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Results of subionospheric radio LF monitoring prior to the Tokachi (M=8, Hokkaido, 25 September 2003) earthquake

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Abstract. Results of simultaneous LF subionospheric monitoring over two different propagation paths prior to the very strong Tokachi earthquake (near the east coast of Hokkaido Island, 25 September 2003) of magnitude 8.3 are presented firstly. Nighttime amplitude fluctuations of the Japanese Time Standard Transmitter (JG2AS, 40 kHz) signal received at Moshiri (Japan, 142° E, 44° N) and at Petropavlovsk-Kamchatski (Russia, 158° E, 53° N) were analyzed. As a possible precursory signature we observed synchronous intensification of quasi periodical 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 increase of loss in the ionosphere by the enhancement of turbulence. This is due to dissipation of internal gravity waves (IGW) at the lower ionosphere heights. A scheme for seismo-IGW-planetary waves (PW) interconnection has been justified to explain the observed connection with strong earthquakes. It considers the seasonal variability in the signal.

1 Introduction

Earthquake prediction is represented as a two stage problem. The first stage includes an extensive search for precursory phenomena in different fields, methods of their determination and recognition and development of appropriate models to explain physical mechanisms for the observed effects. The second stage will include elaboration of the algorithms, techniques and specific technical systems for earthquake prediction based on positive results in the previous stage. In the present study we are on the first stage. Thus it is important to study the strongest seismic events which are expected to provide the most prominent accompanying phenomena in the Earth and near-earth environment.

VLF/LF sub-ionospheric radio sounding techniques have been involved in the solution of the earthquake prediction problem for the last two decades. These techniques are based on the detection of disturbances in the lower ionosphere, which can be of seismic origin. Some promising results had been obtained in this direction that demonstrate anomalous deviations in phase or/and amplitude (Gokhberg et al., 1989; Morgounov et al., 1994) and terminator time position (Hayakawa et al., 1996; Molchanov et al., 1998) in diurnal runs 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 crust, related to earthquake preparation, to the lower ionosphere have been discussed recently by Hayakawa (2001) and Pilipenko et al. (2001). Three types of the lithosphere-atmosphere-ionosphere coupling have been proposed in those papers to summarize the notions in the field. 1) Electromagnetic coupling is connected with the direct penetration of the DC electric field induced due to the appearance of seismo-related electric charges on the earth surface. It can lead to the substantial modifications of ionosphere properties. 2) Chemical coupling is determined by the 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) Dynamic coupling implies influence of atmospheric wave processes originating near the earth surface on 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 of 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 ionosphere heights. The possible mechanisms of IGW generation in the lithosphere outlined by Hayakawa (2001) and Pilipenko et al. (2001) include so-called seismo-gravitational oscillations of the Earth with periods from a few tens of minutes to few hours (Lin’kov et al., 1998), gas yield from preparatory

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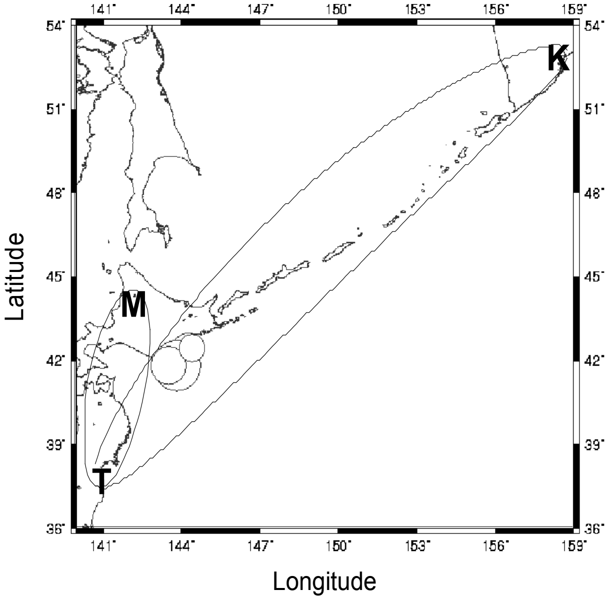

Fig. 1. Tokachi earthquake map and LF propagation paths employed for monitoring. Moshiri and Petropavlovsk-Kamchatski observatories, and JG2AS transmitter are marked in the figure with the bold letters **M**, **K**, and **T** respectively.

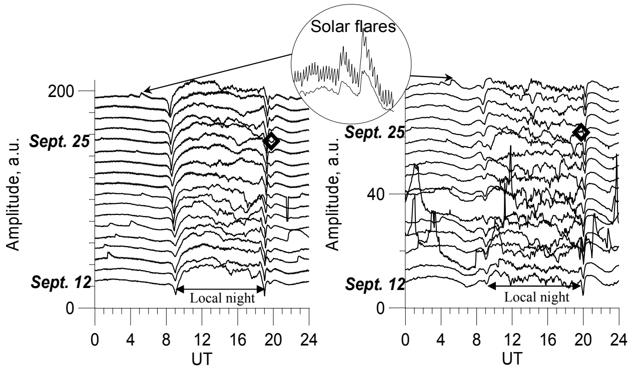

Fig. 2. Examples of daily amplitude runs measured in Petropavlovsk-Kamchatski (left) and Moshiri (right) around the date of the Tokachi earthquake. The earthquake time 25 September 2003, 19:50 UT (or 26 September 04:50 JST) is marked by a rhomb. The nighttime conditions over both propagation paths are marked by two-sided arrows. Synchronous perturbations in the signals caused by solar flares are demonstrated in the inset.

zone (Voitov and Dobrovolsky, 1994), and periodic heating of seismic faults (Gokhberg et al., 1996).

As was shown by Molchanov and Hayakawa (1998) 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. Initially proposed hypothesis on 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 lithosphere to ionosphere in order to explain the effects observed in subionospheric VLF radio signals (Molchanov et al., 2001).

Consistent with present-day concepts, planetary waves originate in the troposphere and stratosphere and penetrate to lower ionosphere 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 theory (Salby, 1981a, b) PWs will be trapped by the westward winds that dominate during summer time 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 penetration of PW from the winter hemisphere, and breaking of gravity waves whose transmission through the stratosphere is modulated by planetary waves (Smith, 1996; Namboothiri et al., 2002 and references therein).

We present results of LF subionospheric monitoring performed simultaneously at two widely separated receiving stations during the Tokachi earthquake that included a few shocks of magnitude more than 8 on the Richter scale. In this study we show additional evidence for planetary wave influence on the lower ionosphere through the modulation of the upward propagating IGW on accordance of 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 (JG2AS, 40 kHz; Fukushima Prefecture, 37.37° N, 140.85° E) was monitored at two different locations. These are Moshiri station at Hokkaido and the station at Petropavlovsk-Kamchatski that operates as 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 paths. The positions of the events corresponding to the Tokachi earthquake are marked with large empty circles in the map (Fig. 1).

For receiving and round-the-clock logging of the VLF/LF signals, a modification of the OmniPAL receiver (Dowden et al., 1988) was used. A vertical electric component was received with rod antennas installed on the roofs of laboratory buildings at both locations.

Daily amplitude runs measured at both observatories around the date of the Tokachi earthquake are plotted in Fig. 2. The different character 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

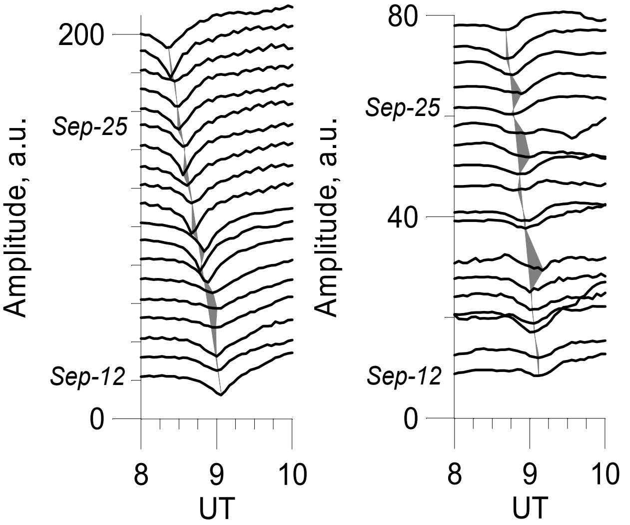

Fig. 3. Terminator time deviations in signals received at Petropavlovsk-Kamchatski and Moshiri demonstrate relatively quiet behavior. Maximal deviations do not exceed 15 min.

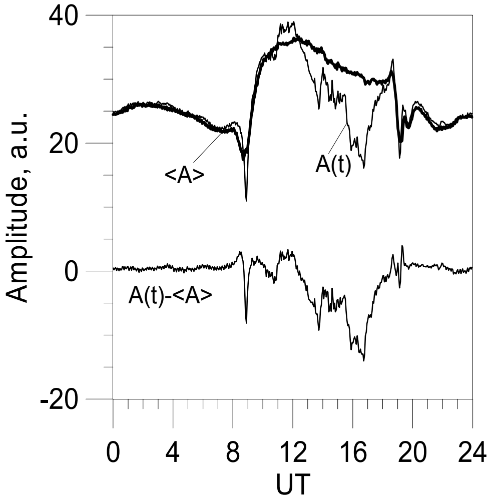

Fig. 4. An example of anomalous fading of the amplitude on September 18, 7 days before the date of the Tokachi earthquake. Average $<A>$, current $A(t)$ and differential $A(t)-<A>$, amplitude variations of the signal received at Petropavlovsk-Kamchatski are presented for this particular day.

(JG2AS – Moshiri) we note stronger fluctuations during the nighttime period in comparison with the longer path possibly due to of its proximity to the interference minimum as it can be concluded from comparison of average day-time and night-time levels. It is known that during daytime strong disturbances in VLF/LF signals occur due to additional ionization of the lower ionosphere by X-ray solar flares. They lead to increases of the VLF/LF signal amplitudes because of increased conductivity of the upper waveguide wall. Such disturbances in the signals are observed simultaneously. It is shown in Fig. 2 (inset). 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 the solar flare effects (fast growth and relatively slow decaying), 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

In a case study of different strong earthquakes Molchanov and Hayakawa (1998) have shown an effectiveness terminator time method for the revealing of precursory phenomena in VLF signals. Terminator times are determined by the positions of characteristic minima occurring in diurnal dependencies of amplitude and phase of VLF/LF signals when terminator crosses a propagation path during the evening and morning periods of time. Terminator minima occur due to the interference between different waveguide modes and their positions are sensitive to ionospheric irregularities along a propagation path as was shown by Hayakawa et al. (1996) for the case of relatively short ($\sim$1000 km) and close to perpendicular to terminator propagation paths.

To explore the possibility of the terminator time method application to the Tokachi 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 ($\sim$45 min) observed for the Kobe earthquake (Hayakawa et al., 1996). Possibly reduced sensitivity of the VLF signals to ionospheric disturbances during the day-night transition period is connected with a specific (near meridian) orientation of the propagation paths.

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 time lag for averaging to achieve a compromise between contradictive requirements of removing seasonal changes of night time duration and smoothing stochastic fluctuations in the signal amplitude. Some of average $<A>$, current $A(t)$, and differential $A(t)-<A>$ dependencies of the signal amplitude are shown in Fig. 4. They demonstrate an anomalous nighttime deviation observed at Petropavlovsk-Kamchatski on 18 September.

To emphasize and to 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 the low amplitude variations with high dynamic range. We choose an alternative to the linear and logarithmic scaling that is determined by the next expression: $A(a) = \exp\left[\lg(a)\right]$. In such a way we reduce both

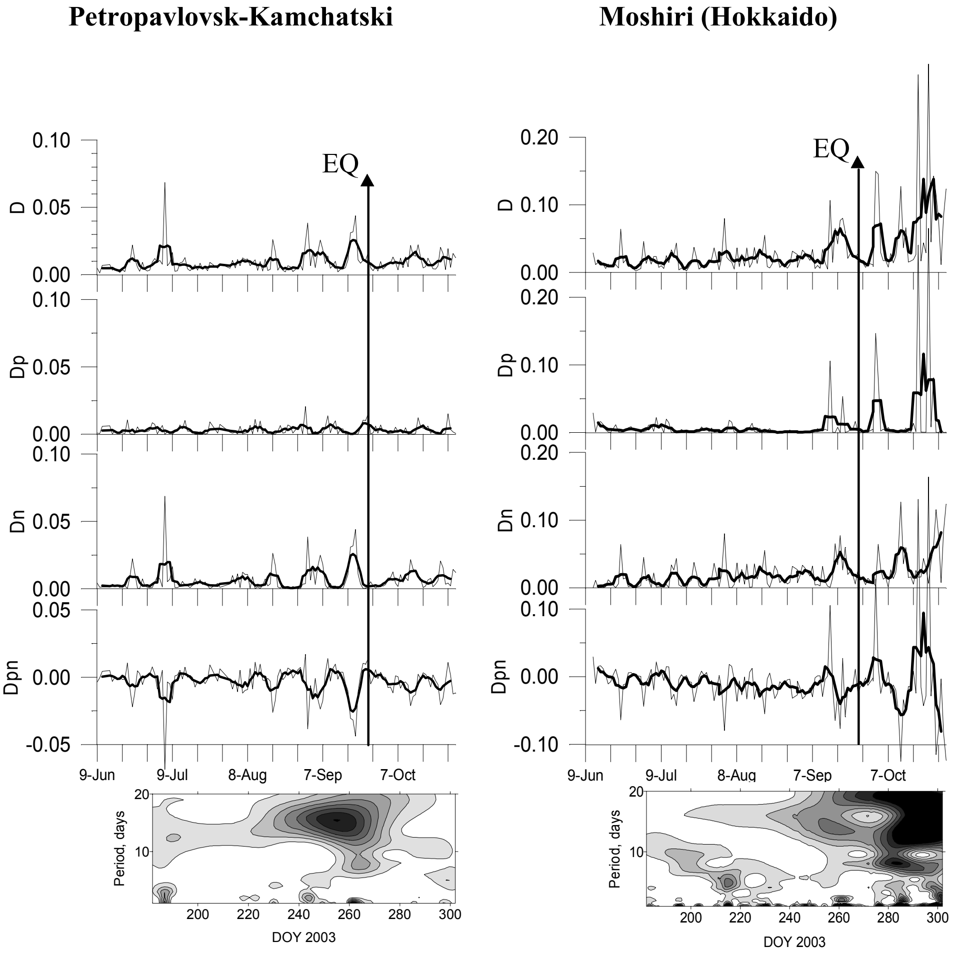

Fig. 5. Day-to-day variations of different fractions of dispersion of the nighttime deviations in signal of JG2AS received at Petropavlovsk-Kamchatski and Moshiri. The spectrograms at lower parts of the graphs show the Morlet wavelet transforms of the $Dpn=Dp-Dn$ dependencies. The earthquake time is shown by the vertical arrow.

the influence of low and high abnormal deviations that is important to the analysis of the 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 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 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 earthquake (25 September 2003) is 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 18 August and are characterized by considerable fading of the signal that demonstrated in Fig. 4. The strongest peaks appear in the "negative" fraction of the dispersion a week before the earthquake (18–20 September) and a day before in the "positive" fraction of the dispersion. Simultaneously such enhancements a week before the date are observed in both 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 planetary wave becomes most clear from the D_{pn} dependences 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 shrinks. The stronger perturbations in the signal received at Moshiri after the time of the earthquake could take place as a result of specific propagation conditions on this path.

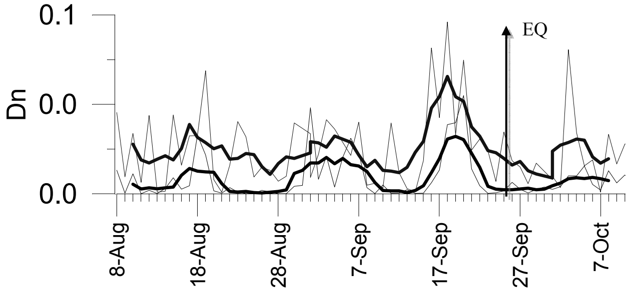

Fig. 6. Synchronous 16-day wave packets observed in variations of the signals received at Moshiri (upper curve) and at Petropavlovsk-Kamchatski (lower curve) before the Tokachi earthquake on 25 September 2003. Bold curves are the 5-day running means.

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 planetary waves in both diagrams started approximately one month before the earthquake.

A magnified view of the variations of the 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 through 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 on about the year time span obtained for the JG2AS – Petropavlovsk-Kamchatski propagation path to compare LF and seismic data. For this analysis we selected relatively shallow earthquakes of 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 is characterized by appearance of deviations which are comparable or stronger than those preceding the main event, i.e. the Tokachi 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 to the end of September we can observe a gradual intensification of signal dispersion with period of the quasi-16-day oscillations. This intensification is observed in signals propagating over both paths, as was noted before.

Gravity waves 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 and references therein; Hayakawa, 2001). To demonstrate a correspondence between the planetary wave's manifestation in the day-to-day variations of the LF signal and its fluctuations in the frequency range of gravity waves, 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 −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.

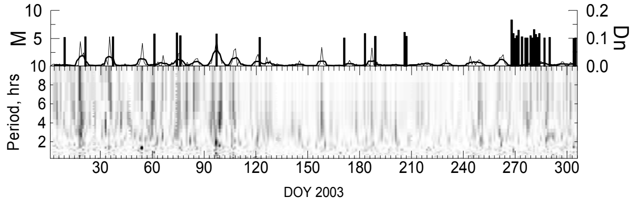

Fig. 7. Comparison between seismic activity and intensification of gravity and planetary wave's signature in the signal received at Petropavlovsk-Kamchatski during January–October, 2003.

We can find a correspondence between the peaks of the dispersion and the intensification of oscillations within the GW frequency range (1–8 h). The intensification of such fluctuations occurs as a quasi-periodical process with the planetary waves periodicity. This circumstance provides a good evidence for the modulation of GW by PW appearing in the observations.

4 Discussion and conclusion

As was shown previously a planetary wave periodicity is attributed to day-to-day variations in both the transitional terminator interval (Molchanov and Hayakawa, 1998; Hayakawa, 2001) and the nighttime fluctuations (Shvets et al., 2004) in VLF signals. We should note that the precursory signatures found by Hayakawa et al. (1996) using the terminator time method also appeared as a development and intensification of oscillations in the VLF signal before the Kobe earthquake with the planetary waves periodicity. So, in searching for anomalous deviations of the VLF/LF signal parameters related to seismic activity, we need to consider the influence of the planetary waves 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 the strong dependence between a value of subionospheric signal anomaly and the power of a probable GW source. In our supposition concerning a seismic origin of the LF perturbations observed the contradiction between these perturbation values and magnitudes of associated earthquakes can be explained by nonlinear interaction between GWs and PWs accounting for a seasonal variability

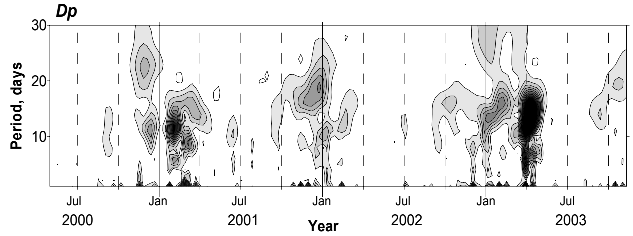

Fig. 8. Wavelet diagram of the positive fraction of dispersion of the LF signal on the propagation path JG2AS-Petropavlovsk-Kamchatski during the period 2000–2003.

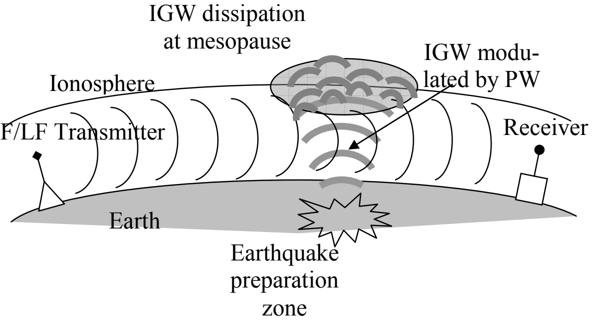

Fig. 9. A scheme for seismo-IGW-PW interconnection to explain observed effects in LF propagation.

of PW activity at 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 earthquake. They could be explained by enhanced penetration of the PWs to the lower ionosphere heights and their nonlinear interaction with GWs. Under such consideration we also expect that the phase relationship between possible precursory effects and seismic events will be exposed to an external factor, i.e. planetary waves.

Shown in Fig. 8 is the wavelet diagram of the positive fraction of nighttime dispersion variations in the JG2AS signal measured at Kamchatka. It demonstrates the clear seasonal variability of the nighttime amplitude fluctuations. We can observe the repeating maxima of them during winter months over more than 3 years time span. The maximal spectral density of these variations concentrated in the range of the 16-day planetary waves periods. Such a seasonal variability can be explained by the seasonal dependence of the planetary waves penetration to the lower ionosphere driven by stratospheric winds. The minor peaks observed during summer – autumn months are rather characterized by the gravity wave activity. It is expected to be dominating during summer months when westward stratospheric background winds trap the planetary waves and prevent their direct penetration into the lower ionosphere heights.

The results of analysis of LF data set obtained during 2000–2003 show clear seasonal variations of the planetary wave 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 ionosphere profile along a 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 increase of the losses in the lower ionosphere. This supposition is consistent with experimental results by Lastovicka et al. (1993) who demonstrated the effects of losses increase in the lower ionosphere related to the gravity wave activity intensification.

The observed perturbations in the LF signals appeared synchronously on the both propagation paths before the Tokachi earthquake. This circumstance would seem to require dimensions of corresponding irregularities in the lower ionosphere of order 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 planetary waves affecting the properties of the lower ionosphere. But as it follows from theoretical predictions, the maximal intensity of the planetary waves at lower ionosphere heights is reached during winter months. So, the second mechanism seems to be preferred involving the penetration of internal gravity waves modulated by the planetary waves 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 gravity and planetary waves influence is summarized in Fig. 9 to explain the observed effects on the LF propagation. IGW excited by processes in the Earth crust, connected with earthquake preparation, propagate to mesopause heights and 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 ionosphere heights.

The following conclusions have been made by concluding this paper.

1. Simultaneous two-stationed LF subionospheric monitoring for to the Tokachi earthquake (M=8.3) happened on 25 September 2003 have been performed.

2. Synchronous occurrence of wave packets with the period of quasi 16-day was observed before the earthquake

in the signal of JG2AS received both at Moshiri and Petropavlovsk-Kamchatski.

3. The strongest deviations observed in the signals were, as a rule, depletions of amplitude that can be explained by an increase in loss along the monitored propagation paths. This may be influenced by enhancement of turbulence due to dissipation of atmospheric gravity waves at the lower ionosphere heights.

4. A scheme for seismo-IGW-planetary waves (PW) interconnection has been proposed to explain observed possible connection with strong earthquakes that consider the seasonal variability in the signal.

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