wave number vector $\mathbf{k}$, α is the recombination coefficient, $C_s = (k_B T_e / m_i)^{1/2}$ is the ion-sound velocity, and $\mathbf{L}_\perp$ is the scale of the electron density gradient perpendicular to $\mathbf{B}$ and parallel to $\mathbf{E}$, taken positive if $\mathbf{E} \cdot \nabla N_0 > 0$.

The theoretical estimates for the case of the Kushida's observations can be obtained from eq. [2] for the typical sporadic E conditions. The recombination

effects, i.e., the coefficient α in eq. [2], can be neglected in the case of metallic ions. The theory predicts that for the production of irregularities with $\lambda \approx 2.5\text{ m}$ (corresponding to the radio frequency $\sim 80\text{ MHz}$), a combination of ambient electric field $5\text{--}10\text{ mV/m}$ (which is still apparently less than necessary for the two-stream instability) and density gradients with $L_\perp \approx 0.5\text{--}5\text{ km}$ could be sufficient to generate meter-scale plasma irregularities at Es-layer boundaries.

Conclusion. *Further possible way to study the Kushida effect.* In the previous sections, we showed that, in principle, the Kushida effect is physically feasible. However, there seem to be no well-established specific reasons for the seismo-active region to become the source of atmospheric IGW before EQs. If some of the proposed mechanisms, including the long-period seismo-gravitational oscillations of the Earth, non-steady heating of near-surface atmosphere, and non-stationary yield of lithospheric gases, worked and IGWs are generated, under favorable conditions, they can reach the ionosphere. Then, shear in the IGW-related neutral velocity may produce a sporadic E-layer, which in turn may provide the plasma gradients at the layer boundaries necessary for the excitation of small-scale plasma irregularities. As an observational support for the suggested mechanism, one may mention the detection of radar echoes from Es-layer which also was supposedly related to the modified gradient drift instability of the plasma gradients inside the inhomogeneous layer.³⁵⁾

The future experiments should prove if there is actually any association between Kushida's anomalies and short-lived sporadic E-layers. It may be mentioned, that there exist indications of increased probability of Es-layer in the ionosphere before EQs.⁴⁾ As an indirect indication of the significance of IGW for the production of the Kushida effect, the occurrence of quasi-periodic ($\sim 10\text{ min}$) variations of baseline of back-scattered VHF FM signals⁹⁾ can be noticed.

The ionospheric irregularities are known to be produced during magnetic storms. We examined the geomagnetic environment during several most prominent precursory events forecasted by Kushida, such as 1995/01/17 (Kobe, M7.2), 1995/07/30 (Ibaraki-ken, M5.0), 1996/08/11 (Akita-ken, M5.9), 2000/10/06 (Tottori-ken, M7.3). We have checked the magnetic storm occurrence according to D_{st} index, provided by the Kyoto World Data Center (<http://swdcd.kugi.kyoto-u.ac.jp/>) and the sub-storm activity according to magnetograms from Circum-Pan Magnetic Network (<http://stdb2.stelab.nagoya-u.ac.jp/>). All of these anom-

alies occurred during geomagnetically quiet periods, without concurrent or preceding magnetic storms or substorms.

The following experimental tests can be suggested for further verification of Kushida effect and proposed physical mechanism:

- Overlapping observations with Kushida's technique and VHF and ionospheric observations which can detect unambiguously the occurrence of meters-scale irregularities, such as MU radars;
- Analysis of ground-based observation of geochemical process and search for their periodicity in the period range ~5 min –2 hours;
- Examination of other possibilities of small-scale plasma irregularities by IGW (e.g., gradient-drift instability at vertical plasma gradient³⁶⁾).

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