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Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008 M_w7.9 Wenchuan earthquake

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[1] The global ionospheric map (GIM) is used to observe variations in the total electron content (TEC) of the global positioning system (GPS) associated with 35 $M \geq 6.0$ earthquakes that occurred in China during the 10-year period of 1 May 1998 to 30 April 2008. The statistical result indicates that the GPS TEC above the epicenter often pronouncedly decreases on day 3–5 before 17 $M \geq 6.3$ earthquakes. The GPS TEC of the GIM and electron density profiles probed by six microsatellites of FORMOSAT3/COSMIC (F3/C) are further employed to simultaneously observe seismoionospheric anomalies during an M_w7.9 earthquake near Wenchuan, China, on 12 May 2008. It is found that GPS TEC above the forthcoming epicenter anomalously decreases in the afternoon period of day 6–4 and in the late evening period of day 3 before the earthquake, but enhances in the afternoon of day 3 before the earthquake. The spatial distributions of the anomalous and extreme reductions and enhancements indicate that the earthquake preparation area is about 1650 km and 2850 km from the epicenter in the latitudinal and longitudinal directions, respectively. The F3/C results further show that the ionospheric F_2 peak electron density, N_mF_2, and height, h_mF_2, significantly decreases approximately 40% and descends about 50–80 km, respectively, when the GPS TEC anomalously reduces.

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1. Introduction

[2] It has been known that large earthquakes are often preceded or accompanied by signals of different nature: electric, magnetic, electromagnetic, or luminous, although seismic waves are the most obvious manifestation [*Bolt*, 1999; *Freund*, 2000]. Recently, anomalous variations in the ionospheric F_2 peak electron density N_mF_2 recorded by ionosondes and the total electron content (TEC) derived by ground-based receivers of the global positioning system (GPS) appearing before earthquakes have received considerable discussions [*Liu et al.*, 2000, 2001; *Hayakawa and Molchanov*, 2000; *Pulinets and Boyarchuk*, 2004; *Kamogawa*, 2006; *Rishbeth*, 2006], where the N_mF_2 and GPS TEC are, in general, highly correlated [*Liu et al.*, 2001, 2004a, 2004b]. A statistical investigation based on 184 $M \geq 5.0$ earthquakes during a 6-year period of 1994–1999 in the Taiwan area demonstrates that the abnormal decrease of the ionospheric N_mF_2, in terms of the corresponding plasma frequency f_oF_2, in the afternoon period of 1200–1800 LT occurs significantly within 1–5 days before the earthquakes [*Chen et al.*, 2004; *Liu et al.*, 2006]. An extension work also shows that the ionospheric GPS TEC pronouncedly reduces in the afternoon period of 1200–1800 LT and especially evening period of 1800–2200 LT within 5 days prior to 20 $M \geq 6.0$ earthquakes in Taiwan during September 1999 to December 2002 [*Liu et al.*, 2004b].

[3] The global ionosphere map (GIM) (ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex) of the total electron content (TEC) constructed with about 200 of worldwide ground-based receivers of the GPS is routinely published in a 2-h time interval. Similar to a Geostationary Meteorological Satellite hourly observing clouds for the metrological weather, the GIM can be used to observe signatures of the lithospheric, atmospheric, and ionospheric weather (such as thunderstorm, ionospheric storm, and earthquake). In this paper, we first statistically examine variations of the GPS TEC extracted from the GIM over 35 $M \geq 6.0$ earthquakes occurring in China during the 10-year period of 1 May 1998 to 30 April 2008 (Table 1). On the basis of the statistical results, we investigate temporal and spatial signatures of seismoionospheric electron density anomalies

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Table 1. Earthquakes $M \geq 6.0$ That Occurred in China From 1 May 1998 to 30 April 2008[a]

Year	Month	Day	Hour	Minute	Latitude (°N)	Longitude (°E)	M
1998	5	28	21	11	37.58	79.01	6
1998	7	20	1	5	30.2	88.36	6
1998	8	27	9	3	39.51	77.26	6.4
1998	11	19	11	38	27.27	101.03	6.1
1999	3	28	19	5	30.65	79.66	6.7
1999	4	8	13	10	43.61	130.34	6.4
2000	1	14	23	37	25.59	101.19	6.4
2000	9	12	0	27	35.44	99.44	6.7
2001	2	23	0	9	29.55	101.14	6
2001	3	5	15	50	34.43	86.91	6.4
2001	4	12	10	47	24.96	99.13	6
2001	5	23	21	10	27.58	100.97	6
2001	10	27	5	35	26.33	100.62	6.1
2001	11	14	9	26	35.92	90.53	8.2
2002	6	28	17	19	43.68	130.66	6.9
2002	6	29	6	54	34.21	94.27	6.1
2002	9	15	8	39	44.79	129.9	6.2
2003	2	24	2	3	39.58	77.33	6.6
2003	4	17	0	48	37.56	96.52	6.6
2003	7	7	6	55	34.51	89.37	6
2003	7	21	15	16	25.99	101.27	6.3
2003	10	25	12	41	38.39	100.97	6.1
2003	12	1	1	38	42.96	80.71	6.1
2004	3	27	18	47	33.95	89.37	6.2
2004	7	11	23	8	30.61	83.57	6.6
2005	2	14	23	38	41.66	79.57	6.2
2005	4	7	20	6	30.62	83.73	6.6
2005	6	1	20	6	28.93	94.6	6.1
2007	5	5	8	51	34.34	82.08	6.2
2007	6	2	21	34	23.08	101.13	6.7
2007	6	23	8	17	21.44	99.95	6.1
2007	7	31	15	7	27.49	126.66	6.3
2007	8	7	0	2	27.39	126.63	6.4
2008	1	9	8	26	32.39	85.27	6.8
2008	1	16	11	54	32.44	85.18	6.2

[a] See http://www.csndmc.ac.cn/newweb/catalog_direct_link.htm.

induced by a devastating earthquake with magnitude M_w7.9 occurring in eastern Sichuan (Wenchuan), China (30.986°N, 103.364°E, depth 19 km), at 0628:01 UT on 12 May 2008 (http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/us2008ryan.php).

2. $M \geq$ 6.0 Earthquake in China

[4] Figure 1 illustrates locations of the 35 $M \geq 6.0$ earthquakes together with Wenchuan earthquake in China. We extract the GPS TEC over each epicenter from the GIM during the 35 earthquake periods. To detect abnormal signals of the GPS TEC variations, a quartile-based process is performed. At each time point, we compute the median $\tilde{M}$ of every successive 15 days of the GPS TEC as well as find the deviation between the observed GPS TEC on the 16th day and the computed median $\tilde{M}$. To provide the information about the deviation, we also calculate the first (or lower) and the third (or upper) quartiles, denoted by LQ and UQ, respectively. Note that under the assumption of a normal distribution with mean $\overline{m}$ and standard deviation σ for the GPS TEC, the expected value of $\tilde{M}$ and LQ or UQ are $\overline{m}$ and 1.34σ, respectively [*Klotz and Johnson*, 1983]. To have a stringent criterion, we set the lower bound, $LB = \tilde{M} - 1.5(\tilde{M} - LQ)$ and upper bound, $UB = \tilde{M} + 1.5(UQ - \tilde{M})$. Therefore the probability of a new GPS TEC in the interval (LB, UB) is approximately 65%. The median together with the associated LB and UB then provide references for the GPS TEC variations on the 16th day. Thus when an observed GPS TEC on the 16th day is greater or smaller than its previous 15-day-based median by UB or LB, we declare an upper or lower abnormal GPS TEC signal. Since the GPS TEC time resolution is 2 h, there are 12 data points per day. If more than one third (= 4/12) of the upper or lower abnormal signals appear in one day, and the observed GPS TEC is greater or smaller than the associated UB or LB, we then declare the upper or lower anomalous day detected.

[5] Figure 2 displays the GPS TEC above the Wenchuan epicenter isolated from the GIM database, and the upper (enhancement) and lower (reduction) anomalies appearing before and after the earthquake. The *Dst* index shows that the geomagnetic activity is relatively quiet. It can be seen that the GPS TEC anomalously reduces during 0600–1000 UT (the afternoon period of 1300–1700 LT; LT = UT+7 h) on 6, 7, and 8 May as well as 1400–1700 UT (the late evening period of 2100–2400 LT) on 9 May 2008. Meanwhile, there is a GPS TEC anomalous enhancement occurring in the afternoon period of 9 May 2008. In general, the reduction anomaly day occurs more frequently before than after the Wenchuan earthquake. Figure 3 summarizes that counts of the enhancement and reduction anomaly days appear from day 15 before to day 15 after the 35 $M \geq 6.0$ earthquakes. Note again that the reduction anomalies occur more frequently than the enhancement ones, and the reduction anomalies appear significantly frequently on day 3–5 prior to 17 $M \geq 6.3$ out of the 35 $M \geq 6.0$ earthquakes.

3. M_w7.9 Wenchuan Earthquake

[6] The temporal anomalies appearing above the Wenchuan epicenter in Figure 2 shows that the ionospheric GPS TEC significantly reduces in the afternoon period on 6, 7, and 8 May (day 6–4 before the earthquake) as well as in late evening on 9 May (day 3 before). In fact, the epicentral GPS TEC at 0800 UT (1500 LT) on 6 May and at 0600 UT (1300 LT) on 8 May reach their time point extreme minima (reductions) of 1–30 days before the Wenchuan earthquake. This indicates that the GPS TECs around the epicenter not only statistical significantly reduce (exceeding the LB) but also extremely (with a chance of 3.3% = 1/30) decrease during the four time periods.

[7] To see if the GPS TECs in the earthquake region extremely decrease during the four periods, a spatial analysis is conducted. The GIM 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. For each grid point, to have a more stringent criterion, we now compute the median of the GPS TEC at a certain time point during 1–30 days before the earthquake (12 April to 11 May 2008). We then find for each time point the difference between the observed GPS TEC and the associated median at grid point. Here, the median represents the undisturbed background GPS TEC, while the negative (positive) difference indicates the reduction (enhancement) of the GPS TEC. Among the available 30 differences at each time and grid point, the extreme reduction is of primary interest. Figure 4 displays, in particular, the GIMs

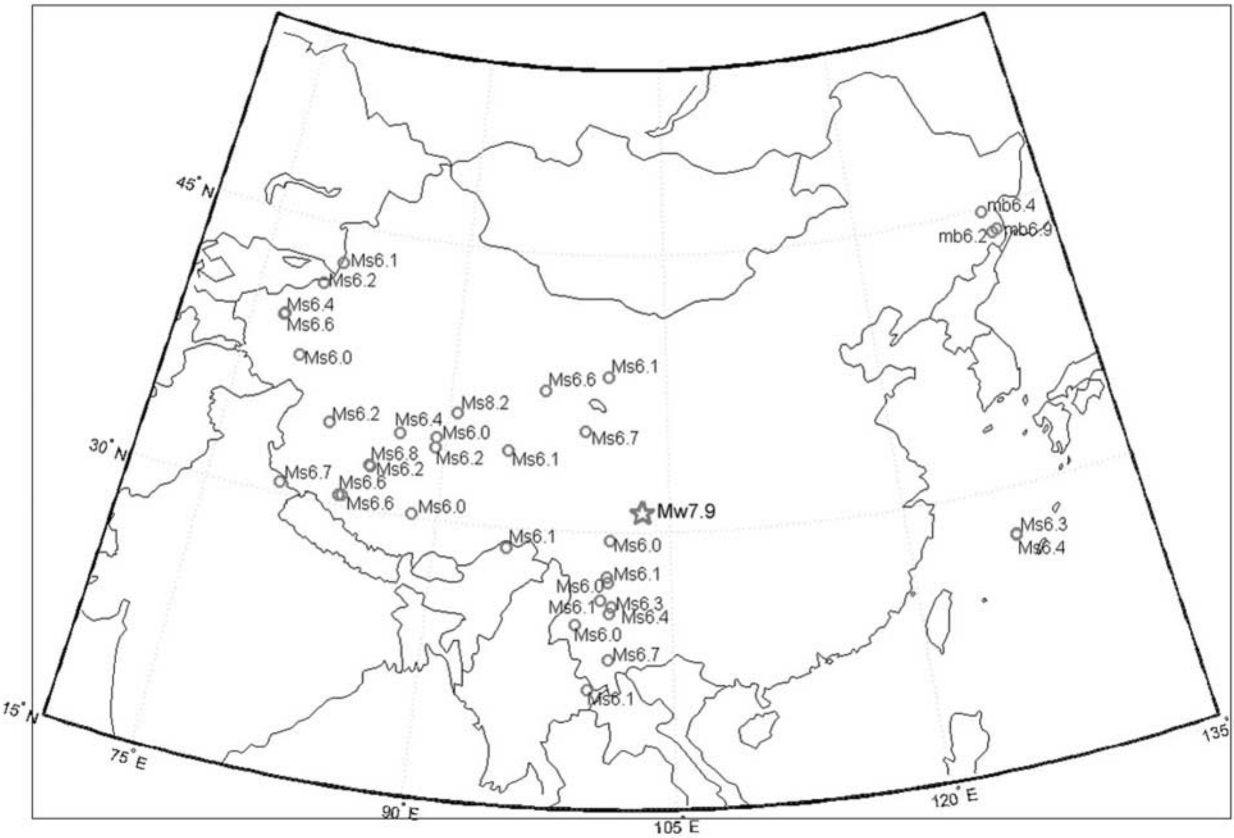


Figure 1. Locations of the 35 $M \geq 6.0$ earthquakes together with Wenchuan earthquake that occurred in China during 1 May 1998 to 12 May 2008. The star symbol denotes the Wenchuan earthquake. The earthquake catalog is retrieved from China Earthquake Administration (http://www.csndmc.ac.cn/newweb/catalog_direct_link.htm).

at 0800 UT, day 6 before the earthquake (6 May 2008), the associated median, and the grid points with the extremely reduced difference occurring on 6 May 2008. The magnified plot in Figure 4 shows the difference of 6 May from its associated median and the 30-day extreme minimum (or reduction) on the day in detail. Figure 4 reveals that the GPS TEC at 0800 UT on 6 May 2008 and the associated median yield remarkable enhancements of the equatorial ionization anomaly (EIA) [*Ratcliffe*, 1974] centering at about 20°N and 0°N, and ranging from 90 to 120°E in the northern and southern hemisphere, respectively. It is interesting to observe that the 30–40% drastic reduction of the GPS TEC with respect to the associated median and the extreme minimum generally appear near and south of the forthcoming Wenchuan epicenter, nearby the northern EIA crest. Taking into account the EIA and/or local time effects, a sequence of GIMs for global fixed local time at 1500 LT is also examined. It is found that the severe reductions and extreme minima in the GPS TEC are once again mainly located around the forthcoming epicenter and EIA region (Figure 4). Note that the extreme minima appear in the northern hemisphere and its geomagnetic conjugate points of the southern hemisphere at both 0800 UT and global fixed 1500 LT.

[8] To find spatial distributions of these anomalies, sequences of GIMs at 0600 and 1400 UT during the 30-day period before the earthquake are further investigated. Figure 5 displays that severe reduction and extreme minimum in the GPS TECs generally occur near the north and/or east side of the Wenchuan epicenter but slight enhancement in the west side at 0600 UT on 6, 7, and 8 May 2008, as well as at 1400 UT on 9 May 2008. Note that the local time of 0600 and 1400 UT at the Wenchuan area are the afternoon period of 1300 LT and the late evening period of 2100 LT, respectively. To remove the local time effects, again sequences of GIMs at the fixed global times of 1300 and 2100 LT on the four days are also examined. Overlaps (or superimposition) of the extreme minima observed at 0600 UT or global fixed 1300 LT on 6, 7, and 8 May 2008 shown in Figure 5 confirms that the GPS TEC significantly reduces around the epicenter in the afternoon period of day 6 to 4 before the Wenchuan earthquake.

[9] Although the statistical result in this paper shows that the ionospheric GPS TEC tends to reduce day 3–5 before the 17 $M \geq 6.3$ in China. Figure 2 depicts that these is a significant enhancement in the GPS TEC at about 1000 UT on 9 May 2008, day 3 before the earthquake. Similar to Figure 4, we display GPS TEC observations, the associated medians and extreme enhancements at 1000 UT and global fixed 1700 LT on 9 May 2008 as well as the magnified plots. Figure 6 illustrates that the GPS TEC in south and southeast of the epicenter together with their geomagnetic conjugate points yield significant and extreme enhancements.

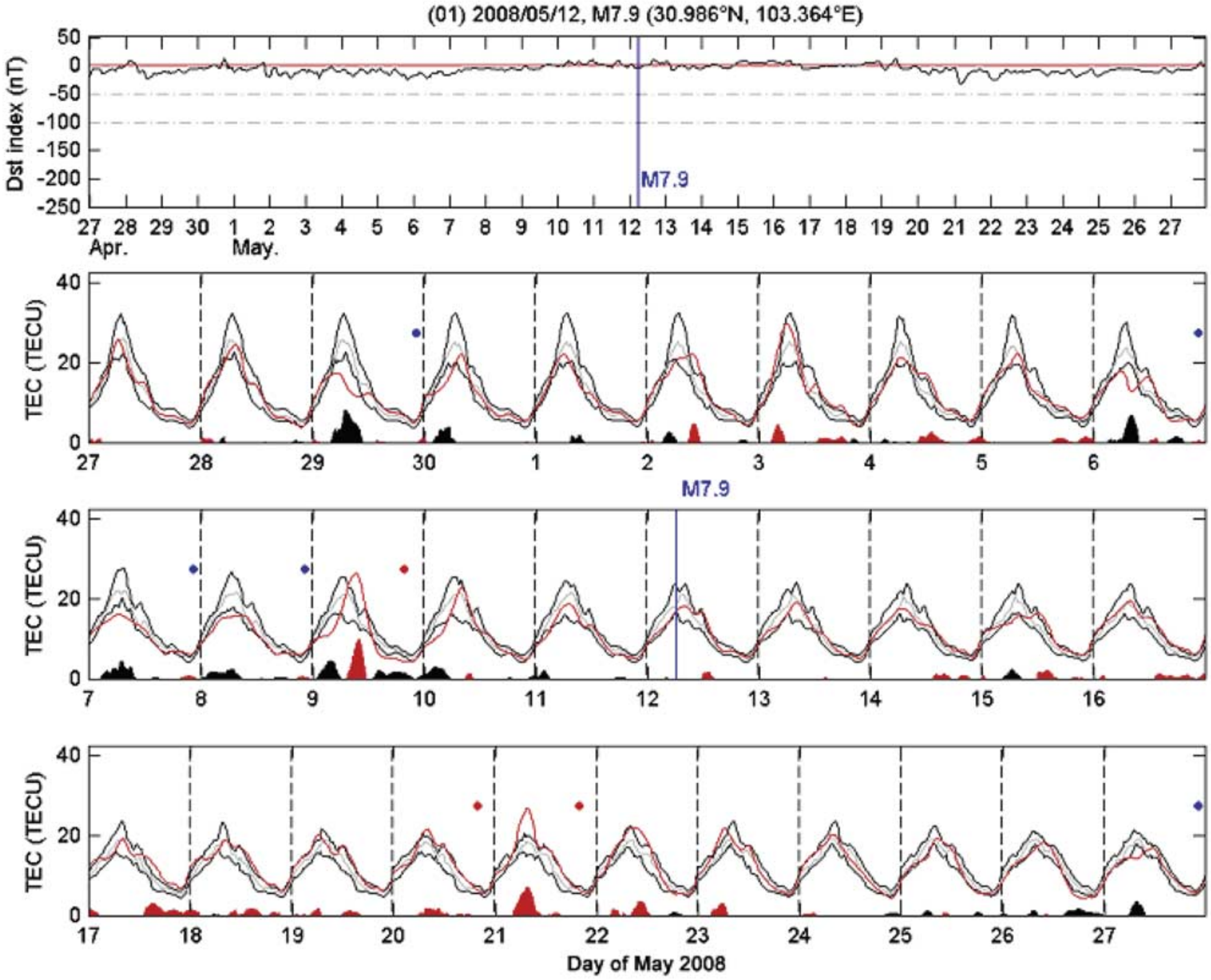


Figure 2. A time series of GPS TEC right above the Wenchuan epicenter extracted from GIMs in May 2008. The M_w7.9 Wenchuan earthquake occurred at 0628:01 UT on Monday, 12 May 2008. The top plot displays variations of the *Dst* index, which shows the geomagnetic activity being generally quiet. The red, gray, and two black curves denote the observed GPS TEC and associated median and upper/lower bound (*UB*/*LB*), respectively. Red and blue dots represent the upper and lower anomalous days identified by the computer routine, respectively. The *LB* and *UB* are constructed by the 1–15 previous days' moving median ($\tilde{M}$), lower quartile (*LQ*), and upper quartile (*UQ*). Here, $LB = \tilde{M} - 1.5(\tilde{M} - LQ)$ and $UB = \tilde{M} + 1.5(UQ - \tilde{M})$. Red and black shaded areas denote differences of *O-UB* and *LB-O*, respectively, where *O* is observed GPS TEC.

[10] To further understand the anomalies in the vertical distribution of the ionospheric electron density above the epicenter, six microsatellites of FORMOSAT3/COSMIC (F3/C) [*Cheng et al.*, 2006], are used. Each satellite houses a GPS occultation experiment (GOX) payload (space-based GPS receiver) applying a powerful technique of the atmospheric radio occultation [*Yunck*, 2002] to globally derive the vertical profile of electron density in the ionosphere. The median and lower and upper quartiles of the electron density profiles observed during the 15-day period from 21 April to 5 May 2008, which is day 7–22 before the earthquake, are computed as references. Figure 7 presents electron density profiles observed over the epicenter during the afternoon period of 1300–1700 LT on 6, 7, 8, and 9 May and the late evening period 2100–2400 LT on 9 May, together with the associated references. The F3/C GOX observations demonstrate that the ionospheric N_mF_2 in the afternoon period on 6, 7, and 8 of May and in the late evening period of 9 May are significantly less than their associated medians by about 30–50%. Moreover, it is found that the F_2 peak height, h_mF_2, descends from about 300 km to 250–220 km altitude which is approximately 50–80 km lower than the associated median on the four anomalous days. By contrast, at 1000 UT on 8 May 2008 the N_mF_2 significantly enhances but the h_mF_2 remains the same as the associated median at about 300 km altitude when the GPS TEC of the GIM around the epicenter significantly enhances.

4. Discussion and Conclusion

[11] This study shows that the GPS TEC pronouncedly reduces 3–5 days before the 17 $M \geq 6.3$ earthquakes in

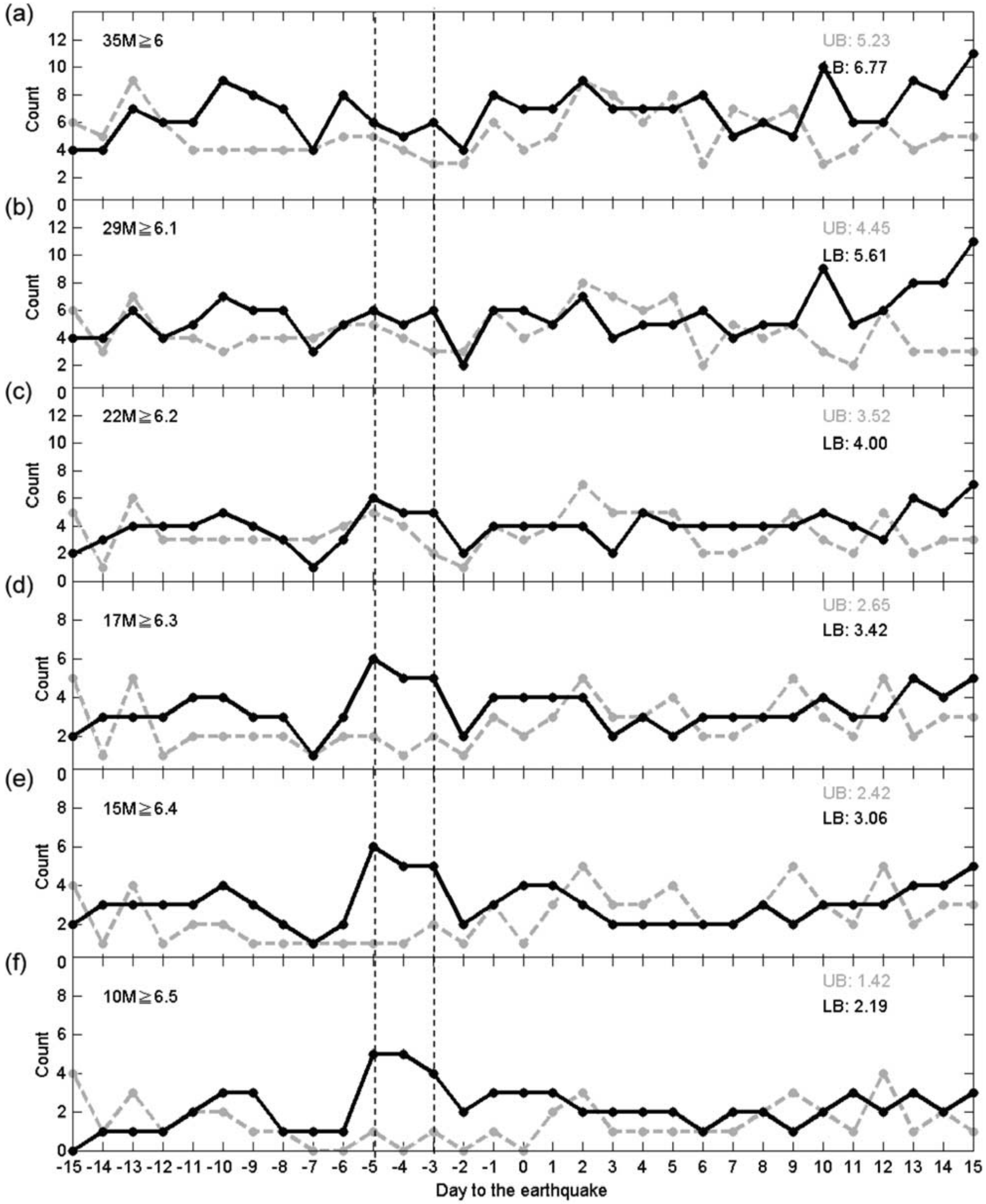


Figure 3. Counts of the upper and lower anomalous days appear 15 days before and after the 35 $M \geq 6.0$ earthquakes in China during 1 May 1998 to 11 May 2008. Dashed gray and solid black curves denote counts of the upper and lower anomalous days, respectively. (a) 35 $M \geq 6.0$, (b) 29 $M \geq 6.1$, (c) 22 $M \geq 6.2$, (d) 17 $M \geq 6.3$, (e) 15 $M \geq 6.4$, and (f) 10 $M \geq 6.5$. Gray and black numbers in each plot are the overall averages of the upper and lower anomalous days, respectively. The two vertical lines represent day 3–5 before the earthquakes.

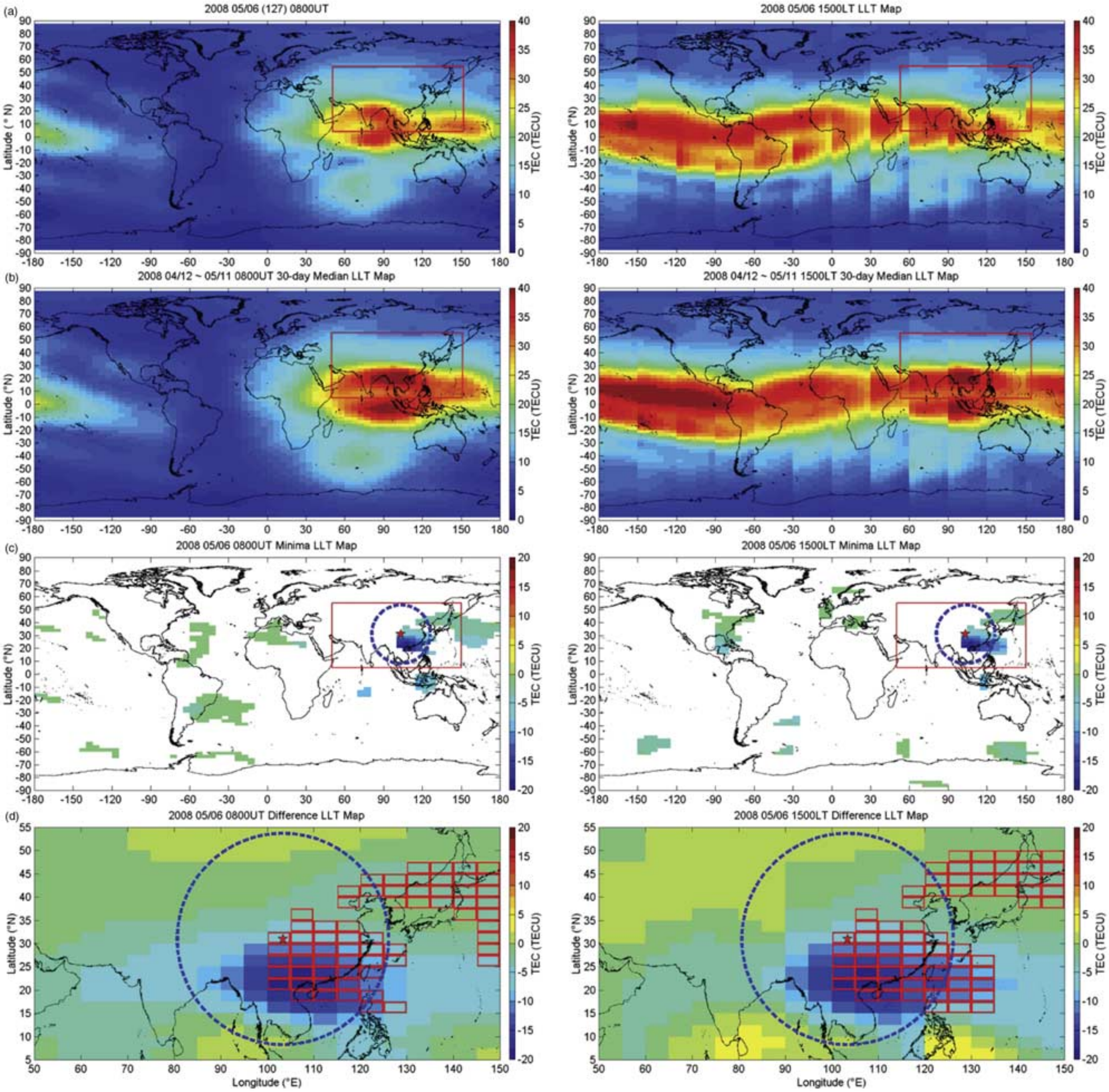
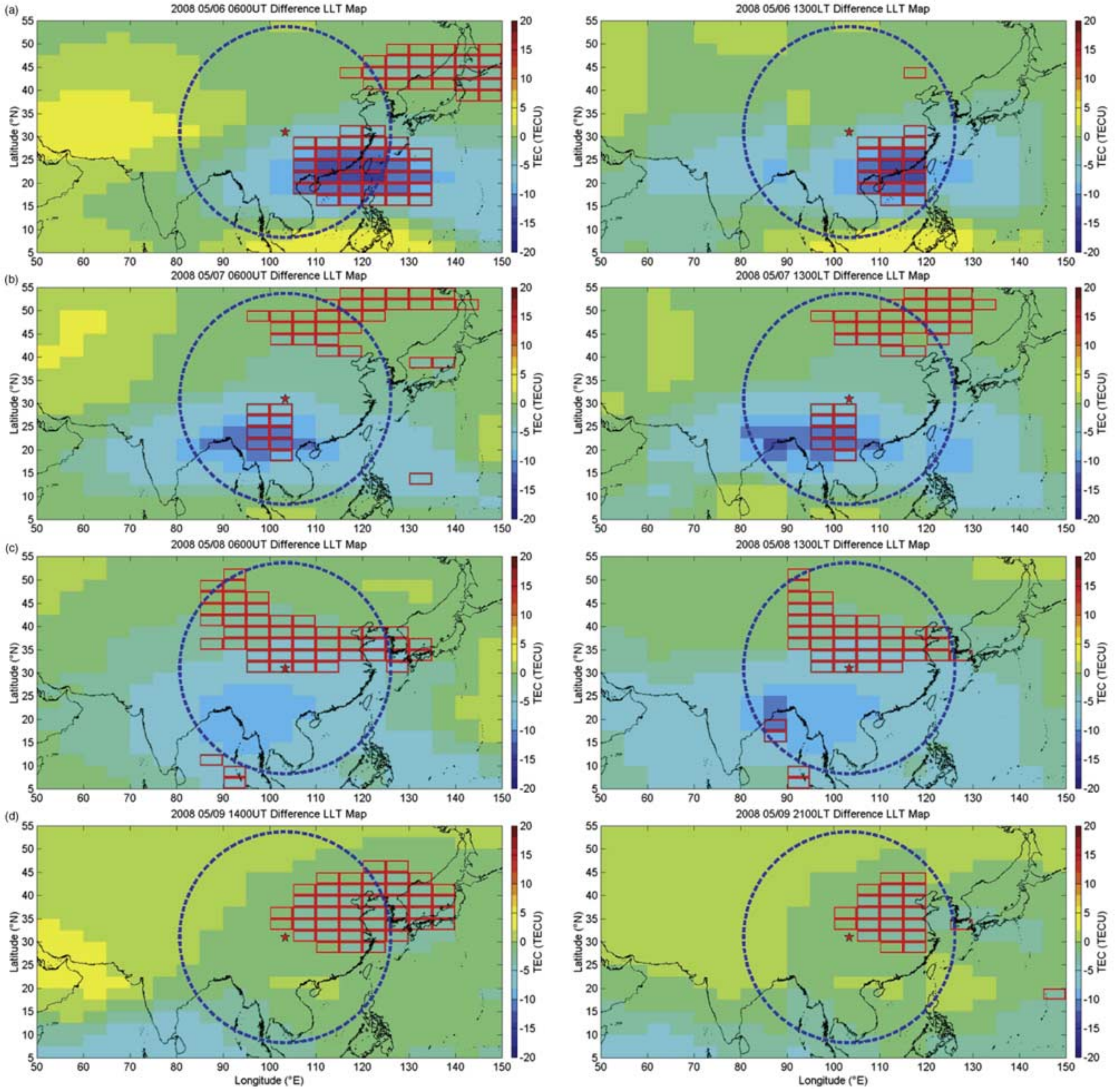


Figure 4. The GIMs observed at 0800 UT and global fixed 1500 LT on day 6 before the 2008 M_w7.9 Wenchuan earthquake. Figures 4a–4d (left) and Figures 4a–4d (right) are GIMs at 0800 UT and global fixed local time of 1500 LT, respectively. Figure 4a is observed on 6 May 2008 (day 6 before the earthquake), Figure 4b is the medians of the period of 1–30 days (12 April to 11 May 2008) before the earthquake, and Figure 4c denotes the extreme decreases of the 30-day period that appeared on 6 May 2008. The color denotes the difference of the TEC observed on 6 May 2008 from the associated median. It can be seen that the ionospheric GPS TECs around the Wenchuan epicenter marked by the dashed circle drastically reduce by about 30–40%. The circle with the radius R = 2495 km stands for the earthquake preparation area of the lithosphere [*Dobrovolsky et al.*, 1979]. Figure 4d is the magnified difference between 6 May 2008 and the associated median. The red grids denote the 30-day extreme decreases. The red grids of the two magnified appeared around 30–50°N, 115–150°E might be related to the 7 May 2008 M7.0 (36.23°N, 141.61°E; D51 km) earthquake. The GIM grid points lie between ±87.5°N and ±180°E with 2.5° and 5° grid intervals in the latitudinal and longitudinal directions, and therefore each map has 5040 (= 70 × 72) grid points in total.

China which generally agrees with the previous studies in Taiwan [*Liu et al.*, 2000; *Chen et al.*, 2004; *Liu et al.*, 2004b, 2006]. Meanwhile, the reduction anomaly of the ionospheric electron density appears more often before larger earthquakes but less likely away from the epicenter [*Liu et al.*, 2006]. For the 20 September 1999 M_w7.6 Chi-Chi earthquake, in particular, the spatial analyses reveal that the ionospheric GPS TECs centering on the epicenters


(a) 2008 05/06 0600UT Difference LLT Map

2008 05/06 1300LT Difference LLT Map

(b) 2008 05/07 0600UT Difference LLT Map

2008 05/07 1300LT Difference LLT Map

(c) 2008 05/08 0600UT Difference LLT Map

2008 05/08 1300LT Difference LLT Map

(d) 2008 05/09 1400UT Difference LLT Map

2008 05/09 2100LT Difference LLT Map

Figure 5. The ionospheric GPS TEC anomalies of the GIMs observed on days 6 to 3 prior to the Wenchuan earthquake. Figures 5a–5d (left) and Figures 5a–5d (right) are GIMs of the universal time and global fixed local time, respectively. Figures 5a, 5b, and 5c are the difference between the observations and the associated medians at 0600 UT and global fixed 1300 LT on 6, 7, and 8 May 2008, respectively. The color denotes the difference of the TEC on the observation day to the associated median, and the red grids represent the extreme decreases. Figure 5d is at 1400 UT and global fixed 2100 LT on 9 May 2008. It can be seen that the ionospheric GPS TECs around the epicenter significantly reduce.

notably decreased 3–4 days before the earthquake [*Liu et al.*, 2001]. As a matter of fact, the GPS TECs under study reduce significantly in an area of about 10–15° in latitude and 15–30° in longitude from the epicenter during the afternoon periods of day 6–4 (6–8 May 2008) and the evening period on day 3 (9 May 2008) before the Wenchuan earthquake. Since 1° corresponds to about 110 km in latitude and 95 km in longitude, the anomalous size of the Wenchuan earthquake is 1650 km(= 110 km/° × 15°) and 2850 km(= 95 km/° × 30°) in the latitudinal and the longitudinal directions, respectively. Note that in the lithosphere the earthquake preparation area can be estimated by $R = 10^{0.43M}$, where R is the radius of the earthquake preparation zone and M is the earthquake magnitude [*Dobrovolsky et al.*, 1979]. For the M_w7.9 Wenchuan earthquake, we obtain R = 2495 km (Figure 4). Therefore, the observed anomaly area is smaller in the latitudinal direction but slightly larger in the longitudinal direction than the estimated preparation zone. Meanwhile, the F3/C GOX observes tremendous amount of the electron density

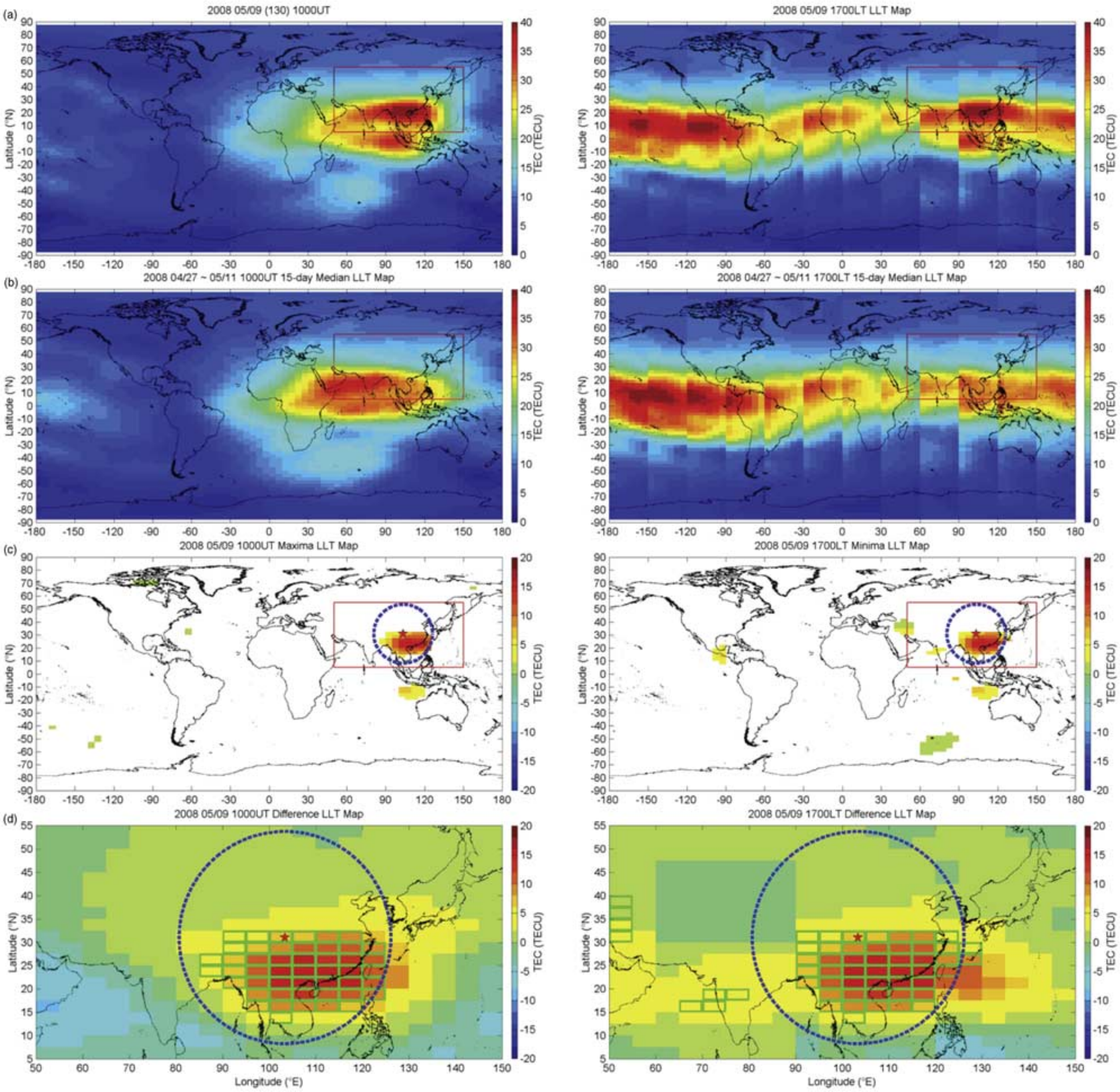


Figure 6. Similar to Figure 4, the GIMs observed at 1000 UT and global fixed 1700 LT on day 3 before the 2008 M_w7.9 Wenchuan earthquake. Figures 6a–6d (left) and Figures 6a–6d (right) are GIMs at 1000 UT and global fixed local time of 1700 LT, respectively. Figure 6a is observed on 9 May 2008 (day 3 before the earthquake), Figure 6b is the medians of the period of 1–30 days (12 April to 11 May 2008) before the earthquake, and Figure 6c denotes the extreme enhancements in each grid point of the 30-day period that appeared on 9 May 2008. The color denotes the difference of the TEC observed on 9 May 2008 from the associated median. It can be seen that the ionospheric GPS TECs around the Wenchuan epicenter marked by the blue dashed circle with the radius R = 2495 km drastically increase by about 40–50%. Figure 6d is the magnified difference between 9 May 2008 and the associated median. The green grids denote the 30-day extreme enhancements.

losses from the ionosphere ranging form 200 to 600 km altitude on those four anomalous days. Comparing to the associated median, the N_mF_2 decreases more than 30–50% and the h_mF_2 at about 300 km altitude descends about 50–80 km on the decreased anomaly days. Note that such a reduction in the ionosphere shall needs enormous power and/or energy to modify the electron density in the ionosphere volume of 6.8×10^9 km^3 (= 3.14 × 1650 km × 3300 km × 400 km).

[12] *Freund* [2000] conducts laboratory experiments compressing rocks to mimic tectonic plate shifts, and shows that mobile positive holes can be activated in the crest by microfractures during the dilatancy of earthquake preparation [*Bolt*, 1999]. The diffusion and outflow of these holes

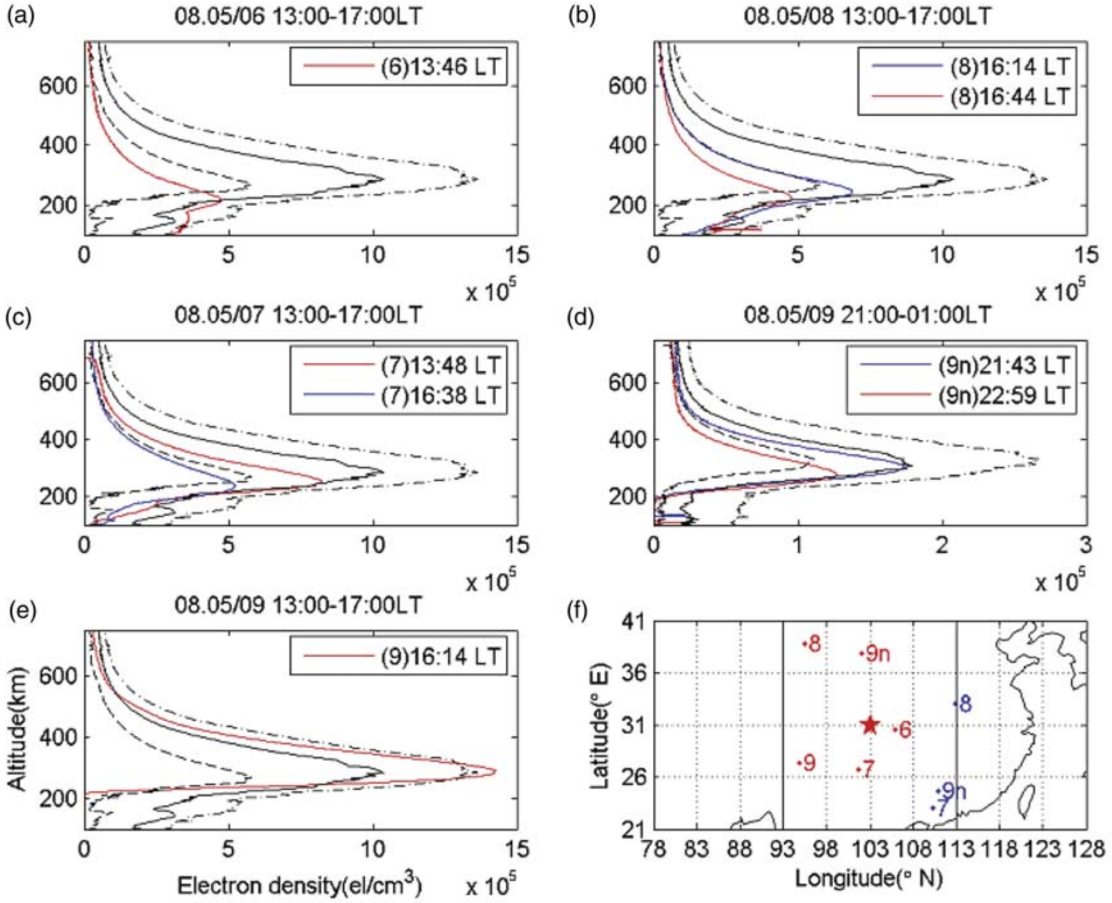


Figure 7. The ionospheric electron density profiles above the epicenter observed on days 6 to 3 before the Wenchuan earthquake by FORMOSAT3/COSMIC satellites. Figures 7a, 7b, and 7c are the vertical profiles of electron density observed during 1300–1700 LT on 6, 7, and 8 May (day 6, 5, and 4 before), respectively, and Figure 7d is for 2100–0100 LT on 9 May 2008 (day 3 before the earthquake). Figure 7e is the vertical profiles of electron density observed during 1300–1700 LT on 9 May 2008 (day 3 before the earthquake). Figure 7f displays locations of the vertical profiles where the star and numbers denote the epicenter and days of May, and "n" indicates nighttime (i.e., late evening). The red curves represent the observed profiles, while the solid and dashed curves in each plot are the associated median and upper/lower quartiles of the same local time period during 21 April to 5 May 2008 (7 to 22 days before the earthquake). It confirms that the electron density significantly decreases on the four anomalous days before the earthquakes.

can further generate currents, radiations, electric fields, magnetic fields, etc. on the Earth surface [*Freund*, 2000]. Enhanced emission of infrared radiations from the epicenter in 6 days leading up the Wenchuan earthquake were spotted by satellites while very colorful earthquake clouds near the fault zone and epicenter were also recorded few tens minutes before the earthquake [*Ouzounov et al.*, 2008]. These observations indicate that the electromagnetic environment has been significantly changed, and radiations, low-frequency electric fields, magnetic fields, etc., have been activated around the forthcoming epicenter area during the earthquake preparation period. It is possible that the seismo-generated radiations cause the plasma thermal expansions and then result in a large volume of the ionospheric electron density reduction (Figures 4 and 5). Alternatively, the seismo-generated radiations can also possibly provide the thermal energy to electrons, similar to photoelectrons caused by the solar radiations. Scientists find that the photoelectrons have a significant impact on the electric potential along magnetic field lines [*Winningham and Gurgiolo*, 1982] and most likely result in a field-aligned outward electric field in the ionosphere (for details, see *Tam et al.* [2007]). Meanwhile, the diffusion and outflow of the positive holes can also result in an upward electric field on the Earth surface [*Freund*, 2000]. The dip angle of the Earth's magnetic field is about 45° around the Wenchuan epicenter (30.986°N, 103.364°E). The outward and upward electric fields outflow electrons and ions (i.e., plasma) along the Earth's magnetic field line, similar to the polar wind [*Tam et al.*, 2007], to the magnetosphere, which results in the GPS TEC and N_mF_2 significant reductions. In fact, the large amount of the outflow plasma from the upper ionosphere can easily lower the h_mF_2 altitude and reduce the N_mF_2 electron density significantly.

[13] On the other hand, the perpendicular component of the upward electric field and the Earth's magnetic field would also be able to produce a westward plasma E × B drift [*Kelley*, 1989] which in turn results in the extreme reductions of the GPS TEC mainly in the east side of the Wenchuan epicenter (Figures 4 and 5). Moreover, the perpendicular component of the electric field in the northern hemisphere can be mapped to the conjugate point in the southern hemisphere where the similar westward plasma E × B drift causes the GPS TEC reductions in the east side of the earthquake longitude (Figure 4c).

[14] Although the generated mechanism is not understood, Figures 2 and 6 as well as *Zhao et al.* [2008] observe the enhanced anomalies in the afternoon period of 9 May 2008 (day 3 before the earthquake). The enhanced GPS TEC around the epicenter suggests a downward electric field on the Earth's surface somehow occurring. The eastward plasma E × B drift causes the GPS TEC enhancement slightly shifting to the east side of the Wenchuan epicenter (Figure 6). Similarly, the perpendicular component of the electric field in the northern hemisphere is further mapped to the conjugate point in the southern hemisphere where again the eastward plasma E × B drift causes the GPS TEC enhancement in the east side of the earthquake longitude (Figure 6).

[15] In conclusion, the significantly anomalous reductions and enhancements in the GPS TEC of the GIM and the electron density of the F3/C indicate that the seismo-generated electromagnetic emissions as well as field-aligned and vertical electric fields before the Wenchuan earthquake are essential and important.

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