Temporal and spatial precursors in the ionospheric global positioning system (GPS) total electron content observed before the 26 December 2004 M9.3 Sumatra–Andaman Earthquake

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[1] We report seismo-ionospheric precursors of anomalous decreases in the total electron content (TEC) appearing day 5 prior to an M9.3 earthquake, the largest one in the last five decades, which occurred in Sumatra-Andaman, Indonesia on 26 December 2004. Sequences of global ionosphere maps of the TEC derived from worldwide ground-based receivers of the global positioning system (GPS) are used to statistically study the temporal and spatial precursors of the earthquake. It was found that the temporal precursor of the GPS TEC around the epicenter was significantly reduced during the afternoon period on d 5 before the earthquake. The spatial precursors prominently, persistently, and simultaneously appear around the epicenter and its conjugate areas of the Sumatra-Andaman earthquake.

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1. Introduction

[2] Large earthquakes are often preceded or accompanied by signals of different nature: electric, magnetic, electromagnetic, or luminous, but seismic waves are the most obvious manifestation [*Bolt*, 1999; *Huang and Ikeya*, 1998; *Freund*, 2000; *Du et al.*, 2002; *Nagao et al.*, 2002; *Huang and Liu*, 2006]. Recently, ionospheric phenomena occurring before earthquakes have received considerable attention [*Pulinets and Boyarchuk*, 2004]. Of special interests are seismo-ionospheric anomalies, which appear a few days before large earthquakes. For example, it is found that the ionospheric electron density at the F2-peak, in terms of the plasma frequency foF2, observed by a local ionosonde [*Liu et al.*, 2000], and/or the total electron content (TEC), integrated the electron density from ground-based receivers to satellites of the global positioning system (GPS) [*Liu et al.*, 2001; 2004a], were anomalously reduced in the afternoon period on day 3 and 4 before the 21 September 1999 M7.6 Chi-Chi earthquake. Statistical investigations show that the abnormal decrease of the ionosonde foF2 in the afternoon period between 12:00 and 18:00 LT (local time) occur significantly within 1–5 d before 184 ($M \geq 5.0$) earthquakes in Taiwan during 1994–1999 [*Chen et al.*, 2004; *Liu et al.*, 2006]. These results demonstrate that the anomaly appears more often before larger earthquakes, but less likely when the epicenter is further away from the local ionosonde station. In addition, some studies also observe similar anomalous reduction features of the ionospheric GPS TEC appearing in the afternoon and evening periods within day 1–5 before 20 $M \geq 6.0$ earthquakes in Taiwan during the 5 yr period of 1999–2003 [*Liu et al.*, 2004b] and within day 1–6 before 35 $M \geq 6.0$ earthquakes in China during the 10 yr period of 1998–2008 [*Liu et al.*, 2009].

[3] Although many convincing results have been reported, scientists still raise the question if there are any seismo-ionospheric precursors before recent disastrous earthquakes [*Kamogawa*, 2006; *Rishbeth*, 2006]. Therefore, we focus on, in particular, an M9.3 earthquake reported by the U.S. Geological Survey with the origin time at 0058:53 UT (universal time) on December 26, 2004 and the epicenter located at 3.30°N, 95.95°E off the west coast of northern Sumatra (Aceh province), the rupture length of 1300 km extending from northwestern Sumatra to the Andaman Islands. (http://earthquake.usgs.gov/eqinthenews/2004/usslav/). Note that this Sumatra-Andaman (or Aceh) earthquake has been ranked as the largest earthquake after the 1952 Kamchaka earthquake. The land surface uplift is estimated to be up to 10 m on the Nicobar Islands and displacements of the adjacent seabed generated damaging tsunami waves that killed more than 280,000 people at countless coastal communities around the Indian Ocean [*Kruger et al.*, 2005; *Gower*, 2005].

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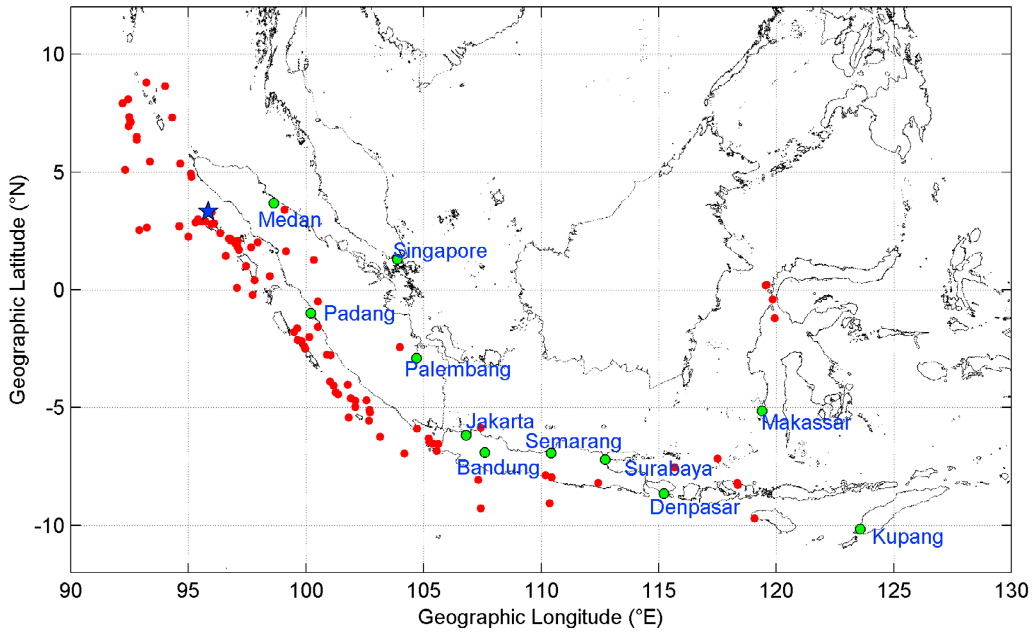

Figure 1. Locations of 100 M ≥ 6.0 earthquakes occurring in Indonesia from May 1 1998 to December 31, 2008. The earthquakes are isolated from the U. S. Geological Survey, (http://neic.usgs.gov/neis/epic/epic_global.html). The blue star denotes the Sumatra-Andaman earthquake. A detailed catalog is given in Table 1.

[4] To search for possible precursors before earthquakes occurring in a large area, such as Indonesia (Figure 1), we examine the global ionosphere maps (GIM) (http://www.cx.unibe.ch/aiub/ionosphere.html) of the GPS TEC, which is routinely published in a 2 hr time interval for monitoring global ionospheric (or solar terrestrial) weather, similar to a Geostationary Meteorological Satellite hourly observing clouds for the metrological weather. The spatial resolutions of the GIM on the ±87.5°N latitude and ±180°E longitude are 2.5° and 5°, respectively. Therefore, each map consists of 5040 (70 × 72) grid points (Figure 2).

[5] In this paper, we first statistically examine temporal variations of the GPS TEC extracted from the GIM over the epicenters of 100 M ≥ 6.0 earthquakes occurring in Indonesia from 1 May 1998 to 31 December 2008 listed in the United States Geological Survey, USGS, (http://neic.usgs.gov/neis/epic/epic_global.html). On the basis of the statistical results, we investigate temporal and spatial precursors of seismo-ionospheric GPS TEC associated with the 26 December 2004 M9.3 Sumatra-Andaman earthquake.

2. Temporal Precursor

[6] Figure 1 illustrates locations of the 100 M ≥ 6.0 earthquakes together with the 2004 M9.3 Sumatra-Andaman earthquake in Indonesia (for details see Table 1). We extract the GPS TEC over each epicenter from the GIM 1–30 d before and after each 100 earthquakes. 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 d of the GPS TEC as well as find the deviation between the observed one 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 assuming a normal distribution with mean $\bar{m}$ and standard deviation σ for the GPS TEC, the expected values of LQ and UQ should be $\bar{m} - 0.67\sigma$ and $\bar{m} + 0.67\sigma$, 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 68%. The median together with the associated *LB* and *UB* then provide references for the GPS TEC variations on the 16th day. Therefore when an observed GPS TEC on the 16th day is not in the associated (LB, UB), we declare an upper or lower abnormal GPS TEC signal. Since the GPS TEC time resolution is 2 hr, there are 12 data points per day. If more than one third (4/12) of the upper or lower abnormal signals successively appear in one day, and the observed GPS TEC is greater or smaller than the associated *UB* or *LB*, we then consider the upper or lower anomalous (enhancement or deduction precursor) day being detected. The probability of having a daily anomaly by observing four or more signals (low or upper) is about 0.22, that of the successively appearing anomalies should be even less.

[7] Take the Sumatra-Andaman earthquake as an example. Figure 3 displays the GPS TEC above the epicenter isolated from the GIM database 15 d before and after (from 11 December 2004 to 10 January 2005) the earthquake. The Dst index shows that except for a moderate geomagnetic storm with a maximum depression −61 nT (nano Tesla) occurring on December 13, 2006, the geomagnetic activity is relatively quiet (http://wdc.kugi.kyoto-u.ac.jp/dst_provisional/200412/index.html). It can be seen that the GPS TEC anomalously reduces during 0400–0800 UT (the afternoon period of 1000–1400 LT; LT = UT + 6 hr) on

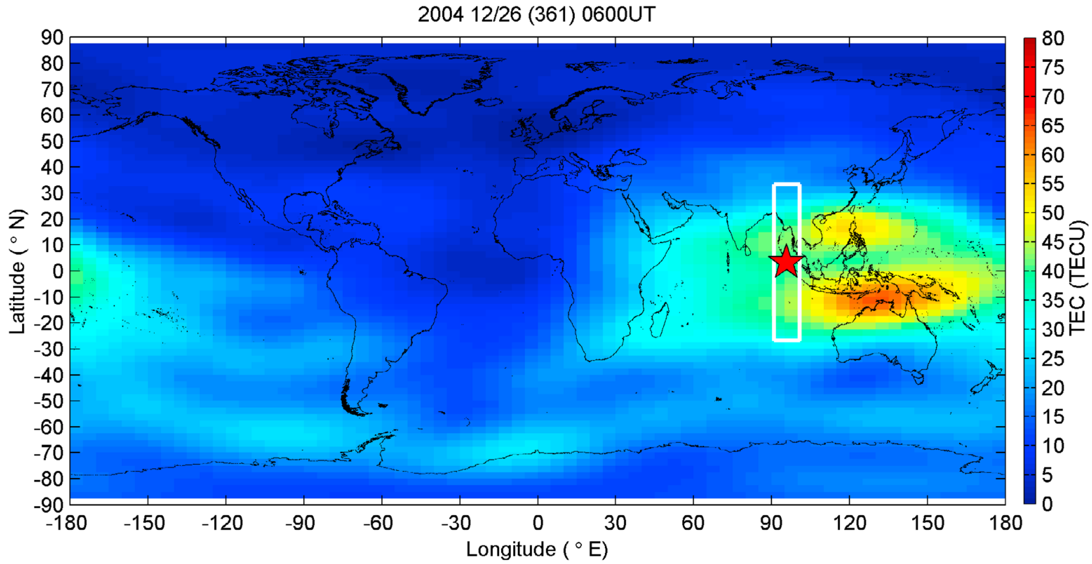

Figure 2. The snap shoot of GIM at 0600 UT on the day of 26 December 2004 Sumatra-Andaman earthquake. Two equatorial ionization anomaly (EIA) crests of dense GPS TEC bands at low latitudes centered about 20°N and 10°S geographic latitudes straddle the geomagnetic equator and range from 60°E to –160°E. The red star denotes the Sumatra-Andaman epicenter. 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. A white rectangle between ±30°N and 95±5°E is employed to extract data from the GIMs to develop latitude-time-TEC plots along the 95.95°E Sumatra-Andaman earthquake longitude during 25 November–27 December 2004.

13–16, 18–19, and 21 December 2004 which are day 13–11, 8–9, and 5 before the earthquake, respectively. Liu et al. (A statistical study on the characteristics of ionospheric storms in the EIA region: GPS TEC observed over Taiwan, submitted to *Journal of Geophysical Research*, 2010) statistically studied the ionospheric GPS TEC response to 248 geomagnetic storms in low latitudes, such as in Taiwan, during 1994–2003. They found the negative effect of GPS TEC reductions can last as long as 4 d after moderate storms (Dst $\leqq -50$nT). On the basis of *Liu et al.* [2010], the anomalous reductions of the GPS TEC on 13–16 December are possibly either induced or contaminated by the moderate −61 nT geomagnetic storm on December 13, 2004. Among the rest of the three reduction anomalies, the one on the 21 December 2004 (day 5 before the earthquake) not only yields the lowest TEC but also falls in the leading time of 1–5 and/or 1–6 d reported by *Chen et al.* [2004] and *Liu et al.* [2000, 2004b, 2006, 2009]. Meanwhile, there is a GPS TEC anomalous enhancement and reduction occurring in the afternoon period of 29 December 2004 and 5–8, 10 January 2005, which are days 3, 10–13, and 15 after the earthquake, respectively. In general, the anomalous reduction day occurs more frequently before than after the Sumatra-Andaman earthquake.

[8] To find characteristics of the temporal precursors, the GPS TEC extracted from the GIM database over the 100 M ≥ 6.0 earthquake epicenters in Indonesia during the 10 yr period of 1 May 1998 to 31 December 2008 is statistically examined. Both the enhancement and reduction anomalies of each earthquake event are identified as the Sumatra-Andaman earthquake (as shown in Figure 3). Figure 4 summarizes that cumulative percentages of the anomalous enhancement and reduction days that appear day 15 before and after the 100 M ≥ 6.0 earthquakes, which has been subdivided into 12 magnitude categories from M ≥ 6.0 to M ≥ 7.1. It can be seen that for M ≥ 6.0−6.7 the percentages of the anomalous enhancement and reduction fluctuate about 20%. For M ≥ 6.8 the percentages of the anomalous enhancement increase up to 25%–40% on days 9–15 before and after the earthquakes, while the anomalous reductions occur frequently on days 1–7 before and after the earthquakes.

[9] To investigate the reliability of the anomaly [e.g., *Huang*, 2006], a stochastic test [*Manly*, 2007] is conducted based on a simulation study that involves 10,000 random samples each containing 100 earthquakes. Note that the GIM TEC is derived from the spherical harmonic expansion over 100+ continuously operating GPS receivers in the global network, the adjacent seven grids, including 1925 (110 km/° × 2.5°/*y*-grid × 7 *y*-grid) in the latitudinal and 3850 (110 km/° × 5°/*x*-grid × 7 *x*-grid) km in the longitudinal direction, might be correlated. Figure 1 and Table 1 indicate that the 100 earthquakes occur within a region of 2200 km (10°N–10°S in latitude) and 3300 km (90°E–120°E in longitude). This suggests that the 100 earthquakes occur within the region where the GIM TEC might be correlated. For simplicity, we assume that all the 100 earthquakes in the simulation study occur at a center of their locations 0°N, 105°E and consider the randomness only in terms of occurrence during the 10 yr period.

[10] We repeatedly took a random sample of size 100 from the earthquakes in Table 1 during the 10 yr period and produce anomaly percentages for each of the 10,000 replications. The averaged percentages of the enhancement and reduction 15 d before and after the earthquakes of the 10,000 replications are 19.1 ± 0.1% and 21.6 ± 0.1%, respectively, which agree with the estimation of 20% in

Table 1. Earthquakes M ≥ 6.0 Occurred in Indonesia from 1 May 1998 to 1 December 2008

Year	Month	Day	Hour	Minute	Latitude (°N)	Longitude (°E)	M
1998	5	21	5	34	0.21	119.58	6.7
1998	8	10	9	52	7.32	94.31	6
1998	9	28	13	34	−8.19	112.41	6.6
1998	10	10	16	32	−0.4	119.84	6
1999	2	23	7	27	0.2	119.54	6.2
1999	8	14	0	16	−5.89	104.71	6.4
1999	11	11	18	5	1.28	100.32	6.2
1999	12	21	14	14	−6.84	105.56	6.5
2000	6	4	16	14	−4.72	102.09	7.9
2000	6	6	9	58	−5.09	102.7	6.2
2000	6	7	23	45	−4.61	101.9	6.7
2000	6	9	8	0	−5.55	102.68	6
2000	9	1	11	56	1.44	96.59	6
2000	9	12	16	27	−5.43	101.82	6
2000	9	22	18	22	−4.96	102.1	6.2
2000	10	25	9	32	−6.55	105.63	6.8
2000	10	30	12	1	−9.71	119.07	6
2001	1	16	13	25	−4.02	101.78	6.9
2001	2	13	19	28	−4.68	102.56	7.4
2001	2	16	5	59	−7.16	117.49	6.1
2001	3	15	1	22	8.66	94.01	6
2001	5	25	5	6	−7.87	110.18	6.3
2002	1	15	7	12	−6.31	105.21	6.1
2002	6	27	5	50	−6.96	104.18	6.5
2002	10	3	19	5	−7.53	115.66	6
2002	10	6	15	46	−8.2	118.34	6.3
2002	11	2	1	26	2.82	96.08	7.4
2003	5	14	7	40	−8.06	107.32	6
2004	2	22	6	46	−1.56	100.49	6
2004	4	16	21	57	−5.21	102.72	6
2004	5	11	8	28	0.41	97.82	6.1
2004	7	25	14	35	−2.43	103.98	7.3
2004	12	26	0	58	3.3	95.98	9
2004	12	27	9	39	5.35	94.65	6.1
2004	12	29	5	56	8.79	93.2	6.2
2004	12	31	2	24	7.12	92.53	6.1
2005	1	1	6	25	5.1	92.3	6.7
2005	1	2	15	35	6.36	92.79	6.4
2005	1	9	22	12	4.93	95.11	6.1
2005	1	15	13	47	−6.46	105.24	6
2005	1	23	20	10	−1.2	119.93	6.3
2005	1	24	4	16	7.33	92.48	6.3
2005	1	26	22	0	2.7	94.6	6.2
2005	2	5	4	3	2.26	94.99	6
2005	2	9	13	27	4.8	95.12	6
2005	2	26	12	56	2.91	95.59	6.8
2005	3	28	16	9	2.09	97.11	8.6
2005	3	30	16	19	2.99	95.41	6.3
2005	4	3	3	10	2.02	97.94	6.3
2005	4	8	5	48	−0.22	97.73	6.1
2005	4	10	10	29	−1.64	99.61	6.7
2005	4	11	6	11	2.17	96.76	6.1
2005	4	16	16	38	1.81	97.66	6.4
2005	4	28	14	7	2.13	96.8	6.2
2005	5	10	1	9	−6.23	103.14	6.3
2005	5	14	5	5	0.59	98.46	6.7
2005	5	18	11	37	5.44	93.36	6.1
2005	5	19	1	54	1.99	97.04	6.9
2005	6	8	6	28	2.17	96.72	6.1
2005	7	5	1	52	1.82	97.08	6.7
2005	7	24	15	42	7.92	92.19	7.2
2005	11	19	14	10	2.16	96.79	6.5
2006	4	19	20	36	2.64	93.23	6.2
2006	4	25	18	26	1.99	97	6.3
2006	5	16	15	28	0.09	97.05	6.8
2006	5	26	22	53	−7.96	110.45	6.3
2006	6	21	12	34	6.94	92.45	6
2006	6	27	18	7	6.5	92.79	6.3
2006	7	17	8	19	−9.28	107.42	7.7
2006	7	19	10	57	−6.53	105.39	6.1
2006	7	27	11	16	1.71	97.15	6.3
2006	8	11	20	54	2.4	96.35	6.2
2006	9	21	18	54	−9.05	110.36	6
2006	12	1	3	58	3.39	99.08	6.3
2007	1	8	12	48	8.08	92.44	6.1
2007	3	6	3	49	−0.49	100.5	6.4
2007	4	7	9	51	2.92	95.7	6.1
2007	7	25	23	37	7.16	92.52	6.1
2007	8	8	17	5	−5.86	107.42	7.5
2007	9	12	11	10	−4.44	101.37	8.5
2007	9	13	3	35	−2.13	99.63	7
2007	9	14	6	1	−4.07	101.17	6.4
2007	9	19	7	27	−2.75	100.89	6
2007	9	20	8	31	−2	100.14	6.7
2007	9	26	15	43	−1.79	99.49	6.1
2007	9	29	5	37	2.9	95.52	6
2007	10	4	12	40	2.54	92.9	6.2
2007	10	24	21	2	−3.9	101.02	6.8
2007	11	25	16	2	−8.29	118.37	6.5
2007	12	22	12	26	2.09	96.81	6.1
2008	1	4	7	29	−2.78	101.03	6
2008	1	22	17	14	1.01	97.44	6.2
2008	2	20	8	8	2.77	95.96	7.4
2008	2	24	14	46	−2.4	99.93	6.5
2008	2	25	8	36	−2.49	99.97	7.2
2008	3	3	2	37	−2.18	99.82	6.2
2008	3	15	14	43	2.71	94.6	6
2008	3	29	17	30	2.86	95.3	6.3
2008	5	19	14	26	1.64	99.15	6
2008	11	22	16	1	−4.35	101.26	6.4

http://earthquake.usgs.gov/earthquakes/world/historical.php

Figure 4. We then compute the *p*-value of the stochastic test as the proportion of the replications with anomaly percentage greater than the corresponding observed one in Figure 4 for various magnitudes 15 d before and after the earthquakes. Note that the *p*-value is used to measure how likely the observed anomaly percentage is obtained when the observed anomaly is simply random. Hence, the smaller the *p*-value means the less likely the observed anomaly percentage being random. Therefore, when the *p*-value is less than, say, 0.05, we can say the observed anomaly percentage is statistical significant.

[11] Figure 5 displays the computed *p*-value of various magnitudes M ≥ 6.0–7.1 within 15 d before and after the earthquakes. It can be seen that the enhancement anomalies on days 14–9, 4 before and days 8–12, 14–15 after as well as the reduction anomalies on day 7, 5–4 before and day 1–6 after about the M ≥ 6.8 earthquakes are statistically significant. These results show that the seismo-ionospheric anomalies occur in Indonesia are rather complex. Nevertheless, the *p*-value on day 5 before the M ≥ 7.0 earthquakes 0.017 indicates that the reduction anomalies before the M ≥ 7.0 earthquakes in Figure 4 and that on 21 December 2004, day 5 before the Sumatra-Andaman earthquake, in Figure 3 are reliable.

3. Spatial Precursor

[12] We apply spatial analyses to further confirm the day 5 before reduction anomaly being related to the Sumatra-Andaman earthquake by extracting the GPS TEC along the longitude of the epicenter 95.95°E (see Figure 2) to produce

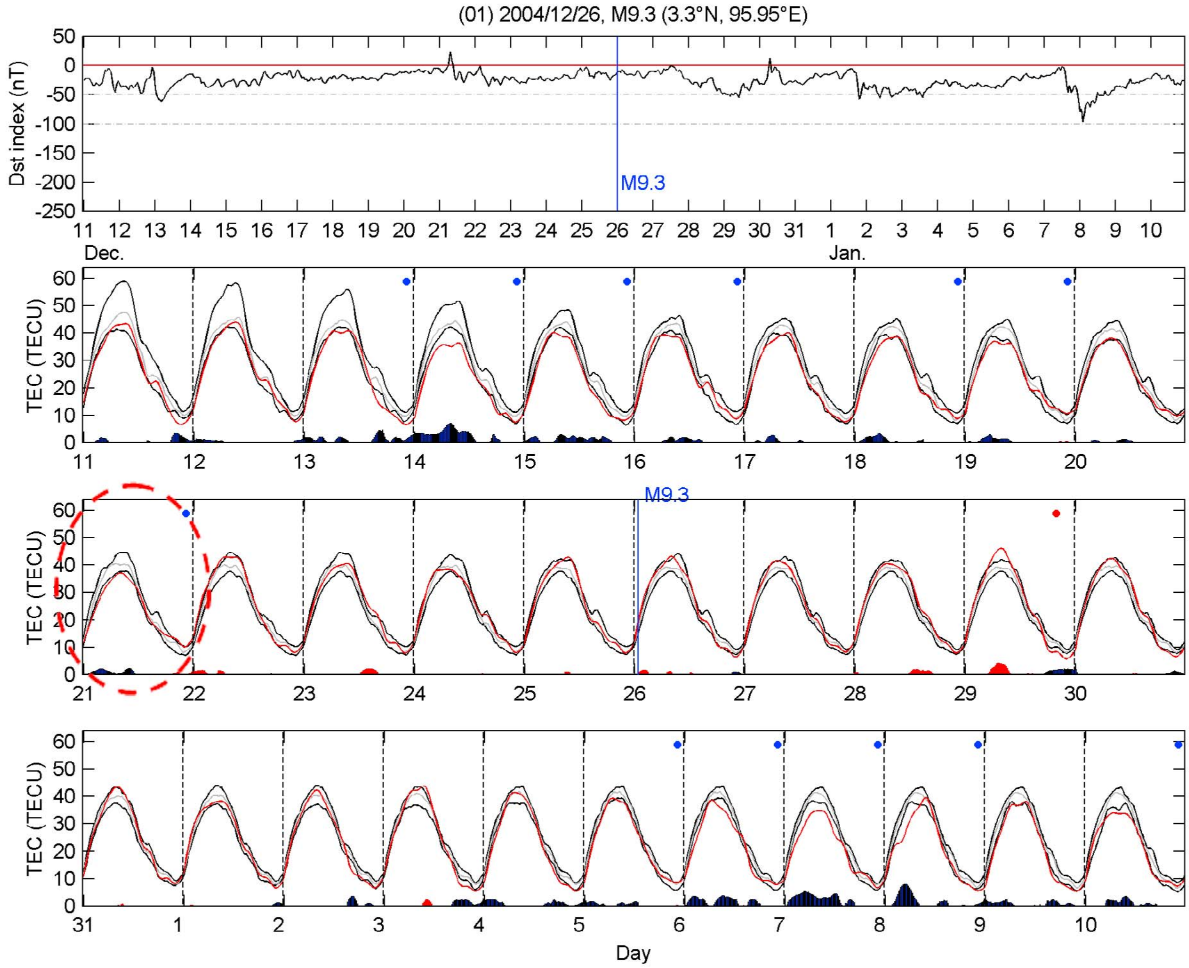

Figure 3. A time series of the GPS TEC right above the epicenter extracted from GIMs 15 d before and after the M9.3 Sumatra-Andaman earthquake. The earthquake occurred at 3.30°N, 95.95°E at 0058:53 UT on 26 December 2004 which is denoted by the vertical line. The top panel displays variations of the Dst index, which shows except a moderate geomagnetic storm with a maximum depression −61 nT occurring on 13 December 2006, the geomagnetic activity being relatively quiet. The red, gray, and two black curves denote the observed GPS TEC, associated median and upper and lower bound (*UB*/*LB*), respectively. Red and blue dots represent the upper and lower anomalous days identified by the computer routine, respectively. Red and black shaded areas respectively denote differences of *O-UB* and *LB-O*, where *O* is observed GPS TEC. The red dashed circle denotes a possible seismo-ionospheric anomaly.

latitude-time-TEC (LTT) plots of the 32 d (including 1–30 d before, the day of, and 1 d after the earthquake) period from 26 November to 27 December 2004 (Figure 6). It can be seen from the LTT plots that the ionospheric GPS TEC between about 20°S and 30°N along the epicenter longitude yields the lowest value during 0400–0800 UT (10:00–14:00 LT in the Sumatra area) on 21 December 2004, which is day 5 before the Sumatra-Andaman earthquake. The reduction anomaly in the temporal/spatial LTT plot (Figure 6) agrees with that in the time series (temporal) TEC over the earthquake epicenter (Figure 3).

[13] To find the spatial distribution of the reduction anomaly detected in Figures 3 and 6, sequences of GIM at three time points of 0400, 0600, and 0800 UT observed 1–30 d (26 November– 25 December 2004) before the earthquake are investigated in detail. We find, for each grid point, the median and the extreme minimum of the 30 d period, which respectively represents the background and the precursor of the three GIM sequences. Figure 7 shows the median, the observed, and difference of the observed from the median at 0400, 0600, and 0800 UT on 21 December 2004 (left panels). It finds that the extreme minimum (GPS TEC reduction) of each grid, where the observation is extremely or significantly lower than the associated median, tends to appear around the Sumatra-Andaman epicenter on 21 December 2004. The Sumatra-Andaman epicenter is at 3.30°N, 95.95°E (−6.72°N, 167.67°E geomagnetic) while the corresponding geomagnetic equator is located at 10.02°N, 95.69°E geographic, and the conjugate point around 6.72°N, 167.67°E geomagnetic (about 16.74°N, 95.69°E geographic). It can be seen that the extreme minima form a “closed lip-shape” being approximately symmetrical

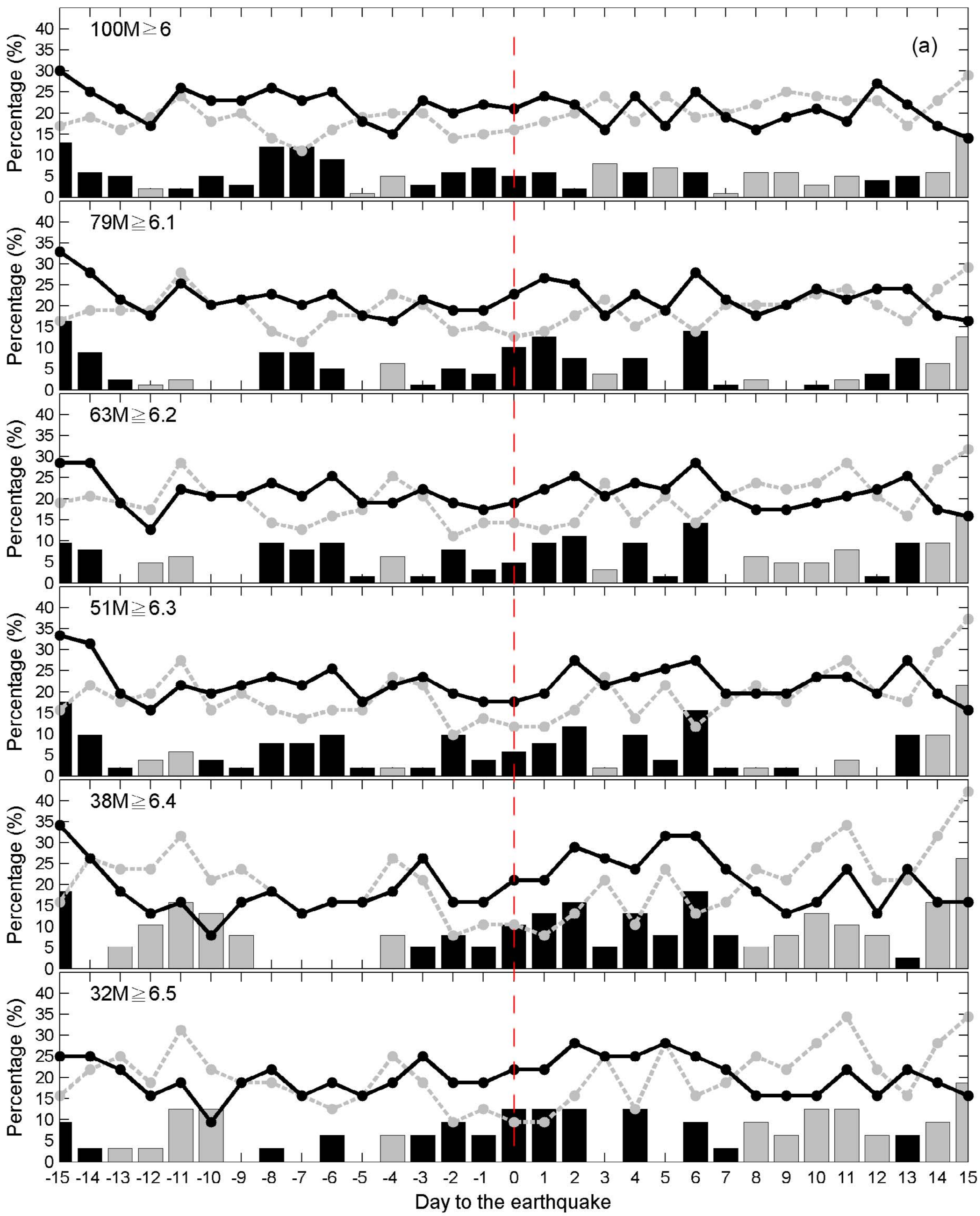

Figure 4. Percentages of the upper and lower anomalous days appear 15 d before and after the 100 M ≥ 6.0 earthquakes in Indonesia during 1 May 1998 to 31 December 2008. (a) M ≥ 6.0–6.5 and (b) M ≥ 6.6–7.1. The percentage is the cumulative counts of the anomaly dividing by the numbers of the earthquakes. The red line denotes the earthquake day. Dashed gray and solid black curves denote percentages of the upper and lower anomalous days, respectively. The vertical black and black bars denote the difference in percentage between the reduction and enhancement precursors. The black (gray) stands bar stands for that the percentage of the reduction minus that of the enhancement (of the enhancement minus that of the reduction).

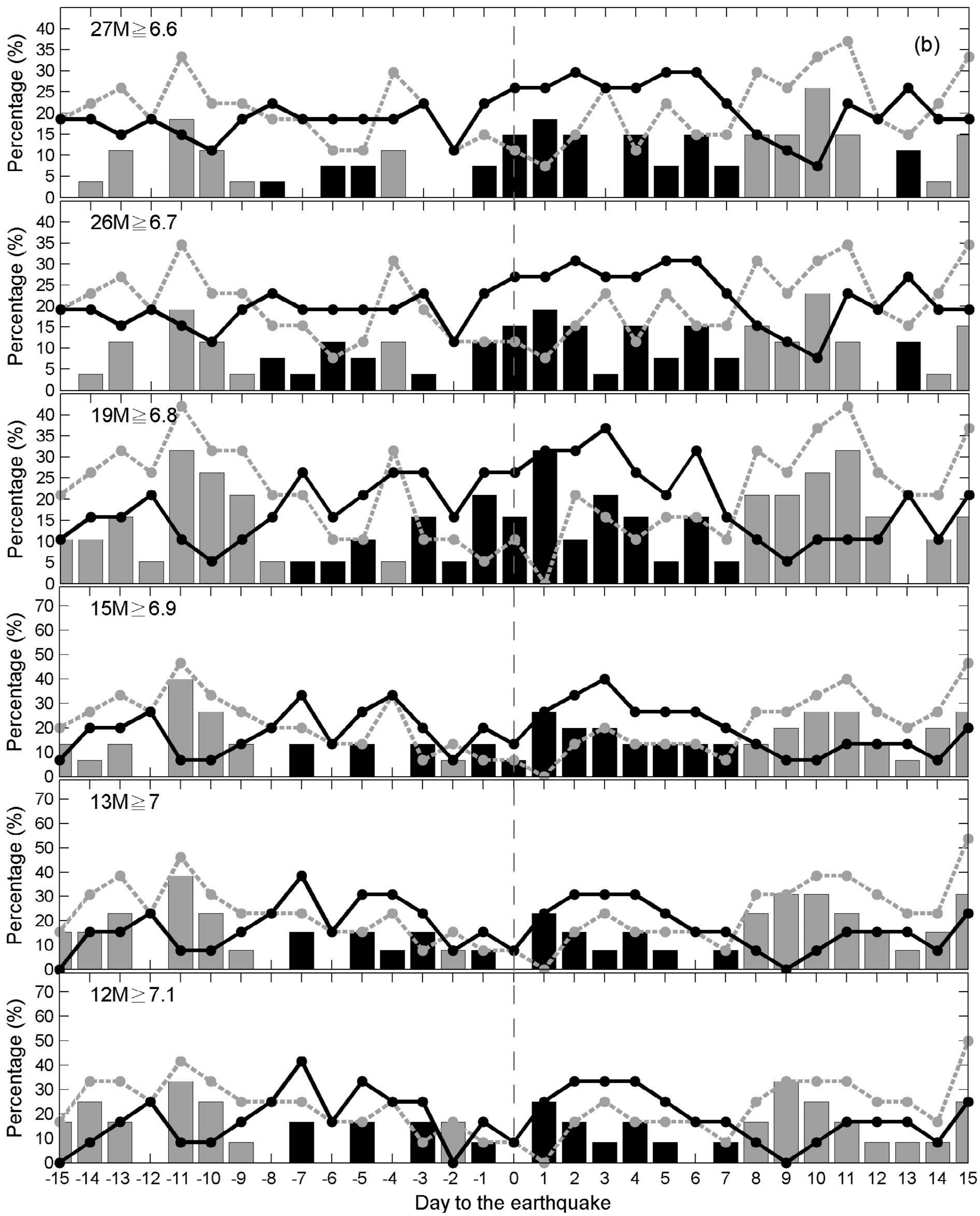

Figure 4. (continued)

to the epicenter latitude at 0400 and 0600 UT, and an "open lip-shape" to the magnetic equator at 0800 UT. Taking into account possible local time effects, sequences of GIMs at the fixed global local time of 10:00, 12:00, and 14:00 LT during the 30 d period are studied by the same process (right panels in Figure 7). We again observe that the extreme minima forming with the open lip-shape appear in symmetrical to the magnetic equator at the global fixed 10:00

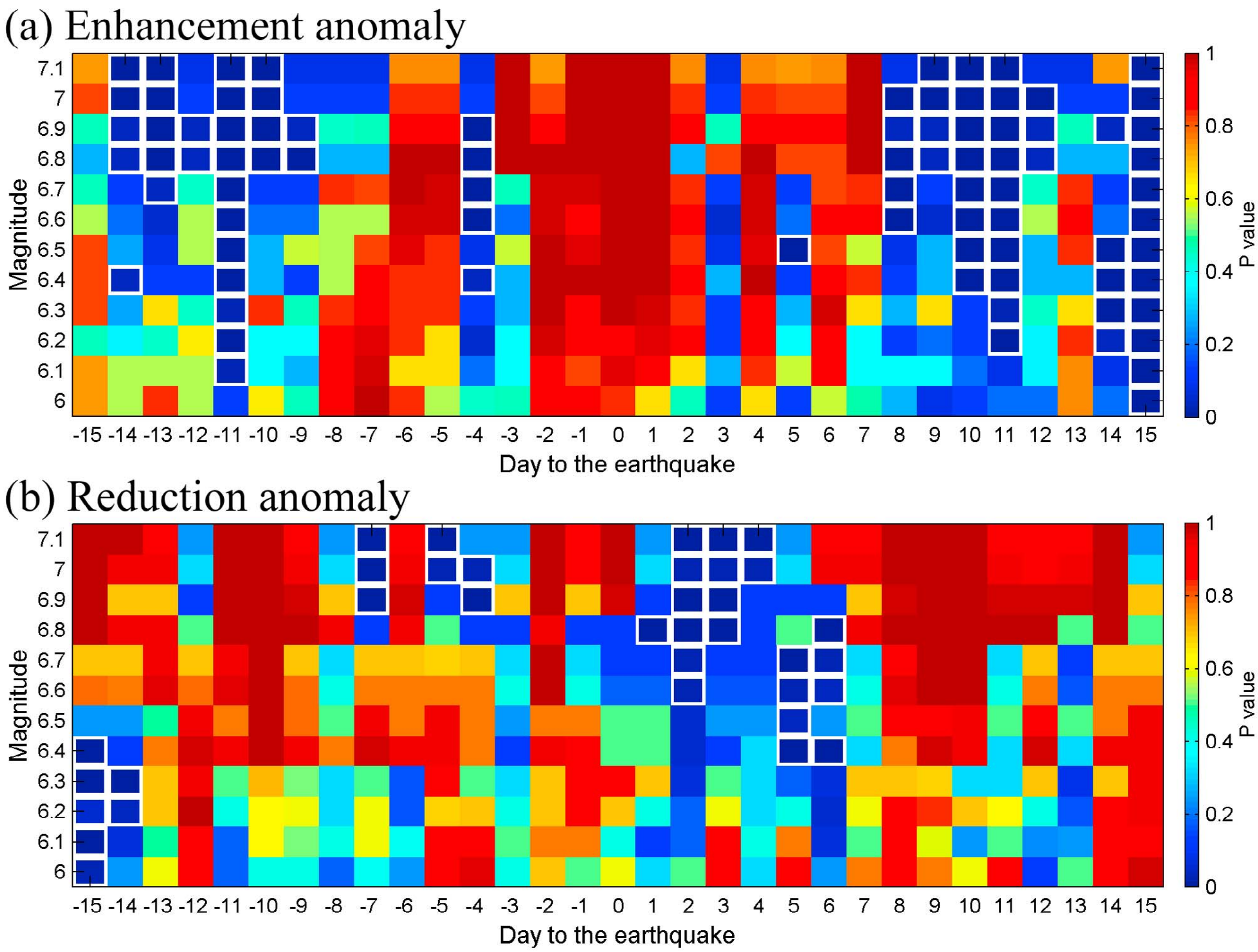

Figure 5. The p-value of various magnitudes 15 d before and after the 100 earthquakes computed by randomizing 10,000 times of the stochastic test. (a) The enhancement anomaly, and (b) the reduction anomaly. The white hatched symbol denotes the p-vale less than 0.05, which is statistically significant.

and 14:00 LT, and those with the closed lip-shape to the epicenter latitude at the 12:00 LT. These lip-shape extreme minima approximately lie about ±20°N (2.5° × 8 y-grid) from the epicenter (3.30°N, 95.95°E), which are approximately equivalent to 4400 (110 km/° × 2 × 20°) km in latitude. On the other hand, the extreme minima of the lip-shape anomaly range from 4950 to 9900 km (45°E to 90°E) in the longitudinal direction and shifts westward. *Dobrovolsky et al.* [1979] show 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. For the M9.3 Sumatra-Andaman earthquake, we obtain R = 10,000 km (Figure 6). The preparation area with a diameter of about 20,000 ($2R$) km is, which is approximatly one half of the Earth's circumference 20,002 (3.14 × 6370) km, about four times in the latitudinal and two times the longitudinal direction greater than the lip-shape region of the extreme minima observed in this paper. Note that the extreme minima persistently appears around the epicenter while those outside of the estimated preparation zone do not constantly exist elsewhere.

4. Discussion and Conclusion

[14] The TEC derived from the GIM and/or ground-based GPS receiver networks are ideally used to observe the

Figure 6. A sequence of daily latitude-time-TEC plots along the Sumatra-Andaman earthquake longitude 95.95°E during the 30 d period of 26 November to 27 December 2004. Each plot is constructed by twelve 2 hr GIMs from 0000 to 2400 UT. For the same latitude of the two selected grid points between 90°E and 100°E are averaged to stand for TEC value in the 95.95°E earthquake longitude. Since each time interval has 12 latitudinal grid points between 30°N and −30°N, each daily plot has 144 (12 × 12) grid points. The horizontal axis denotes the universal time (UT). It can be seen that the TEC crests on 21 December (red dashed rectangle) yield the lowest values during about 0600–1000 UT (or 12:00–16:00 LT at Sumatra, Indonesia). Note that, along the Sumatra longitude 95.95°E, LT = UT + 06:00. Therefore, the GPS TEC anomalously reduces during the afternoon period of 12:00–16:00 LT on 21 December 2004.

temporal and spatial variations simultaneously. The temporal variations are useful in finding the duration and the lead time of the seismo-ionospheric precursors. Figure 3 reveals that the reduction anomalies appearing in the noon and afternoon period of 13–16 and 18–19, 21 December are possibly associated with the 13 December moderate geo-

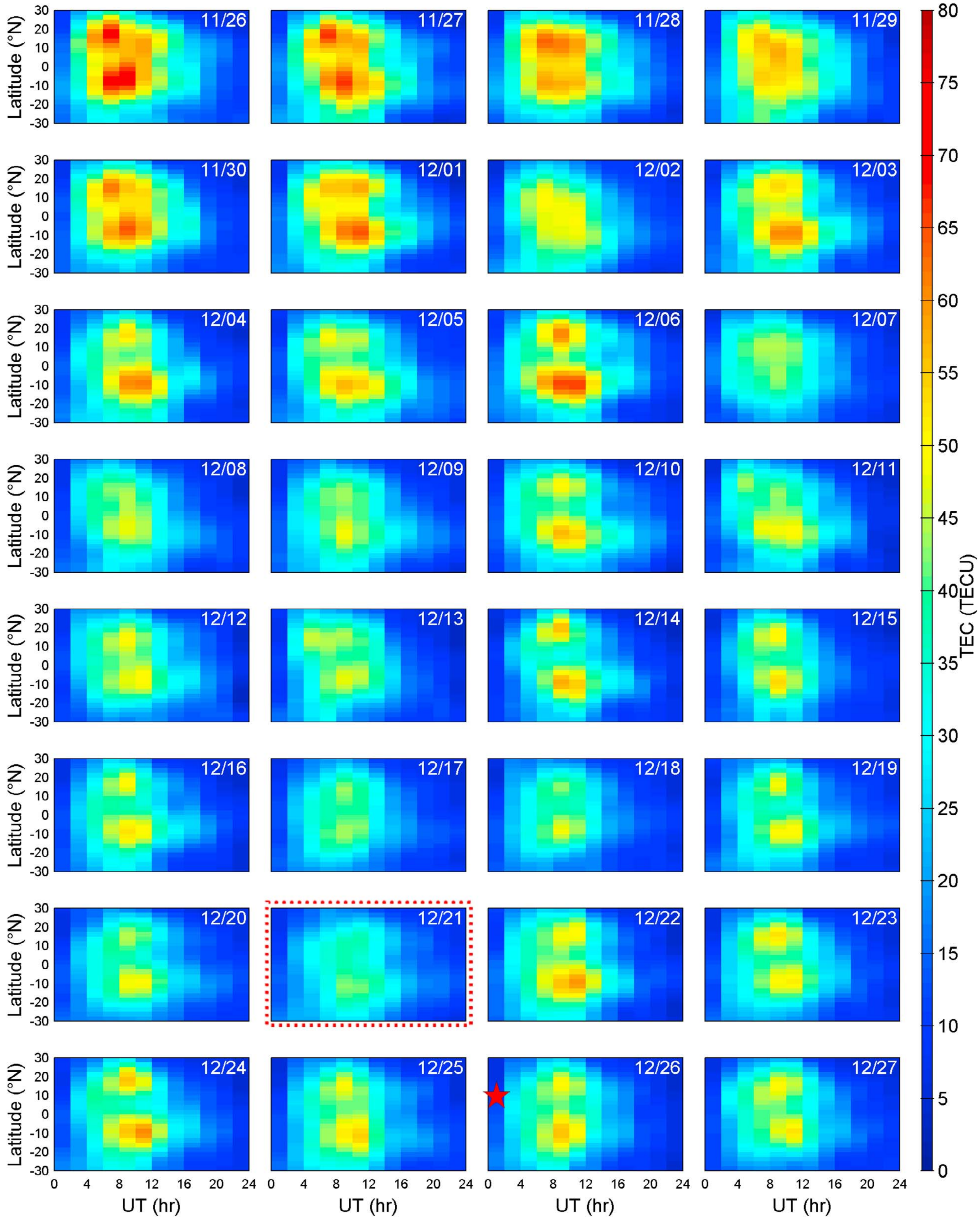

Figure 6

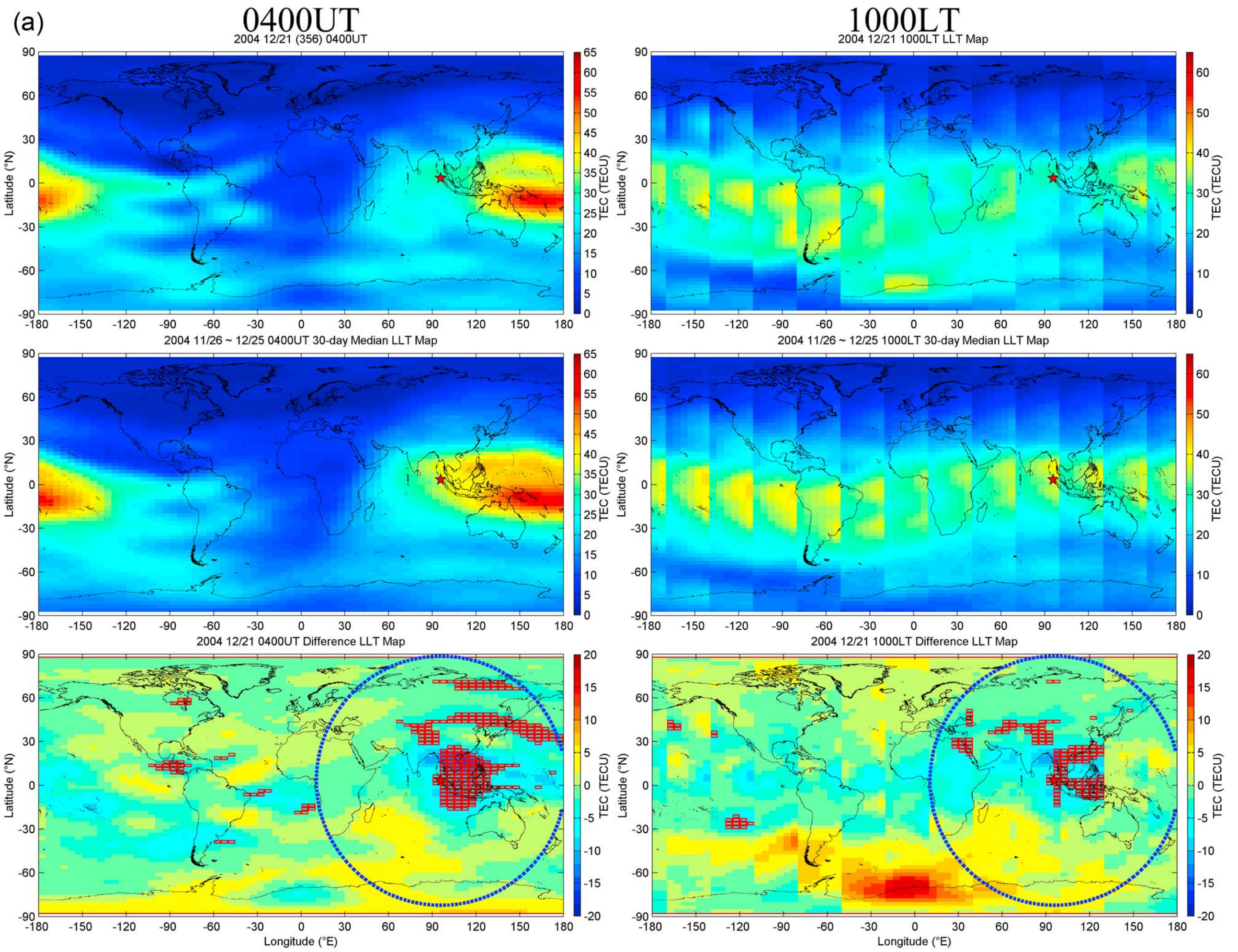

Figure 7. The observation, the 30 d median, and the difference between the two on 21 December 2004. (a) 0400 UT and fixed global 10:00LT, (b), 0600 UT and fixed global 12:00 LT, and (c) 0800 UT and fixed global 14:00 LT. LT = UT + 6 hr at Sumatra. The median at each grid point is computed from 1–30 d before the Sumatra-Andaman earthquake, 26 November–25 December 2004. The color bards of the top and middle panels stand for the observation on December 21, 2004 and the median in the TEC unit (1 TECu = 10^{16} el m^{-3}), respectively, while those of the bottom panels denote the differences of observation from median. The hatched area in red denotes the extreme minimum at each grid point during 1–30 (24 November to 25 December 2004) days before the earthquake. The blue dashed circle with the radius R = 10,000 km stands for the earthquake preparation area of the lithosphere [*Dobrovolsky et al.*, 1979].

magnetic storm and the Sumatra-Andaman earthquake, respectively. The cumulative results of the 100 M $\geq$ 6.0 earthquakes in Indonesia of Figure 4 reveal that the reduction anomalies appear more frequently days 1–7 before and after the M $\geq$ 6.8 earthquakes. The stochastic test of Figure 5 reveals that the reduction anomalies on day 15–14, 7, and 5–4 before and day 1–6 after the M $\geq$ 6.8 earthquakes are statistically significant. The *p*-value on day 5 before the M $\geq$ 7.0 earthquakes 0.017 in Figure 5 indicates that the reduction anomalies on 21 December are most likely related to the Sumatra-Andaman earthquake. The LTT plots of Figure 6 demonstrate that the GPS TECs around the epicenter latitudes on 21 December yield their extreme minima in 1–30 d before the earthquake. The GPS TEC variations in Figure 3 and the LTT plots in Figure 6 indicate that the seismo-ionospheric reduction anomalies last about 6 hr, 0004–0008 UT (00:10–00:14LT in Sumatra) on 21 December 2004. To find whether the observed reduction anomaly on 21 December 2004 is a coincident result from other geophysical casuals, the spatial distributions of the anomalies are examined. Figure 7 shows that the anomaly persistently appears around the epicenter at the three universal and fixed global local times on 21 December 2004. These strongly suggest that the anomaly is the seismo-ionospheric precursor of the Sumatra-Andaman earthquake.

[15] A detailed study of Figure 6 shows that the northern and southern lip tend to be symmetric to either the epicenter at 0400 UT; 0600 UT, and 12:00 LT or the geomagnetic equator at 10:00 LT, 0800 UT, and 14:00 LT. These indicate that both the geographic (or epicenter, earthquake prepara-

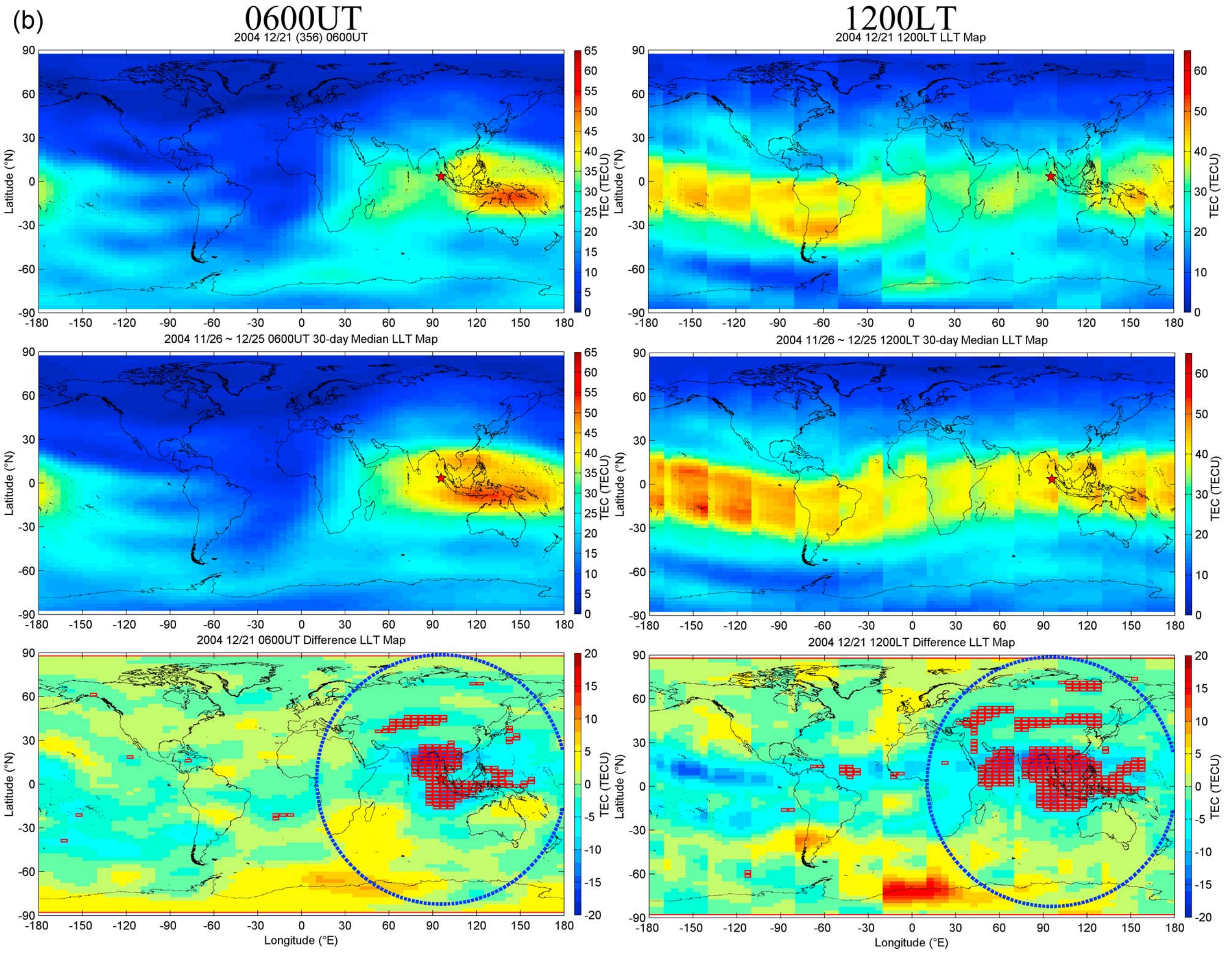

Figure 7. (continued)

tion) and geomagnetic (or equator, conjugate) effects should be taken into account. The daily plasma **E** × **B** fountain, where **E** is the dynamo-electric field and **B** is the Earth's magnetic field respectively in the horizontal eastward and northward direction, at the geomagnetic equator, becomes pronounced at 09:00–10:00 LT and diminishes at about 17:00–18:00 LT [*Hanson et al.*, 1966]. The two EIA (equatorial ionization anomaly) crests are a result of the uplift of the ionospheric plasma fountain at the equator to the apex of the magnetic field line and the subsequent diffusion down along the field lines to higher latitudes [*Namba and Maeda*, 1939; *Appleton*, 1946]. *Liu et al.* [2010] statistically investigated variations of the EIA crest of the GPS TEC associated with 150 $M \leqq 5.0$ earthquakes in Taiwan during 2001–2007, and found that the EIA crest significantly moves equatorward and appears in an earlier time of the afternoon period 5 d before the earthquakes. They propose that seismo-environment changes or/and seismo-electromagnetic signal appearances around the epicenter during the earthquake preparation period, which are mapped along the Earth's magnetic field lines, perturb the dynamo-electric field, and in turn affect the plasma fountain and the EIA in the ionosphere. Figure 7 reveals that the lip-shape precursor around the epicenter, located closely to and/or almost coincidently with the two EIA crests, appears in time zones up to 6 hr, 10:00–14:00 LT in Sumatra. The coincidence in the local times of the precursor (or the reduction anomaly) occurrence and the equatorial plasma fountain indicates that the electromagnetic environment and the dynamo-electric field have been changed and perturbed.

[16] Meanwhile, *Ouzounov et al.* [2005] examined outgoing long-wavelength radiations (OLR) by means of satellite thermal infrared observed by NOAA/AVHRR, MODIS. They compared the reference fields for the months of December between 2001 and 2004, and report strong OLR anomalous +80 W m^{-2} signals exceeding two standard deviation σ along the epicentral area on 21 December 2004, 5 d before the event. The coincidence between the OLR and the GIM TEC again indicates that the seismo-electromagnetic environment around the epicenter changes before the Sumatra-Andaman earthquake.

[17] The rupture length of the earthquake over 1150 km [*Kruger et al.*, 2005] confirms that the preparation area of the M9.3 Sumatra-Andaman earthquake can be at least as

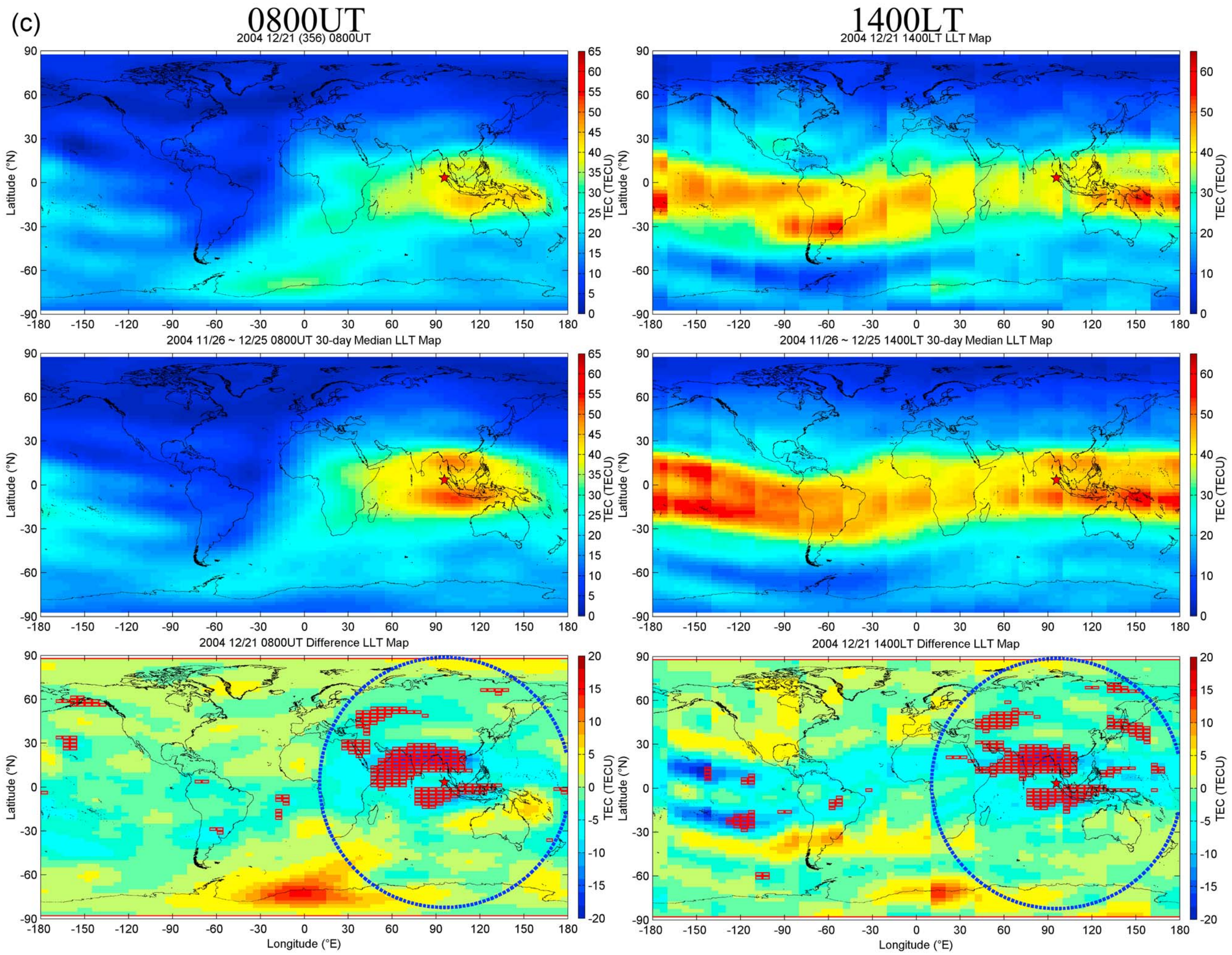

Figure 7. (continued)

large as about thousands of kilometers in radius from the epicenter. Therefore, if there are any leakages of the energies cumulated during the earthquake preparation, which might be in various forms, such as thermal, electric, magnetic, electromagnetic, etc. [*Hayakawa and Molchanov*, 2000], they could easily disturb the atmospheric dynamo-electric field, significantly reduce the fountain effect, and anomalously decrease ionospheric TEC, about 40s% to the median, on 21 December 2004. In conclusion, with robust statistical analyses of the median/quartile-base and the stochastic test, the temporal and spatial precursors of the GPS TEC show that the seismo-electromagnetic environment around the epicenter has significantly changed on day 5 before the Sumatra-Andaman earthquake. To indentify seismo-ionospheric precursors, both temporal and spatial statistical analyses are required. The results confirm that the seismo-electromagnetic environment changes and the ionospheric conjugate effects play important roles.

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