Possible Short-Term Ionospheric Precursors of Strong Crustal Earthquakes

L. P. Korsunova, A. D. Legenka and V. V. Hegai

Abstract We have studied changes in the ionosphere prior to crustal earthquakes with magnitudes of $M \geq 6.5$ based on the data from the ground-based stations of vertical ionospheric sounding in Japan for the period 1968–2004 (32 cases). The data are analyzed based on hourly measurements of the virtual height and frequency parameters of the sporadic E layer and critical frequency of the regular $F2$ layer for the period of three days prior to the earthquakes provided that strong geomagnetic disturbances are absent. In the studied intervals of time before all earthquakes, anomalous changes were discovered both in the frequency parameters of the Es and $F2$ ionospheric layers and in the virtual height of the sporadic E layer. The changes were observed on the same day at stations spaced apart by several hundred kilometers. It is found that the lead-time of these ionospheric anomalies preceding the seismic impact is sensitive to the magnitude of the subsequent earthquakes and it tends to increase with the rise of the earthquake magnitude. It is concluded that such ionospheric disturbances can be short-term ionospheric precursors of earthquakes.

Keywords Crustal earthquakes · Ionospheric disturbances · Ionospheric precursors of earthquakes

1 Introduction

Over the last decade, studies of the earthquake preparation processes and their influence on the Earth's ionosphere have significantly progressed due to in situ [11, 15] and GPS satellite measurements [12, 16, 17]. Satellite observations have made it possible to acquire information on the state of the ionosphere in poorly accessible,

---

L. P. Korsunova (✉) · A. D. Legenka · V. V. Hegai
IZMIRAN, Kaluzhskoe Hwy 4, 108840 Moscow, Troitsk, Russian Federation
e-mail: lpkors@rambler.ru

A. D. Legenka
e-mail: leg@izmiran.ru

V. V. Hegai
e-mail: hegai@izmiran.ru

T. B. Yanovskaya et al. (eds.), *Problems of Geocosmos—2018*, Springer Proceedings in Earth and Environmental Sciences, https://doi.org/10.1007/978-3-030-21788-4_17

seismically active regions, while the dense network of GPS stations has provided almost uninterrupted monitoring of changes in this state over large areas. An important achievement in the study of seismo-ionospheric disturbances based on GPS network data is the refinement of spatial scales of the disturbances for strong earthquakes: several thousand kilometers along the parallel and approximately one thousand and half kilometers along the meridian [18, 19]. However, the main information on seismogenic effects in the ionosphere was obtained from ground based stations of the vertical ionospheric sounding (VIS) [2, 7, 10, 13, 14]. The long-term observations of such effects have made it possible to reveal a number of features typical for seismo-ionospheric disturbances in the period of preparation of earthquakes and after.

The studies of seismogenic disturbances in the ionosphere were conducted in two directions: detailed studies of individual earthquakes and their influence on the ionosphere in different regions of the Earth [2–4] and statistical analysis of the effects of several earthquakes in a specific seismically active zone [7, 8, 10]. While every earthquake is unique, it turned out to be possible to identify the most typical properties of ionospheric disturbances preceding the main impact with some lead-time [4, 8–10].

In the works [7, 13], it was shown that the lead-time (ΔT) of the detected ionospheric disturbances preceding earthquakes (IDPE) is from one day to several weeks, depending on the magnitude of the earthquake and the distance from the observation point to the epicenter. These disturbances can be ionospheric earthquake precursors (IEPs) of various immediacy (in particular, medium-term, MIEPs, or short-term, SIEPs). SIEPs are of the largest practical significance, as they occur from one to three days before the earthquake and can be used for further prediction of major seismic events as part of the general picture of pre-earthquake anomalies in other geophysical fields. At the same time, SIEPs are the least studied, since the “immediacy” of a given disturbance is rather difficult to determine in epignosis. Studies of SIEP were significantly moved forward by the paper of Hobara and Parrot [4], who thoroughly considered the disturbances in the $foF2$ critical frequencies during long intervals of time before and after a strong earthquake with $M = 8.3$, which were detected by multiple vertical-sounding stations at a distance from 400 to 3000 km from the epicenter. Hobara and Parrot [4] showed that possible SIEPs of this earthquake occur on the same day at all stations within the preparation zone ($r \leq 1500$ km, where r is the radius of the earthquake preparation zone on the Earth’s surface). Therefore, with comparison of the times of occurrence of seismo-ionospheric disturbances at two or more stations spaced apart from each other within one region, it is possible to identify a SIEPs by the proximity of these times.

Thus, the objective of the present work is to identify possible SIEPs preceding earthquakes with $M \geq 6.5$ with a lead-time from several hours to 3 days based on the data of VIS ground base stations at different positions in the region of Japan.

2 Procedure of Data Analysis

This study used the data from hourly ionospheric measurements at VIS ground based stations Kokobunji ($\varphi = 35.7°$N, $\lambda = 139.5°$E), Akita ($\varphi = 39.7°$N, $\lambda = 140.1°$E), and Wakkanai ($\varphi = 45.4°$N, $\lambda = 141.7°$E) in the time interval of four days, including the day of the earthquake. A requirement for the ionospheric data was the absence of significant geomagnetic planetary disturbances, i.e., the three-hour Kp indexes of geomagnetic activity should not exceed the level of 3_+ in the specified time intervals before each earthquake. Only strong crustal earthquakes with $M \geq 6.5$ and a hypocenter depth of $h \leq 60$ km for the period 1968–2004 were considered. Thirty-two earthquakes were selected in this way. We analyzed the daily variations in the $F2$-layer critical frequency ($foF2$) and Es-layer blanketing frequency (f_bEs), which characterize the electron density in the maxima of the corresponding layers; the daily variations in the virtual height of the sporadic E-layer ($h'Es$) were analyzed as well. Further, we calculated the deviations of the above-mentioned ionospheric parameters from monthly median values for each hour of the day at all stations in the preparation zone of a given earthquake; the radius of the zone was determined as $r_D = 10^{0.43M}$ km, in accordance with [1]. The relative variations $\Delta f_bEs/f_bEs_{\mathrm{med}}$ and $\Delta foF2/foF2_{\mathrm{med}}$ were obtained for the frequency parameters. The interquartile range (IQR) was chosen as a measure of scatter due to random deviations. The IQR is the difference between the upper and lower quartiles of a given parameter calculated on a three-day interval for any of the abovementioned parameters ($Y(t_i)$, where t_i is the point of the reference time). In this case, the "noise" bands $K\pm = [\Delta Y(t_i)]_{\mathrm{MED}} \pm 0.75\ IQR$ or $K\pm = [\Delta Y(t_i)/Y_{\mathrm{med}}(t_i)]_{\mathrm{MED}} \pm 0.75\ IQR$ restrict possible variations of the parameters, which are explained by random deviations with a certain degree of probability. As follows from the encyclopedia [5], in the case of the normal distribution of the "error" of $\Delta Y(t_i)$ or $\Delta Y(t_i)/Y_{\mathrm{med}}(t_i)$, the value 0.75 IQR approximately corresponds to one standard deviation. The $\Delta Y(t_i)$ and $\Delta Y(t_i)/Y_{\mathrm{med}}(t_i)$ values that exceed the limits of the corresponding "noise" bands were attributed to anomalous $Y(t_i)$ values if the duration of such a disturbance (τ) was $1\ \mathrm{h} \leq \tau \leq 3\ \mathrm{h}$ (see also [7, 10]).

The pre-earthquake ionospheric disturbances discovered in the investigation below occur on the same day above different stations, although the distances between the stations and the epicenters of the respective earthquakes differ by several hundred kilometers. This fact disagrees with the patterns of MIEP occurrence (see [6, 7]) but is in close agreement with the features of IEP occurrence before a strong earthquake with $M = 8.3$ in the same region [4], which were obtained from the data on the variations in the critical frequency of the $F2$ ionospheric layer.

The features of the occurrence of possible SIEPs before crustal earthquakes are illustrated by Fig. 1, which shows the time variations in the ionospheric parameters at two stations, Kokobunji and Akita, separated from each other by a great-circle distance $R \approx 480$ km. The variations in the planetary Kp-index are shown at the top panel; the time of the earthquake is marked with a dashed line and an arrow; and

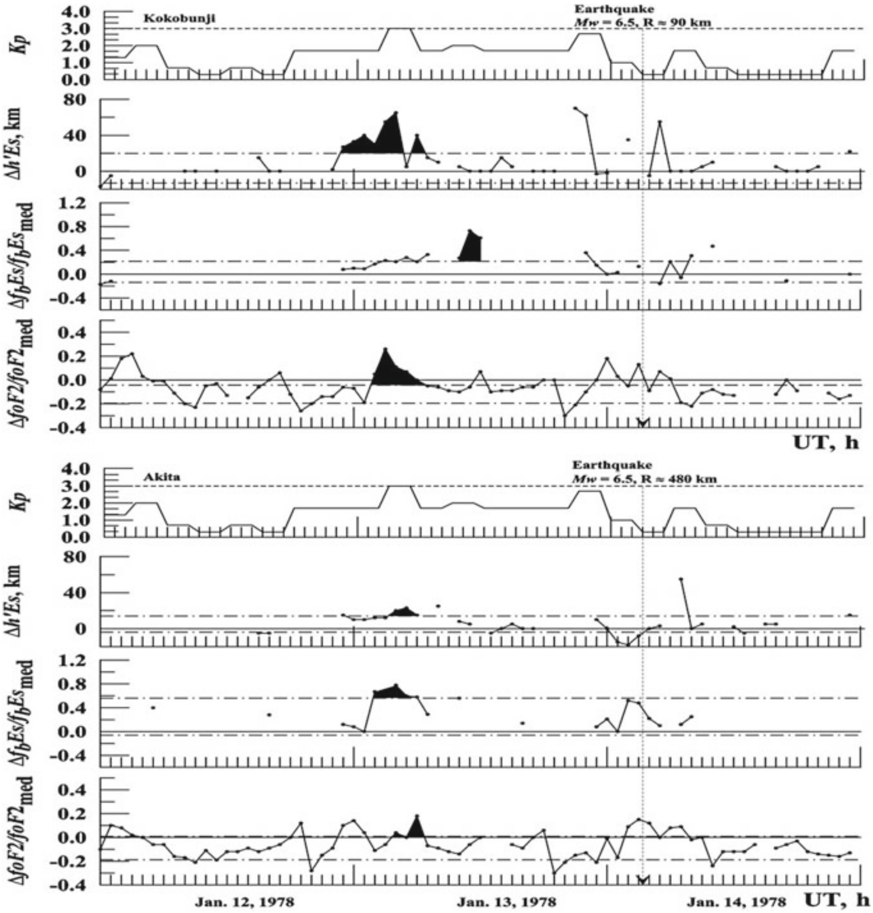

Fig. 1 The time variations in the ionospheric parameters at two stations, Kokobunji and Akita, separated from each other by a great-circle distance $R \approx 480$ km. The black “surges” in all parameters mark possible SIEPs for the earthquake of January 14, 1978 with $M = 6.5$

the dash-dotted lines show the $K\pm$ levels. The black “surges” in all parameters mark possible SIEPs for the earthquake of January 14, 1978 with $M = 6.5$.

A similar analysis was performed for the ionospheric measurement data of VIS ground based stations at different positions before all other crustal earthquakes with $M = 6.5$–7.4 (32 events, as mentioned above). This made it possible to identify pre-earthquake disturbances in the parameters of the Es and $F2$ layers observed during the same day, which allowed us to identify them as possible SIEPs.

3 Results and Discussions

Analysis of the identified ionospheric disturbances preceding earthquakes of different magnitudes at VIS ground based stations separated from the epicenters by a distance from 90 to 1000 km showed the following.

1. Possible seismo-ionospheric anomalies in the *Es* layer are characterized by an increase in the virtual height of the layer and in the electron density as compared to the background; the critical frequency of the $F2$ ionospheric layer (and corresponding electron density at the layer maximum) can either increase (positive anomaly) or decrease (negative anomaly); however, negative anomalies are predominant (24 cases out of 32).
2. The lead-times (ΔT) of possible ionospheric anomalies before earthquakes with $M = 6.5$–7.4 vary from 0.5 to 2.5 days, increasing with the rise of the earthquake magnitude.

In order to obtain the quantitative characteristics of the supposed dependence of the lead-times (ΔT) on the magnitude for the identified pre-earthquake ionospheric disturbances (possible SIEPs), we plotted the logarithms of these times (lg[ΔT]) as functions of magnitudes (M) for all 32 earthquakes using the data of Kokobunji station; the times ΔT were determined from the extrema in the parameters $\Delta h'Es$ ($\Delta T_{h'Es}$) and $\Delta foF2/foF2_{\mathrm{med}}$ (ΔT_{foF2}). The linear regressions obtained by the method of least squares (with the corresponding correlation coefficients ρ) have the following form:

$$\mathrm{lg}[\Delta T_{h'Es}] = 0.35M - 2.46, \quad \rho = 0.616 \tag{1}$$

$$\mathrm{lg}\big[\Delta T_{foF2}\big] = 0.47M - 3.28, \quad \rho = 0.728 \tag{2}$$

Additionally, the same procedure was performed for 20 earthquakes from the full set, for which all values of the 3 h planetary *Kp* indexes during three days prior to the corresponding earthquake did not exceed the level of 3_0 (level *Q*, or “quiet”, i.e. no significant geomagnetic disturbances). For geomagnetically quiet conditions (level *Q*) the following linear regressions were obtained:

$$\mathrm{lg}[\Delta T_{h'Es}] = 0.3M - 2.12, \quad \rho = 0.622 \tag{3}$$

$$\mathrm{lg}\big[\Delta T_{foF2}\big] = 0.47M - 3.24, \quad \rho = 0.803 \tag{4}$$

Figure 2 illustrates the above relationship (4).

That being said, the correlation coefficients for the *Q* level are higher when similar parameters are compared. It has also turned out that the correlation coefficients for the ΔT_{foF2} dependences are significantly higher than those for the corresponding $\Delta T_{h'Es}$ dependences. This implies that, if the epignosis results are used to predict earthquakes with account of the ionospheric changes, the variations in the $F2$-layer

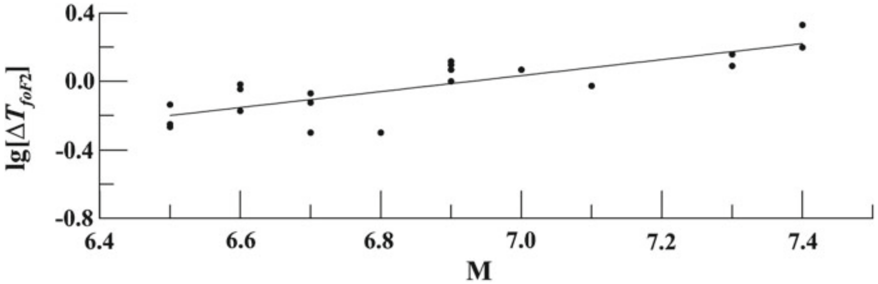

Fig. 2 The "cloud" of $\lg[\Delta T_{foF2}]$ values (points) and the dependence (4) is given by a solid line

critical frequency provide a higher accuracy of the determination of the possible time of the underground shock based on a SIEPs identified by the above-mentioned technique.

It is of interest to compare our results of the determination of the lead-time of a possible SIEPs (ΔT) (dependence (4) with the highest correlation coefficient $\rho = 0.803$) with those obtained earlier [20] from the electricity measurements in the near-surface atmospheric layer. For the upper limit of the magnitude range, $M = 7.4$, in accordance with Zubkov [20], we obtain $\Delta T(M = 7.4)_{\mathrm{Zubkov}} = 1.84$ day for short-term earthquake precursors, while we have $\Delta T_{\mathrm{foF2}}(M = 7.4) = 1.73$ day in our case. These values are in rather close agreement, which is also evidence that our identification of possible SIEPs from the measurement data of the *Es* and $F2$ layer parameters was correct.

4 Conclusions

Analysis of the changes in the ionospheric parameters of the *Es* and $F2$ layers for three days prior to strong crustal earthquakes with $M = 6.5$–7.4 based on the observations of VIS ground based stations at different positions in the region of Japan allowed us to identify the following features of possible SIEPs:

1. In the case of possible SIEPs, the frequency parameters of the *Es* and $F2$ layers deviate from quiet background values by at least 20%, and the virtual height of the sporadic *Es* layer deviates by more than 30 km for epicentral distances of ~300 km.
2. Anomalous changes in these ionospheric parameters are detected on the same day at stations spaced apart by several hundred kilometers.
3. The lead-time of the possible SIEPs prior to underground impact is mainly determined by the energy of the upcoming earthquake and increases with a rise of its magnitude M. The maximum lead-time for the seismic impact in the specified range of magnitudes is 2.5 days.

4. For possible SIEPs, the inverse proportional dependence of lead-times ΔT on the epicentral distances R from the observational station is absent. At the same time, such dependence is typical for possible MIEPs. This is the main difference in the dependences of lead-times ΔT of possible IEPs of various immediacy.

The described features may eventually make it possible to distinguish SIEPs from other ionospheric anomalies not in epignosis but in real-time quiet geomagnetic conditions, which is important for prediction of seismic hazard in comprehensive forecasts of strong earthquakes with account of the ionospheric data.

References

1. Dobrovolsky, I.P., Zubkov, S.I., Myachkin, V.I.: Estimation of the size of earthquake preparation zones. Pure. appl. Geophys. **117**(5), 1025–1044 (1979)
2. Hegai, V.V., Legenka, A.D., Kim, V.P.: Unusual enhancement of ionospheric F2 layer critical frequency before the 23 August 2011 Virginia (USA) earthquake. Open Trans. Geosci. (GEOS) **1**(1), 39–43 (2014)
3. Heki, K.: Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake. Geophys. Res. Lett. **38**, L17312 (2011). https://doi.org/10.1029/2011GL047908
4. Hobara, Y., Parrot, M.: Ionospheric perturbations linked to a very powerful seismic event. J. Atmos. Sol.-Terr. Phys. **67**(7), 677–685 (2005). https://doi.org/10.1016/j.jastp.2005.02.006
5. Klotz, S., Johnson, N.L.: Encyclopedia of statistical sciences. Wiley, New Jersey (1983)
6. Korsunova, L.P., Khegai, V.V.: Medium-term ionospheric precursors to strong earthquakes. Int. J. Geomagn. Aeron. **6**, GI3005 (2006). https://doi.org/10.1029/2005gi000122
7. Korsunova, L.P., Khegai, V.V.: Analysis of seismoionospheric disturbances at the chain of Japanese stations for vertical sounding of the ionosphere. Geomagn. Aeron. (Engl. Transl.) 48(3), 392–399 (2008)
8. Korsunova, L.P., Hegai, V.V.: Ionospheric precursors of crustal earthquakes in the northwestern part of the Asia-Pacific seismic belt. Open Trans. Geosci. (GEOS) **1**(1), 25–33 (2014)
9. Korsunova, L.P., Hegai, V.V.: Effectiveness criteria for methods of identifying ionospheric earthquake precursors by parameters of a sporadic E-layer and regular F2-layer. J. Astron. Space Sci. **32**(2), 137–140 (2015)
10. Liu, J.Y., Chen, Y.I., Chuo, Y.J., Chen, C.S.: A statistical investigation of pre-earthquake ionospheric anomaly. J. Geophys. Res. **111**, A05304 (2006). https://doi.org/10.1029/2005JA011333
11. Parrot, M., Berthelier, J.J., Lebreton, J.P., Sauvaud, J.A., Santolik, O., Blecki, J.: Examples of unusual ionospheric observations made by the DEMETER satellite over seismic regions. Phys. Chem. Earth. Parts A/B/C **31**(4), 486–495 (2006). https://doi.org/10.1016/j.pce.2006.02.011.2006
12. Perevalova, N.P., Sankov, V.A., Astafyeva, E.I., Zhupityaeva, A.S.: Threshold magnitude for ionospheric TEC response to earthquakes. J. Atmos. Sol.-Terr. Phys. **108**, 77–90 (2014). https://doi.org/10.1016/j.jastp.2013.12.014
13. Perrone, L., Korsunova, L.P., Mikhailov, A.V.: Ionospheric precursors for crustal earthquakes in Italy. Ann. Geophys. **28**(4), 941–950 (2010)
14. Pulinets, S.A., Boyarchuk, K.A.: Ionospheric Precursors of Earthquakes, 315 p. Springer, Berlin (2004)
15. Sarkar, S., Gwal, A.K., Parrot, M.: Ionospheric variations observed by the DEMETER satellite in the midlatitude region during strong earthquakes. J. Atmos. Sol.-Terr. Phys. **69**(13), 1524–1540 (2007)
16. Saroso, S., Liu, J.Y., Hattori, K., Chen, C.H.: Ionospheric GPS TEC anomalies and $M \geq 5.9$ earthquakes in Indonesia during 1993–2002. Terr. Atmos. Ocean. Sci. 19(5), 481–488 (2008). https://doi.org/10.3319/tao.2008.19.5.481(t)

17. Xia, C., Yang, S., Xu, G., Zhao, B., Yu, T.: Ionospheric anomalies observed by GPS TEC prior to the Qinghai Tibet region earthquakes. Terr. Atmos. Ocean. Sci. **22**(2), 177–185 (2011). https://doi.org/10.3319/TAO.2010.08.13.01(TibXS)
18. Zakharenkova, I.E., Shagimuratov, I.I., Tepenitzina, NYu., Krankowski, A.: Anomalous modification of the ionospheric total electron content prior to the 26 September 2005 Peru earthquake. J. Atmos. Sol.-Terr. Phys. **70**(15), 1919–1928 (2008). https://doi.org/10.1016/j.jastp.2008.06.003
19. Zakharenkova, I.E., Shagimuratov, I.I., Krankowski, A., Lagovsky, A.F.: Precursory phenomena observed in the total electron content measurements before great Hokkaido earthquake of September 25, 2003 ($M = 8.3$). Stud. Geophys. Geod. **51**(2), 267–278 (2007)
20. Zubkov, S.I.: Times of the occurrence of earthquake precursors. Izv. Akad. Nauk SSSR: Fiz. Zemli. (5), 87–91 (1987). (in Russian)