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Temporal and spatial characteristics of VTEC anomalies before Wenchuan *Ms*8.0 earthquake

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Abstract: GPS and the COD VTEC data were studied in search of ionospheric VTEC changes in space and time that might be associated with the Wenchuan *Ms*8.0 earthquake on 12 May, 2008. The result shows several significant anomalous decreases at 12:00 UT – 16:00 UT on April 29 and an anomalously increase at 14:00 UT – 18:00 UT on May 9. The anomalies had two humps, that were located on both sides of the geomagnetic equator and had a tendency of drifting towards the equator. Since the observed anomalies cannot be attributed to any other causes and since they occurred close to the time of the earthquake, we consider them to be possibly premonitory to the earthquake.

Key wards: GPS; TEC(Total Electron Content); ionospheric anomaly; Wenchuan *Ms*8.0 earthquake; precurgor

1 Introduction

Various geophysical and geochemical methods have been studies for application to earthquake prediction[1-3]. Recently, the search of ionospheric anomalies before strong earthquakes together with the study of related mechanisms has become an active field of research[4-25].

Earthquake-related ionospheric disturbances was first studied for the 1964 great Alaska earthquake; the results showed some possible anomalous changes associated with the earthquake[4-5]. Since then, similar studies have been carried out in more than 20 countries and regions all over the world. The results generally confirm that ionospheric anomalies do exist before strong earthquakes[6-23].

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An *Ms*8.0 earthquake occurred at 14:28 (06:28 UT) on 12 May, 2008 in Wenchuan (31.0°N, 103.4°E), China, at a depth of 14 km (Fig. 1(a)). Since its occurrence, many researchers have used ionosonde and GPS TEC data to study ionosphere variations before this earthquake[20-23]. In this paper, we report a study of temporal and spatial ionospheric VTEC variations about the time of the earthquake, using the GPS data from the Crustal Movement Observational Network of China and the COD VTEC data.

2 Observation and methodology

The ionosphere, which is about 60 to 1000 km above the Earth's surface, is usually represented by a thin spherical layer in the GPS TEC studies. In this paper, we take a height of 350 km for this layer, which is in the middle of the height range of highest TEC value (300 – 400 km). The ionosphere is a dispersive medium and the slant TEC (STEC) can be derived from GPS data. Then the STEC values can be converted to VTEC

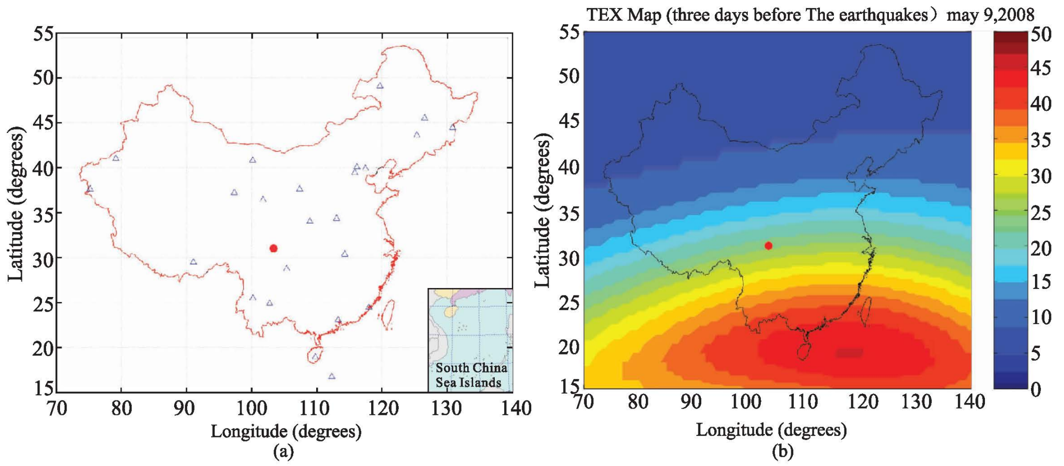

Figure 1 (a) Locations of GPS station and (b) the distribution of VTEC over the epicenter. (The triangles show the GPS station and the red dot shows the epicenter of the Wenchuan *M*s8.0 earthquake.)

by spherical harmonics mapping function at the ionospheric pierce point (see reference [24] for the specific calculation). Both VTEC and STEC are in TECu unit (1 TECu = 1016 el/m^2). We examined GPS data from the 24 stations of Crustal Movement Observational Network of China (Fig. 1(a)) during the time interval of 12 April to 22 May. The sampling rate is 30 seconds, and the cut-off angle is 15°. The calculated VTEC values are evenly distributed over each grid (1° × 1°), the scope is 70°E – 140°E in longitude and 15°N – 55°N in latitude. Based on this method, we obtained VTEC maps over the epicenter area during the period from 12 April to 22 May. Fig. 1 (b) shows, as an example, the VTEC distribution over the epicenter at 08:00 UT on May 9.

We have obtained the time series of VTEC values over a given point after each observation session. In order to identify the ionospheric disturbances effectively, we have adopted the method described in paper[25]. We defined the upper and lower bounds of normal background variation by computing the mean $\overline{X}_K^{ij}$ and the associated standard deviation σ_K^{ij}, where $\overline{X}_K^{ij}$、σ_K^{ij} may be written as

$$\begin{cases} \overline{X}_K^{ij} = \dfrac{1}{N}\sum_{L=K+1}^{K+N} X_L^{ij}, K=0,1\cdots \\ \sigma_K^{ij} = \sqrt{\dfrac{1}{N}\sum_{L=K+1}^{K+N}(X_L^{ij}-\overline{X}_K^{ij})^2}, K=0,1,\cdots \end{cases} \quad (1)$$

If the observed VTEC value examined in the following day falls outside of the bounds, we consider it an anomaly. When drawing the VTEC anomaly map, we use the following mapping function

$$\begin{cases} F_K^{ij}=0, |X_{N+1+K}^{ij}-\overline{X}_K^{ij}| \leqslant \alpha\sigma_K^{ij}, i=1,\cdots,m, \\ \quad j=1,\cdots,n \\ F_K^{ij}=X_{N+1+K}^{ij}-(\overline{X}_K^{ij}-\alpha\sigma_K^{ij}) \\ F_K^{ij}=X_{N+1+K}^{ij}-\overline{X}_K^{ij} > \alpha\sigma_K^{ij}, K=0,1,\cdots \\ F_K^{ij}=X_{N+1+K}^{ij}-(\overline{X}_K^{ij}-\alpha\sigma_K^{ij}) \\ F_K^{ij}=X_{N+1+K}^{ij}-\overline{X}_K^{ij} < -\alpha\sigma_K^{ij}, K=0,1,\cdots \end{cases} \quad (2)$$

Where $m \times n$ is the number of the VTEC grid points; K, the serial number in time of some grid point, $\overline{X}_K^{ij}$, the mean value of the VTEC at grid (i,j) in the continuous N days; and σ_K^{ij}, the standard deviation. N is taken as 10; and α, 2.

3 Data analysis and interpretation

We computed the VTEC time series from 20 days before to 10 days after the earthquake, that is from April

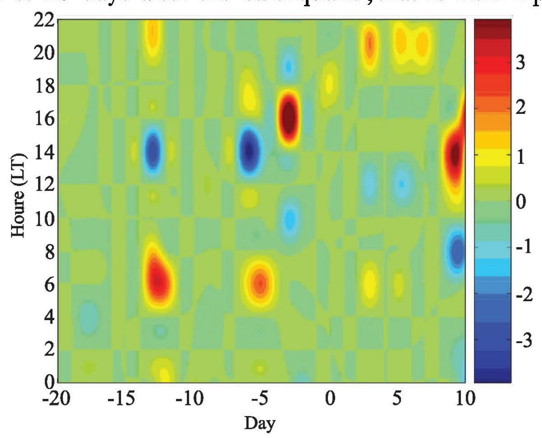

Figure 2 VTEC time series over the epicenter from April 22 to May 22

22 to May 22, over the epicenter of Wenchuan earthquake(Fig. 2, where the time axis is in units of days before(−)and after(+)the earthquake). As shown in Fig. 2, the ionospheric VTEC over the epicenter was relatively stable(within the bounds) most of the time, except 13 days(April 29) and 6 days(May 6) before earthquake, when it abnormally decreased(colored in blue in the figure), and 9 days (May 21) after the earthquake, when it abnormally increased(red). This result is similar to those reported in the literature[21−23]. The specific occurrence time of the anomalies is different on different days: Decreases at 12:00 − 16:00UT 13 days and 6 days before the earthquake but increase at 04:00-08:00UT 13 days and 6 days before earthquake and at 14:00-18:00UT three days before the earthquake. This shows that the time when the VTEC anomalies appear is partial.

By using the same method, we obtained the two-dimensional distribution of △*VTEC* over China. Fig. 3 shows the distribution of △*VTEC* at 08:00 UT and at 10:00 UT three days(May 9) before the earthquake. From Fig. 3 we can see that the *VTEC* value around the epicenter evidently increased and the maximum amplitude is about 5 TECu. The most distinctive feature of the positive anomalies is that they have a large − scale structure about 40°(80° E − 120°E) in longitude and 15°(19° N − 34° N) in latitude. There is anomalous hump around the epicenter as shown in Fig. 3(a) and 3 (b). But the position of the anomalous hump was changing with time, being located to the southeast of the epicenter at 08:00 UT and to the south of the epicenter at 10:00UT.

In order to see the full extent of the spatial distribution of the VTEC anomalies at different times more clearly, we used the VTEC data from COD data center, and plotted the two-dimensional △*VTEC* maps over all the world. The COD VTEC maps were generated every two hours, with a resolution of 5° in longitude and 2.5° in latitude, and have been used by many workers to study the large-scale structures of the ionospheric VTEC anomalies[20,23]. As shown in Fig. 4, the ionospheric VTEC over the epicenter is usually quite stable in time and space, except a significant decrease on May 6 and an increase on May 9 around the epicenter. The decrease over the epicenter was accompanied by another decrease located at the magnetic conjugate region of the southern hemisphere, and the two negative "humps" were both moving toward the equator. Similar feature of positive humps is true for the anomaly on May 9. This feature is consistent with the description of previous studies[21−23]: As shown in Fig. 4, the anomaly did not stay over the epicenter but moves towards the equator for a distance about equal to the range between the local geographic latitude and geomagnetic latitude; the maximum distance between the humps is about 11°. This shows that the position where the VTEC anomalies appear is also partial.

Ionospheric VTEC[26−27] can be affected by many environmental variables, such as geomagnetic activity and space weather. Thus we have to check the variability of the geomagnetic *K*p index before the earthquake. Fig. 5 shows the variation of the geomagnetic *K*p index from April 24 to May 24 2008. From this figure we can see that the geomagnetic *K*p index value is close to 4, except

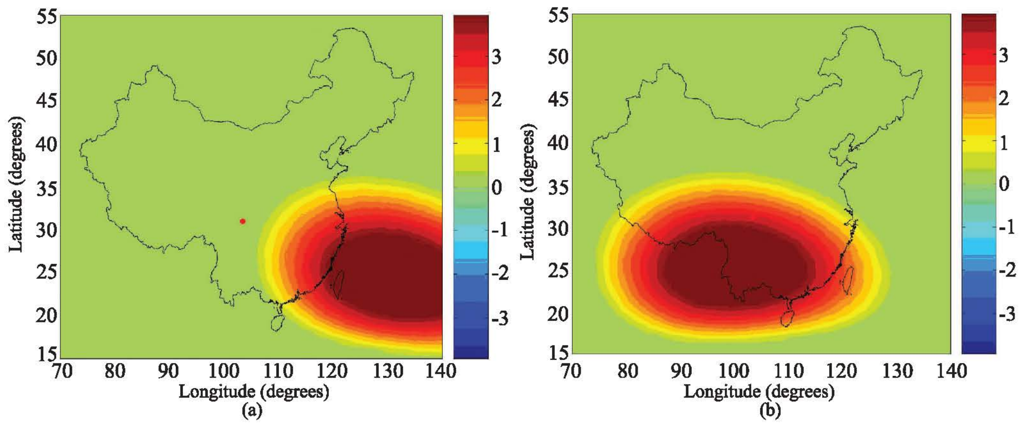

Figure 3 The distribution of △*VTEC* prior to earthquake((a) at 08:00 UT on May 9; (b) at 10:00 UT on May 9. Red dot represents the epicenter)

on May 1,2,6 and 21, when it is larger than 4. Thus, there is a possibility that the decrease on April 29, May 6 and May 21 may be associated with geomagnetic activity. However, during the interval between May 6 and May 21, the geomagnetic activity was quiet and the space weather did not show any large-scale abnormal fluctuation. Therefore, we exclude all the space environmental factors and consider the abnormal ionospheric VTEC increase on May 9, or 3 days before the earthquake, to be related to the earthquake.

4 Discussion and conclusion

By using ground-based GPS VTEC observation and the COD VTEC data, we detected several transient ionospheric anomalies 13 days (April 29), 6 days (May 6) and 3 days (May 9) before the Wenchuan earthquake in the region over the epicenter. The anomalous decrease occurred at about 12:00 UT – 16:00 UT on April 29 and May 6, while the anomalous increase at about 14:00 UT – 18:00 UT on May 9. There were two anomalous VTEC humps at both sides of the equator, one over the epicenter and the other in the magnetic conjugate region of the southern hemisphere; these humps trend to move towards the equator. We have excluded the impact of solar and geomagnetic activities, and concludes that the abnormal increase on May 9 is probably precursory to the earthquake. This observation shows that

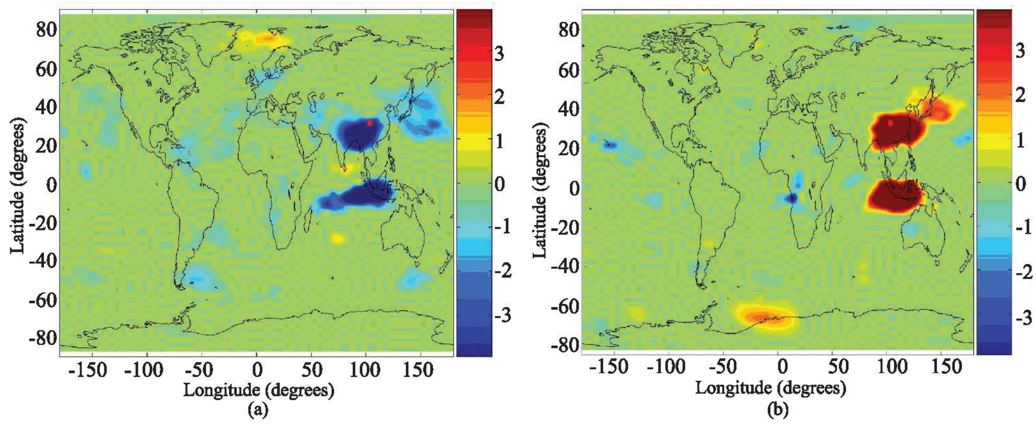

Figure 4 Global distribution of $\Delta VTEC$ before the earthquake ((a) at 08:00 UT on May 6; (b) at 10:00 UT on May 9. Red dot represents epicenter)

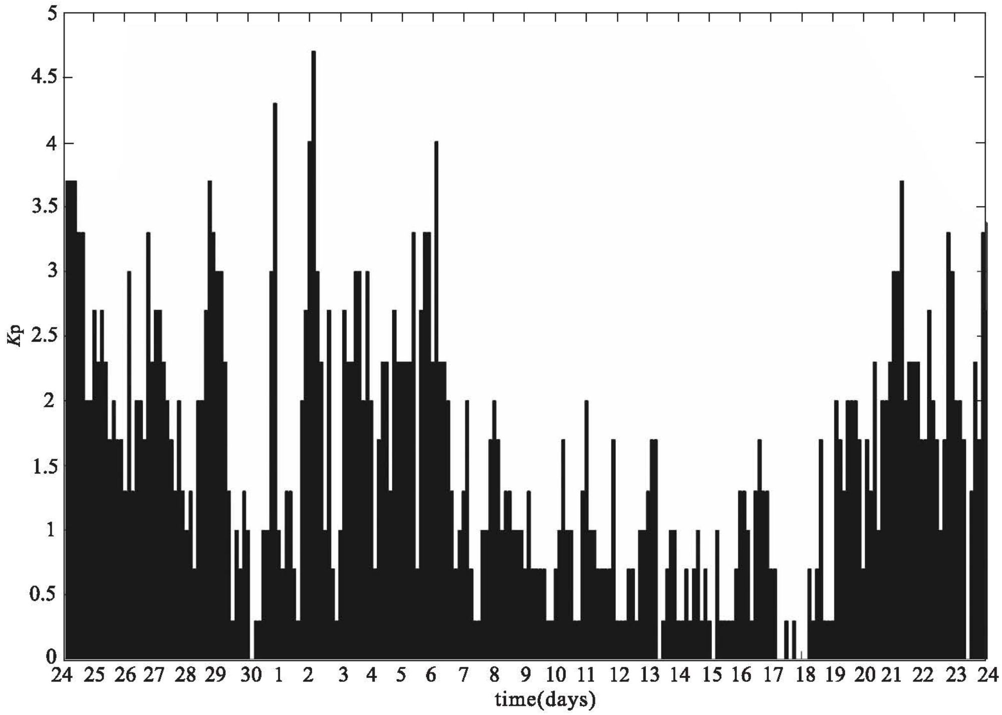

Figure 5 Variation of the geomagnetic Kp index from April 24 to May 24, 2008 (UT)

the seismo-ionospheric effect is indeed detectable[8-12].

Seismo-ionospheric coupling is a very complex physical and chemical processes[28-29]. Despite many attempted studies, there is still a lack of reasonable model. Actually, we do not even have any convincing evidence for these anomalies to be directly caused by the corresponding earthquakes. In searching ionospheric VTEC anomalies, we found that the detection method used plays a critical role. To better understand the seismic-ionosphere relation and to objectively identify earthquake-related ionospheric anomalies among background variations, caused by man and other space environmental variables, will require further in-depth studies.

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