Geodesy and Geodynamics 2013,4(4):26-32

http://www.jgg09.com
Doi:10.3724/SP.J.1246.2013.04026

Ionospheric disturbances around the time of the *Ms*7.0 Lushan earthquake

Zhou Yiyan[1,2,3], Wu Yun[1,2], Yang Jian[1,2], Zhu Fuying[1,2] and Zhao Bin[1,2]

[1] *Institute of Seismology, China Earthquake Administration, Wuhan* 430071, *China*

[2] *Key Laboratory of Earthquake Geodesy, China Earthquake Administration, Wuhan* 430071, *China*

[3] *School of Geodesy and Geomatics, Wuhan University, Wuhan* 430079, *China*

Abstract: Variations of Vertical Total Electron Content (VTEC) in the ionosphere are investigated around the time of the *Ms*7.0 Lushan earthquake. A time-series analysis shows an anomalous VTEC increase 15 days before, as well as some anomalous VTEC decreases 5 days before and 8 hours after the earthquake. Each of these anomalies lasted more than 4 hours and drifted from east to west. The anomalous increase 15 days before the earthquake is significantly larger than the solar-terrestrial background noise, and is thus considered to be probably related to the earthquake.

Key words: GPS; VTEC; ionospheric anomalies; earthquake

1 Introduction

Many monitoring techniques have been used in attempts to detect anomalous geophysical changes that might be premonitory to earthquake occurrence. Due to complexity of earthquake-preparation process, however, identifying true earthquake precursors from anomalous geophysical signals is still a world-class problem.

In recent decades, the study of ionospheric disturbances possibly related to earthquakes has attracted much attention. Anomalous changes of the total electron content or peak electron density NmF2 a few days before strong earthquakes have been reported for many seismic events[1-16]. In the meantime, many theoretical and experimental studies have been made, and some physical mechanisms of seismo-ionospheric effects have been proposed. Among them, electromagnetic (EM) emission released by rock failure or atmospheric gravity waves (AGW) excited by tectonic activity in earthquake preparation zone is most popular[10,17-26].

In this study, we used a GPS technique to examine the ionospheric variations around the time of the *Ms*7.0 Lushan earthquake (epicenter: 30.3°N, 103.0°E) which occurred at 00:02UT (LT = UT+8) on 20 April 2013, in Sichuan Province, China. As an ionospheric-sounding technique with high efficiency and low cost, GPS has been widely used in space-weather research. By adopting two ultra-high-frequency waves, the VTEC derived from GPS measurements is a feasible and high-precision parameter in investigating the seismo-ionospheric disturbances. With increasing number of ground-based GPS receivers, it may provide simultaneously and continuously monitoring of the variations of ionospheric VTEC on a large spatial scale[27-29]. Therefore, if any pre-earthquake ionospheric anomalies do exist, the GPS VTEC technique should be able to detect them.

2 Data processing

Total Electron Content (TEC) is an ionospheric parameter for space-weather research and is defined as the line integral of electron density along the propagation path of the radio wave from a GPS satellite to a ground

Received:2013-07-21; Acceptd:2013-10-16

Corresponding author: E-mail: zhouyyhb@aliyun.com

This work is supported by the National Science Foundation of China (41174030), the Special Fund for Seismic Research (201108004) and the Technology Foundation for Selected Overseas Chinese Scholar, Ministry of Personnel of China (2012).

receiver. Since ionosphere is a dispersive medium, we can derive the absolute TEC with high precision from the geometry-free linear combination of phase-smoothed pseudo-range[30,31].

However, the estimation of the differential instrumental biases introduced by the satellite and receiver is vital for accurate calculation of TEC. In order to estimate instrumental biases, a single-layer VTEC model in a sun-fixed coordinate system is usually introduced[31]. The single-layer ionospheric model which assumes that all the electrons are concentrated in a thin spherical layer at a height of 350 km above the Earth's surface, so that we can convert the slant TEC into VTEC at the Ionospheric Pierce Point (IPP), which is the intersection of the receiver-satellite line-of-sight with the single-layer spherical shell. Details about the estimation of the instrumental biases can be found in previous papers[32-35]. In this study, we adopted the VTEC model of spherical harmonic expansion, and used the least-squares fitting to estimate instrumental biases and ionospheric-model coefficients. After all the IPP VTEC values were computed, the VTEC over any given point in the observation area was obtained with the inverse distance-squared-weighting method[36]. To reduce the effects of large ionospheric horizontal gradients, GPS signals at elevation angles less than 45° were not considered. After an observation session, the time series of VTECs over any given observation site was obtained.

Due to its similarity of diurnal variation in the ionosphere, the VTEC over a given point can not generate large day-to-day variations on a timescale of a few days, unless there are sudden changes in the solar-terrestrial environment. Under the assumption of a normal distribution for the VTEC, we computed the mean value u of VTEC values during the previous 10-day and the associated standard deviation σ to construct the upper bound $u+2\sigma$ and the lower bound $u-2\sigma$ for identifying ionospheric anomalies. If any observed VTEC value during the next day exceeds the lower or upper bound for more than 2 hours, we declare them to be a negative or positive anomaly, respectively.

3 Analysis and interpretation

By using the observations of the Crust Network Observation Center China (Fig. 1), we examined the VTEC variations in unit of TECu (10^{16} electrons/m^2) at a sampling interval of 30 seconds for the Lushan earthquake.

We computed the time series of ionospheric VTECs over GPS station SCTQ, which is closest to the epicenter of Lushan earthquake. As shown in figure 2, a positive anomaly appeared 15 days before and two negative anomalies appeared 5 days before and 8 hours after the earthquake.

To show the spatial distribution of the amplitudes of the ionospheric VTEC anomalies, we used the corresponding upper or lower bound as a reference and plotted the differential two-dimensional VTEC (ΔVTEC) maps for several time intervals during the three anomalous periods, based on data from all stations around the epicenter (within 70°–140°E; 15°–55°N) (Figs. 3–5). Here, ΔVTEC < 0 stands for negative anomalies and ΔVTEC>0 stands for the positive anomalies.

From figures 3–5, we may see that all the three VTEC anomalies drifted from east to west, and lasted more than 4 hours. Unfortunately, due to limited observation area, we can't determine exactly how long the anomalies lasted. In view of the strong influence of solar and geomagnetic activities on the ionosphere, the solar-terrestrial environment should be taken into consideration in order to determine whether the anomalies are related to the earthquake. Figure 6 shows variations of solar F10.7 flux and geomagnetic activity indices Dst before and after Lushan earthquake. As seen in figure 6, the solar and geomagnetic activities were both

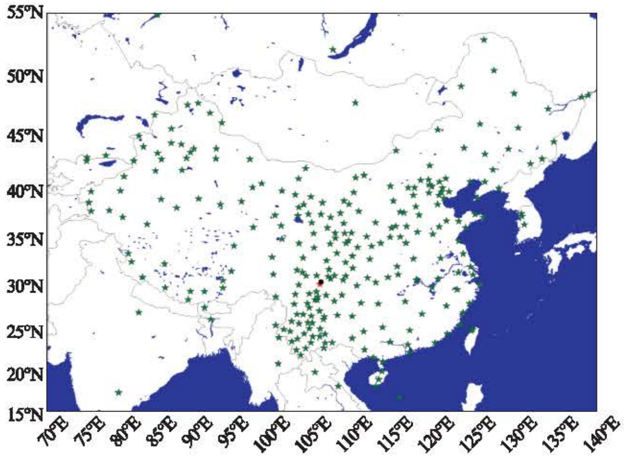


Figure 1 Distribution of the GPS stations (green stars) and epicenter (black circle point), The red star indicates the position of SCTQ station

fairly quiet during the three-week period that covers these anomalies. Since all the anomalies show local effects (Figs. 3, 4 and 5), they should not have come from solar or geomagnetic variations.

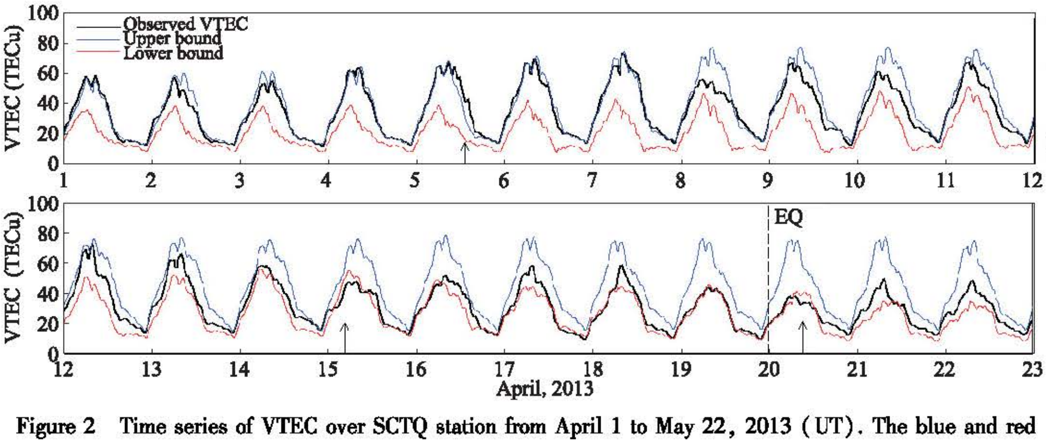


Figure 2 Time series of VTEC over SCTQ station from April 1 to May 22, 2013 (UT). The blue and red curves represent, respectively, the upper and lower bounds of the observed VTEC values (black). The black arrows point to the anomalies. The vertical dashed line indicates the time of Lushan earthquake

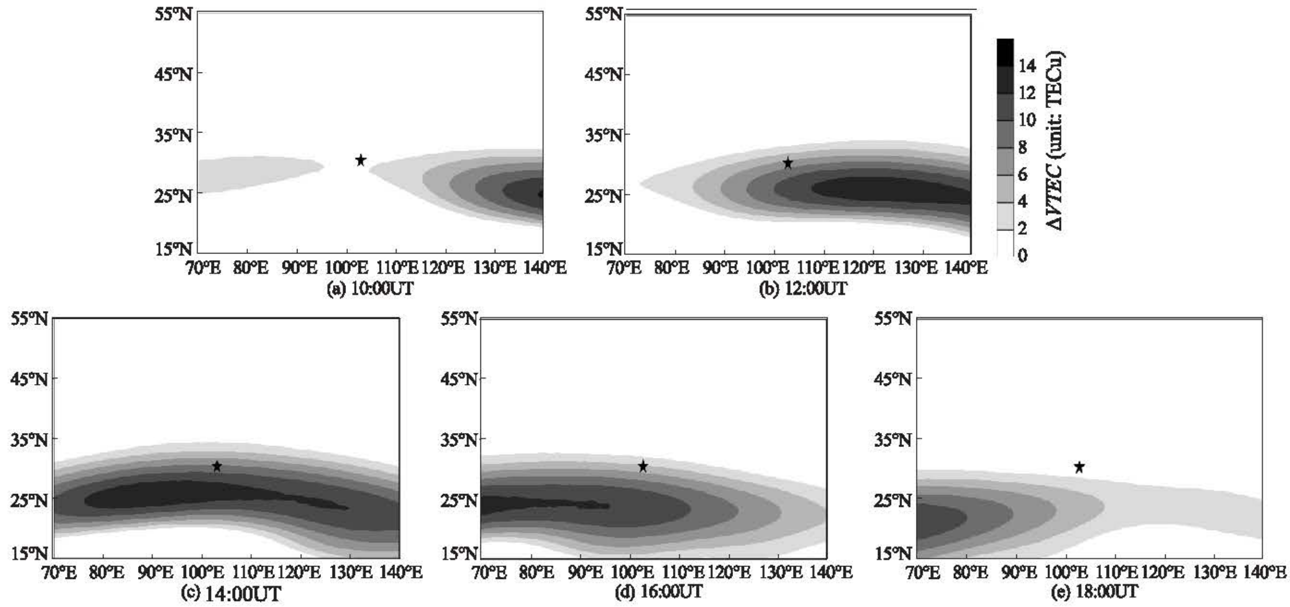


Figure 3 The observed *ΔVTEC* distributions around the epicenter (black star) of Lushan earthquake at different times on April 5, 2013

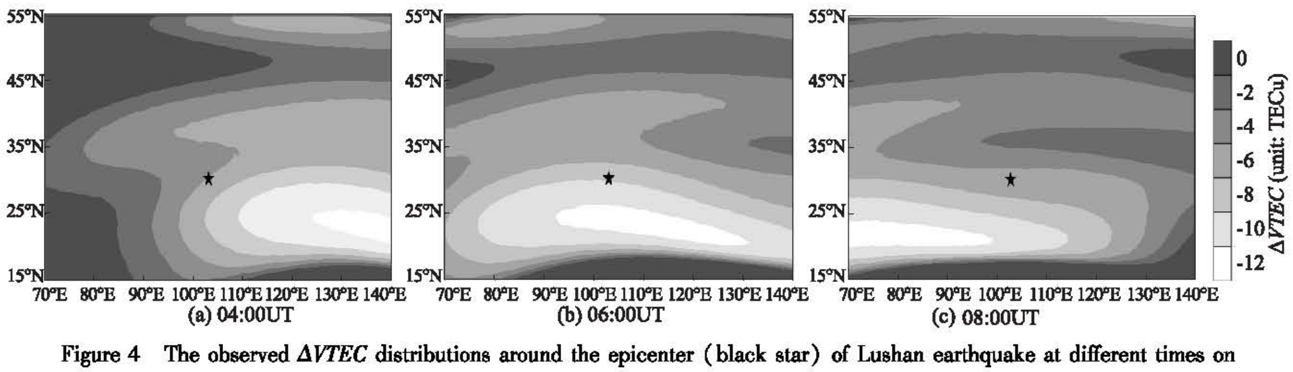


Figure 4 The observed *ΔVTEC* distributions around the epicenter (black star) of Lushan earthquake at different times on April 15, 2013

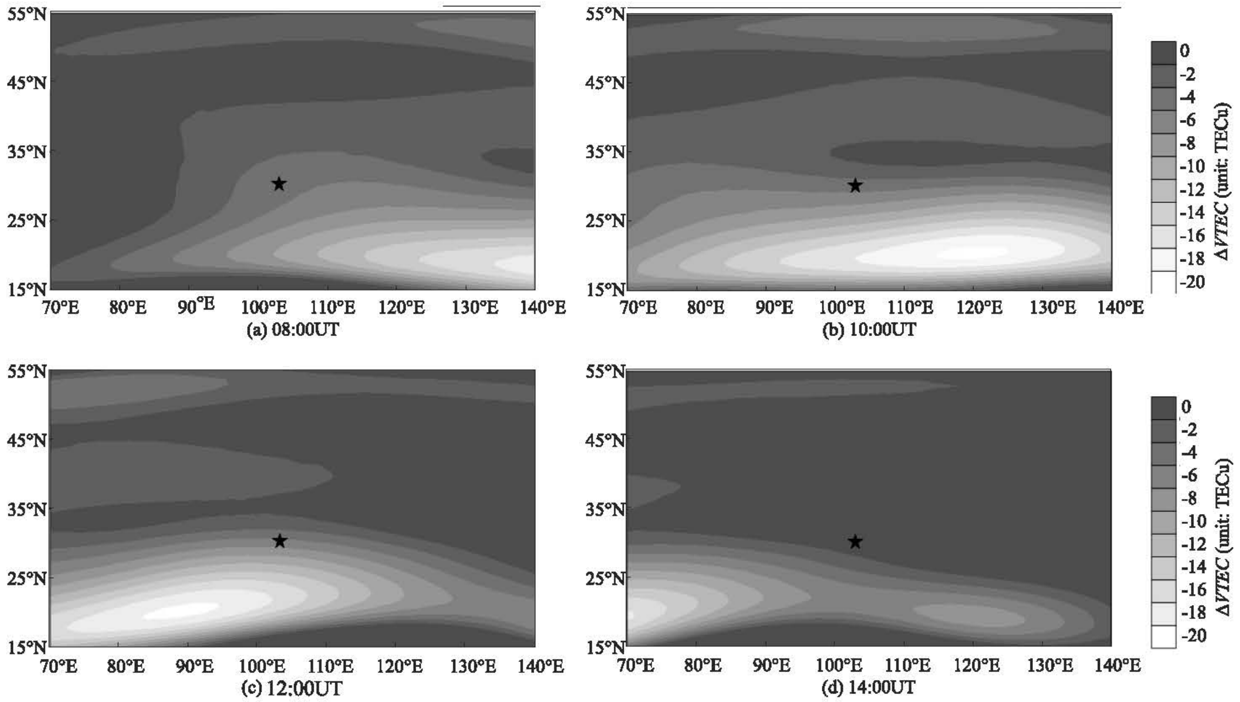


Figure 5 The observed *ΔVTEC* distribution around the epicenter (black star) of Lushan earthquake at different times on April 20, 2013

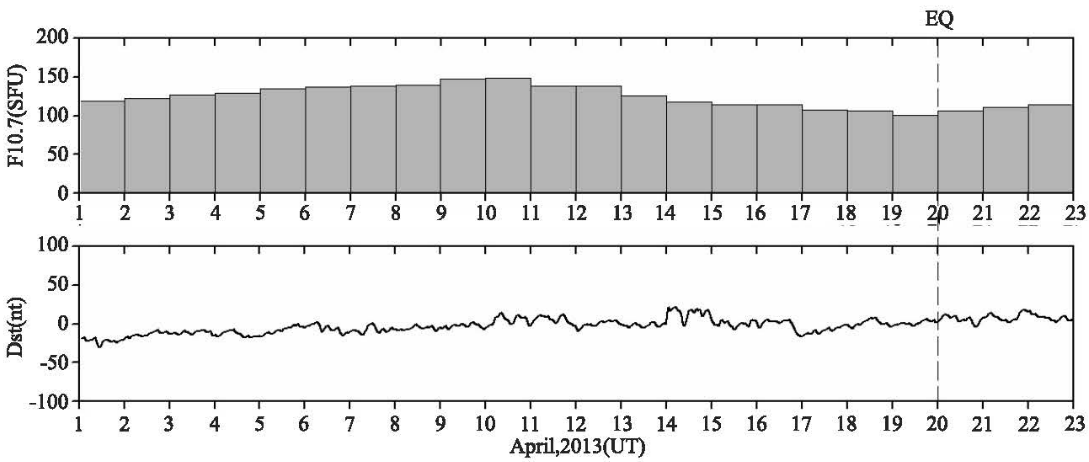
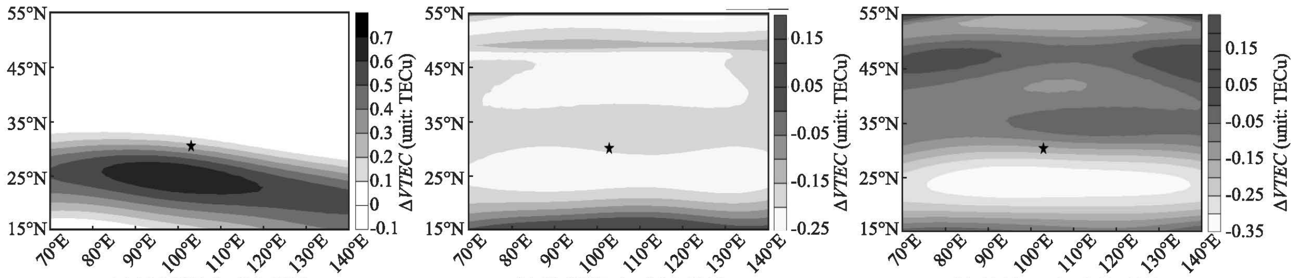


Figure 6 The solar F10.7 flux and the geomagnetic Dst index from April 1 to 22, 2013 (UT). The vertical dashed line indicates the time of Lushan earthquake

However, we are still not sure that all these anomalies were related to the earthquake, because such day-to-day ionospheric VTEC variations may be caused by disturbances in the lower thermosphere[37], which usually do not exceed 30%[10,38-40]. So, any smaller anomalies cannot be attributed to the earthquake without further investigation. Figure 7 shows the spatial distribution of the relative VTEC variability at the times of the three anomalies. As seen from figure 7, the anomaly amplitude on April 5, 2013 far exceeded the limit of 30%. Moreover, its spatial extent was larger than 1500 km in latitude and 7000 km in longitude (Fig. 7(a)). Thus, we may exclude meteorological effects as the cause of this anomaly, and claim it to be related to the earthquake.

This is not the case for the other two anomalies on April 15 and 20, however, because the maximum amplitudes were around 30% (Figs. 7(b) and 7(c)). Thus, we are not sure whether these anomalies are related to the earthquake.



(a) 16:00UT, April 5, 2013 (b) 08:00UT, April 15, 2013 (c) 10:00UT, April 20, 2013

Figure 7 Relative variability of the VTEC values (to values one day before) around the epicenter (black star) of Lushan earthquake at the 3 peak times of ionospheric anomalies.

4 Conclusion and discussion

By analyzing ground-based GPS VTEC data, we found a positive and a negative ionospheric anomaly 15 and 5 days, respectively, before Lushan earthquake, and a negative anomaly 8 hours afterwards. All these anomalies lasted more than 4 hours and drifted from east to west. In view of the solar-terrestrial environment and the characters of the ionospheric disturbances, we conclude that the anomaly on April 5 is probably related to the earthquake, but are not sure whether the other two anomalies are related to the earthquake or caused by thermospheric disturbance.

Seismo-ionospheric effect was previously studied for the 2008 Wenchuan earthquake[41-43], which was located not far from the Lushan earthquake. In that case, the ionospheric anomalies occurred only 3 days before Wenchuan earthquake, which is consistent with the time scale (0-5 days) summarized by Pulinets et al[10] and Liu et al[7,44]. However, the seismo-ionospheric anomalies appeared 15 days before Lushan earthquake, which is far away from the above-mentioned time scale. Therefore, it is necessary for us to further uncover the truth of the different time scale.

Two mechanisms for seismo-ionospheric effects were proposed: Ionospheric oscillation caused by lithospheric outgassing along and in the vicinity of the earthquake-generating fault[16]; $E \times B$ drift generated by penetration of ionosphere by earthquake-related extra electric field on the Earth's surface[10,45]. By using a quasi-electrostatic model for atmosphere-thermosphere-ionosphere coupling, Kim and Hegai[46], Pulinets et al[47] and Sorokin et al[48] showed that a strong vertical electric field on the Earth surface could penetrate into the ionosphere and modify its dynamics and electron density distribution prior to earthquake occurrences.

The long-distance east-to-west drift of the anomalies observed in this study (Fig. 3), however, cannot be easily explained by either of the above-mentioned mechanisms. Thus, further investigation is needed, regarding the mechanism of seismo-ionospheric anomalies.

At the present, no substantial breakthrough has been made in earthquake forecast, especially in short-term forecast. Identifying different precursor signals and studying their statistical features are still major aspects in the research of earthquake forecast. As far as the time scale of seismo-ionospheric precursors is concerned, the ionospheric precursors provide a possibility for realizing short-term forecast.

Acknowledgments

We thank the Crust Network Observation Center China for providing the GPS observation data, the World Data Center for Geomagnetism, Kyoto for providing geomagnetic equatorial Dst index, and the NOAA National Geophysical Data Center for providing the data of solar F10. 7 flux.

References

[1] Davies K and Baker D M. Ionospheric effect observed around the time of Alaska earthquake of March 28, 1964. Journal of Geophysical Research, 1965, 70(9): 172-179.

[2] Hayakawa M and Fujinawa Y. Electromagnetic phenomena related to earthquake prediction. Terra Scientific Publishing Company, Tokyo, Terrapub, 1994.

[3] Calais E and Minster J B. GPS detection of ionospheric TEC perturbations following the January 17, 1994, Northridge earth-

quake. Geophysical Research Letters, 1995, 22: 1045-1048.

[4] Chmyrev V M, Isaev N V, Serebryakova O N, et al. Small-Scale Plasma inhomogeneities and correlated ELF emissions in the ionosphere over an earthquake region. Journal of Atmospheric and Solar-Terrestrial Physics, 1997, 59(9): 967-974.

[5] Liperovsky V A, Pokhotelov O A, Liperovskaya E V, et al. Modification of sporadic E-layers caused by seismic activity. Surveys in Geophysics, 2000, 21: 449–486.

[6] Liu J Y, Chen Y I, Chuo Y J, et al. Variations of ionospheric total electron content during the Chi-Chi earthquake. Geophysical Research Letters, 2001, 28: 1383–1386.

[7] Liu J Y, Chuo Y J, Shan S J, et al. Pre-earthquake ionospheric anomalies monitored by GPS TEC. Annales Geophysicae, 2004, 22: 1585–1593.

[8] Gaivoronskaya T V and Pulinets S A. Analysis of F2-layer variability in the areas of seismic activity. Preprint IZMIRAN, Moscow, 2002, 2(1145):1–20.

[9] Plotkin V V. GPS detection of ionospheric perturbation before the 13 February 2001, El Salvador earthquake. Natural Hazards and Earth System Sciences, 2003, 3: 249–253.

[10] Pulinets S A, Boyarchuk K. Ionospheric precursors of earthquakes. Berlin: Springer, 2004.

[11] Trigunait A, Parrot M, Pulinets S A, et al. Variation of ionospheric electron density during the Bhuj seismic event. Annales Geophysicae, 2004, 22: 4123–4131.

[12] Krankowski A, Zakharenkova I E and Shagimuratov I I. Response of the ionosphere to the Baltic Sea earthquake of 21 September, 2004. Acta Geophysica, 2006, 54(1): 90–101.

[13] Zakharenkova I E, Krankowski A and Shagimuratov I I. Modification of the low-latitude ionosphere before December 26, 2004 Indonesian earthquake. Natural Hazards and Earth System Sciences, 2006, 6: 817–823.

[14] Zakharenkova I E, Shagimuratov I I, Tepenitzina N Yu a, et al. Anomalous modification of the ionospheric total electron content prior to the 26 September 2005 Peru earthquake. Journal of Atmospheric and Solar-Terrestrial physics, 2008, 70: 1919–1928.

[15] Hasbi A M, Mohd Ali M A and Misran N. Ionospheric variations before some large earthquakes over Sumatra. Natural Hazards and Earth System Sciences, 2011, 11:597–611.

[16] Huijun Le, Libo Liu, Jann-Yeng Liu, et al. The ionospheric anomalies prior to the M9. 0 Tohoku-Oki earthquake. Journal of Asian Earth Sciences, 2013, 62:476–484.

[17] Lin'kov E M, Petrova L N and Osipiv K S. Seismic gravitational pulsations of the Earth and atmospheric disturbances as possible precursors of strong earthquakes. Transaction of USSR Academy of Science, Earth Science, 1991, 306: 13–16.

[18] Shalimov S L and Gokhberg M B. Lithosphere-Ionosphere coupling mechanism and its application to the earthquake in Iran on June 20, 1990. A review of ionospheric measurements and basic assumptions. Physics of the Earth and Planetary Interiors, 1998, 105: 211–218.

[19] Gokhberg M B and Shalimov S L. The lithosphere and ionosphere relationship and its modeling. Russian J. Earth Sciences, 2000, 2(2): 95–108.

[20] Pilipenko V, Shalimov S, Uyeda S, et al. Possible mechanism of the over-horizon reception of FM radio waves during earthquake preparation period. Proceedings of the Japan Academy, ser. B, 2001, 77: 125–130.

[21] Varotsos P, Hdjicontis V and Nowick A. The physical mechanism of seismic electric signals. Acta Geophysica Polonica, 2001, 49: 416–421.

[22] Hayakawa M and Molchanov O A. Seismo-electromagnetics: lithosphere-atmosphere-ionosphere coupling. Terra Scientific Publishing Company, Tokyo, Terrapub, 2002.

[23] Molchanov O, Fredorov E, Schekotov A, et al. Lithosphere-atmosphere-ionosphere coupling as governing mechanism for preseismic short-term events in atmosphere and ionosphere. Natural Hazards and Earth System Sciences, 2004, 4: 757–767.

[24] Rapoport Y, Grimalsky V, Hayakawa M, et al. Change of ionosphere plasma parameters under the influence of electric field which has lithospheric origin and due to radon emanation. Physics and Chemistry of the Earth, 2004, 29: 579–587.

[25] Yoshida S and Ogawa T. Electromagnetic emissions from dry and wet granite associated with acoustic emission. Journal of Geophysical Research, 2004, 109(B9): B09204.

[26] Kamogawa M. Preseismic lithosphere-atmosphere-ionosphere coupling. EOS, Transactions of the American Geophysical Union, 2006, 87(40): 417–424.

[27] Mannucci A J, Wilson B D, Yuan D N, et al. A global mapping technique for GPS-derived ionospheric electron content measurements. Radio Science, 1998, 33(3): 565–582.

[28] Jakowski N, Heise S, Wehrenpfennig A, et al. GPS/GLONASS-based TEC measurements as a contributor for space weather forecast. Journal of Atmospheric and Solar-Terrestrial physics, 2002, 64: 729–735.

[29] Otsuka Y, Ogawa T, Saito A, et al. A new technology for mapping of total electron content using GPS network in Japan. Earth Planets Space, 2002, 58(5): 529–534.

[30] Schaer S. Mapping and Predicting the Earth's Ionosphere Using the Global Positioning System. Astronomical Institute, University of Berne, Switzerland, 1999.

[31] Azpilicueta F, Brunini C and Radicella S M. Global ionospheric maps from GPS observations using modip latitude, Advance in Space Research, 2006, 38: 2324–2331.

[32] Wilson B D and Mannucci A J. Instrument biases in ionospheric measurements derived from GPS data. Proceedings of ION GPS'93, Salt Lake City, 1993.

[33] Sardon E, Rius A and Zarraoa N. Estimation of the transmitter and receiver differential biases and the ionospheric total electron content from global positioning system observations. Radio Science, 1994, 29(3): 577–586.

[34] Ma G and Maruyama T. Derivation of TEC and estimation of instrumental biases from GEONET in Japan. Annales Geophysicae, 2003, 21(10): 2083–2093.

[35] Gao Y, Heroux P and Kouba J. Estimation of GPS receiver and satellite L1/L2 signal delay biases using data from CACS. Proceedings of KIS-94, Banff, Canada, August 30-September 2,

1994.

[36] Komjathy J. Global ionospheric total electron content mapping using the global positioning system. Fredericton: University of New Brunswick, 1997.

[37] Kazimirovski E S. Coupling from below as a source of ionospheric variability: a review. Annals of Geophysics, 2002, 45: 1-29.

[38] Forbes J M, Palo S E and Zhang, X L. Variability of the ionosphere. Journal of Atmospheric and Solar-Terrestrial Physics, 2000, 62: 685-693.

[39] Rishbeth H and Mendillo M. Patterns of F2-layer variability. Journal of Atmospheric and Solar-Terrestrial physics, 2001, 63: 1661-1680.

[40] Mendillo M, Rishbeth H, Roble R G., et al. Modelling F2-layer seasonal trends and day-to-day variability driven by coupling with the lower atmosphere. Journal of Atmospheric and Solar-Terrestrial physics, 2002, 64: 1911-1931.

[41] Zhao B, Yu T, Wang M, et al. Is an unusual large enhancement of ionospheric electron density linked with the 2008 great Wenchuan earthquake? J. Geophys. Res., 2008, 113, A11304.

[42] Liu J Y, Chen Y I, Chen C H, et al. Seismoionoshperic GPS total electron content anomalies observed before the 12 May 2008 *M*w7.9 Wenchuan earthquake. J. Geophys. Res., 2009, 114, A04320.

[43] Zhang X, Shen X, Liu J, et al. Analysis of ionospheric plasma perturbations before Wenchuan earthquake, Nat. Hazards Earth Syst. Sci., 2009, 9: 1259-1266.

[44] Liu J Y, Chen Y I, Chuo Y J, et al. A statistical investigation of pre-earthquake ionospheric anomaly, J. Geophys. Res., 2006, 111, A05304.

[45] Freund F. Time-resolved study of charge generation and propagation in igneous rocks. J. Geophys. Res., 2000, 105, 11001-11019.

[46] Kim V P and Hegai V V. A possible presage of strong earthquakes in the nighttime mid latitude associated with earthquakes. Atmospheric and Ionoshperic Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Company, 1999, 619-627.

[47] Pulinets S A, Boyarchuk K A, Hegai V V, et al. Quasielectrostatic model of atmosphere-thermosphereionosphere coupling. Adv. Space Res., 2000, 26(8): 1209-1218.

[48] Sorokin V M, Chmyrev V M and Yaschenko A K. Electrodynamic model of the lower atmosphere and the ionosphere coupling. J. Atmos. Sol. Terr. Phys., 2001, 63: 1681-1691.