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A statistical analysis of ionospheric anomalies before 736 *M*6.0+ earthquakes during 2002–2010

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[1] This paper presents a statistical study of the pre-earthquake ionospheric anomaly by using the total electron content (TEC) data from the global ionosphere map. A total of 736 $M \geq 6.0$ earthquakes in the global area during 2002–2010 are selected. The anomaly day is first defined. Then the occurrence rates of abnormal days for both the days within 1–21 days prior to the earthquakes (P_E) and the background days (P_N) are calculated. The results show that the values of P_E depend on the earthquake magnitude, the earthquake source depth, and the number of days prior to the earthquake. The P_E is larger for earthquakes with greater magnitude and lower depth and for days closer to the earthquakes. The results also show that the occurrence rate of anomaly within several days before the earthquakes is overall larger than that during the background days, especially for the large-magnitude and low-depth earthquakes. These results indicate that the anomalous behavior of TEC within just a few days before the earthquakes is related with the forthcoming earthquakes with high probability.

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1. Introduction

[2] The study of the ionosphere state prior to the occurrence of large earthquakes has attracted geophysicists' attention for many years and it has also been one of the most important tasks of modern geophysics and radio physics due to the massive destruction of the great earthquakes such as the recent earthquakes including the 2008/5/12 Wenchuan, the 2010/1/12 Haiti, the 2010/2/27 Chile and the 2010/4/14 Yushu earthquake (http://earthquake.usgs.gov/earthquakes/world/world_deaths.php). Thus the ionospheric anomalies before the earthquake near the epicenter are studied widely by many geophysicists and a number of papers have reported on deviations in the daily values of the critical frequency of the F_2 layer (f_oF_2) and/or total electron content (TEC) in the vicinity of an epicenter within some days prior to the main shock [e.g., *Pulinets*, 1998; *Pulinets et al.*, 2003, 2007; *Zhao et al.*, 2008, 2010; *Liu et al.*, 2001, 2004, 2006a, 2009; *Zakharenkova et al.*, 2007].

[3] There are many reports about the pre-earthquake ionospheric anomalies (PEIA) for some special earthquake events from the 1970s, while it is not sufficient to draw the conclusion that these anomalies are really related to the incoming earthquake because the ionospheric F_2 layer has significant day-to-day variation [*Forbes et al.*, 2000; *Rishbeth and Mendillo*, 2001; *Mendillo et al.*, 2002] and it might link with the lower atmosphere. Thus there are also still the debates or doubts about pre-earthquake ionospheric anomaly [e.g., *Kamogawa*, 2006; *Rishbeth*, 2006a, 2006b]. To obtain the more convincible results, the statistical analysis of the ionospheric change (f_oF_2 or TEC) before earthquakes is effective and also is needed. *Liu et al.* [2006b] statistically investigated the relationship between variations of f_oF_2 and 184 earthquakes with magnitude $M \geq 5.0$ during 1994–1999 in the Taiwan area and found the numbers of earthquakes with PEIA increase with the earthquake magnitude but decrease with the distance from the epicenter to the ionosonde station. These results indicate that the PEIA is energy related.

[4] In this study, we carry out another statistical analysis by investigating the TEC anomalies some days before more than 700 earthquakes with magnitude $M \geq 6.0$ during 2002–2010 in the Global area. The TEC anomalies on the days far away from the earthquake day are also calculated to be the background variations and are compared with those before the earthquakes.

2. Data Source

[5] The worldwide earthquakes with $M \geq 6.0$ during the years 2002–2010 are selected for the analysis in this study. The information of earthquakes is obtained from the Website of USGS (http://earthquake.usgs.gov/earthquakes/eqarchives/epic/). To avoid the interference of the magnetic storm, the earthquakes occurring within 4 days after the magnetic storm ($Dst \leq -40$ nT or the decrease amplitude of Dst index within a day larger than 40 nT) are excluded. In addition, to avoid possible confounded effects from adjacent earthquakes, the earthquakes occurring at the similar location but with the short interval (<15 days) from the previous

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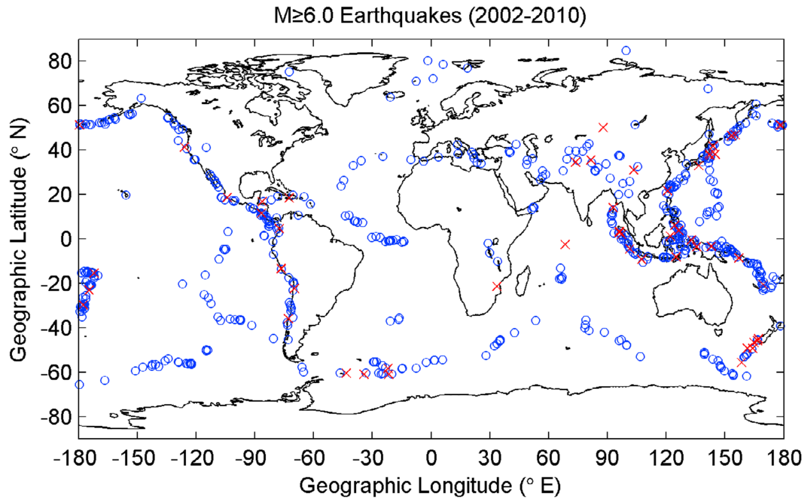

Figure 1. Locations of the $M \geq 6.0$ earthquakes. The circles denote the earthquakes with $M < 7.0$, and the crosses denote the earthquakes with $M \geq 7.0$.

ones are also excluded. Finally, total 736 $M \geq 6.0$ earthquakes during 2002–2010 are selected. Figure 1 illustrates the location of the earthquakes. Then we classified these earthquakes by magnitudes (6.0–7.1) and depths (≤20, 30, and 40 km) as listed in Table 1.

[6] The data of total electron content (TEC) are used to investigate the ionospheric variations before earthquakes and during background days. The global ionosphere map (GIM) (ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex) of the TEC constructed with more than 200 worldwide ground-based GPS receivers is routinely published at Center of Orbit Determination in Europe (CODE) in a 2 h time interval. The vertical total electron content (VTEC) is modeled in a solar-geomagnetic reference frame using a spherical harmonics expansion. Piecewise linear functions are used for representation in the time domain. Then we calculated the more dense data with 25 time points from 00 UT to 24 UT with an hour interval by the linear interpolation. The GIM covers ±87.5° latitude and ±180° longitude ranges with spatial resolutions of 2.5° and 5°, respectively. Therefore, each map consists of 5183 (= 71 × 73) grid points. We selected the nearest grid to the epicenter as the earthquake associated point and calculated its TEC variation. Based on *Dobrovolsky et al.* [1979], the earthquake preparation area on the ground can be estimated by $Ra = 10^{0.43M}$, where Ra is the radius of the preparation zone and M is the earthquake magnitude. For example, for the M6.0, M6.5, and M7.0 earthquakes, the values of Ra approximately equal 380, 623, and 1050 km, respectively, which correspond to 3.5 degree, 6 degree, 10 degree. Note that, this radius is the value on the ground and the disturbed region in the ionosphere might be larger. Thus the resolution of 2.5 ° and 5° (latitude and longitude) of GIM TEC is enough to record the possible ionospheric disturbance at the nearest grid to the epicenter.

3. Statistical Method

[7] To detect abnormal signals of the GPS TEC variations, a quartile-based process is performed. At each time point on any day, we compute the median (m) and standard deviation σ for the GPS TEC of 1–15 days before the day. Then according to the classical method, the upper boundary (UB) is set as m + σ and the lower boundary (LB) is set as m–σ. If the TEC value at this time point is larger than the upper bound UB or smaller than the value of LB, this time point is defined as an abnormal point.

[8] If there are more than six successive abnormal points (corresponding to 6 h) in a day and the largest deviation from the median is larger than a certain percentage R (such as 60%, 80%, or 100%), this day would be considered as an abnormal day with the abnormal level R. For each earthquake, each day (1–21 days) before the earthquake can be checked to be an abnormal day with R > 60%, or >80%, or even >100%, or to be not an abnormal day. Then we can calculate the number of abnormal days with different deviation level R within the T days before the earthquake, which is noted as $N_{R,T}$.

[9] To calculate the occurrence rate of abnormal day for the earthquakes satisfied some certain conditions (for example magnitude $M \geq 6.5$ and depth $D \leq 20$ km), we need to find these earthquakes and then calculate the occurrence rate of abnormal day for each earthquake. First, we calculate the value of $N_{R,T}$ for each earthquake. To avoid the interference of the magnetic disturbed condition, the days related with the magnetic disturbed activity are excluded. If a

Table 1. Earthquake Numbers According to the Classification of Magnitudes and Depths

	Depth ≤ 20	Depth ≤ 30	Depth ≤ 40
$M \geq 6.0$	490	602	736
$M \geq 6.1$	372	468	573
$M \geq 6.2$	293	369	454
$M \geq 6.3$	226	292	362
$M \geq 6.4$	167	221	273
$M \geq 6.5$	132	177	221
$M \geq 6.6$	103	139	176
$M \geq 6.7$	70	99	130
$M \geq 6.8$	57	78	104
$M \geq 6.9$	43	60	79
$M \geq 7.0$	36	48	66
$M \geq 7.1$	29	39	53

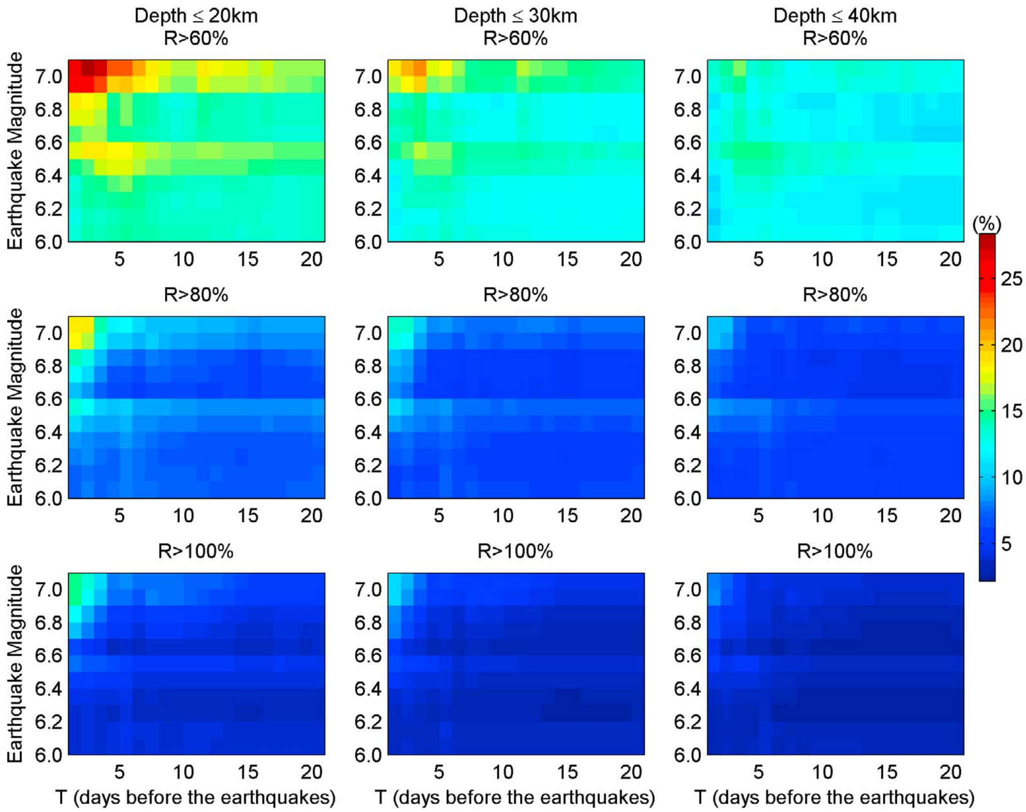

Figure 2. Occurrence rate of anomalies of R > 60%, 80%, and 100% within T days before earthquakes (P_E) of depth ≤ 20, 30, and 40 km, respectively.

magnetic disturbed day with $Dst < -40$ nT (or the decrease of Dst index within a day larger than 40 nT) occurred, this disturbed day and following 3 days are excluded. The number of these days is noted as ΔS. So the number of total days calculated are $T - \Delta S$. Thus the occurrence rate of abnormal day for the nth earthquake (P_{En}) can be calculated as the ratio of the number of the abnormal days to the total quiet days: $N^n_{R,\ T} / (T - \Delta S_n)$.

[10] If the number of these earthquakes is K (for example, $K = 132$ for $M \geq 6.5$ and $D \leq 20$ km, as shown in Table 1), Then the occurrence rate of abnormal day of this kind of earthquake (P_E) is defined as the mean of the P_{En}. That is,

$$P_E = \frac{1}{K}\sum_{n=1}^{K}\frac{N^n_{R,T}}{T - \Delta S_n} \times 100\%. \quad (1)$$

[11] To compare the ionosphere behavior in several days before the earthquakes to that during background days, the occurrence rate of abnormal day during background days is also calculated. For each earthquake, we selected the 61–300 days before the earthquake as the background days. Note that, there may be other earthquakes with $M \geq 6.0$ at the adjacent place during these background days. If another earthquake with $M \geq 6.0$ occurred at the adjacent place (within 5 degree from the epicenter) during the background days, the 15 days before and after this earthquake are excluded. In addition, the magnetic disturbed days are also excluded. If a magnetic disturbed day with $Dst < -40$ nT (or the decrease of Dst index within a day larger than 40 nT) occurred, this disturbed day and following 3 days are excluded. The number of these disturbed days and the days related to the other earthquakes is noted as ΔW. Thus the number of total background days is $K \times 240 - \Delta W$. For each earthquake, the number of the abnormal days with the abnormal level R during the 61–300 days before the earthquake can be calculated, and it is noted as N_R. Then the occurrence rate of abnormal day during background days, P_N, can be calculated as follows:

$$P_N = \frac{\sum_{n=1}^{K} N^n_R}{K \times 240 - \Delta W} \times 100\%. \quad (2)$$

4. Results and Discussion

[12] According to the method described above, we calculated the occurrence rate of abnormal days for different magnitude and different depth earthquakes. Figure 2 shows the occurrence rate of the abnormal days with R > 60%, 80%, and 100% within T days before different magnitude earthquakes with the depth $D \leq 20$, ≤ 30, and ≤ 40 km, respectively. From Figure 2, one can find that for the earthquakes of depth ≤ 20 km, there is the larger occurrence rate of anomalies for the larger-magnitude earthquakes. For example, the left upper panel (R > 60%) shows that the largest value of P_E increases from ~13% for the earthquakes of $M \geq 6.0$ to ~27% for the earthquakes of $M \geq 7.0$. Figure 2

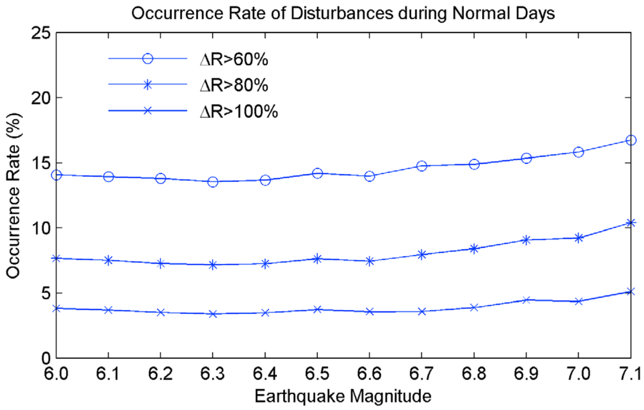

Figure 3. Occurrence rate of anomalies of $R > 60\%$, 80%, and 100% during background days (P_N).

also shows that the occurrence rate of anomalies decreases with the value of T increasing. For example, as for the $M \geq 7.0$ earthquakes, the P_E ($R > 60\%$) decreases from ~27% within 1 day to ~16% within 20 days; the P_E ($R > 80\%$) decreases from ~19% within 1 day to ~10% within 20 days; the P_E ($R > 100\%$) decreases from ~16% within 1 day to ~7% within 20 days. In addition, the statistical results show that the occurrence rate of abnormal increase is much higher than that of abnormal decrease. For example, about 30% of the abnormal days is due to below lower boundary and 70% is due to excess upper boundary for $R > 60\%$ and $D \leq 20$ km.

[13] From Figure 2, one can also see that the value of P_E decreases gradually when the earthquakes with the deeper depth are involved in the statistic. For example, for the anomaly of $R > 60\%$, the largest value of P_E decreases from ~27% of depth ≤ 20 km to ~16% of depth ≤ 40 km; for the anomaly of $R > 100\%$, it decreases from ~16% of depth ≤ 20 km to ~8% of depth ≤ 40 km. These results show that the disturbances before the earthquakes might be related to the earthquake source depth, with the occurrence rate of anomalies decreasing with depth. In addition, we also calculated the TEC disturbances according to latitude classification, and the results do not show clear difference between different latitude regions. In this study, there are 217 earthquakes in the low-latitude and equatorial anomaly region (geomagnetic latitude lower than 15 degrees) and 519 earthquakes in the other regions.

[14] To further show what extent are the ionospheric anomalies before the earthquakes different from the day-to-day variation, the occurrence rate of abnormal day during background days (P_N) is calculated and the values of P_N for the earthquakes of depth ≤ 20 km are plotted in Figure 3. Figure 3 shows that the value of P_N is about 14~16% for $R > 60\%$, 7~10% for $R > 80\%$, and 3~5% for $R > 100\%$. The result also shows that the value of P_N seems to increase very slightly with the earthquake magnitude increasing (beginning from M6.6).

[15] Figure 4 shows the ratio of the occurrence rate for the earthquakes of depth ≤ 20 km (P_E) to the occurrence rate during corresponding background days (P_N), P_E/P_N. The results show that almost all of the values of P_E/P_N are larger than 1.0, which means the occurrence rates of anomalies within several days before the earthquakes are indeed greater than that during the background days far away from the earthquakes. Same as the distribution of P_E, the value of P_E/P_N decreases with the days further from the earthquakes and increases with the earthquake magnitude increasing. The largest value of P_E/P_N reaches ~1.8, 2.3, and 3.6 for $R > 60\%$, 80%, and 100%, respectively. These so large differences of the occurrence rate of anomaly between the days prior to earthquakes and the background days strongly indicate again that the anomalous behavior of TEC within just a few days before the earthquakes is related with the forthcoming earthquakes with high probability.

5. Summary and Conclusion

[16] In this study, more than 700 earthquakes of $M \geq 6.0$ during 2002–2010 are selected to do the statistical analysis on the pre-earthquake ionospheric anomalies by using the TEC data from GIM. The anomaly day is defined as described in section 3. Then the occurrence rate of anomaly day within a few days (from 1 to 21) prior to the earthquakes is calculated. To compare the ionosphere behavior before the earthquakes to that during background days and show what extent are the ionospheric anomalies before the earthquakes different from the day-to-day variation, the occurrence rate of abnormal day during background days is also calculated.

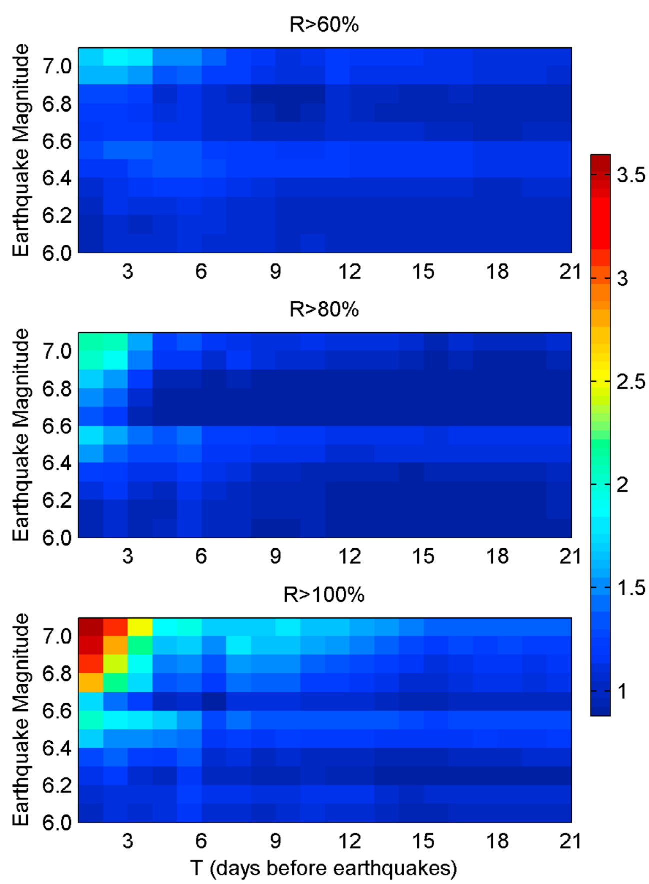

Figure 4. The ratio of the occurrence rate related with the earthquakes of depth ≤ 20 km (P_E) to the occurrence rate during background days (P_N), P_E/P_N.

[17] The statistical results show that there is the larger occurrence rate of anomaly for those earthquakes with larger magnitude and lower depth. In addition, the occurrence rate of anomaly decreases with the day further from occurrence of the earthquakes. That is, there is the larger occurrence of anomaly in the closer days to the occurrence of the earthquakes. The comparing of occurrence rate of anomaly between the days prior to the earthquakes and the background days far away from occurrence of the earthquakes shows that the occurrence rate of anomaly is overall larger within several days before the earthquakes than during the background days, especial for the earthquakes of $M \geq 7.0$ and depth ≤ 20 km. These results indicate that there are likely some ionospheric anomalies related with the energy released before the main shock of some earthquakes.

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