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Sub-ionospheric very low frequency perturbations associated with the 12 May 2008 $M = 7.9$ Wenchuan earthquake

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Abstract. The present study reports the VLF (very low frequency) sub-ionospheric perturbations observed on transmitter JJI (22.1 kHz), Japan, received at the Indian low-latitude station, Allahabad (geographic lat. 25.41° N, long 81.93° E), due to Wenchuan earthquake (EQ) that occurred on 12 May 2008 with the magnitude 7.9 and at the depth of 19 km in Sichuan province of Southwest China, located at 31.0° N, 103.4° E. The nighttime amplitude fluctuation analysis gives a significant increase in fluctuation and dispersion two days before EQ, when it crosses 2σ criterion. However, there was no significant change observed in the amplitude trend. The diurnal amplitude variation shows a significant increase in the amplitude of JJI signal on 11 and 12 May 2008. The gravity wave channel and changes in the electric field associated with this EQ seem to be the potential factors of the observed nighttime amplitude fluctuation, dispersion, and significant increase in the signal strength.

1 Introduction

The very low frequency (VLF; 3–30 kHz) signals propagate through waveguide formed below by the Earth's surface (ocean or ground) and above by the D region ionosphere called as Earth–ionosphere waveguide (EIWG). The measurement of VLF signals generated by navigational transmitters has emerged as one of the reliable tools for remote detection of the D region perturbations associated with earthquakes (e.g. Gokhberg et al., 1989; Hayakawa et al., 1996, 2010; Rozhnoi et al., 2007), which seems to be promising for short-term earthquake predictions. The earthquake anomalies usually happen in the D, E, and F region and may be observed 1 to 10 days prior to the earthquake and continue up to few days after it (Akhoondzadeh, 2012). The E and F region effects of the pre-seismic activity can be investigated using ionospheric electron density variations (Akhoondzadeh, 2012; Yao et al., 2012).

Wenchuan earthquake (EQ) occurred on 12 May 2008 at 06:28:01 UT in Wenchuan County in Sichuan province of Southwest China, located at 31.0° N, 103.4° E, with magnitude of 7.9 and a shallow depth of about 19 km. There occurred 149 to 284 major aftershocks. Tremors were felt in almost all major Asian countries. As per the tectonic observatory (http://earthquake.usgs.gov/), it occurred due to striking of thrust on the northwestern margin of the Wenchuan basin. The huge amount of energy was released by the earthquake such that the tremors were felt several thousand kilometers away from the epicenter.

There have been several studies on the effect of Wenchuan EQ on the upper ionosphere (F region) using ground- and satellite-based techniques. Zhao et al. (2008) analyzed ionosonde data at Wuhan (30.5° N, 114.4° E) and Xiamen (24.4° N, 123.9° E) stations close to the earthquake's epicenter and found large enhancement in the maximum ionospheric electron density at F2 peak ($N_m F_2$). They related the abnormal enhancement in $N_m F_2$ to seismo-ionospheric signature. Liu et al. (2009) found that GPS TEC (total electron content) above the epicenter anomalously decreased in the afternoon period on days 6 to 4 before EQ and in the late evening period on day 3 before the earthquake, but enhanced in the afternoon on day 3 before the EQ. Pulinets et al. (2010) analyzed GPS TEC data from IGS network over Chinese region and found a decrease in TEC before EQ and a sharp increase just after the EQ. Xu et al. (2011a) analyzed ionosonde data from Chongqing station (29.55° N, 106.54° E) and found significant disturbance in f_oF_2 on 9 May 2008 at 17:00 UT. The enhancement was about 67 % over the normal day values and lasted about 3 h. The French microsatellite DEMETER (The Detection of Electromagnetic Emission Transmitted from Earthquake Regions) data also had been utilized extensively to study the F region perturbations associated with Wenchuan EQ (Zhang et al., 2010; Sarkar and Gwal, 2010). Zhang et al. (2010) analyzed electron density data recorded by probes onboard DEMETER. They found reduction in electron density 3 days prior to the EQ above the northeast of the epicenter. Sarkar and Gwal (2010) estimated ion density variation and increase in vertical and horizontal component of electric field 4–8 days before the EQ.

In this paper we present the effects of the 12 May 2008 Wenchuan EQ ($M = 7.9$) on sub-ionospheric VLF propagation with transmitter-receiver great circle path length (TRGCP) of about ∼4800 km between JJI (22.2 kHz) VLF transmitter and Allahabad (geographic lat. 25.41° N, long. 81.93° E) receiving station. Nighttime amplitude fluctuation analysis method and diurnal variation of signal amplitude show evidence that observed sub-ionospheric VLF amplitude variations were most likely due to EQ-associated lower ionospheric changes. Our results, along with earlier results published on this EQ, conclude that entire ionosphere was perturbed by the great Wenchuan EQ.

2 VLF data and analysis

The JJI (32.04° N, 130.81° E), Japan, VLF transmitter amplitude and phase were recorded with Stanford University developed AWESOME VLF receiver (Singh et al., 2010) installed at a quiet location near Allahabad (geographic lat. 25.41° N, long. 81.93° E; geomagnetic lat. 16.05° N, long. 153.70° E), India. For the present study only signal amplitude has been used as JJI is a phase unstable transmitter. Figure 1 illustrates the location of JJI transmitter, receiving station Allahabad, TRGCP, earthquake epicenter and wave sensitive area (fifth Fresnel zone). The epicenter is about 87 km off the TRGCP. A total of 22 days (20 April 2008 to 16 May 2008) data have been used. Due to technical problem, the data after 5 days of EQ and from 24–28 April could not be recorded.

We have used nighttime fluctuation (NF) and terminator time (TT) methods to investigate the seismo-ionospheric effects of this EQ as used in various previous works (e.g. Shvets et al., 2004; Hayakawa et al., 1996). In TT method attention is paid to the time of terminator (around the sunrise and sunset of local time) and time shifts are analyzed near the terminator time before and after the EQ (Hayakawa et al., 1996). The TT method is more effective for VLF signals propagating in the east–west meridian plane and for short propagation path (≤1000 km) (Hayakawa, 2007). In our JJI narrowband VLF data, we did not observe any significant change in the terminator times (as evident from Fig. 2 of daily amplitude variations plot) probably due to long propagation path ∼4800 km and time difference of 3.5 h between India and Japan local times. The NF method has been well explained by many researchers (e.g. Shvets et al., 2004; Hayakawa et al., 2010) and is suitable to study EQ effects on long propagation path (>1000 km). In this method particular attention has been given to the data during the local nighttime portion of 19:00–03:00 LT at the receiving station during which entire path (transmitter-receiver great circle path) is in dark and the mean nighttime amplitude, dispersion and nighttime fluctuation are estimated. We have used VLF amplitude for a local night (about 8 h from 19:00 LT to 03:00 LT to avoid terminator effect in VLF data) and estimated the difference $dA(t)$ for a particular day as $dA(t) = (A(t) - \langle A(t) \rangle)$, where $A(t)$ is the VLF amplitude at time t on that particular day and $\langle A(t) \rangle$ is the average value at the same time for 22 days from 20 April–16 May 2008. We have estimated three parameters as defined by Hayakawa et al. (2010) using difference $dA(t)$: (1) trend (T), average of nighttime amplitude difference $dA(t)$ for each day; (2) dispersion (D), standard deviation (SD) of nighttime amplitude difference $dA(t)$ for each day; and (3) nighttime fluctuation (NF), $(dA(t))^2$ over relevant night hours, which gives one datum for each day. We have also used additional statistical analysis as suggested by Hayakawa et al. (2010) where normalized values of trend (T), dispersion (D) and fluctuation (F) as normalized trend (NT*), normalized dispersion (ND*) and normalized fluctuation (NF*) are calculated to avoid variability in different propagation path. The

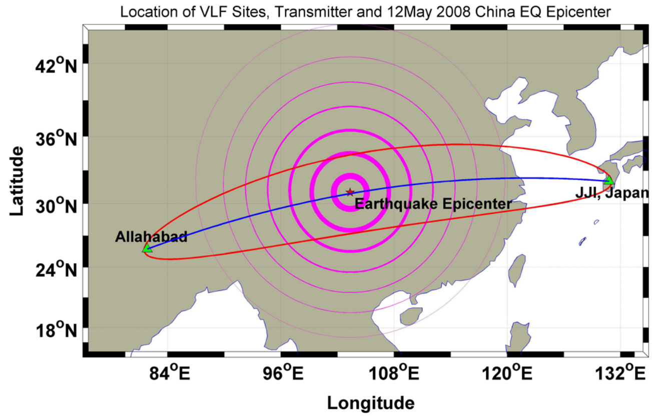

Fig. 1. The great circle path (GCP) between JJI VLF Transmitter, Japan, and Allahabad, AWESOME receiving station, India. The conjugative circles show effects of Wenchuan EQ on surrounding region with decreasing EQ intensity as one moves from epicenter. Wave sensitive area defined by 5th Fresnel zone is also plotted.

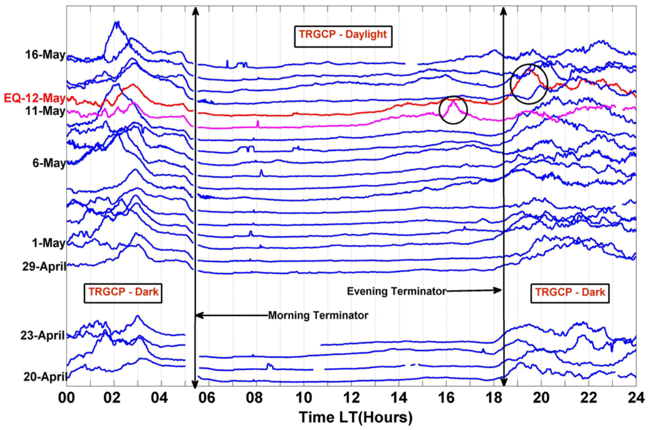

Fig. 2. Sequential plot of 24 h amplitude data of JJI VLF transmitter, Japan, observed at Allahabad, India. Vertical arrows indicate morning and evening terminator times. The circle on 11 and 12 May 2008 indicates unusual increase in the VLF amplitude.

normalization is defined; as for an EQ on particular date, we estimate the trend on this day and we then calculate the average < trend > over ± 15 days around this date. The normalized trend NT* = (trend- < trend >)/σ_T where σ_T is standard deviation for 21 selected days. In the same way, normalized dispersion (ND*) and normalized fluctuation (NF*) are calculated.

3 Results and discussion

3.1 Amplitude perturbations

Sequential plot of daily amplitude variations for JJI signal received at Allahabad for 24 h (in LT) from 20 April to 16 May 2008 is shown in Fig. 2. It can be seen from Fig. 2 that there was no clear terminator time variation (no significant shift in morning and evening terminator time), but the daily amplitude variations show a clear enhancement in the amplitude on 11 and 12 May 2008. Enhancement in the amplitude on 11 and 12 May was ~4 and 5.5 dB, respectively, above the 20-day average (excluding 11 and 12 May) and also above the standard deviation as shown in Fig. 3. On 11 and 12 May, enhancements started same time around 14:00 LT and came to normal level at around 17:00 LT on 11 May, but it was full day above the standard deviation on 12 May. The enhancement in the VLF amplitude was most likely due to additional ionization (basically increase in electron concentration) produced by this earthquake in the lower ionosphere. We have looked for four possible mechanisms for electron density enhancement in the D region and hence the enhancement in JJI VLF amplitude: solar flares (Zigman et al., 2007), geomagnetic storm (Peter et al., 2006), lower ionospheric heating due to lightning discharges causing early/fast VLF events (Inan et al., 1996), and seismic origin due to 12 May 2008 EQ. We have examined details of all possible events; solar flare events are of few minute duration whose effect can be easily identified in the VLF amplitude data. We checked and found that there were no flare events during period of data considerations (http://www.spaceweather.com/). The geomagnetic storms can have considerable effect on the lower ionosphere, which can last up to 1–2 days after onset of geomagnetic storm. We have examined geomagnetic conditions from 20 April–20 May 2008 by looking at Dst and Kp index values (http://wdc.kugi.kyoto-u.ac.jp/). The geomagnetic conditions were quiet (Dst < −20 nT) except during 23–25 April when Dst reached −40 nT. Kp values during above period were low except on 23 April and 2 May when it crossed level 4. Thus there was no significant geomagnetic activity to affect the lower ionosphere during period of the VLF data presented, so geomagnetic activity effect is ruled out. Early/fast VLF events are of small durations (from few tens to hundred seconds) (Inan et al., 1996), so their effect can also be distinguished easily and cannot be the reason for observed long time-scale amplitude enhancement (Helliwell et al., 1973). The most likely reason for amplitude enhancement is seismo-ionospheric origin caused by 12 May 2008, Wenchuan EQ. The most reasonable mechanism for observed enhancement in the amplitude is the quasi-static electric field, which can modify lower ionospheric properties. Electric field generated due to different processes during EQ preparation can penetrate into the ionosphere and can modify the ionospheric properties (Kim et al., 2002; Pulinets and Boyarchuk, 2004). But it is still an open question of how the anomalous electric field on the tectonic faults penetrates into the ionosphere. Recently, Pulinets (2009) explained coupling process in terms of global electric circuit, which provides a reasonable explanation of the existence of an up/downward vertical atmospheric electric field between the ground and ionosphere. This quasi-electrostatic electric field hypothesis is supported by observations of electric field perturbations before Wenchuan EQ (Sarkar and Gwal 2010; Pulinets et al., 2010; Xu et al., 2011b). Pulinets et al. (2010) have observed anomalies in GPS TEC, change in the position and shape of equatorial anomaly crest and variations in vertical electron density profiles before and after the Wenchuan EQ. They concluded, on the basis of proper physical model, that observed anomalies were caused by additional electric field (zonal and meridional) generated during the Wenchuan EQ preparation and following the EQ occurrence. Xu et al. (2011b) have estimated about ~2 mV m^{-1} enhancement in the electric field in the F2 region of ionosphere on 9 May 2008, 3 days prior to the EQ from five low-latitude, ground-based ionosondes around the epicenter. They also observed anomalous electric field on the ground of tectonic faults ~1000 V m^{-1}, which was 10 times higher than fair weather ground electric field. Fuks et al. (1997) suggested that anomaly in VLF phase and amplitude passing over seismoactive region is due to increase

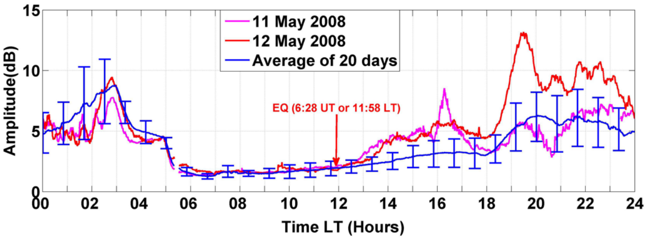

Fig. 3. Comparison of 11 and 12 May 2008 VLF amplitude enhancement with average of 20 days. Arrow indicates EQ timing in UT and LT on 12 May 2008.

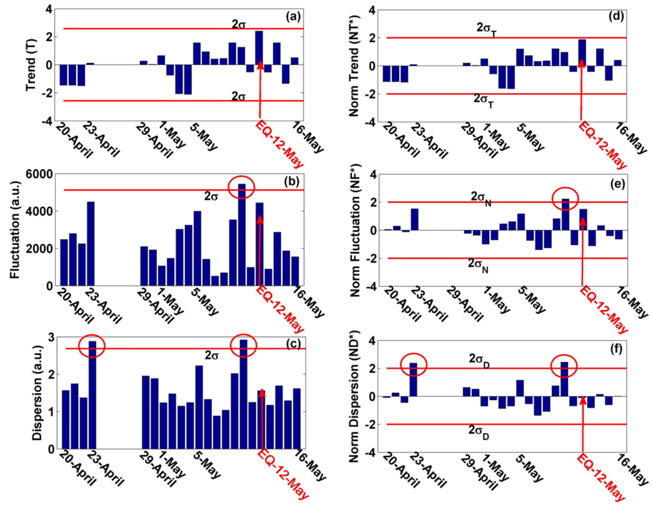

Fig. 4. Nighttime fluctuation analysis for **(a)** trend, **(b)** fluctuation, **(c)** dispersion **(d)** norm-trend, **(e)** norm-fluctuation and **(f)** norm-dispersion. The horizontal line in each panel shows 2σ criteria to define the anomalous day.

in lower ionospheric conductivity, which is caused by electric field increase before an EQ. The proposed mechanism to explain amplitude enhancement indicates towards chemical channel (quasi-static electric field effect) of lithosphere–atmosphere–ionosphere coupling process (Hayakawa et al., 2010), which suggests that atmospheric electric field generated on or near the ground surface during earthquake preparation can cause significant ionospheric anomalies.

3.2 Nighttime fluctuation method

Figure 4a, b and c show trend, fluctuation and dispersion, and Fig. 4d, e and f show normalized trend, normalized fluctuation and normalized dispersion. The horizontal line in each panel shows two standard deviation (2σ) criteria to define the anomalous day. The nighttime fluctuation analysis shows that the trend and normalized trend (Fig. 4a and d) approached the $2\sigma_T$ criterion line on EQ day (12 May) but did not exceed $2\sigma_T$. The fluctuation and normalized fluctuation (Fig. 4b and e) exhibit a significant increase exceeding $2\sigma_{\mathrm{NF}}$ criterion 2 days before the EQ (10 May). Figure 4c and f show significant increase in dispersion and normalized dispersion on 23 April and 10 May and 2 days before the EQ (exceeding $2\sigma_D$ criterion). Generally, the VLF/LF anomalies take place 5 to 7 days (approximately 1 week) before the earthquake (Hayakawa et al., 2010) and in our case the anomaly was observed 19 and 2 days before the EQ. As each EQ is different and seismo-ionospheric study is in its developing stage, it is worth comparing our results with previous case studies of individual EQ and statistical study on many years of earthquake data. As a case study we can mention work by Horie et al. (2007), who studied the effect of great Sumatra EQ on 26 December 2004 with magnitude $M = 9.0$ and at depth 30 km. They applied nighttime amplitude fluctuation analysis method for NWC-Japan VLF propagation path and observed significant enhancements in fluctuations, 4 days before the EQ. Our results also show similar enhancement in amplitude fluctuations but 2 days before the EQ. Recently, a statistical study using long period data (7 yr) was done by Hayakawa et al. (2010). They applied nighttime fluctuation analysis method and concluded that for shallow EQ (depth < 40 km) normalized trend showed significant decrease before the EQ, whereas normalized fluctuation and dispersion showed significant increase before the EQ. Our analysis for Wenchuan EQ, which occurred at a shallow depth of 19 km, also shows similar results for amplitude fluctuation and dispersion (significant increase) but no significant change in trend. The observed VLF propagation anomalies in trend, fluctuation and dispersion have been explained in terms of acoustic and gravity wave channel, also called atmospheric gravity wave (AGW) channel by many previous researchers (Molchanov et al., 2001; Shvets et al., 2004; Hayakawa et al., 2010), which are generated near seismo-active region and travel up to the ionosphere and modify the ionospheric properties.

Explanation for diurnal amplitude perturbation and nighttime fluctuation analysis results indicated that quasi-static electric field and AGW seem to be associated with this earthquake and we suggest that, in order to understand lithosphere–atmosphere–ionosphere coupling process, one should consider both chemical and AGW channels.

4 Summary

The Wenchuan EQ that occurred on 12 May 2008 with magnitude 7.9 and depth 19 km, was one of most devastating EQ events in recent years. Because of its higher magnitude and lower depth, it had its effect on upper ionosphere as reported by recent studies using ionosonde, GPS and satellite data (Zhao et al., 2008; Liu et al., 2009; Sarkar and Gwal, 2010). Our results using VLF sub-ionospheric technique show the evidence of lower ionospheric (D region) perturbations associated with this earthquake during its preparation time. The mechanism of seismo-ionosphere is still in process of development. We have tried to explain observed results for this earthquake in light of two plausible coupling mechanisms: chemical channel (quasi-static electric field) and acoustic and gravity wave (atmospheric gravity wave) channel. Our results, along with earlier published results on seismo-ionospheric effects of this earthquake, support both the hypothesis in order to understand lithosphere–atmosphere–ionosphere coupling process. Thus sub-ionospheric VLF/LF signal monitoring, combined with ground-based and satellite-based observations of ionospheric disturbances associated with seismo-electric signals, has potential to be a future powerful tool of earthquake monitoring and forecasting.

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References

Akhoondzadeh, M.: Anomalous TEC variations associated with the powerful Tohoku earthquake of 11 March 2011, Nat. Hazards Earth Syst. Sci., 12, 1453–1462, doi:10.5194/nhess-12-1453-2012, 2012.

Fuks, M., Shubova, R. S., and Martynenko, S. I.: Lower ionosphere response to conductivity variations of the near-earth atmosphere, J. Atmos. Sol. Terr. Phys., 59, 961–965, 1997.

Gokhberg, M. B., Gufeld, I. L., Rozhnoi, A. A., Marenko, V. F., Yampolsky, V. S., and Ponomarev, E. A.: Study of seismic influence on the ionosphere by super long wave probing of the Earth-ionosphere waveguide, Phys. Earth Planet. Int., 57, 64–67, 1989.

Hayakawa, M.: VLF radio sounding of ionospheric perturbations associated with Earthquakes, Sensors, 7, 1141–1158, 2007.

Hayakawa, M., Molchanov, O. A., Ondoh, T., and Kawai E.: On the precursory signature of Kobe earthquake in subionospheric VLF propagation, J. Comm. Res. Lab., 43, 169–180, 1996.

Hayakawa, M., Kasahara, Y., Nakamura, T., Muto, F., Horie, T., Maekawa, S., Hobara, Y., Rozhnoi, A. A., Solovieva, M., and Molchanov, O. A.: A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes, J. Geophys. Res., 115, A09305, doi:10.1029/2009JA015143, 2010.

Helliwell, R. A., Katsufrakis, J. P., and Trimpis, M. L.: Whistler induced amplitude perturbation in VLF propagation, J. Geophys. Res., 78, 4679–4688, 1973.

Horie, T., Yamauchi, T., Yoshida, M., and Hayakawa, M.: The wavelike structures of ionospheric perturbation associated with Sumatra earthquake of 26 December 2004, as revealed from VLF observation in Japan of NWC signals, J. Atmos. Sol. Terr. Phys., 69, 1021–1028, 2007.

Inan, U. S., Pasko, V. P., and Bell, T. F.: Sustained heating of the ionosphere above thunderstorms as evidenced in "early/fast" events, Geophys. Res. Lett., 23, 1067–1070, doi:10.1029/96GL01360, 1996.

Kim, V. P., Pulinets, S. A., and Hegai, V. V.: Theoretical model of possible disturbances in the nighttime mid-latitude ionospheric D-region over an area of strong earthquake preparation, Radiophys. Quantum Radioelect., 45, 262–268, 2002.

Liu, J. Y., Chen, Y. I., Chen, C. H., Liu, C. Y., Chen, C. Y., Nishihashi, M., Li, J. Z., Xia, Y. Q., Oyama, K. I., Hattori, K., and Lin, C. H.: Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008 Mw7.9 Wenchuan earthquake, J. Geophys. Res., 114, A04320, doi:10.1029/2008JA013698, 2009.

Molchanov, O. A., Hayakawa, M., and Miyaki, K.: VLF/LF sounding of the lower ionosphere to study the role of atmospheric oscillations in the lithosphere-ionosphere coupling, Adv. Polar Upper Atmos. Res., 15, 146–158, 2001.

Peter, W. B., Chevalier, M. W., and Inan, U. S.: Perturbations of Midlatitude Subionospheric VLF Signals Associated with Lower Ionospheric Disturbances during Major Geomagnetic Storms, J. Geophys. Res., 111, A03301, doi:10.1029/2005JA011346, 2006.

Pulinets, S. A.: Physical mechanism of the vertical electric field generation over active tectonic fault, Adv. Space Res., 44, 767–773, 2009.

Pulinets, S. A. and Boyarchuk, K.: Ionospheric Precursors of Earthquakes, Springer, Berlin, 162 pp., 2004.

Pulinets, S. A., Bondur, V. G., Tsidilina, M. S., and Gaponova, M. V.: Verification of the concept of seismoionospheric coupling under quiet heliogeomagnetic conditions, using the Wenchuan (China) earthquake of May 12, 2008, as an example, Geomagnetism Aeronom., 50, 240–252, 2010.

Rozhnoi, A., Molchanov, O., Solovieva, M., Gladyshev, V., Akentieva, O., Berthelier, J. J., Parrot, M., Lefeuvre, F., Hayakawa, M., Castellana, L., and Biagi, P. F.: Possible seismo-ionosphere perturbations revealed by VLF signals collected on ground and on a satellite, Nat. Hazards Earth Syst. Sci., 7, 617–624, doi:10.5194/nhess-7-617-2007, 2007.

Sarkar, S. and Gwal, A. K.: Satellite monitoring of anomalous effects in the ionosphere related to the great Wenchuan earthquake of May 12, 2008, Nat. Hazards, 55, 321–332, doi:10.1007/s11069-010-9530-9, 2010.

Shvets, A. V., Hayakawa, M., Molchanov, O. A., and Ando, Y.: Study of ionospheric response to regional seismic activity by VLF radio sounding, Phys. Chem. Earth, 29, 627–637, 2004.

Singh, R., Veenadhari, B., Cohen, M. B., Pant, P., Singh, A. K., Maurya, A. K., Vohat, P., and Inan, U. S.: Initial results from AWESOME VLF receivers: Setup in low latitude Indian region under IHY2007/UNBSSI program, Current Science, 98, 398–405, 2010.

Xu, T., Wu, J., Zhao, Z., Liu, Y., He, S., Li, J., Wu, Z., and Hu, Y.: Brief communication "Monitoring ionospheric variations before earthquakes using the vertical and oblique sounding network over China", Nat. Hazards Earth Syst. Sci., 11, 1083–1089, doi:10.5194/nhess-11-1083-2011, 2011a.

Xu, T., Hu, Y., Wu, J., Wu., Z., Li, C., Xu., Z., and Suo, Y.: Anomalous enhancement of electric field derived from ionosonde data before the great Wenchuan earthquake, Adv. Space Res., 47, 1001–1005, 2011b.

Yao, Y. B., Chen, P., Zhang, S., Chen, J. J., Yan, F., and Peng, W. F.: Analysis of pre-earthquake ionospheric anomalies before the global $M = 7.0+$ earthquakes in 2010, Nat. Hazards Earth Syst. Sci., 12, 575–585, doi:10.5194/nhess-12-575-2012, 2012.

Zhang, X., Shen, X., Liu, J., Ouyang, X., Qian, J., and Zhao, S.: Ionospheric perturbations of electron density before the Wenchuan Earthquake, Int. J. Remote Sens., 31, 3559–3569, 2010.

Zhao, B., Wang, M. Yu, T., Wan, W., Lei, J., Liu, L., and Ning, B.: Is an unusual large enhancement of ionospheric electron density linked with the 2008 great Wenchuan earthquake?, J. Geophys. Res., 113, A11304, doi:10.1029/2008JA013613, 2008.

Zigman, V., Grubor, D., and Sulic, D.: D-region electron density evaluated from VLF amplitude time delay during X-ray solar flares, J. Atmos. Terr. Phys., 69, 775–792, doi:10.1016/j.jastp.2007.01.012, 2007.