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Experimental Evidence of the Correlation between Possible Precursors of Earthquakes in Near-Surface Quasistatic Electric Fields and in the Ionosphere

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Abstract—We consider data obtained when the parameters of the ionospheric E_s and F2 layers and the vertical gradient of the electric potential in the surface atmosphere were simultaneously measured during the preparatory period of crustal earthquakes with $M = 5.0$–6.2 in the Kamchatka region. The appearance of anomalously high E_s, accompanied by an increase in frequency parameters of the sporadic layer and the regular F2 layer, was detected on days when possible earthquake precursors, as determined earlier, occurred in atmospheric electric fields. The presumed earthquake precursors in the ionosphere are divided into two groups with different earthquake lead times ranging from several hours to two weeks. Empirical dependences are presented that connect the lead time of an earthquake (from the moment of the appropriate anomaly's occurrence in the ionosphere or in the atmospheric electric field to the moment of the shock) and the epicentral distance to the observation point with the earthquake magnitude. These dependences are different for the two groups of presumed earthquake precursors, but they are close inside each group of possible precursors isolated on the basis of quasistatic electric field measurements and revealed in ionospheric parameter variations.

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INTRODUCTION

The appearance of seismoionospheric disturbances in the preparatory period of earthquakes (EQs) is of substantial interest, as it is important both for understanding the nature of interaction between the lithosphere and ionosphere and for possible practical application for purposes of prediction. Two main mechanisms of such interaction are often discussed: electromagnetic models and the influence of acoustic gravity waves (AGW) [Sorokin, 1998; Pulinets and Boyarchuk, 2004]. Since precursor effects vary greatly and have different durations and various values of deviations from their background values, for every individual case there is one mechanism or another of seismoionospheric interaction that is most appropriate.

As an example, the hypothesis of the influence exerted upon the ionosphere by an AGW of analogous scale (an increase in the activity of which has actually been observed in seismically active periods [Khusamiddinov, 1983]) is often used for the interpretation of disturbances with duration $\tau = 1.5$–2.5 h in the daily variations in the frequency parameters of the F2 layer and E_s layers with spatial scales of $l \geq 500$ km. It has been found, however [Korsunova and Khegai, 2008], that the apparent velocities of ionospheric disturbance propagation with $\tau = 2$–3 h (identified as the medium-term precursors of EQs) are about 4–8 km/h and are comparable to the velocities of the displacements of boundaries of the EQ preparatory area in the Earth's crust [Sidorov, 1979]. These velocities are smaller than those of AGWs by two orders of magnitude and this hypothesis thus cannot be a satisfactory explanation of the observable ionospheric disturbances.

The appearance of anomalously high E_s at h = 120–140 km in the EQ period preparatory, a basic morphological sign in identifying ionospheric precursors [Korsunova and Khegai, 2008], fits the model calculations with allowance for the influence of electric fields on the ionosphere [Kim et al., 1993; Sorokin et al, 2006]. An important contribution to understanding the nature of such interaction can come from simultaneously measuring the electric fields in the atmosphere and the ionospheric parameters in any seismic active region. Such measurements are performed at the geodynamical proving ground at Paratunka near Petropavlovsk–Kamchatskii at the Institute of Space Physics Research and Radiowave Propagation, Far East Division, Russian Academy of Sciences.

The first results from comparing measurements, performed during an EQ preparatory period, of the ionospheric parameters and the vertical component of the electric field in the near-surface atmosphere (E_z) were published by Mikhailov et al. (2002). They considered the correlation between variations in the F2 layer and the quasistatic field but failed to obtain a clear correlation between E_z behavior and changes in the F2 region of the ionosphere, since they used only one ionospheric parameter (critical frequency of the F2 layer f_0F2) and the masking effect of magnetic disturbances.

Anomalies of the electric field in the atmosphere that could be attributed to EQ precursors and the velocities of their propagation were discussed by Mikhailov (2007). It has been found that the propagation velocities of these anomalies have values on the order of unities of kilometers an hour, which is close to the values of the apparent velocities of propagation of the ionospheric disturbances attributed to EQ precursors by Korsunova and Khegai (2008). This served as a starting point for this work, which is aimed at discovering the correlation between anomalies in quasistatic electric fields in the near-surface atmosphere and in the ionosphere during EQ preparatory periods. We applied the technique of considering simultaneous measurements of the parameters of ionospheric E_s and F2 layers [Korsunova and Khegai, 2008] to search for ionospheric earthquake precursors (IEPs).

We used data from measurements performed by the ionospheric station at Paratunka (φ = 52°58.3′ N, λ = 158°14.9′ E) for February–March 1992, September–October 1999, and September–October 2002. For September–October 1999, the complete processing of ionospheric observations was performed in increments of 30 min; for the remaining months, the data from hourly measurements by the same station were used from the archive of the NOAA's National Geophysical Data Center (the Space Physics Interactive Data Resource, or SPIDR). The more detailed processing of ionospheric measurements is necessary due to the rare cases of the sporadic E layer occurring over the considered periods of time (equinoxes), and to the existence of two sporadic formations that are not represented in the archive's hourly data. Measurements of electric fields in the atmosphere for the above months have been considered in detail elsewhere [Mikhailov et al., 2002; Mikhailov, 2007]. The same measurements were also used in the present study in juxtaposition with variations in the ionospheric parameters during EQ preparation.

METHOD OF ANALYSIS

The method of IEP extraction proposed earlier by Korsunova and Khegai (2006) on the basis of simultaneous measurements of the parameters of the E_s and F2 layers has been tested and validated [Korsunova and Khegai, 2008]. The basic criterion for discovering precursors is the occurrence of anomalously high E_s with a duration $\tau \sim 2$ h at altitudes of 10 km or higher, and that are greater than the background values for the actual altitude of the formation of the sporadic layer $h'E_s$. In addition, only cases in which the increase in $h'E_s$ was accompanied by spikes in the E_s frequency parameters (blanketing frequency f_bE_s and limiting reflection frequency f_0E_s), and in the critical frequency of the regular F2 layer (f_0F2) with the same duration, were considered. This method made it possible to detect IEPs for 33 powerful EQs with $M \geq 6$ that occurred in Japan between 1985 and 2001.

Weaker EQs with $M < 6$ are characteristic of Kamchatka, so weaker ionospheric effects preceding EQs may be expected, as the values of seismoionospheric disturbances depend on magnitude M of the coming EQ [Korsunova and Khegai, 2006]. Nevertheless, the criteria proposed above for the determination of precursors have been used for Kamchatka as well. In contrast to the work of Korsunova and Khegai (2006), however, the values averaged over 10 magnetically calm days preceding an EQ were used as background values for the ionospheric parameters, since the effect of magnetic disturbances on the parameters of the F2 layer is quite high at the considered latitude.

To discern the presumed ionospheric EQ precursors, the deviations of the current magnitudes of the investigated values ($h'E_s$, f_bE_s, f_0E_s, f_0F2) from the background values were found for every hour of the day, and for every 30 min for the control periods of 1999. The ratios of these quantities' deviations to the background values ($(\Delta f_b/f_b)E_s$, $(\Delta f_0/f_0)E_s$, Δf_0F2/f_0F2) were calculated for the frequency parameters. The analysis was performed for the period from the 24 hours preceding the moment of the EQ to the moment of the precursor's appearance. All cases fitting the above indications were noted (a detailed description of the technique is given in [4]).

Figure 1 presents deviations of the basic ionospheric parameters with a sampling time of 30 min during the preparatory period for the September 18, 1999, EQ with $M = 6.0$ and the values for the E_z-component of the electric field [Mikhailov, 2007]. The distance from the EQ epicenter to the observation point (R) was 190 km. The moment of shock is marked with the dashed line with the arrow. The time of the occurrence of the electric earthquake precursor (EEP) was determined by the moment of a negative dip in the E_z time variations, and the time of the IEP's occurrence was determined by the registration of an anomalously high E_s (of the h type, marked with a bold dotted line in Fig.1). The darkened spikes in the ionospheric parameters satisfying the above criteria are attributed to the presumed precursors. In the bottom panel, changes in the K_p-index [Solar Geophyical Data, 1999] are given for the same time period. It is seen that

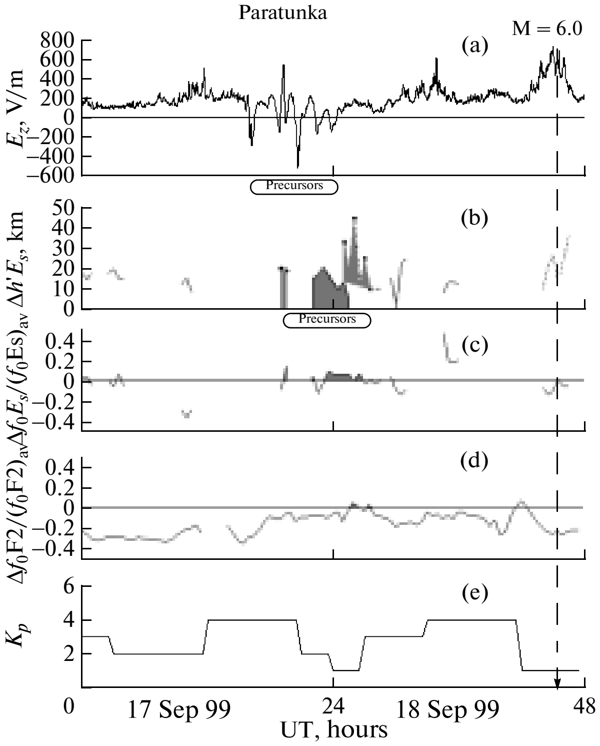

Fig. 1. Variations in (a) the vertical gradient of electric potential, (b–d) the parameters of the ionosphere, and (e) the K_p index over the September 18, 1999, earthquake's period of preparation.

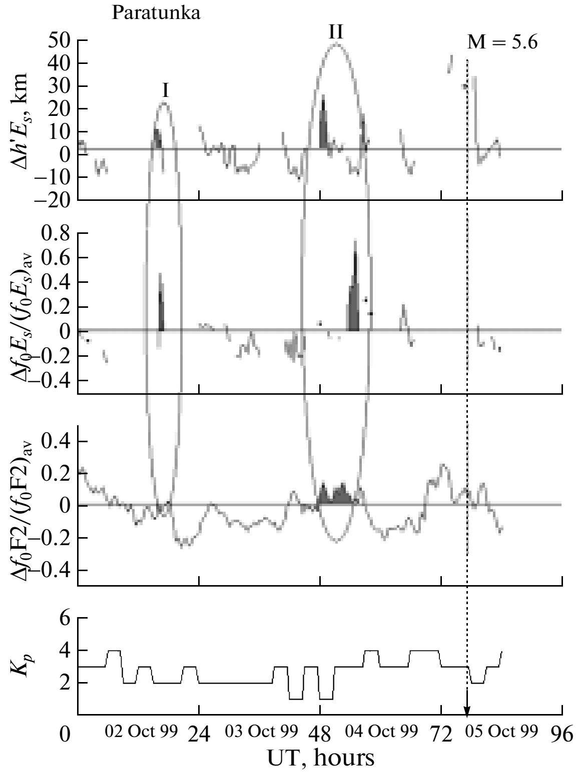

Fig. 2. Temporal variations in the deviation of parameters of the ionosphere and (bottom panel) changes in K_p index over the period of preparation for the October 5, 1999, earthquake. The two groups of the presumed precursors are marked with Roman numerals I and II.

the September 18, 1999, EQ preparation occurred during magnetic disturbances; this is why the positive deviations in the frequency parameters of the E_s and F2 layers are very small. Their simultaneous occurrence with the anomalies in E_z and $h'E_s$ over the same time period and the violation of the observable tendency toward negative deviations in f_0F2 testify to their seismic nature. In the absence of data on the E_s-layer, however, it is difficult to separate IEPs only on the basis of f_0F2 during magnetic disturbances [Mikhailov et al., 2002]. A comparison of changes in the ionospheric parameters and the E_z-component of the electric field shows that the EQ precursor in the electric field appears earlier than that the precursor in the ionosphere. In addition, spikes corresponding to an increase in the E_z-component of the electric field were noted in the E_s-parameters several hours before the underground shock.

An analysis of temporal variations in the ionospheric parameters during EQ preparation in the absence of appreciable geomagnetic disturbances (when the daily averaged magnetic index $A_p \leq 17$ nT) shows that two groups (I and II) of considerable deviations in the E_s-parameters can be isolated that satisfy the morphological signs of IEP identification [Korsunova and Khegai, 2008] and differ in the lead time of the EQ moment, i.e., IEPs of the first and second order of urgency, respectively. This is illustrated by Fig. 2, which is plotted according to half-hourly ionospheric data in which both IEP groups are shown (the designations are the same as in Fig. 1).

It is seen that these groups differ not only in the underground shock's lead time ΔT but also in the values of deviations inside the groups and in their durations. The greatest deviations in the ionospheric parameters are observed in group II in the E_s-layer. The durations of spikes and their number in group II also exceed their respective values in group I, of which solitary spikes of short duration are characteristic.

Variations in the quasistatic electric field in September–October 2002 [Mikhailov, 2007], were compared to the appropriate changes in the E_s and F2 layers using the hourly data. The moment of the occurrence of EQ precursors and their lead time relative to the main shock ΔT were determined. The results from this comparison are given in the table, along with the parameters of the analyzed EQs.

Unfortunately, there are no data on the electric field for March 1992, and the EQ precursor in group II (the dashes in the table) is not identified clearly for the

Characteristics of the ionospheric and electric precursors of earthquakes

EQ date and time	M	R, km	Group I				Group II			
			IEP		E_z		IEP		E_z	
			Date and time	ΔT, day	Date and time	ΔT, day	Date and time	ΔT, day	Date and time	ΔT, day
Oct. 8, 2002 09 h 19 min	5.0	120	Oct. 6, 2002 22 h	1.5	Oct. 6, 2002 23 h	1.4	Oct. 7, 2002 20 h	0.5	Oct. 7, 2002 17 h	0.7*
Oct. 3, 2002 15 h 57 min	5.2	280	Oct. 2, 2002 20 h	0.8	Oct. 2, 2002 21 h	0.8*	Oct. 3, 2002 06 h	0.4	Oct. 3, 2002 04 h	0.5
Oct. 20, 2002 01 h 35 min	5.3	110	Oct. 16, 2002 22 h	3.2	Oct. 16, 2002 15 h	3.4	Oct. 18, 2002 23 h	1.1	Oct. 18, 2002 23 h	1.1*
Oct. 5, 1999 05 h 02 min	5.6	190	Oct. 2, 1999 15 h 30 min	2.6	Oct. 2, 1999 12 h	2.7	Oct. 4, 1999 00 h	1.2	–	–
Mar. 2, 1992 14 h 08 min	6.0	160	Feb. 25, 1992 19 h	5.8	–	–	Feb. 29, 1992 15 h	1.9	–	–
Sep. 18, 1999 21 h 29 min	6.0	190	Sep. 14, 1999 07 h 30 min	4.6	Sep. 14, 1999 06 h	4.7	Sep. 17, 1999 19 h	1.1	Sep. 17, 1999 16 h 30 min	1.2*
Mar. 5, 1992 14 h 39 min	6.1	130	Feb. 21, 1992 10 h	13.2	–	–	Mar. 2, 1992 22 h	2.7	–	–
Oct. 16, 2002 10 h 12 min	6.2	160	Oct. 4, 2002 20 h	11.6	Oct. 4, 2002 14 h	11.8	Oct. 14, 2002 14 h	1.8	Oct. 14, 2002 22 h	1.5*

October 5, 1999, EQ. The EQ precursors attributed earlier [Mikhailov, 2007] on the basis of measurements of the electric field only are marked with asterisks. In the remaining cases, weak concave disturbances are revealed in the behavior of the electric field within the daily interval centered with respect to IEP occurrence. The moment of such a disturbance occurring with maximum amplitude and the ΔT corresponding to it are indicated in the table, from which it follows that anomalies in E_z appear either somewhat earlier than in the ionosphere or at the same time as with ionospheric anomalies.

RESULTS AND DISCUSSION

The results from the analysis of variations in ionospheric parameters over the periods preceding six EQs show that we can distinguish two groups of spikes with duration $\tau \sim 1–2$ h that correspond to the signs of EQ precursors and, as a rule, are accompanied by specific dips in variations of the E_z-component of the electric field. The appearance of such spikes is typically observed during daylight hours. The duration of spikes in E_s for group II is basically equal to $\tau \sim 1.5–2$ h, or somewhat more than that of the spikes in group I. The IEP groups with a short lead time (which we have already designated as IEPs of the second order of urgency) exhibit the most deviations in ionospheric parameters. As follows from the table, the greater the magnitude M of the subsequent EQ, the earlier the occurrence of precursors in both groups when the epicentral distances are equal. This is characteristic of IEPs we studied earlier [Korsunova and Khegai, 2006]. For the first time, however, we have detected the existence of two IEP groups differing not only in the value of ΔT but also in the amplitude of deviations.

For variations in the E_z-component of the electric field in the near-surface atmosphere, it is also possible to isolate two groups of specific disturbances prior to an EQ that differ in structure and in time of their occurrence. These moments in time are indicated in the table, from which it follows that variations in the E_z-component are observed on the same days as those in the ionosphere, though the moments of their occurrence are different. Depending on the moment of occurrence, they are assigned to group I or II in the table.

An analysis of the amplitudes of electric field disturbances indicates that such disturbances with a negative sign and amplitudes of –200 V/m to –1500 V/m dominate in group II. In group I, deviations in the electric field represent minor sign-alternating concave disturbances ±(150–300) V/m with $\Delta\tau \sim 1–1.5$ h. These distinctions in the amplitude of their changes and in their duration are analogous to the already noted IEP features of the corresponding groups. We may therefore assume that the appearance of two groups of different EQ precursors (in the electric field and in the ionosphere) corresponds to different phases of EQ preparation.

It should be noted that the EQ precursors in electric fields with a long lead time (3–26 days) for EQs with $M = 5.0–6.4$ have been observed in China [Hao et al., 2000]; these probably correspond to EEPs that

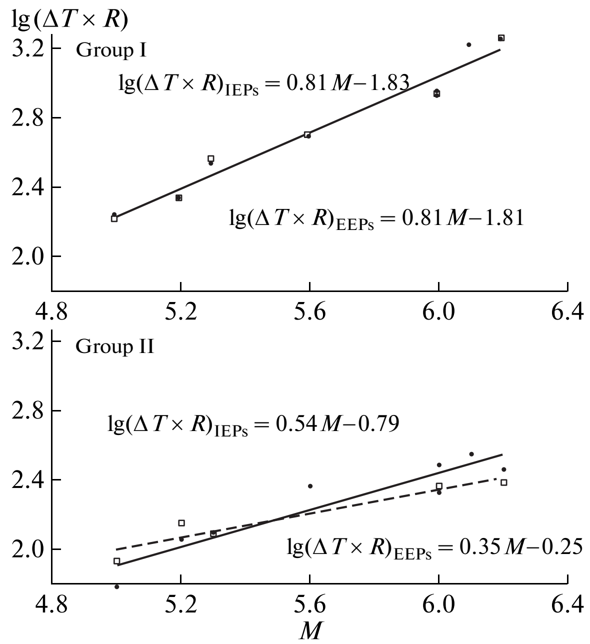

Fig. 3. Logarithms of the product of EQ lead time (ΔT, day, and fraction of the day) and the epicentral distance (R, km), depending on EQ magnitude (M) for two groups of the presumed EQ precursors, and the approximating straight lines (solid lines are approximations for IEPs, dashed lines are approximations for EEPs).

we identify as being of the first order of urgency. For EQ in the Kamchatka region, we can distinguish with confidence precursors that, according to our classifications, fit the characteristics of those of the second order of urgency from variations in the E_z-component of the electric field within 24 hours of the EQ moment [Rudenko, 2000; Smirnov, 2005]. This could be due to the values of seismogenic E_z-anomalies of the second order of urgency usually being several times greater than the field variations for the first order of urgency, so that it is difficult to isolate them from the daily variations in E_z. The greatest values for the lead time of an EQ moment (2, 3, and 6 months) are observed for anomalies in variations of gradient and phase velocities of ultralow frequency (f = 0.03–0.1 Hz) for geomagnetic disturbances prior to EQs with epicentral distances R < 150 km and M = 5.8 and 6.4 in Japan [Ismailov et al., 2006]. Although the nature of these anomalies may be different from those we detected in the ionosphere and the variations in the vertical gradient of the electric potential, their occurrence testifies to the prolonged period of EQ preparation, which includes several different phases.

Tendencies of variation in the logarithm of the product of EQ lead time (ΔT) and the epicentral distance (R) in dependence on EQ magnitude (M) are shown in Fig. 3 for both groups of EQ precursors (the dots represent IEPs, the squares represent EEPs).

The approximating straight lines were drawn on the basis of the least square method. The following expressions were derived for the EQ precursors of group I:

$$\begin{aligned} \log(\Delta T \times R)_{\mathrm{IEP}} &= 0.81M - 1.83; \\ \log(\Delta T \times R)_{\mathrm{EEP}} &= 0.81M - 1.81. \end{aligned} \quad (1)$$

The following expressions were derived for the EQ precursors of group II, which is closer to the EQ moment:

$$\begin{aligned} \log(\Delta T \times R)_{\mathrm{IEP}} &= 0.54M - 0.79; \\ \log(\Delta T \times R)_{\mathrm{EEP}} &= 0.35M + 0.25. \end{aligned} \quad (2)$$

It can be seen from Fig. 3 that the empirical dependences are close to on another for group I in particular. This confirms the correlation between E_z-anomalies of seismogenic origin and the occurrence of disturbances in ionospheric parameters that can be attributed to IEPs. In addition, formulas (1) are very close to the dependence obtained earlier [Sidorin, 1979] for EQ precursors propagating in the Earth's crust:

$$\log(\Delta T \times R) = 0.72M - 0.72. \quad (3)$$

This allows them to be correlated with the same phase of EQ preparation. The differences in the free term of formulas (1)–(3) probably represent structural peculiarities of the Earth's crust in the zone of EQ preparation. The physical importance of the high correlation between $\log(\Delta T \times R)$ and EQ magnitude M for terrestrial EQ precursors was considered earlier [Sidorin, 1979] on the basis of the theory of inclusion and a representation of the EQ hotbed as a growing zone with increased fracturing. The borders of the EQ preparation zone were defined by the radius $r = 10^{0.43M}$ km [Dobrovolsky et al., 1979], from which it follows that $\log r$ is linearly dependent on magnitude M. This means that in the right-hand parts of the empirical dependences presented in this work, the size of the EQ preparation zone appears in an explicit form that grows as EQ magnitude increases. The greater the energy (magnitude) of the building EQ, the earlier its precursors may occur, and consequently the longer the time ΔT of the lead by a precursor of the EQ moment. The inversely proportional dependence of the lead time upon the epicentral distance to the observation point results from the finiteness of the velocity of propagation of the edge of the EQ preparation zone: the closer it is to the observation point, the earlier it will be reached by the edge, and more time will elapse until the EQ moment than for points located closer to the limiting radius of the EQ preparation zone. According to studies performed earlier [Sidorin, 1979], allowing for this factor and multiplying the lead time ΔT (the lead of the EQ moment by the precursor) by the epicentral distance R for the appropriate group of precursors raises the correlation coefficient from a value of 0.71 (when the dependence on the epicentral distance is ignored) to a value of 0.94 (when this dependence is taken into consideration).

As has already been shown [Korsunova and Khegai, 2008], we can estimate the apparent velocities of the displacement of disturbances from the seismic source in the atmosphere and ionosphere on the basis of expressions (1) and (2). When a disturbance propagates for a distance of 100 to 200 km at $M = 6.0$, we obtain the apparent velocities of its displacement: $V =$ 0.7–0.8 km/h for group I and $V_{\text{IEP}} = 3$ km/h, $V_{\text{EEP}} =$ 3.7 km/h for group II. According to (3), we obtain $V =$ 0.3 km/h for the same EQ magnitude and the indicated epicentral distances. A comparison of the obtained apparent velocities shows that disturbances of group I in the ionosphere and in electric fields follow the edge of the EQ preparation area as it expands over the Earth's surface. The obtained velocities of propagation for seismogenic disturbances of group II almost coincide with the apparent velocities of displacement for disturbances in the ionosphere, according to data from vertical sounding stations in Japan (4.4 ± 3.3 km/h) [Korsunova and Khegai, 2008], and with EEP velocities obtained earlier [Mikhailov, 2007]. The similar time moments of the occurrence of EEPs and IEPs for simultaneous observations at one point, the agreement of disturbance structures for both groups of precursors, and the conformity of the apparent velocities of propagation in atmospheric electric fields and in the ionosphere indicate a physical mechanism of seismoionospheric interaction based on the modification of quasielectrostatic fields in the near-surface atmosphere and their further influence on the ionosphere [Pulinets et al, 2000]. As follows from this model, one important factor in the influence of the near-surface quasielectrostatic field is the emanation of radioactive gases from subsoil waters and the Earth's surface over the period of EQ preparation. We may assume that the area of the increased egress of radioactive gases follows the expanding border of the EQ preparation zone on the Earth's surface, which is determined by the influx of subsoil waters into microfractures of the stressed part of the Earth's crust. Indeed, an increase in the concentration of radon has in many cases been observed in subsoil waters and the Earth's surface layers several days prior to an EQ [Virk, Singh, 1994; Steintz et al., 1996]. The further verification of the physical mechanisms of interaction between the lithosphere and ionosphere suggested in [Pulinets et al., 2000] requires the arranging of complex experiments with simultaneous measurements of the concentration of radon, aerosols, atmospheric electrostatic fields, meteorological parameters, and ionospheric characteristics at several points. In this respect, Russia's most promising range for geodynamic experiments is Kamchatka, with its high level of seismic activity.

CONCLUSIONS

Our study allows us to draw the following conclusions:

1. Two groups of possible earthquake precursors have been isolated with different lead times of the earthquake moment (ΔT) ranging from several hours to two weeks (which probably correspond to different phases of earthquake preparation) from the data of simultaneous measurements of parameters in the ionospheric E_s and F2 layers and the vertical gradient of electric potential in the near-surface atmosphere (E_z) over the period of preparation for crustal earthquakes with $M = 5.0$–6.2 in the Kamchatka region. The amplitudes of the presumed precursors in the group that is closer to the moment of the earthquake are substantially higher than those of the other group.

2. Empirical dependences have been obtained that indicate a tendency toward variations in the lead time of the earthquake moment by the presumed precursors, the distance from the observation point to the epicenter, and the earthquake magnitude. These dependences are close to the observed anomalies in the ionosphere and in the surface electric fields, testifying to their correlation in the interaction between the lithosphere and ionosphere during earthquake preparation.

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