INTERNATIONAL JOURNAL OF GEOMAGNETISM AND AERONOMY
VOL. 6, GI3005, doi:10.1029/2005GI000122, 2006

Medium-term ionospheric precursors to strong earthquakes

L. P. Korsunova, and V. V. Khegai

Institute of Terrestrial Magnetism and Radio Wave Propagation, Troitsk, Moscow Region, Russia

Received 21 March 2006; revised 1 June 2006; accepted 14 August 2006; published 28 November 2006.

[1] An attempt is made to determine the most typical changes in parameters of the ionospheric $F2$ and E_s layers during the 7 days prior to an earthquake. Earthquakes with magnitudes $M > 6$ in the Pacific region in the vicinity of Japan are considered. Hourly measurement data at Kokubunji ionospheric station for 40 earthquakes with epicenter distances $R < 1000$ km are used. Seismoionospheric disturbances are detected on the basis of analysis of the derivations of current values of the ionospheric layer parameters from the running medians. A method of identification of precursors on the basis of some set of morphological signs is proposed. It is shown that different times of appearance of precursors are caused by their dependence on the magnitude of the coming earthquakes and the distance from the observational point to the epicenter. For $M = 6 - 7$ and $R < 600$ km this time is from 1 to 6 days. Empirical dependencies of the time of appearance of ionospheric precursors and the value of seismogenic disturbances in ionospheric layer parameters are obtained and may be used for prediction purposes. *INDEX TERMS:* 7223 Seismology: Earthquake interaction, forecasting, and prediction; 2435 Ionosphere: Ionospheric disturbances; 0342 Atmospheric Composition and Structure: Middle atmosphere: energy deposition; *KEYWORDS:* VLF waves propagation; Ionospheric waveguide; Ionospheric irregularities.

Citation: Korsunova, L. P., and V. V. Khegai (2006), Medium-term ionospheric precursors to strong earthquakes, *Int. J. Geomagn. Aeron., 6,* GI3005, doi:10.1029/2005GI000122.

1. Introduction

[2] The events in December 2004 in the Indian Ocean showed that not enough attention has been paid until recently to studies of earthquakes and of their impact on the environment. It is especially true for strong carpet earthquakes with magnitude $M > 6$ causing the strongest damages to the population and economics of the countries located in epicenter zones. For a development of a working system of earthquake forecast, both the knowledge on the earthquake mechanism and revealing of their precursors according to the data of various geophysical fields, and in particular on the basis of ionospheric parameters measurements, are needed. The data obtained earlier on ionospheric precursors to earthquakes [*Liperovsky et al.*, 1992; *Silina et al.,* 2001; *Strakhov and Liperovsky*, 1998] provide information on their most general features that cannot be used for forecasting needs. According to the results of spectral analysis the disturbances in ionospheric parameters with periods 1.5–2 hours are singled out both in the F region [*Korsunova et al.,* 1996; *Liperovsky et al.*, 1992; *Pulinets and Liu,* 1998] and in the sporadic E layer [*Korsunova et al.*, 1999; *Silina et al.*, 1998]. Just these perturbations being averaged for concrete hours demonstrates growth (or decrease) of the critical frequencies of ionospheric layers for tens percent with respect to the undisturbed state of the ionosphere. The discussed perturbations in ionospheric parameters are discovered mainly within 1–3 days before the earthquake and can serve as precursors to the event. It should be mentioned that these data were obtained for large amount of earthquakes with $M < 6$ and hence they are statistically meaningful. It is much more complicated to reveal precursors to earthquakes with $M > 6$, for which statistical analysis does not give reliable results [*Pulinets*, 1998].

[3] *Hobara and Parrot* [2005] investigated the regular $F2$ layer for the period more than 80 days before the earthquake with $M \simeq 8.3$. Statistically meaningful anomalies were revealed only 1–2 days before the event. Similar result was obtained earlier for the earthquake with $M > 7$ in Argentine [*Rios et al.,* 2004] and in Japan according to the E_s data [*Ondoh*, 2003]. However, all mentioned above anomalies in the ionosphere are related to short-term earthquake

1524–4423/06/2005GI000122$18.00

precursors. The absence of medium-term precursors in the study by *Hobara and Parrot* [2005] confirms that their mean-square amplitude deviation does not exceed 20%. So, they cannot be discovered by usually accepted statistical methods.

[4] From the other side, in the measurements of the geophysical fields on the ground medium-term precursors are singled out reliably enough. For such precursors the period before the earthquake comprises from several days to one month [*Sidorin,* 1979]. The appearance of the medium-term precursors can be expected in the ionosphere also, taking into account the influence of the seismic processes on the ionosphere due, for example, of electric fields. Indeed, the link between quasistatic electric fields in the near Earth ionosphere with seismic events was proved experimentally [*Smirnov*, 2005], and the influence of the quasistatic electric fields on the ionosphere was discussed theoretically by *Pulinets and Liu* [1998]. At last, complex experiment in which the E_z component of the electric field, radon concentration, and ionospheric parameters were measured simultaneously at Kamchatka, confirmed the existence of lithosphere-atmosphere-ionosphere interaction [*Mikhailov et al.,* 2002].

[5] We proposed a new approach to revealing earthquake precursors on the background of the total variability of the ionosphere. This approach uses the set of the data on simultaneous measurements of several parameters of ionospheric layers: the critical frequency of the regular $F2$ layer (f_oF2), blanketing frequency of the sporadic E layer (f_bE_s), and its virtual height ($h'E_s$). This approach made it possible to find some regularity in the time of appearance of ionospheric precursors for various earthquakes, the regularity agreeing with the results of observations of surface geophysical fields. Moreover, empirical dependencies of the value of deviations of ionospheric parameters on the earthquake magnitude and the epicenter distance were obtained.

2. Method of Studies

[6] Usually, to reveal disturbances in ionospheric parameters, one calculates their deviations from the mean or median values over some period of time. In our study, we used running medians obtained for each hour of the day on the basis of the 10 previous days for each analyzed day of the earthquake preparation period. This period was 7 days including the day of the earthquake. To determine the input of the assumed seismogenic disturbance into the quiet state of the ionosphere and exclude the dependence on the local time and season, for each hour of the entire period under study the value $\Delta f/f_\mathrm{m} = (f - f_\mathrm{m})/f_\mathrm{m}$ (where f_m is the running median and f is the critical frequency for the $F2$ layer and blanketing frequency for E_s) was determined for the frequency parameters. This is a significant difference from earlier publications on detection of seismoionospheric disturbances [*Silina et al.*, 2001] where the deviations relative to the critical frequency itself averaged over several earthquakes were calculated. This led to an underestimation of the disturbance relative value at the increase of the critical frequency and to its overestimation at the frequency decrease. The variations of the $\Delta f/f_\mathrm{m}$ and $\Delta h'E_s = h' - h'_\mathrm{m}$ value from one hour to another show the dynamics of the disturbance in the lower and upper ionosphere at the preparation of each particular earthquake.

[7] Using this method, we processed the hourly data of the measurements at Kokubunji ionospheric station (φ = 35.7°N, λ = 139.5°E) for 40 earthquakes with $M \geq 6$ and the hypocenter depth $h < 50$ km having occurred in the Pacific region in 1985–2000. Only the cases were considered when the ionospheric station was within the zone of earthquake preparation ($r \leq e^M$, km, where r is the radius of the preparation zone). The data on the earthquake parameters were taken at http://www.neic.cr.usgs.gov. Kokubunji station is the only station in this seismically active region for which the most complete set of ionospheric parameters for many years has been published (Communications Research Laboratory, 1985–2000, Ionospheric data in Japan, http://wdc-c2.nict.go.jp/index_eng.html, World Data Cent. for Ionosphere, Tokyo).

[8] As an example of the above described data processing, Figure 1 shows the variations in the parameters of the E_s and $F2$ layers in the period of preparation of the 20 November 1996 earthquake (M = 6.8; r = 211 km is the distance from the epicenter to the station). Time is counted from the beginning of the minus sixth day (0000 LT) prior to the day of the earthquake (the seventh day). The dashed line shows the earthquake moment. It follows from Figure 1 and the analysis of other earthquakes that during the preparation period at Kokubunji station, parameter deviations of both signs are detected but sharp positive "spikes" 2–3 hours long prevail. Just such spikes were discussed by *Korsunova et al.* [1996], *Liperovsky et al.* [1992], and *Silina et al.* [2001].

[9] The value of some spikes in frequency and height parameters can reach 50% and more and 40–60 km, respectively. The mean values of the deviations from the running median are ±20% and ±10 km for the frequencies and virtual heights, respectively.

[10] As should be expected, parameters of the sporadic E layer are more variable than parameters of the regular $F2$ layer and anomalous spikes in the E_s layer with duration 2–3 hours are noticed within the whole period of observations. Such spikes can be caused by various meteorological factors that do not influence the behavior of the $F2$ layer. That is why the excess by the spike amplitude the averaged value or mean-square deviation cannot be chosen as a criterion for ionospheric precursor, especially in the E_s layer. From the other side, for all considered earthquakes, as well as for that one presented in Figure 1, there is only one group of spikes in all ionospheric parameters that manifest itself in 24-hour interval. For the earthquake on 20 November 1996 this group manifest itself 5.5 days prior the moment of the earthquake (black peaks indicate the moment of the group appearance). For other earthquakes this period comprises 1–6 days.

[11] During the preparation period, the appearance of anomalous spikes was close in time for all three parameters only once. The time of appearance of these spikes relative to the earthquake moment differs considerably for earthquakes of different energetic class and different epicenter distances. The performed calculations showed that the value of the de-

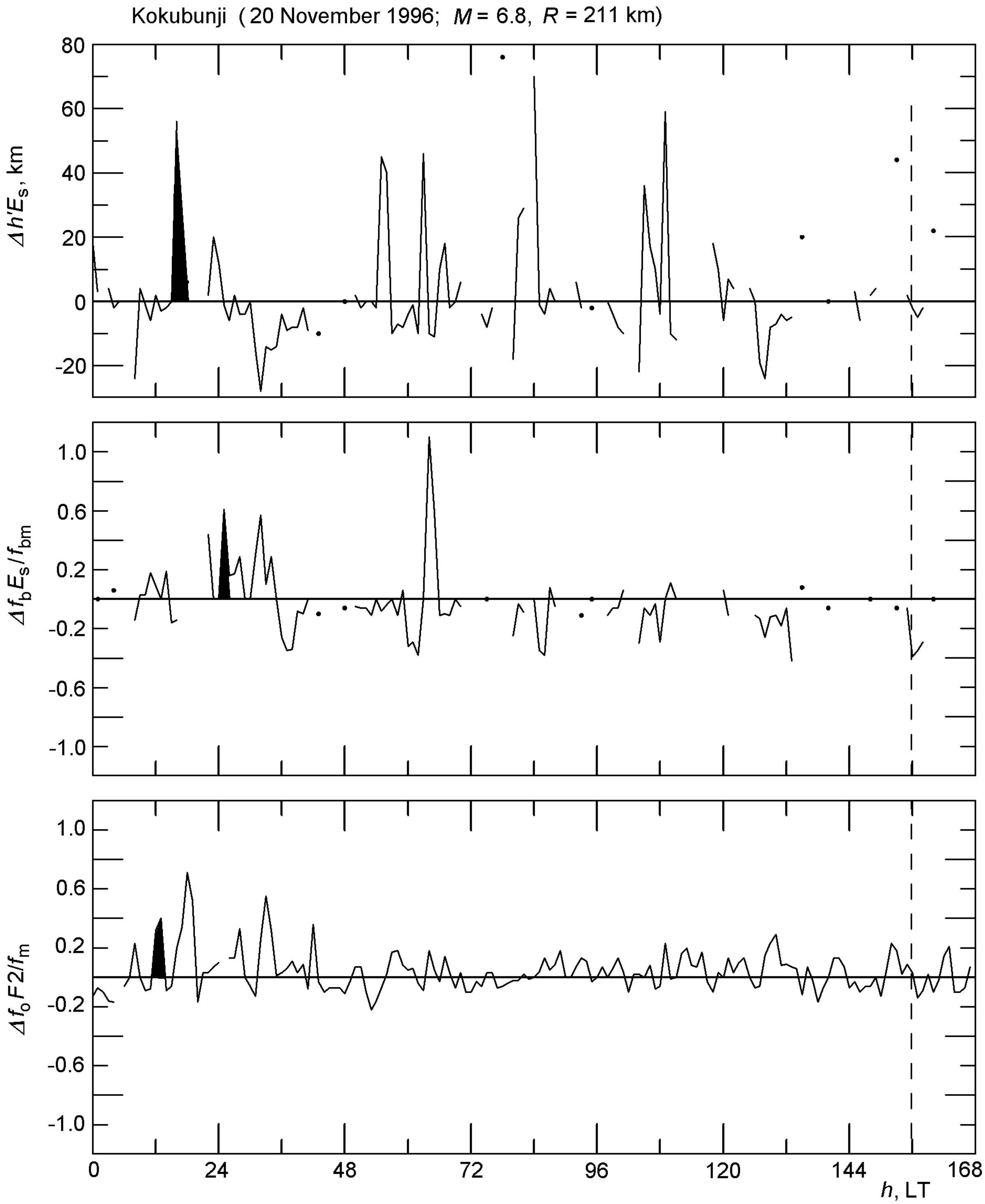

Figure 1. Hourly deviations of the virtual height of the sporadic E layer, screening frequency of E_s, and blanketing frequency of the $F2$ layer in the period of preparation of the 20 November 1996 earthquake.

viations of the ionospheric layer parameters differs slightly if one uses 27-day running medians or monthly mean values, but this choice does not influence on the appearance of the anomalous spikes and their features.

[12] Earlier, *Korsunova and Khegai* [2005] have shown that spikes groups with duration 2–3 hours that appear simultaneously in the E_s and $F2$ layers are not connected with magnetic disturbances, because for the considered earthquakes

Table 1. Parameters of Earthquakes and Their Precursors for Epicenter Distances $R < 600$ km

	Date	M	R, km	T, days	$\Delta f_o F2/f_m$	$\Delta f_b E_s/f_{bm}$	$\Delta h' E_s$, km
1	12 Aug. 1985	6.3	306	1.3	0.2	0.35	30
2	12 Feb. 1986	6.1	165	1.0	0.2	0.29	15
3	6 Feb. 1987	6.5	242	1.7	0.26	0.48	40
4	7 April 1987	6.6	276	2.2	0.28	0.59	50
5	23 April 1987	6.6	246	3.5	0.25	0.44	30
6	2 Nov. 1989	7.4	541	12.5	0.17	1.62	65
7	20 Feb.1990	6.4	112	3.5	0.2	0.7	80
8	5 Aug. 1990	6.0	156	1.0	0.25	0.31	40
9	24 Sept. 1990	6.5	280	1.6	0.25	0.2	38
10	3 Sept. 1991	6.4	236	1.5	0.27	0.33	40
11	18 July 1992	7.0	533	2.0	0.23	0.78	30
12	7 Feb. 1993	6.6	294	2.5	0.18	0.31	48
13	7 Jan. 1995	7.0	556	4.0	0.21	1.0	50
14	10 Jan. 1995	6.0	167	1.0	0.26	0.47	15
15	17 Jan. 1995	6.9	426	4.0	0.27	0.5	60
16	16 Feb. 1996	6.7	316	3.0	0.23	0.38	21
17	11 Sept. 1996	6.2	131	1.5	0.27	0.35	46
18	20 Nov. 1996	6.8	211	5.5	0.4	0.57	56
19	30 Sept. 1997	6.5	469	1.0	0.17	0.25	50
20	9 July 2000	6.6	185	2.6	0.29	0.52	32
21	21 July 2000	6.2	160	1.5	0.26	0.37	26
22	6 Oct. 2000	7.0	577	3.3	0.21	0.56	30

at the stage of the preparation the daily mean index was $Ap < 15$ nT. All mentioned above allows us to suppose that the discussed groups of perturbations in ionospheric parameters are caused by the processes connected with the preparation of the earthquake. Hence they can be considered as ionospheric precursors to earthquakes.

[13] On the basis of the analysis of ionospheric parameter deviations in the period of preparation of 40 earthquakes in the vicinity of Kokubunji station, we proposed a method of detection of ionospheric precursors of earthquakes using the following set of morphological signs: (1) the presence in the hourly deviations of ionospheric parameters of spikes group (that appear in the E_s and $F2$ layers simultaneously) with duration 2–3 hours; (2) the excess by the spikes amplitudes of the 20% and 10 km values of deviations in the frequency parameters of the ionospheric layers and in $\Delta h' E_s$, respectively.

[14] We consider the disturbances in ionospheric parameters satisfying these requirements as medium-term earthquake precursors. These disturbances will be discussed below.

3. Results

[15] Using the above described method, *Korsunova and Khegai* [2005] earlier processed the ionospheric data for 17 earthquakes under more hard conditions for their choice: the absence of strong geomagnetic disturbances in the earthquake preparation periods. The results obtained in this paper confirm the regularities in the appearance of medium-term ionospheric precursors of earthquakes found for magnetically quiet conditions: prevailing of anomalous positive spikes 2–3 hours long in all ionospheric parameters exceeding the chosen value for the deviations determined in the previous section. Most often the ionospheric precursors are detected around the noon and midnight, but the daytime is prevailing (29 cases out of 40). The disturbances in the regular $F2$ layer most often goes ahead of the disturbances in the sporadic E layer parameters (32 cases). No increase in the spikes amplitude is observed to the earthquake moment. The most important parameter characterizing the process of earthquake preparation is the time interval between the appearance of the anomalous spikes and the shock moment. We call it the advance time (T) of the appearance of an ionospheric precursor, the value of T being measured in diurnal intervals (24 hours).

[16] Table 1 shows the data on the term of appearance of ionospheric precursor and corresponding values of the deviations in the parameters of the $F2$ and E_s layers for the epicenter distances $R \leq 600$ km in the conditions of the absence of strong geomagnetic disturbances. The performed analysis showed that at large distance and under disturbed magnetic field, the value of seismogenic disturbances decreases considerably, especially in the $F2$ layer, so it is difficult to detect them on the background of the general ionospheric variability. For powerful earthquakes with $M > 7$, the precursor effects are detected even at distances of the order of 1000 km. The value of the effect is different in the $F2$ and E_s layers: in the E_s layer it is higher by a factor of 1.5–2. Taking into account the comments made, one may state that the analysis of the changes in the critical frequency of the $F2$ layer only cannot in the real conditions provide com-

plete enough description of the ionospheric reaction to an earthquake preparation.

[17] On the other hand, the sporadic E layer parameters are in a significant degree influenced by the dynamic processes in the environment (IGW, turbulence) [*Chimonas*, 1974; *Chavdarov et al.,* 1975; *Ovezgel'dyev et al.*, 1977], so the use of the E_s layer only for revealing of seismoionospheric effects is also able to lead to wrong conclusions. This is why we emphasize the need to consider simultaneously changes in the $F2$ and E_s layer parameters. This makes it possible to identify the ionospheric effects of earthquake preparation with more reliability. In our study, changes in the height of the sporadic E layer are a determining factor satisfying the above presented requirements, as the virtual heights of the sporadic E layer are close to the real heights because of the small width of this layer.

[18] The analysis in the ionospheric precursors for all the considered earthquakes showed that the advance of their appearance and quantitative characteristics are determined by the earthquake magnitude and the epicenter distance: the higher the magnitude and the closer the epicenter, the earlier the precursor is observed and the larger is its value. Figure 2 shows the obtained empirical dependencies of the advance in precursor appearance and values of the deviations in the ionospheric parameters on the earthquake magnitude at Kokubunji station for 33 earthquakes with the epicenter distances $R < 1000$ km. The earthquakes for which the preparation period coincided with strong geomagnetic disturbances (the daily mean index $Ap > 20$ nT) were excluded, because in these conditions (as it has been noted above), detection of the precursors in f_oF2 becomes problematic. The empirical dependence for the precursor appearance time for 33 earthquakes at $Ap < 20$ nT may be presented by the following expression $\lg(TR) = 1.14M - 4.72$ obtained using the least square method. This expression agrees qualitatively with the expression obtained by us earlier on the basis of 12 earthquakes for magnetically quiet conditions: $\lg(TR) = 1.33M - 5.96$ [*Korsunova and Khegai*, 2005], though the coefficients in the right-hand side of the approximating lines differ significantly. The inclusion into the analysis of the earthquakes with magnetically disturbed preparation period ($Ap > 20$ nT) leads to the dependence $\lg(TR) = 1.15M - 4.78$ which almost coincide with the previous one. The latter fact means that the differences in the coefficients of the approximating lines manifest the errors in determination of the precursor appearance time in the real conditions. For the sporadic E layer, which is the determining parameter while choosing the precursors, this difference leads to the change in the product $T \times R$ by a factor of 1.2 in the magnitude range 6.0–7.8. Therefore the error in determination of the appearance time of a moderate-term precursor for the known distance is about 20%.

[19] The empirical dependencies for the assumed seismogenic disturbances in the E_s and $F2$ parameters shown in Figure 2 (second through fourth panels from the top) are obtained for the first time. It follows from these dependencies that the stronger the earthquake and the closer the epicenter the more the value of the deviation in ionospheric parameters, this fact agreeing also with the results for the time of precursor appearance T. The slopes of the approximating lines for all three parameters are fairly close to each other (0.65 ± 0.1) but are almost by a factor of 2 less than for $\lg(TR)$. Moreover, it could be noted that the coefficients in the right-hand side of the logarithmic dependencies for the frequency parameters of the $F2$ and E_s layers differ in a lesser degree than for the virtual heights of E_s and the time of precursor appearances. The latter means that the same effects in f_oF2 and f_bE_s may be caused by close but weak earthquakes or by strong but remote ones (see lines 2 and 19 in Table 1). So for forecasting purposes, one can use the empirical dependencies for T, $\Delta h'E_s$, and $\Delta f_b/f_mE_s$, whereas the $F2$-layer parameters are needed to control the correctness of the ionospheric precursors identification. Having determined such dependencies for magnetically quiet conditions and particular observational point using known earthquakes, one can evaluate the magnitude of the earthquake in preparation, the time of the shock, and the distance from the observational point to the epicenter. Approximate estimates of the epicenter location may be made on the basis of a map of the Earth crust fractures where earthquake hypocenters are located most often.

4. Discussion

[20] Earlier the dependency of the appearance time of the precursors on the earthquake magnitude and epicenter distance was found on the basis of the measurements of the surface geophysical fields for a wide energetic class of earthquakes ($K = 10 - 17$): $\lg(TR) = 0.48K - 3$ [*Sidorin*, 1979]. Later, on the basis of the observations of the sporadic E layer in Ashkhabad, *Korsunova et al.* [1999] obtained the following formula for the earthquakes with $K = 11 - 13$: $\lg(TR) = 0.49K - 3.29$. It should be noted that the ground-based measurements and ionospheric observations were performed at different times and different places. The common is the fact that the epicenters of the considered earthquakes were located on the land though in different regions. The similarity of the obtained empirical dependencies shows that the ionospheric precursors are a manifestation in the atmosphere of the processes of earthquake preparation with conservation of their main features, and also that the performed identification of ionospheric precursors of earthquakes on the basis of simultaneous measurements of the $F2$ and E_s parameters is correct.

[21] In this paper the precursor effects in the ionosphere were studied for stronger earthquakes than in [*Korsunova et al.,* 1999] and also for epicenters in the sea. The behavior of the appearance time on the basis of 33 earthquakes in the vicinity of Japan shown in Figure 2 (top) differs from the behavior presented by *Sidorin* [1979] for the fields of surface geophysical parameters: $\lg(TR) = 0.72(M - 1)$. The comparison of the appearance time of ionospheric precursors at stations Kokubunji and Ashkhabad for similar epicenter distances and magnitudes shows that over the land the precursors appear earlier than over the sea surface. Since the method of revealing ionospheric precursors in this paper is the same as used by *Korsunova et al.* [1999], the difference in the coefficients in this dependence for Kokubunji

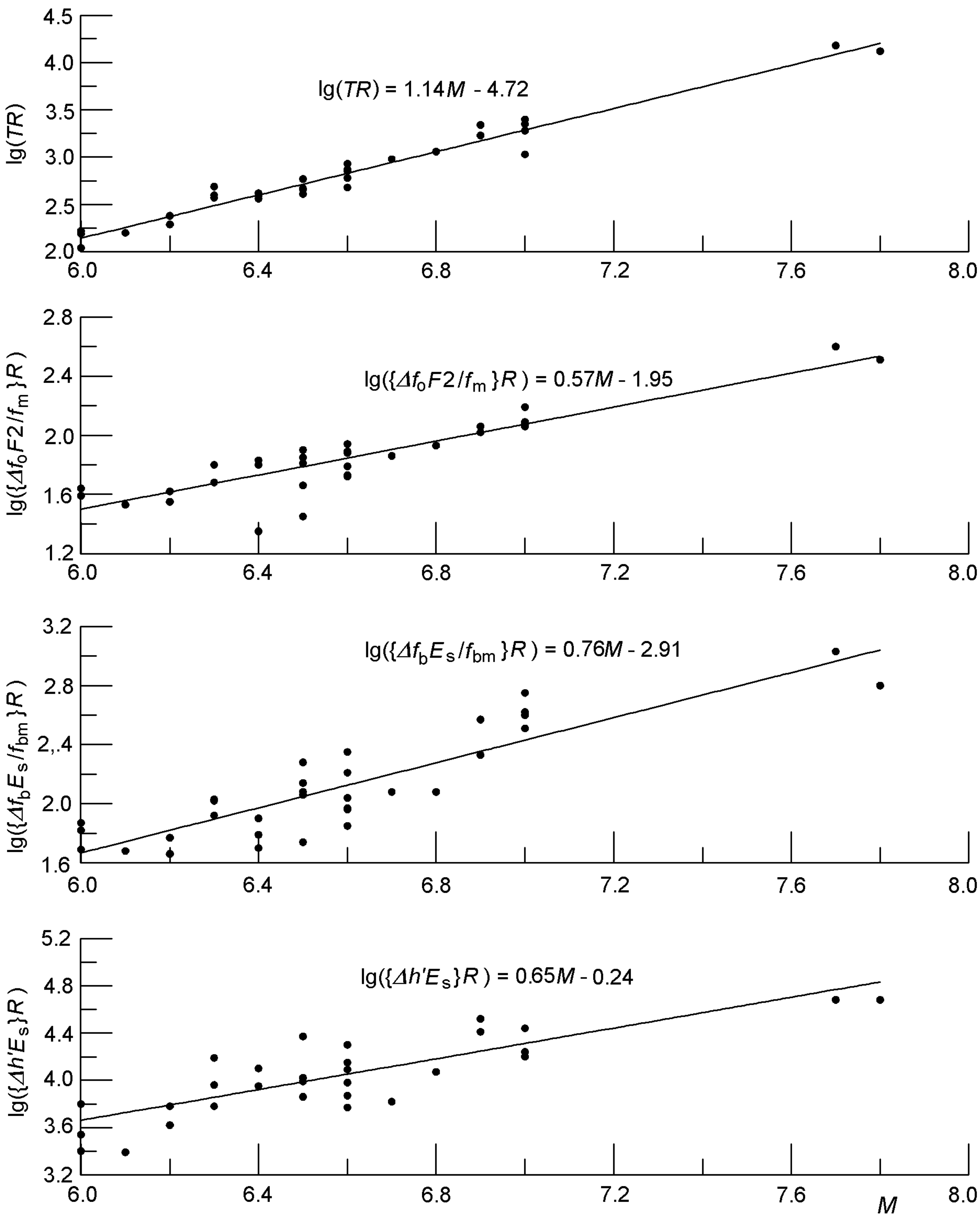

Figure 2. Dependence of time of the precursors' appearance and the value of the deviations of the ionospheric parameters on the magnitude of the following earthquakes for the fixed epicenter distances to Kokubunji station.

and Ashkhabad stations located in the same latitudinal zone manifests some real differences related to the features of earthquake preparation processes in the Central Asian and Pacific regions.

[22] We explain the empirical formula for the appearance time of precursors obtained by *Sidorin* [1979] on the basis of the model presentations of the epicenter of an earthquake in preparation as a zone with an increased fracturing. As far as the fracturing develops, changes in the deformation processes are manifested at longer distances. The time of the earthquake precursor appearance on the Earth's surface at the given epicenter distance is determined by the time of the deformation development up to some threshold value depending on the earthquake magnitude. The time of the appearance of the precursor in the ionosphere is a manifestation of this process in the upper atmosphere, though the mechanism of seismoionospheric interaction explaining quantitatively all the features of the observed precursors is not yet developed.

[23] Currently, two main mechanisms of the seismoionospheric relations are considered: one is related to acoustic gravity waves [*Karimov et al.*, 1990; *Khegai et al.*, 1997; *Pertsev and Shalimov*, 1996], the other is an electromagnetic one [*Gokhberg et al.*, 1988; *Golovkov*, 1983; *Pulinets et al.*, 1998]. *Pulinets et al.* [1998] developed a model making it possible to explain the observed 30% variations in the electron concentration in the $F2$ layer caused by anomalous vertical electric fields (E_z) generated in the period of strong earthquake preparation near the Earth's surface. Under the field value of $E_z \sim 1$ kV m^{-1} at the surface level, the electron concentration in the sporadic E layer increases by an order of magnitude 4 hours after the switching on the field. This fact agrees with the disturbances in E_s observed during preparation of earthquakes with $M > 7$. However, such anomalously high values of the electric field are observed rather seldom [*Smirnov*, 2005], the same as earthquakes with $M > 7$ in concrete region. Moreover, according to model simulations [*Kim et al.*, 1993], because of the influence of seismogenic electrostatic fields, the height of formation of the sporadic E layer grows at ~15 km in comparison with usual conditions. As it follows from the table presented in the text, the growth of the E_s height for the singled out groups of spikes, considered as precursors, is indeed close or exceeds the theoretical value for all earthquakes.

[24] On the other hand, such changes in the electron concentration (especially in the sporadic E layer) may be caused by atmospheric gravity waves with periods of 2–3 hours. *Karimov et al.* [1990] detected an increase in the power of AGW in seismically active periods. In the absence of quantitative calculations of the IGW influence on the electron concentration distribution in the $F2$ and E_s layers, it is difficult to prefer this or that mechanism of seismoionospheric disturbance generation in the ionosphere. One should not exclude a possibility that there is a joint action of both mechanisms if in the process of earthquake preparation both AGW and anomalous electric fields are generated in the epicenter zones. Nevertheless, estimates for the velocities with which seismogenic perturbations propagate in the ionosphere (based on the logarithmic dependence for time of appearance of medium-term precursors) give the value ~3 km h^{-1}. This value deviates substantially from the known velocities of the AGW at the ionospheric heights, but it is close to the values of the velocities with which perturbations propagate in the geophysical fields on the surface of the ground [*Sidorin*, 1979]. The problem of seismoionospheric interaction will be considered later.

5. Conclusions

[25] On the basis of the performed study, the following conclusions may be drawn:

[26] 1. During the period of preparation of carpet earthquakes with $M > 6$, according to the data obtained at Kokubunji station, the groups of spikes are singled out in the ionospheric parameters with duration 2–3 hours which are observed within the same day in the E_s and $F2$ layers with the excess of 20% of the median value for the frequencies and the height of 10 km for the E_s layer. Their appearance within 1–6 days prior the earthquake allows us to refer them to the medium-term precursors of the earthquakes.

[27] 2. The advance time T of the appearance of moderate-term earthquake precursors and the value of the deviations in ionospheric parameters identified as earthquake precursors are found to be related be a logarithmical relation to the earthquake magnitude and the distance from the observational point to the epicenter. Using those relations, one is able to estimate the time and the power of the earthquake in preparation in the particular geographic region.

References

Chavdarov, S. S., Yu. K. Chasovitin, S. N. Chernyshova, and V. N. Sheftel' (1975), *Midlatitude Sporadic E Layer of the Ionosphere* (in Russian), 119 pp., Nauka, Moscow.Nauka, Moscow.

Chimonas, G. (1974), Turbulent diffusion as a controlling factor in sporadic *E*, *J. Atmos. Terr. Phys., 36*(2), 235, doi:10.1016/0021-9169(74)90043-9.

Gokhberg, M. B., V. A. Morgunov, and O. A. Pokhotelov (1988), *Seismo-electromagnetic Phenomena* (in Russian), 174 pp., Nauka, Moscow.

Golovkov, V. P., (Ed.) (1983), *Electric and Magnetic Precursors of Earthquakes,* 135 pp., Phys. Inst. of Uzbek AS, Tashkent.

Hobara, Y., and M. Parrot (2005), Ionospheric perturbations linked to a very powerful seismic event, *J. Atmos. Sol. Terr. Phys., 67*(7), 677, doi:10.1016/j.jastp.2005.02.006.

Karimov, K. A., V. I. Drobzhev, N. R. Solonitsyna, and R. D. Gainutdinova (1990), *Some Ionospheric, Magnetic, and Atmospheric Effects Related to Seismo-tectonic Processes in Kazakhstan and Kyrgizia* (in Russian), 23 pp., ILIM, Bishkek, Kyrgyz Republic.

Khegai, V. V., V. P. Kim, and L. I. Nikiforova (1997), Possible generation mechanism of acoustic-gravity waves in the ionosphere before strong earthquakes, *J. Earthquake Predict. Res., 6*(4), 584.

Kim, V. P., V. V. Khegai, and P. V. Illich-Svitich (1993), On the possibility of the metallic ions layers formation in the nighttime mid-latitude ionosphere before strong earthquake, *Geomagn. Aeron.* (in Russian), *35*(5), 114.

Korsunova, L. P., and V. V. Khegai (2005), Seismo-ionospheric effects of strong carpet earthquakes in the Pacific region, *Geomagn. Aeron.* (in Russian), *45*(5), 1.
Korsunova, L. P., Yu. Karadzhaev, and G. V. Mikhailova (1996), Precursors effects of strong earthquake in different layers of the ionosphere over Turkmenistan, paper presented at International Symposium "Monitoring of the Environment and Problems of Solar-Terresrtrial Physics", Nauka, Tomsk, Russia.
Korsunova, L. P., Yu. Karadzhaev, and G. V. Mikhailova (1999), Ionospheric precursors of strong regional earthquakes, in *Urbanization and Earthquakes* (in Russian), p. 75, ILIM, Ashkhabad, Turkmenistan.
Liperovsky, V. A., O. A. Pokhotelov, and S. L. Shalimov (1992), *Ionospheric Precursors to Earthquakes* (in Russian), 304 pp., Nauka, Moscow.
Mikhailov, Ju. M., G. A. Mikhailova, O. V. Kapustina, A. H. Depueva, P. V. Busevich, G. I. Druzhin, S. E. Smirnov, and D. P. Firsov (2002), Atmosphere-ionosphere interactions in preparing phase of earthquake on complex observations in Kamchatka region, in *Book of Abstracts International Conference on Problems of Geocosmos,* p. 94, INTAS, St. Petersburg.
Ondoh, N. (2003), Anomalous sporadic E-layers observed before 7.2 Hyogo-ken Nanbu earthquake: Terrestrial gas emanation model, *Adv. Polar Upper Atmos. Res., 17,* 96.
Ovezgel'dyev, O., L. P. Korsunova, and V. D. Bakaldina (1977), Sporadic E layer as an indicator of turbulence processes in the lower thermosphere, in *Physical Process in the Upper Atmosphere* (in Russian), p. 15, ILIM, Ashkhabad, Turkmenistan.
Pertsev, N. N., and S. A. Shalimov (1996), Generation of atmospheric gravity waves in a seismically active region and their influence on the ionosphere, *Geomagn. Aeron.* (in Russian), *36*(2), 111.
Pulinets, S. A. (1998), Strong earthquake prediction possibility with the help of topside sounding from satellites, *Adv. Space Res., 21*(3), 455.
Pulinets, S. A., and J. Liu (1998), Ionospheric precursors to earthquakes, in *Short-Term Forecast of Catastrophic Earthquakes Using Radiophysical Ground-Based and Space Methods* (in Russian), p. 26, Inst. of Earth Phys., Moscow.
Pulinets, S. A., V. V. Khegai, K. A. Boyarchuk, and A. M. Lomonosov (1998), Atmospheric electric field as a source of the ionospheric variability, *Progr. Phys. Sci.* (in Russian), *168*(5), 582.
Rios, V. H., W. P. Kim, and V. V. Hegai (2004), Abnormal perturbations in the $F2$ region ionosphere observed prior to the great San Juan earthquake of 23 November 1997, *Adv. Space Res., 33*(9), 323, doi:10.1016/S0273-1177(03)00480-0.
Sidorin, A. Ya. (1979), The dependence of the time of appearance of earthquake precursors on the epicenter distance, *Proc. Acad. Sci. USSR* (in Russian), *25*(4), 825.
Silina, A. S., E. V. Liperovskaya, C. V. Meister, N. E. Vasil'eva, K. V. Popov, and A. M. Toktosopiev (1998), On the problem of characteristic times of ionospheric and electromagnetic effects of earthquake preparation processes, in *Short-term Forecast of Catastrophic Earthquakes Using Radiophysical Ground-Based and Space Methods* (in Russian), p. 99, Inst. of Earth Phys., Moscow.
Silina, A. S., E. V. Liperovskaya, V. A. Liperovsky, and C. V. Meister (2001), Ionospheric phenomena before strong earthquakes, *Nat. Hazards Earth Syst. Sci., 1*(3), 113.
Smirnov, S. E. (2005), Peculiarities of negative anomalies in the quasi-static electric field in the near-surface atmosphere of Kamchatka, *Geomagn. Aeron.* (in Russian), *45*(2), 282.
Strakhov, V. N., and V. A. Liperovsky, (Eds.), (1998), *Short-Term Forecast to Catastrophic Earthquakes Using Radiophysical Ground-Based and Space Methods* (in Russian), 164 pp., Inst. of Earth Phys., Moscow.

L. P. Korsunova and V. V. Khegai, Institute of Terrestrial Magnetism and Radio Wave Propagation, Troitsk, Moscow Region, Russia. (khegai@izmiran.ru)