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ORIGINAL ARTICLE

Anomalous variation in GPS TEC prior to the 11 April 2012 Sumatra earthquake

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Abstract On 11 April 2012, a strong earthquake of magnitude Ms8.6 occurred near the west coast of Northern Sumatra, Indonesia. In this paper, we investigated the morphological characteristics of anomalous variations in Global Positioning System Total Electron Content (GPS TEC) prior to the earthquake by the method of the statistical analysis. It was found the TEC anomaly was firstly decreased, then, it became more enhanced, finally, it decreased, the peak of anomaly enhancement arose from 13:00–17:00 LT on April 5 lasted for ∼4 hours and the anomalous ionospheric regions extended to ∼40° in longitude and ∼20° in latitude, its location did not coincide with the vertical projection of the epicenter, but lies at the north and south of the geomagnetic equator, meanwhile, corresponding ionospheric anomalies are also observed in the magneto conjugate region. Potential causes of these results are discussed,eliminating the ionospheric anomalies that may be caused by solar activities and magnetic storms, it can be concluded that the observed obvious anomalous variation in GPS TEC on April 5 were possibly related to the earthquake.

Keywords Anomalous variation · GPS TEC · Precursors of earthquakes

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1 Introduction

Since the ionospheric anomalies was first discussed for the great Alaska earthquake as early as in 1964 (Bolt 1964; Davies and Baker 1965; Leonard and Barnes 1965), it has been fairly verified that the ionosphere anomalous variation will occur in a few days or hours before the strong earthquakes (Calais 1995; Chmyrev et al. 1997; Liperovsky et al. 2000; Silina et al. 2001; Liu et al. 2001, 2002, 2004, 2008, 2009, 2010, 2011; Gaivoronskaya and Pulinets 2002; Plotkin 2003; Afraimovich et al. 2004; Pulinets and Boyarchuk 2004; Pulinets et al. 2005; Krankowski et al. 2006; Zakharenkova et al. 2007, 2008; Zhao et al. 2008; Lin et al. 2009; Zhou et al. 2009; Hsiao et al. 2010; Lin 2010, 2011; Xiong et al. 2011; Yao et al. 2012), the seismic- ionospheric precursor offers a unique advantage in determining the three elements of earthquake (Pulinets and Boyarchuk 2004). Especially, the peak electron density in the F2-layer is one of the important parameters to study the ionospheric anomaly before the earthquakes (Gaivoronskaya and Zelenova 1991; Depuev and Zelenova 1996; Pulinets 1998; Liu et al. 2000; Silina et al. 2001; Pulinets and Legen'ka 2003; Rios et al. 2004; Pulinets and Boyarchuk 2004; Hobara and Parrot 2005; Liperovskaya et al. 2006; Singh and Singh 2007; Xiong et al. 2008), and the measured ionospheric perturbations following the earthquakes were able to infer source parameters in remarkable agreement with seismic measurements (Afraimovich et al. 2001). For this reason, the ionosondes should be an efficient means to detect the seismo-ionospheric effects. However, compared with the wide distribution of earthquake zones worldwide, there are not more than 300 ionosondes available, especially in the oceans, these is less ionosondes available. On the other hand, only a fraction of them can be continuously operational. Therefore, the temporal and spatial coverage of ionosonde observations are rather limited, and it is very difficult to use the ionosondes to correlate the ionospheric disturbances with seismic activities systematically.

For the frequencies that are used in the GPS system are sufficiently high, the signals are minimally affected by the ionospheric absorption and Earth's magnetic field, both in short-term as well as long-term changes in the ionospheric structure (Rama Rao et al. 2006). The GPS, with the development of the associated ground networks, has opened new possibilities in the detection and imaging of these signals. As a by-product of geodetic measurements, the phase and code measurements from GPS stations can be used to calculate the electron density of the ionosphere between the receiver and the satellite, the GPS observation provide an efficient way to estimate the high-precision TEC values with greater spatial and temporal coverage (Mannucci et al. 1993; Langley et al. 2002; Yuan and Ou 2003). In addition, the ionospheric TEC is very sensitive to the variations of the peak electron density in the F2-layer (Trigunait et al. 2004; Liu et al. 2004). Consequently, the GPS TEC is an ideal physical parameter in estimating spatial sizes and temporal dynamics of seismo-ionospheric effects over earthquake preparation zone, and the GPS have been used to detect the ionospheric perturbation associated to earthquake, especially the recent results (Zhao et al. 2008; Liu et al. 2008; Liu et al. 2009; Zhou et al. 2009; Lin et al. 2009; Zhu et al. 2009; Yu et al. 2009; Hsiao et al. 2010; Xiong et al. 2011; Lin 2011; Yao et al. 2012) about the ionospheric disturbance prior to the Wenchuan Ms8.0 earthquake increased the confidence in seeking the earthquake ionospheric precursors once again. On 11 April 2012,an Ms8.6 earthquake struck the west coast of Northern Sumatra, Indonesia, (Geographic lat.02.311°N, Lon. 93.063°E, depth 22.9 km) as a result of strike-slip faulting within the oceanic lithosphere of the Indo-Australia plate. In this paper, we will use the GPS EC measurement including the Global Ionospheric Maps (GIM) of TEC provided by the International GNSS Service (IGS) network and the high temporal and spatial resolution VTEC data derived from the GPS observation from the reference stations of Crustal Movement Observational Network of China to examine the ionospheric variations prior to the earthquake.

2 GPS TEC measurements and method of analysis

To extract TEC from the GPS observation file, the pseudorange measurements on L1 (1.5754 GHz) and L2 (1.2276 GHz) frequencies have been considered. The ionospheric delay can be expressed in terms of the signal carrier frequency as follows:

$$\delta_{ion}(f_c) = \frac{40.3 \times \mathrm{TEC}}{f_c^2} \quad (1)$$

where $\delta_{ion}(f_c)$ is the signal propagation delay at a given carrier frequency.

$$\mathrm{STEC} = \int_0^s N dr = \left(\frac{f_2^2}{f_1^2 - f_2^2} \frac{2 f_1^2}{K} \Delta P_{1,2} \right) \quad (2)$$

where $\Delta P_{1,2}$ is the difference between time delays measured by the L1 and L2, $K = 40.3\ \mathrm{m^3\ s^{-2}}$, f_1 is the frequency of the L1 wave, and f_2 is the second frequency (L2 wave). As we are mainly concerned with variations of TEC, the above approach is satisfactory. This procedure gives the corrected slant TEC (STEC). The STEC measurements made are the sum of the real slant TEC, the GPS satellite differential delay and the receiver differential delay. Except when at the zenith, the GPS satellite transmits the signal to the reference station through the ionosphere at some oblique angle. To remove the effect of the increased path length due to obliqueness, the STEC needs to be multiplied by a slant factor $S(E)$. Therefore, the vertical TEC can be expressed as:

$$\mathrm{VTEC} = \frac{\mathrm{STEC} - [bR + bS]}{S(E)} \quad (3)$$

where, bR and bS are receivers and satellite biases respectively, Generally speaking, the bias of receiver and satellite pair is assumed to be constant in one day. By a least squares procedure, the instrumental biases of all receiver and satellite pairs and the coefficients of the spherical harmonic expansion can be estimated. E is the elevation angle of the satellite in degrees, here we have taken satellite elevation angle greater than 15°. $S(E)$ is the obliquity factor with zenith angle at the ionospheric pierce point (IPP) and VTEC is the vertical TEC at the IPP calculated from the RINEX file and navigation data by using standard coordinate transformation formulae and corrections in satellite orbits. The mapping function $S(E)$ is usually defined as (Mannucci et al. 1993; Langley et al. 2002)

$$S(E) = \frac{1}{(\cos\chi')} = \left\{ 1 - \left(\frac{R_x \cos\chi}{R_x + h_m} \right)^2 \right\}^{-\frac{1}{2}} \quad (4)$$

where R_x is the mean Earth's radius in km, $h_m = 350$ km is the height of the ionospheric shell above the Earth's surface. Using the phase-smoothed pseudo-ranges and the instrumental biases for all receiver and satellite pairs, we can get the real STEC along all ray paths and the corresponding IPP VTEC. Consequently, the VTEC overhead any given point in the observation area can be resolved through inverse distance squared weighting method. The unit of VTEC and STEC is TECu (1 TECu $= 10^{16}$ electron/m^2).

In order to understand the spatial distribution of the anomalous variation of the ionospheric TEC, we firstly employed the global ionosphere map (GIM) of the total electron content (TEC), which is constructed with about 200 of worldwide ground-based receivers of the GPS and routinely published in a 2-h time interval. It covers ±87.5°N latitude and ±180°E longitude ranges with spatial resolutions of 2.5° and 5°, respectively. Therefore, each map consists of 5040 (= 70 × 72) grid points. Similar to a geostationary meteorological satellite hourly observing clouds for the metrological weather, the GIM of TEC can be used to observe signatures of the ionospheric TEC prior to the earthquakes (Zhao et al. 2008; Zhu et al. 2009; Lin et al. 2009; Yao et al. 2012).

The statistical analysis is a frequently used method in data analysis. It has been previously applied in the description of TEC anomalies associated with earthquakes (Zhao et al. 2008; Zhou et al. 2009; Zhu et al. 2009; Lin et al. 2009). After an observation session, the time series of TECs overhead a given point will be obtained, the upper and lower bounds of TEC variations can be determined at different confidence levels, we compute the mean of the previous 10-day TECs and the associated standard deviation σ to construct the upper bound ($\bar{x} + 2\sigma$) and the lower bound ($\bar{x} - 2\sigma$) under the assumption of a normal distribution for the TEC. The range of ($\bar{x} - 2\sigma, \bar{x} + 2\sigma$) forms the normal reference threshold. If the observed TEC in the following day falls out of either the associated lower or upper bound, we declare that a negative or positive anomaly is detected with a confidence level of about 95 % (Zhou et al. 2009; Zhu et al. 2009).

3 Data analysis and Interpretation

A strong earthquake of magnitude 8.6 occurred near the west coast of Northern Sumatra, Indonesia, at 08:38:37 UT on 11 April 2012 (http://earthquake.usgs.gov/). Based on the analytical method mentioned above, we processed and analyzed the GPS TEC data from 20 days before earthquake to the

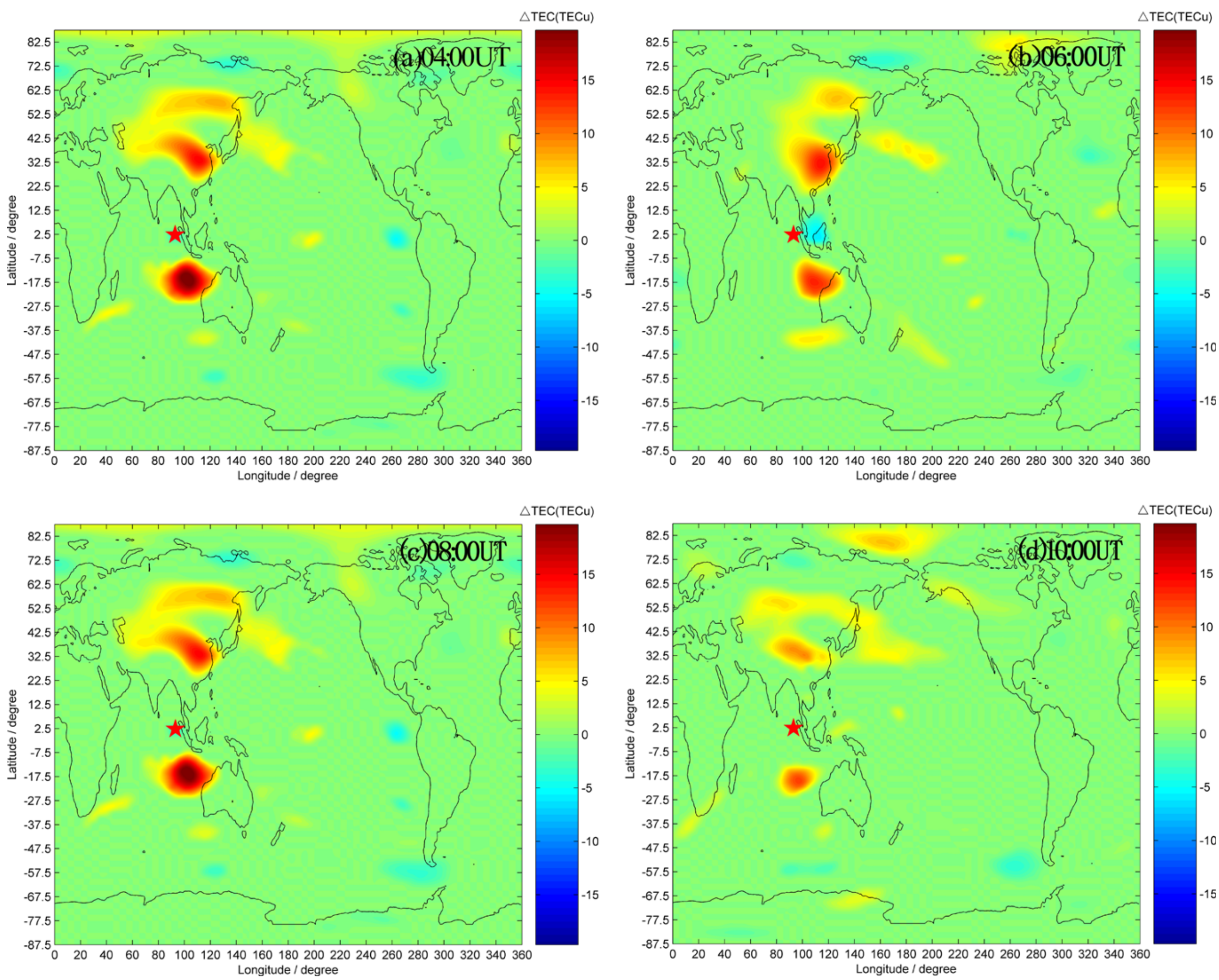


Fig. 1 The global distribution of the ionospheric ΔTEC on 5 April 2012, the sixth day before the earthquake: where the *horizontal axis* represents longitude, *vertical axis* latitude and the *red star* shows the epicenter of the earthquake, Units for the color bar of this image is TECu

day the earthquake occurred, that is from March 21 to April 11, 2012. We computed and obtained the differential two-dimensional TEC (ΔTEC) map at the time of the maximal anomaly, that is 04:00 UT-10:00 UT on the sixth day before the earthquake worldwide (Fig. 1). Figure 1 showed the amplitude-size and spatial coverage of the ΔTEC beyond the upper bound.

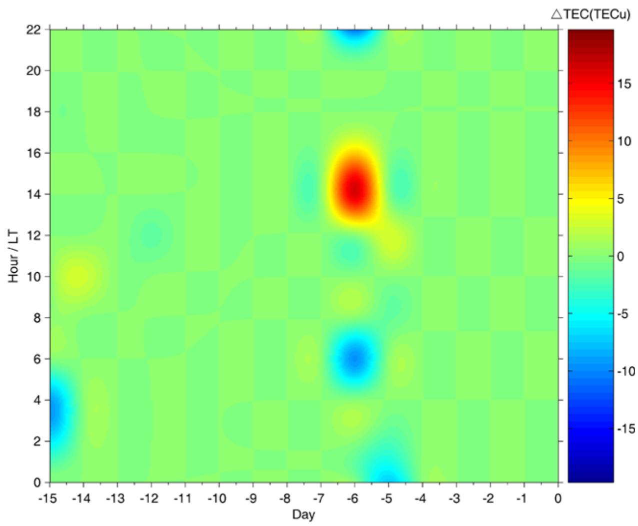
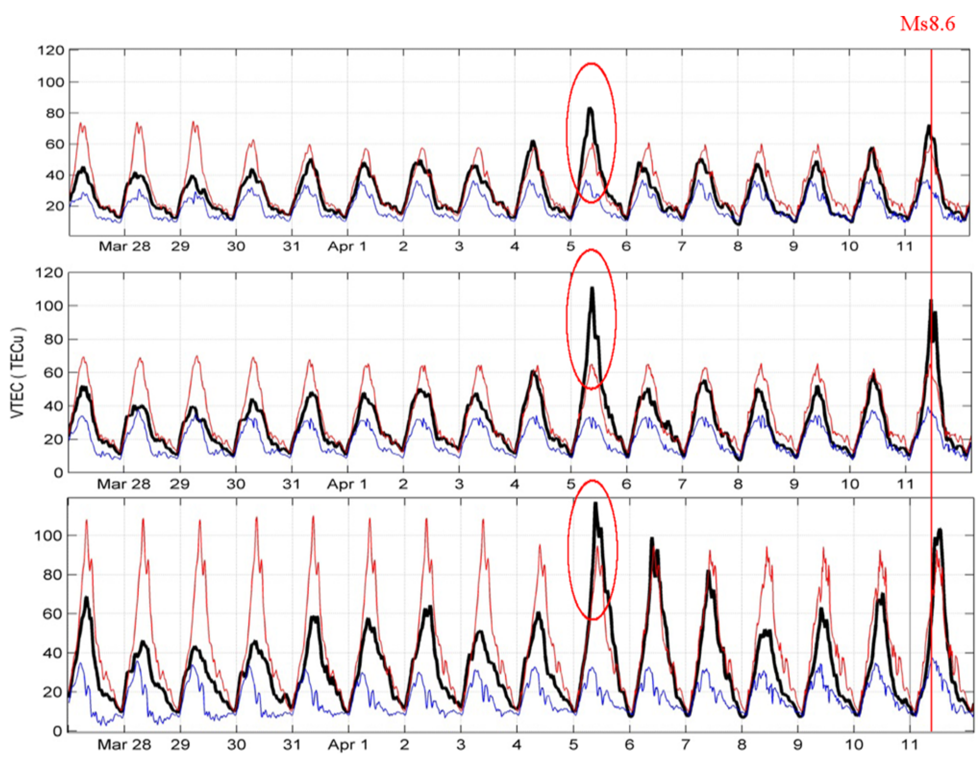


Fig. 2 The distribution of the ionospheric ΔTEC value with time over the study point: the *horizontal axis* represents the time which unit is day, the negative means the day is before the day earthquake occurred and the zero point represents the day earthquake occurred

From Fig. 1 we can clearly see that there is not evident ionospheric TEC disturbance phenomenon in most area except the north and south side of the epicenter, and the obvious feature of the ionospheric TEC disturbance is that the most remarkable positive anomalies lie at the north and south side of the epicenter, and the scope of the ionospheric ΔTEC at 08:00 UT is relatively large (∼15TECu) which large-scale structure is about 40° (80°E–120°E) in longitude and 20° (7.5°S–27.5°S) in latitude. Meanwhile, the ionospheric TEC anomalies also occurred at the magnetic conjugate region of the southern hemisphere which shows good agreement with the characteristics of the hump of TEC anomalies appeared prior to the Wenchuan earthquake (Zhao et al. 2008; Liu et al. 2009; Zhou et al. 2009; Lin et al. 2009; Zhu et al. 2009; Yu et al. 2009).There are also ionospheric TEC anomalies occurred on other days which magnitude and extent is much smaller and there are not clearly ionospheric anomalies at the magnetic conjugate region, so they are not listed here one by one.

In order to identify the temporal characteristic of the ionospheric TEC anomalies more clearly, we choose and pick up one grid point of the anomalous area (32.5°N, 100.0°E). In the same way, we examined the time series of TEC of this point for 15 days before the earthquake, that is from March 28 to April 11. Figure 2 represents the distribution of the ΔTEC value with time over the point, from Fig. 2 we can see some key features of the ionospheric TEC anomalies: (1) the ionospheric variations demonstrated both negative and positive anomalies before

Fig. 3 VTEC time series over the SHAO, WUHN and LUZH station, from March 27 to April 11. The unit of horizontal axis is the day of year, the *red vertical line* denotes the time when the earthquake occurred, the *red line* denote the upper bound and the *blue line* denote low bounds, the *black line* denote the VTEC observation



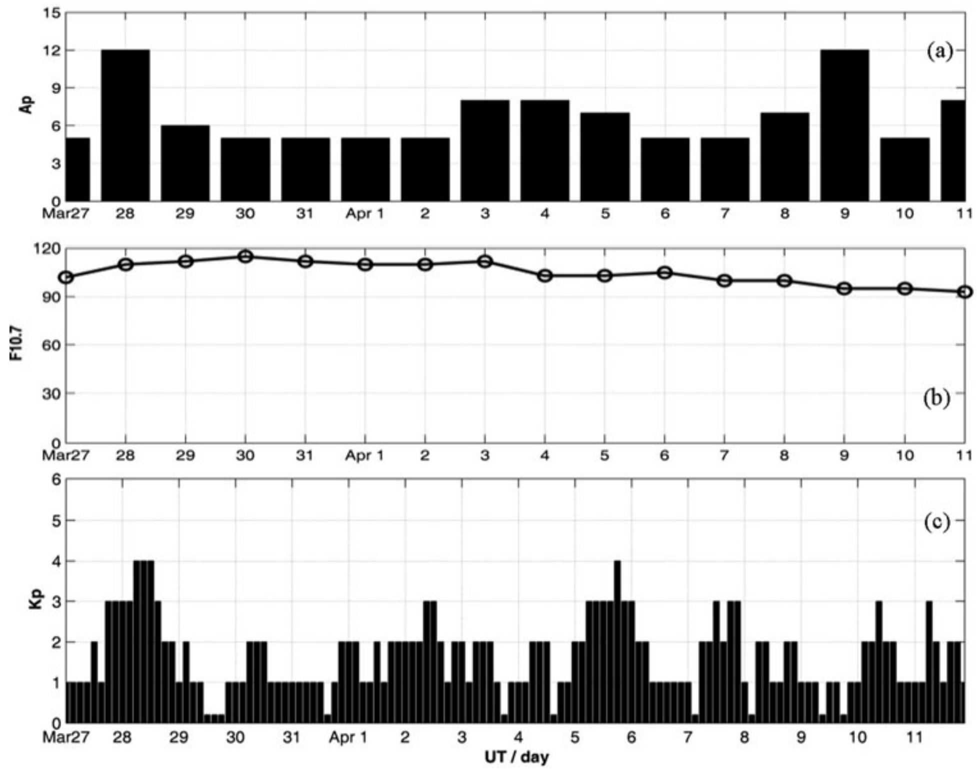


Fig. 4 Time series (from top to bottom) of Ap indices, F10.7 indices, and Kp indices from March 27 to April 11,2012

the earthquake. Negative anomalies first occurred on the 6th day prior to the earthquake, then the positive anomalies, and ended with negative anomalies which last to the 5th day prior to the earthquake, the main form of the anomalous ionospheric TEC are positive anomalies and the maximal relative variability amplitudes on April 5 went beyond the upper bound of ∼15 TECu; (2) The moment when the ionospheric TEC anomalies occurred is mainly on the 5, 6 days prior to the earthquake and the apparent anomalous increase of ionospheric TEC mainly occurred between 13:00 LT and 177:00 LT that is between the afternoon and the evening, and the duration is ∼4 hours, which is similarly consistent with the previous studies (Liu et al. 2009; Zhu et al. 2009).

Using the same processing method mentioned above, we computed the time series of VTECs with a 30-minute resolution from March 27 to April 11 over the SHAO, WUHN and LUZH GPS station which is nearer to the epicenter in China. Figure 3 illustrate the variation of ionospheric VTEC. As can be seen from Fig. 3 that the apparent anomalous increase of ionospheric VTEC almost occurred over the three station 5–7 days before the earthquake, especially the anomalies occurred on the April 5 that is the 6th day before the earthquake is particularly significant, this is basically consistent with the abnormal two-dimensional distribution of TEC on Fig. 2. In other words, with respect to abnormal distribution of two-dimensional GPS TEC, the distribution of VTEC over the three stations are basically the same on the time and the form of the anomalies comparing with the two-dimensional image of the ionospheric TEC. The VTEC over three station increased synchronously increased on the day of earthquake occurred, however, from the two-dimensional image of the GPS TEC, we also found that the location of the abnormal disturbance form was very irregular and far away from the epicenter, so based on previous experience, it can be concluded that the anomalous disturbance on that day may have something to do with space weather.

There are many potential causes of ionospheric TEC anomalies besides the earthquake from lower atmospheric forcing.The most well-known causes are solar flare activity and geomagnetic storms. Figure 4 shows the variation of the geomagnetic Ap indices, F10.7 indices and Kp indices from March 27 to April 11, 2012. As is shown from Fig. 4 that the F10.7 indices are relatively stable in the 15 days before the earthquake which means the solar activity is low overall, and it is in general geomagnetically quiet prior to the earthquake in April except the 3-hours magnetic disturbance with the Kp indices is equal to 4 for ∼3 hours on April 5. Based on previous studies, the disturbances of the ionospheric plasma parameters generated by a geomagnetic storm usually has a global impact, in other words, the anomalies will be observed all over the world. In a word, the solar activity and geomagnetic conditions were relatively quiet during the period under investigation. So it is not hard to conclude that the possible cause of enhancement of GPS TEC occurred on April 5 may be related to the earthquake.

4 Discussion and conclusion

Using the GPS TEC measurements, we detected the ionospheric TEC negative and positive anomalies on the 6th day prior to the Sumatra earthquake by the method of the statistical analysis. After eliminating ionospheric anomalies that may be caused by solar activities or magnetic storms, and considering the spatial and temporal characteristics of the distribution of the anomalies in GPS TEC, we believed that the observed positive TEC anomalies and the structure of the anomalies in the magnetically conjugated region on the 6th day are possibly caused by Sumatra earthquake.In other word,the observed obvious TEC anomalies may be considered as the short-term precursors of this earthquake.

In this paper, the anomalous disturbances of TEC were different from the previous studies, the anomalous decrement then increment and at last the increment of TEC were observed in tandem over the same observation area prior to this earthquake. This phenomenon that both the negative and positive anomalies of TEC were observed in order a few days before an earthquake has been rarely reported up to now. This kind of seismo-ionospheric effect need be further studied. As a case, this paper is only focused on demonstrating the ionospheric variability characters prior to the earthquake. We didn't discuss the physical mechanism of seismo-ionospheric effects. The detailed aspects of the physical mechanism have been studied in many studies (Freund, 2002, 2003; Sorokin et al. 2001; Varotsos et al. 2001; Hayakawa and Molchanov 2002; Pulinets and Boyarchuk 2004; Takeuchi et al. 2006).

This study shows again that the ionospheric perturbations do exist a few days before strong earthquakes. With the development of GNSS occultation technology and the GNSS assimilation techniques, the level of detection of the ionosphere will be further improved. By using the ground technology and the satellite technology jointly, the possibility of obtaining high temporal and spatial resolution three-dimensional ionospheric image is becoming a reality, which will provides unprecedented detail of ionospheric anomalies prior to the earthquake. In the near future,we are confident that the GPS TEC will be very valuable in understanding of the mechanism of seismo-ionospheric coupling.

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