Seismo-ionospheric anomalies in total electron content of the GIM and electron density of DEMETER before the 27 February 2010 M8.8 Chile earthquake

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Abstract

In this paper we examine the pre-earthquake ionospheric anomalies by the total electron content (TEC) extracted from GIM (global ionospheric map) and the electron density (Ne) observed by the DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite during the 2010 M8.8 Chile earthquake. Temporal variations show the nighttime TEC and Ne simultaneously increase 9–19 days before the earthquake. A cross-comparison of data recorded during the period of 1 February to 3 March in 2006–2010 confirms the above temporal anomalies specifically appear in 2010. The spatial analyses show that the anomalies tend to appear over the epicenter.

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1. Introduction

Ionospheric electron density anomalies associated with strong earthquakes have been widely investigated (Liu et al., 2000, 2001, 2004a, 2004b, 2006; Chen et al., 2004; Pulinets and Boyarchuk, 2004; Liperovskaya et al., 2006; Zhao et al., 2008; Kakinami et al., 2010; Jhuang et al., 2010; Písa et al., 2011). Liu et al. (2001) first employ the total electron content (TEC) derived from measurements of local ground-based GPS receivers to study ionospheric electron density variations during the 1999 M7.6 ChiChi earthquake and find that the GPS TEC around the epicenter significantly decrease in the afternoon period 1, 3, and 4 days before the earthquake. Liu et al. (2004a) further statistically examine GPS TEC derived from a local receiver network during the 20 M ≥ 6.0 earthquakes in Taiwan from September 1999 to December 2002. They confirm that the GPS TECs significantly decrease in the afternoon/evening period within 5 days prior to 16 of the 20 earthquakes. Following those, scientists start using the global ionosphere map (GIM) to study anomalous GPS TEC appearing before worldwide devastated earthquakes, such as the 2004 M9.3 Sumatra earthquake (Liu et al., 2010), 2008 M8.0 Wenchuan earthquake (Liu et al., 2009; Jhuang et al., 2010; Kakinami et al., 2010), and 2010 M7.0 Haiti earthquake (Liu et al., 2011). Due to the global coverage of GIM, both temporal and special anomalies are conducted. This result in global effects, such as storms, and local effects, such as earthquakes, can be discriminated.

Meanwhile, the French micro-satellite DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) was designed to detect the ionospheric disturbances during earthquakes (Lagoutte et al.,...
Fig. 1. The $M \geq 6.0$ earthquake distribution in Chile during 1999–2011. The red circles denote the earthquakes with its magnitude. The star denotes the 2010 M8.8 Chile earthquake. The gray curves show the orbits of DEMETER satellite 9 to 19 days before the M8.8 earthquake in the nighttime. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. The temporal distributions of GIM TEC above the 2010 M8.8 Chile earthquake epicenter from 1 February to 3 March, 2010. We compute the TEC around the epicenter by using a linear interpolation of four data points nearest the epicenter (35.91°S, 72.73°W). Since the resolutions of the GIM TEC are 2.5° in latitude and 5° in longitude, we take the data point centers within −37.5° to −35.0°N and 285° to 290°E. We then apply the method in Liu et al. (2011) to identify the ionospheric anomalies. We construct the upper bound ($UB = X + 1.5(UQ-X)$) and lower bound ($LB = X - 1.5(X-LQ)$) as a reference, which $X$, UQ, LQ are the 30-day running median, upper quartile and lower quartile, respectively. Under the assumption of a normal distribution with mean $\mu$ and standard deviation $\sigma$ for the parameter, the construct upper and low bounds are 1.34$\sigma$, respectively. The red, two black, and dashed curves denote the observed TEC (O), associated UB, LB and X, respectively. The red/black areas represent the increase/decrease anomalous strength (O-UB/LB-O). The red/black triangles denote the anomaly days which the observed TEC exceed the associated UBs/LBs for at least 8 hours during 0000–2400LT. The blue line marks the earthquake. 1TECU = $10^{16}$ el/m². (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Scientists (Piša et al., 2011; Ho et al., 2013; Sarkar et al., 2012) employ the DEMETER satellite to detect ionospheric pre-earthquake anomalies. Piša et al. (2011) and Ho et al. (2013) report increases of the ion and electron density (Ne) of the DEMETER over the epicenter 10–20 days before the 27 February 2010 M8.8 Chile earthquake. In this paper, we cross-compare the ground based GIM TEC and space based DEMETER Ne to analyze both temporal and spacial seismo-ionospheric anomalous phenomena during the 2010 M8.8 Chile earthquake.

2. Observation

A magnitude M8.8 earthquake occurred in Chile at 06:34 UT (Universal Time), 27 February 2010 with a depth of 35 km. The epicenter was located at 35.91°S, 72.73°W in the circum-Pacific seismic zone, where is one of the most active seismic areas in the world. Fig. 1 displays the locations of the 2010 M8.8 earthquake and the 79 M ≥ 6.0 earthquakes in this area during 1999–2011.

The GPS TEC of the GIM is published by the Center for Orbit Determination in Europe (CODE) every 2 hours (cf. Schaefer, 1999) with a spatial resolution of 2.5° geographic latitude and 5° geographic longitude. Fig. 2 illustrates the continuous TEC around the epicenter during the M8.8 earthquake. The anomalous TEC enhancements appear during 10-19 February (8-17 days prior to the earthquake) without any decrease anomaly. Since the earthquake preparation is a continuous process, based on statistical results of Liu et al. (2006), we consider a GIM TEC anomalous duration being longer than 8 hours to be an anomaly day. Base on such criteria, the anomaly days can be found on 12, 14, 15, and 16 February (11, 12, 13, 15 days prior to the earthquake, respectively).

The same criteria is applied and expanded to statistically study ionospheric anomalies of GIM TEC during the 79 M ≥ 6.0 earthquakes (Fig. 3). It can be seen anomalies mainly appear 18-26 days before the earthquakes. The decrease anomalies exceeding 40% appear 23 days before 14 M ≥ 6.7 earthquakes, while the increase anomalies...
greater than 30% appear 22, 24, and 26 days before the $M \geq 6.0$ earthquakes.

We cross-compare DEMETER Ne at 1030 and 2230 LT due to its sun-synchronous 680 km altitude orbits with simultaneous and co-located GIM TEC. Fig. 4 displays the DEMETER Ne and GIM TEC 30 days before and after around the M8.8 epicenter. The geomagnetic index $Kp<5$ and solar flux $F10.7<95.5$ reveal that the solar and geomagnetic activities are in a relative quiet condition during this period (Fig. 4a). It can be seen that anomalies of the two quantities in the nighttime are much more pronounced than those in the daytime (Figs. 4b and 4c).

Fig. 4c depicts that the nighttime Ne and TEC anomalously increase on day 9-11, 14, 15, 17, 19, 28 and day 9-12, 18, 26, 30 before the earthquake, respectively. In general, the nighttime GIM TEC and DEMETER Ne tend to yield anomalous increases day 9-19 before the earthquake.

Fig. 5 displays the spatial distributions of the nighttime anomalies in the GIM TEC and DEMETER Ne. Due to the 2-hour time resolution in GIM TEC, we superimpose the nighttime anomalies on 12, 14, 15, and 16 February (see Fig. 2 for detail) and find that the increase anomalies tend to appear over the epicenter together with 4 different
EIA (equatorial ionization anomaly) regions of the Africa sector, Asia sector, Pacific region, and the northern hemisphere of America sector (Fig. 5a). Since Fig. 4c reveals DEMETER Ne yielding the most pronounced increase anomaly on day 17 (10 February) before the earthquake, we then examine the spatial distribution of the associated anomalies. Fig. 5b depicts that the Ne increase anomalies appear specifically over the epicenter, except the others at magnetic equator (345°E, 0°N). To echo Figs. 4c and 5b, Fig. 6 demonstrates that DEMETER Ne yields the most pronounced increase anomaly over the epicenter on day 17 (10 February) before the earthquake.

3. Discussion and conclusion

To see whether the increase anomalies specifically appear during the earthquake, we examine both GIM TEC and DEMETER Ne over the epicenter in the 31-day period of 1 February to 3 March in 2006–2010. Fig. 7 reveals the increase anomaly days of the two quantities specifically appear in 2010. It is interesting to see that neither earthquakes nor increase anomalies can be observed in the rest years. This suggests that the increase anomalies are most likely associated with the M8.8 Chile earthquake. Meanwhile, Fig. 4 illustrates that the increase anomaly days of the TEC and Ne appear 9-19 days before the M8.8 Chile earthquake, which is a much shorter lead time than that of the statistical results of the 79 earthquakes 22-26 days shown in Fig. 3. This generally agrees with the conclusion reached by Liu et al. (2004b) that the larger earthquake has the shorter lead time. It should be mentioned that the number of large earthquakes usually is rather limited and therefore a solid conclusion is difficult to be reached.

Fig. 5a reveals that the increase anomalies in TEC are not only over the epicenter but the 4 different EIA regions. Liu and Watanabe (2008) examine the longitudinal structure of the ionosphere electron density at 400-km altitude at global fixed local time 2100LT and find the 4 increase (peak) regions in March equinox during the low solar flux
Fig. 6. The Ne along the DEMETER satellite path on 17 days before the M8.8 earthquake. The red, black, and dashed curves denote the observation, associated UB, LB, and medians. The color areas represent the increase anomalous strength (O-UB). The map reveals the satellite path with the Ne variations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. The anomaly days observed by GIM (left panel) and DEMETER (right panel) during 1 February to 3 March, 2006 to 2010. The red bars indicate the departures of the observations and upper bounds. The values of GIM TEC are the medians of the departures in each anomaly day. The blue lines denote the date of the 2010 M8.8 earthquake. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
condition. Note that the 4 peak locations generally agree with the increase anomalies in Fig. 5a, except the one over the epicenter.

In conclusion, this study examines the increase anomalies by means of the GIM TEC and the DEMETER Ne. Both the temporal variation and special distribution show that the seismo-ionospheric increase anomalies appear on days 9-19 before the earthquake and specifically over the epicenter.

Reference


Ho, Y.Y., Liu, J.Y., Parrot, M., Pincon, J.-L. Temporal and spatial analyses on seismo-electric anomalies associated with the 27 February 2010 M8.8 Chile earthquake observed by DEMETER satellite, NHESS, submitted for publication, 2013.


