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Subionospheric LF monitoring of ionospheric perturbations prior to the Tokachi-oki earthquake and a possible mechanism of lithosphere-ionosphere coupling

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Abstract: We first present the results of simultaneous monitoring of subionospheric LF propagation over two different paths prior to a very strong Tokachi-oki earthquake (near the east coast of Hokkaido Island on September 25, 2003) with magnitude 8.3. Nighttime amplitude fluctuations of the Japanese Time Standard Transmitter (JJY, 40 kHz) signal received at Moshiri (Japan, geographic coordinates 44°N, 142°E) and at Petropavlovsk-Kamchatski, Russia (53°N, 158°E) were analyzed. As a possible precursory signature we observed synchronous intensification of quasi-periodic 16-day variations of the dispersion in the signals received at both observation stations before the earthquake. The strongest deviations observed as a rule were depletions of signal amplitude probably connected with an increase in loss in the ionosphere by the enhancement of turbulence. This is due to dissipation of internal gravity waves (IGW) at the lower ionospheric heights. A scenario of interconnection between seismo-activity, atmospheric gravity waves and planetary waves, is proposed to explain the observed association with strong earthquakes.

key words: subionospheric LF propagation, earthquakes, ionospheric perturbations

1. Introduction

The effect of earthquakes has been expected to take place mainly in the Earth's crust, but we have found recently a lot of electromagnetic phenomena in the atmosphere as well as in the ionosphere (Hayakawa, 1999; Hayakawa and Molchanov, 2002). It is recently believed that the ionosphere is extremely sensitive to the seismic activity since the clear discovery of ionospheric perturbations for the Kobe earthquake by means of subionospheric VLF monitoring (Hayakawa *et al*., 1996).

VLF/LF subionospheric radio sounding techniques have been studied as a solution of the short-term earthquake prediction for the last decade. These techniques are based on the detection of disturbances in the lower ionosphere, which can be of seismic origin. Some promising results demonstrate anomalous deviations in the VLF phase or/and amplitude (Gokhberg *et al*., 1989; Morgounov *et al*., 1994) and terminator time position (Hayakawa *et al*., 1996; Molchanov and Hayakawa, 1998) in the diurnal patterns of radio signals propagated over paths across the areas of future strong earthquakes.

The possible mechanisms of the energy transmission from processes in the earth's crust related to earthquake preparation, to the lower ionosphere have been discussed recently by Hayakawa and NASDA's Earthquake Remote Sensing Frontier Research (2001), Pilipenko *et al.* (2001) and Hayakawa *et al.* (2004). Three types of the lithosphere-atmosphere-ionosphere coupling have been proposed in those papers. 1) Electromagnetic coupling is connected with the direct penetration of the DC atmospheric electric field induced due to the appearance of seismo-related electric charges on the earth's surface. It can lead to the substantial modifications of ionospheric properties. 2) Chemical coupling is determined by variations of the fair weather electric field in the lower ionosphere due to the enhancement of conductivity of the lower atmospheric layers ionized by radon emanating from seismic faults. 3) Acoustic coupling implies an influence of atmospheric wave processes originating near the earth's surface onto the lower ionosphere. It is known that the atmosphere serves as an amplifier for upward propagating acoustic and internal gravity waves due to the exponential decrease in its density with altitude. So, even very small-amplitude (but large scale as we can assume for the tectonic processes) atmospheric oscillations originated from the near-ground sources can be transformed to high-amplitude waves at the lower ionospheric heights. The possible mechanisms of IGW generation in the lithosphere outlined by Hayakawa and NASDA's Earthquake Remote Sensing Frontier Research (2001) and Pilipenko *et al.* (2001) include so-called seismo-gravitational oscillations of the Earth with periods from a few tens of minutes to a few hours (Lin'kov *et al.*, 1998), gas yield from preparatory zone (Voitov and Dobrovolsky, 1994), and periodic heating of seismic faults (Gokhberg *et al.*, 1996).

As shown by Molchanov and Hayakawa (1998), some precursory signatures in VLF signal appeared as an intensification of background quasi-periodic variations with periods 5–16 days coinciding with the frequency range of planetary waves. Our initially proposed hypothesis on the excitation of PWs by shocks in an earthquake preparatory zone met considerable problems connected partially with too long time of propagation of PWs from the ground to the lower ionosphere. Later the gravity waves modulated by planetary waves were considered as a faster energy carrier from the lithosphere to the ionosphere in order to explain the effects observed in subionospheric VLF radio signals (Molchanov *et al.*, 2001).

Consistent with the present-day concepts, PWs originate in the troposphere and stratosphere and penetrate into the lower ionospheric heights (*e.g.* Namboothiri *et al.*, 2002 and references therein). The upward propagation of PWs is strongly determined by regular stratospheric winds. As predicted by the theory by Salby (1981a,b), PWs will be trapped by the westward winds that dominate during summer and they can propagate through the eastward winter winds to lower ionosphere heights. This prediction is confirmed experimentally by the radar observation of wind variations in the mesosphere and lower thermosphere (MLT) that show seasonal variability of PW activity reaching maximal intensity during winter months. The existence of minor summer maxima in the PW activity in the MLT region is explained by different causes. These are the penetration of PWs from the winter hemisphere, and breaking of gravity waves whose transmission through the stratosphere is modulated by PWs (Smith, 1996;

Namboothiri *et al.*, 2002 and references therein).

We present results of subionospheric LF monitoring performed simultaneously at two widely separated receiving stations during the Tokachi-oki earthquake with magnitude greater than 8. In this study we show an additional evidence for PW influence on the lower ionosphere through the modulation of the upward propagating IGW, and we compare our observational results with the above-mentioned concept of the PW activity in the MLT region.

2. Data acquisition

A signal transmitted by Japanese Time Standard LF station (JJY, 40 kHz) located at the geographic coordinates (37.37°N, 140.85°E) in Fukushima prefecture was monitored at two different locations. These are the Moshiri station in Hokkaido and the station at Petropavlovsk-Kamchatski that is operated as a part of the Russian-Japanese complex geophysical observatory (Uyeda *et al.*, 2002). The third Fresnel zone is plotted in Fig. 1 for each signal propagation path. The positions of the events corresponding to the Tokachi-oki earthquakes are marked with large empty circles in the map (Fig. 1).

For receiving and logging of the VLF/LF signals, JAPAL system (a modification

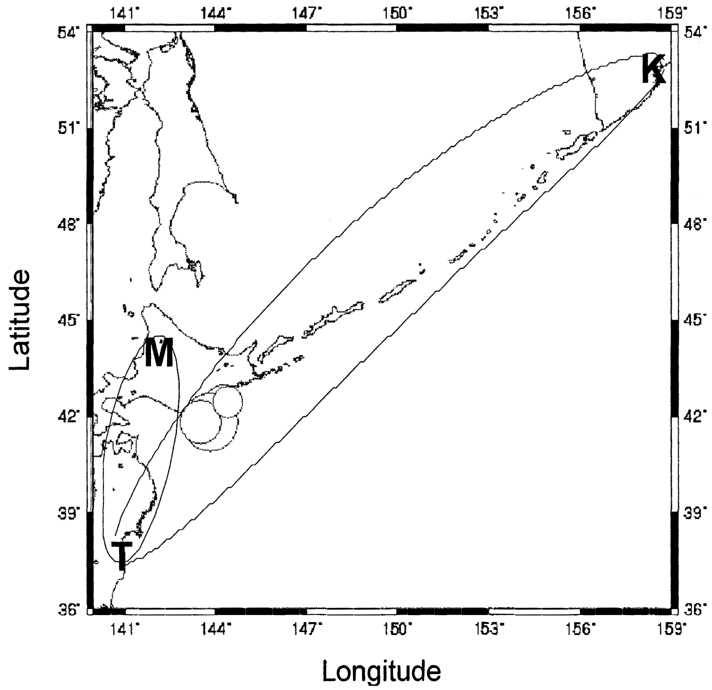


Fig. 1. A map of Tokachi earthquakes and LF propagation paths used for the study. Moshiri and Petropavlovsk-Kamchatski observatories, and JJY transmitter are marked in the figure with the bold letters M, K, and T respectively.

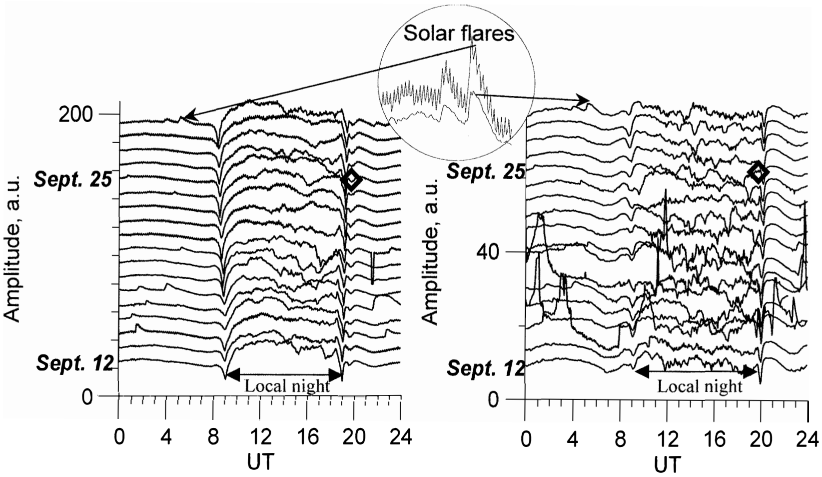


Fig. 2. Examples of daily amplitude variations measured in Petropavlovsk-Kamchatski (left) and Moshiri (right) around the date of the Tokachi earthquake. The earthquake time September 25, 2003, 1950 UT (or September 26, 0450 JST) is marked by a rhomb. The nighttime conditions over both propagation paths are marked by two-sided arrows. Synchronous perturbations in the signals caused by solar flares are demonstrated in the inset.

of the OmniPAL receiver) (Dowden and Adams, 1988) was used. The vertical electric component was received with a rod antenna installed on the roof of laboratory buildings at both locations.

Daily amplitude variations measured at both observatories around the date of the earthquake are plotted in Fig. 2. The different nature of the diurnal dependencies of the signal at these two places is connected with both the different orientation of the propagation paths to the terminator and their different lengths. For the shorter path (JJY–Moshiri) we note stronger fluctuations during the nighttime period in comparison with the longer path possibly due to its proximity to the interference minimum as it can be concluded from a comparison of average day-time and night-time levels. It is known that strong disturbances in VLF/LF signals occur during daytime due to additional ionization of the lower ionosphere by X-ray solar flares. They lead to increases in the VLF/LF signal amplitudes because of increased conductivity of the upper waveguide wall. Such disturbances in the signals are observed simultaneously, and they are shown in an inset of Fig. 2. Very strong (about 10 times over regular signal level) positive excursions of the amplitude of the signal observed at Moshiri during the daytime have a shape that is not typical for solar flare effects (fast growth and relatively slow decay), and seems to be unexplained in terms of waveguide propagation theory. So, we have to suppose another source for these disturbances in the signal. Possibly they are of artificial local origin.

3. Results of the LF data processing on the ionospheric perturbations

In a case study of different strong earthquakes Molchanov and Hayakawa (1998) have shown effectiveness of the terminator time method in revealing any precursory phenomena in VLF signals. Terminator times are determined by the positions of characteristic minima occurring in the diurnal dependencies of amplitude (and phase) of VLF/LF signals when the terminator crosses a propagation path during the evening and morning periods of time. Maekawa and Hayakawa (2005) have investigated the characteristics of terminator times for different propagation directions (EW, NS) and for short and long paths, and we expect clear changes in the terminator time for EW paths. Terminator minima are known to occur due to the interference between different waveguide modes. Their positions are sensitive to ionospheric irregularities along the propagation path as was shown by Hayakawa *et al.* (1996) for the propagation path being relatively short (~1000 km) and nearly perpendicular to terminator line and also as was recently quantitatively studied by Soloviev and Hayakawa (2004).

To explore a possibility of applying the terminator time method to the Tokachi-oki earthquake case, we demonstrate the evolution of the terminator time deviations around the date of the earthquake for both observatories in Fig. 3. We can find that the behavior of these deviations appears to be quiet. Maximal deviations do not exceed 15 min for both observation locations, which is much smaller than the effect (~45 min) observed for the Kobe earthquake (Hayakawa *et al.*, 1996). Possibly reduced sensitivity of the VLF signals to the ionospheric disturbances during the day-night transition period is connected with a specific (near meridian) orientation of the propagation paths (Maekawa and Hayakawa, 2005; Soloviev and Hayakawa, 2004).

In this study we use a technique based on the dispersion of the nighttime deviations of the LF signal amplitude from ±8-day running mean diurnal runs. We choose the 17-day window lag for averaging to achieve a compromise of contradictive requirements between removing seasonal changes of night time duration and smoothing stochastic fluctuations in the signal amplitude. Figure 4 illustrates an example of the average amplitude $<A>$, current amplitude $A(t)$, and difference $A(t)-<A>$. It demonstrates an anomalous nighttime deviation observed at Petropavlovsk-Kamchatski on September 18. To emphasize and distinguish more clearly the deviations in the signal amplitude we applied a nonlinear transform to the original LF data records. The linear scaling of the signal emphasizes the large excursions in amplitude which could be short in time (spikes). The logarithmic scaling acts in an opposite way: it diminishes the large excursions and emphasizes low amplitude variations with high dynamic range. We choose an alternative to the linear and logarithmic scaling that is determined by the next expression: $A(a)=\exp[\log(a)]$. In such a way we reduce both the influence of low and high abnormal deviations that are important in the analysis of integral parameters of the signal. So, below we will operate formally with the value $A(a)$ instead of the signal amplitude. Amplitude dependencies were normalized by an average nighttime signal level to make comparable the relative deviations measured at both observatories.

To search for the most informative parameters together with the total values of the dispersion D we also analyzed its fractions composed of both positive D_{p} and negative D_{n}

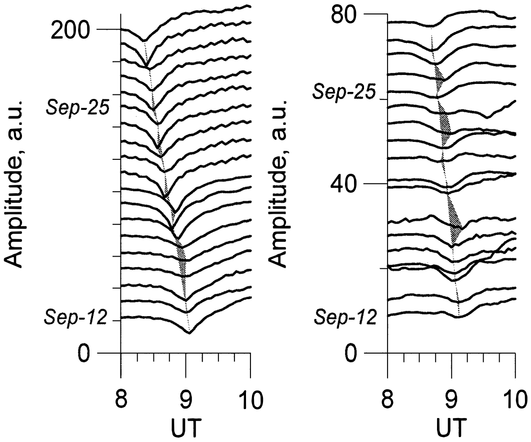


Fig. 3. Deviations in the terminator time on the signals received at Petropavlovsk-Kamchatski (left) and Moshiri (right), demonstrating a relatively quiet behavior. Because the maximal deviations do not exceed 15 min. Black paths indicate the deviation from the average terminator time variation expressed by a dotted line.

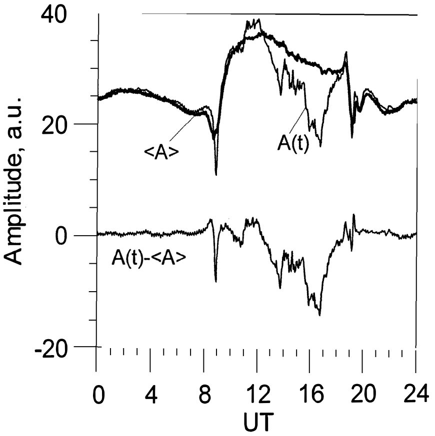
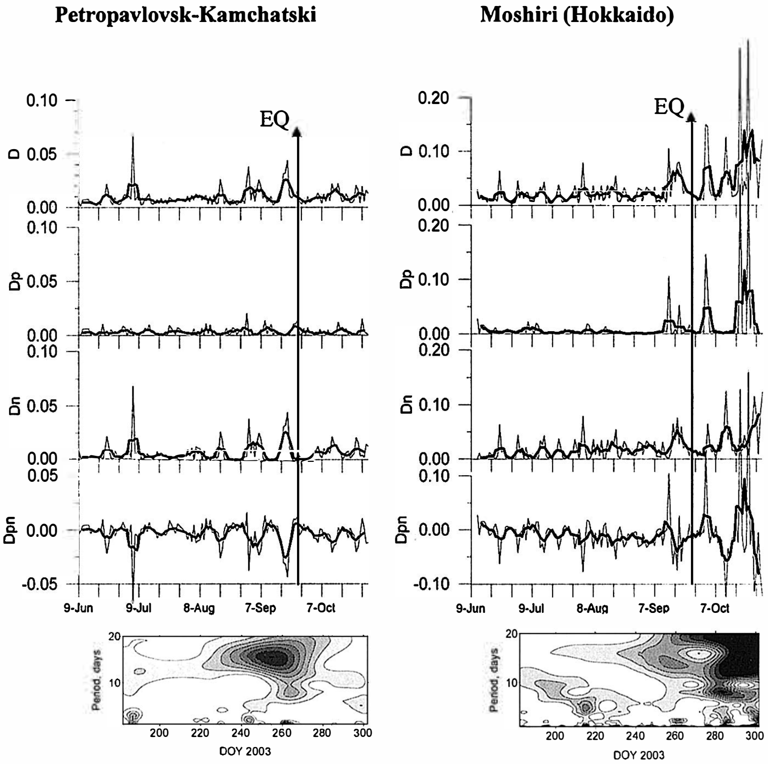


Fig. 4. An example of anomalous fading of the amplitude on September 18, 7 days before the date of the Tokachi earthquake. The variations of average amplitude $<A(t)>$, current amplitude $A(t)$ and differential amplitude $A(t)-<A>$, of the signal received at Petropavlovsk-Kamchatski are presented on this particular day.

deviations and their difference D_{pn}. The dispersion of the amplitude fluctuations was calculated over local nighttime specific for a chosen propagation path and a day of year. Presented in Fig. 5 are the results of analysis from the beginning of June to the end of October, for which simultaneously recorded data for both propagation paths are available. The dispersion dependencies smoothed by 5-day running mean are also plotted in Fig. 5. The time of the Tokachi-oki earthquake (September 25, 2003) is



Petropavlovsk-Kamchatski **Moshiri (Hokkaido)**

Fig. 5. Day-to-day variations of different fractions of dispersion of the nighttime deviations in the signal of JJY received at Petropavlovsk-Kamchatski (left) and Moshiri (right). The spectrograms at lower parts of the graphs show the Morlet wavelet transforms of the $D_{pn} = D_p - D_n$ *dependencies. The earthquake time is shown by the vertical arrow. In the upper panels thin line refers to the daily value and the full line, its corresponding running average ever 5 days.*

marked by vertical arrows. Considering the results from Petropavlovsk-Kamchatski presented in the left column in Fig. 5 we can find anomalous deviations of the LF signal. Such perturbations start from August 18 and are characterized by considerable fading of the signal that is demonstrated in Fig. 4. The strongest peaks appear in the "negative" fraction of the dispersion a week before the earthquake (September 18–20) and a day before the earthquake in the "positive" fraction of the dispersion. Such enhancements a week before the earthquake date are simultaneously observed in both the positive and negative fractions in deviations of the signal received at Moshiri.

A wave-like behavior of deviation intensity with the period of quasi 16-day PW becomes clearest from the D_{pn} dependences at both stations in Fig. 5. We can observe a swinging of this parameter before the earthquake with a gradual increase of its amplitude that reaches a maximal value a week before the earthquake. And just after the event the wave process is seen to shrink. The stronger perturbations in the signal received at Moshiri after the time of the earthquake could take place as a result of

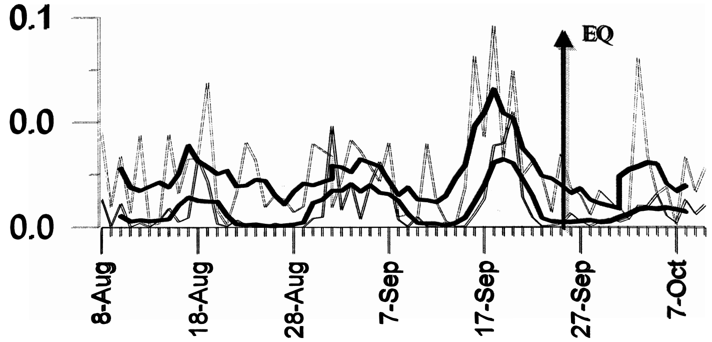


Fig. 6. Synchronous 16-day wave packets observed on the variations of the signals received at Moshiri (upper curve) and at Petropavlovsk-Kamchatski (lower curve) before the Tokachi earthquake on September 25, 2003. Thin curves refer to the daily value and thick curves are the 5-day running means.

specific propagation conditions on this path. Wavelet diagrams showing the time evolution of the spectral content of deviations in both signals are presented in the lower part of the graphs. We can recognize the intensification of oscillations with period corresponding to the quasi 16-day PW in both diagrams started approximately one month before the earthquake. This kind of intensification is found to be very consistent with our previous work (Molchanov and Hayakawa, 1998). A magnified view of the variations of negative fractions of signal dispersion combined for both observation points is shown in Fig. 6. It is important to note that the wave-like variations of the dispersion of signals propagating on those two different paths become almost synchronous during about one month period before the earthquake as is clearly seen from 5-day running means presented in Fig. 6.

Then we analyze an extended data set over the time span of about one year obtained for the JJY–Petropavlovsk-Kamchatski propagation path to compare LF data with the seismic ones. For this analysis we selected relatively shallow earthquakes with magnitude grater than or equal to 5 with depth less than 50 km within the area bounded by the 3rd Fresnel zone and circles of 150 km radius around the transmitter and the receiver. The day-to-day variations of the negative fraction of the dispersion and its 5-day running mean (thin and thick black curves respectively) are presented in Fig. 7 together with the selected earthquakes marked by vertical bars. As we can see from this figure the period from the beginning of the year to the beginning of May (DOY = 122) is characterized by appearance of deviations which are comparable to or stronger than those preceding the main event, *i.e.* the Tokachi-oki earthquake. The number of such anomalies approximately corresponds to the number of earthquakes answering the above selection criteria. The most of them can be associated with earthquakes by the time of occurrence. Then from the beginning of May we observe rather quiet behavior of the signal fluctuations excluding two strong one-day anomalies. Then on the background of relative seismic silence from the end of July (DOY = 213) to the end of September (DOY = 274) we can observe a gradual intensification of signal dispersion with period of the quasi 16-days. This intensification is observed in the signals

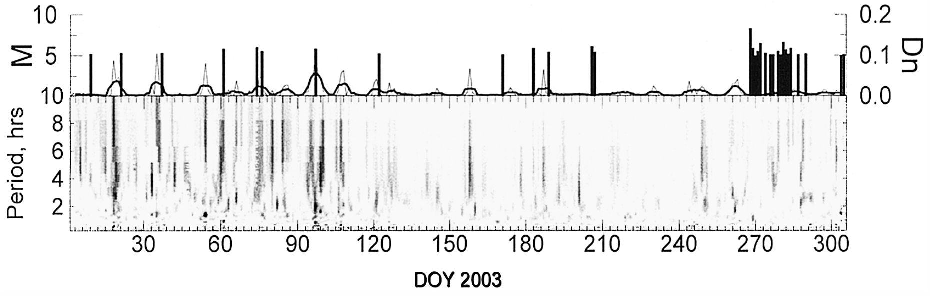


Fig. 7. A comparison between the seismic activity and intensification of fluctuation in the period of gravity and planetary waves in the signal received at Petropavlovsk-Kamchatski during January–October, 2003

propagating over the both paths, as was noted before.

Gravity waves (GWs) are considered as the most probable agent for the energy transportation from the earthquake preparatory processes to the lower ionosphere (see Pilipenko *et al.*, 2001; Hayakawa and NASDA's Earthquake Remote Sensing Frontier Research, 2001; Molchanov *et al.*, 2001; Hayakawa *et al.*, 2004). To demonstrate a correspondence between the PWs manifestation in the day-to-day variations of the LF signal and its fluctuations in the frequency range of GWs, a survey of the frequency spectra of the nighttime fluctuations is presented in the lower part of Fig. 7. The frequency dependence of the average spectra of nighttime fluctuations is well described by a power law with spectral index which is approximately equal to 2 (see *e.g.* Shvets *et al.*, 2004). To emphasize the higher frequency components we have compensated the power dependence in the spectra shown in Fig. 7. We can find a correspondence between the peaks of the dispersion and the intensification of oscillations within the GW frequency range (1–8 hours). The intensification of such fluctuations occurs as a quasi-periodic process with the PW periodicity. This circumstance seems to provide a good evidence for the modulation of GW by PW appearing in the observations.

4. Discussion and conclusion

As was shown previously PW periodicity is found in the day-to-day variations in both the transitional terminator times (Molchanov and Hayakawa, 1998; Hayakawa and NASDA's Earthquake Remote Sensing Frontier Research, 2001) and the nighttime fluctuations (Shvets *et al.*, 2004) in VLF signals. We should note that some precursory signatures found by Hayakawa *et al.* (1996) using the terminator time method also appeared as a development and intensification of oscillations with the PW periodicity in the VLF signal before the Kobe earthquake. So, in searching for anomalous deviations of the VLF/LF signal parameters related to the seismic activity, we need to consider the influence of the PWs on the lower ionosphere as a background process.

Atmospheric processes can crucially affect GW propagation from the ground to the ionosphere. So, we do not expect the existence of strong dependence between the value of subionospheric signal anomaly and the power of a probable GW source. In our

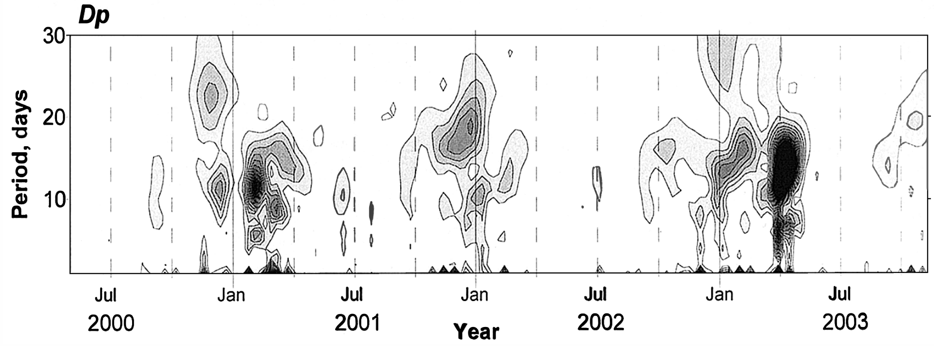


Fig. 8. Wavelet diagram of the positive fraction of dispersion of the LF signal on the propagation path JJY–Petropavlovsk-Kamchatski during the period of 2000–2003.

supposition concerning a seismic origin of the observed LF perturbations, the contradiction between these perturbation values and magnitudes of associated earthquakes can be explained by nonlinear interaction between GWs and PWs accounting for seasonal variability of PW activity in the lower ionosphere. The observed deviations in the LF signal during several winter-spring months are stronger in comparison with the case of the huge Tokachi-oki earthquake. They could be explained by enhanced penetration of the PWs to the lower ionospheric heights and their nonlinear interaction with GWs. Under such a consideration we also expect that the phase relationship between possible precursory effects and seismic events will be exposed to an external factor, *i.e.* PWs.

Shown in Fig. 8 is the wavelet diagram of the positive fraction of nighttime dispersion variations in the JJY signal measured at Kamchatka. It demonstrates clear seasonal variability of the nighttime amplitude fluctuations. We can observe the repeating maxima of them during winter months over the time span of more than 3 years. The maximal spectral density of these variations is concentrated in the range of the 16-day planetary waves periods. Such a seasonal variability can be explained by the seasonal dependence of the PW penetration to the lower ionosphere driven by stratospheric winds. The minor peaks observed during summer–autumn months are rather characterized by the GW activity. It is expected to be dominating during summer months when westward stratospheric background winds trap the PWs and prevent them from direct penetration into the lower ionospheric heights. The results of analysis of LF data set obtained during 2000–2003 show clear seasonal variations of the PW activity with maxima occurring in January–February. It is sufficiently close to the results of radar measurements of winds at MLT region cited in a number of papers (Mitchell *et al.*, 1999; Namboothiri *et al.*, 2002; Luo *et al.*, 2002).

Two concurring mechanisms can be used for explanation of the nighttime amplitude fluctuations: (1) modal interference that can induce the strong variations of the signal due to changes of the effective height of the lower ionosphere or/and (2) electromagnetic wave scattering from local inhomogeneities in the ionospheric profile along the propagation path accompanied with the change of losses. Since the amplitude of negative anomalous deviations corresponding to the signal fading, tends to prevail over the positive ones, we can suppose that this process is mainly connected with an increase in the losses in the lower ionosphere. This supposition is consistent with the previous experimental results by Lastovicka *et al.* (1993) who demonstrated the effects of loss increase in the lower ionosphere related to the GW activity intensification.

The observed perturbations in the LF signals are found to have appeared synchronously on both the propagation paths before the Tokachi-oki earthquake. This circumstance would seem to require dimensions of corresponding irregularities in the lower ionosphere of the order of 300–500 km or more, to overlap both propagation paths. To explain synchronous changes of the signal dispersion over the two paths we can invoke the next mechanisms. The first one is the intensification of global scale PWs affecting the properties of the lower ionosphere. But as it follows from the theoretical predictions, the maximal intensity of the PWs at lower ionospheric heights is reached during winter months. So, the second mechanism seems to be preferred involving the penetration of IGWs modulated by the PWs in the troposphere, stratosphere and ionosphere for the considered autumn period. In this case the influence on the ionosphere will be relatively local and the observed synchronous perturbations of LF signals on the monitored propagation paths provide a possibility for the localization of ionospheric perturbations which are close to their possible source at the earth surface.

Thus, the next scheme of the seismo-ionospheric interaction that includes both GW and PW influence is summarized to explain the observed effects on the LF propagation. The IGWs excited by any processes in the Earth's crust connected with earthquake preparation, propagate to mesopause heights, dissipate increasing turbulence and create additional losses in the lower ionosphere. The intensity of IGW is modulated by PWs due to nonlinear interconnection between them in the troposphere and stratosphere and at the lower ionospheric heights.

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