

Ionospheric GPS TEC Anomalies and $M \geq 5.9$ Earthquakes in Indonesia during 1993 - 2002

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ABSTRACT

Indonesia is one of the most seismically active regions in the world, containing numerous active volcanoes and subject to frequent earthquakes with epicenters distributed along the same regions as volcanoes. In this paper, a case study is carried out to investigate pre-earthquake ionospheric anomalies in total electron content (TEC) during the Sulawesi earthquakes of 1993 - 2002, and the Sumatra-Andaman earthquake of 26 December 2004, the largest earthquake in the world since 1964. It is found that the ionospheric TECs remarkably decrease within 2 - 7 days before the earthquakes, and for the very powerful Sumatra-Andaman earthquake, the anomalies extend up to about 1600 km from the epicenter.

Key words: GPS TEC (Total Electron Content), Pre-earthquake-related anomaly, The Sulawesi earthquakes, The 2004 Sumatra-Andaman earthquake

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1. INTRODUCTION

Indonesia is recognized as one of the most seismically active regions in the world. Although many causes contribute to the geological instability of the area, the main cause is friction between the underlying tectonic plates. Most of Indonesia sits on the Eurasian Plate. When the Eurasian Plate collides with the Indo-Australian Plate to the south and east or the Philippine and Caroline plates to the northeast, the latter of each of these plates slides beneath the Eurasian Plate. The pressure causes geological activity on the Earth's surface that often takes the form of earthquakes or volcanoes.

Regarding Indonesia as a seismically active region, we examine pre-earthquake ionospheric anomalies by total electron content (TEC) derived from a ground based receiver of the Global Positioning System (GPS). GPS receivers can be used to simultaneously and continuously monitor the TEC (for example, Sardon et al. 1994; Leick 1995; Liu et al. 1996). Many electromagnetic phenomena

possibly associated with seismic activities have been extensively discussed in the literature (e.g., Hayakawa and Fujinawa 1994; Hayakawa 1999; Hayakawa and Molchanov 2002; Hattori 2004). Scientists have observed anomalies appearing in electron densities of the ionospheric F region a few days before some strong earthquakes (Pulinets et al. 1994; Pulinets 1998; Liu et al. 2000). Liu et al. (2000, 2006) examined ionospheric plasma frequency (or electron density) recorded by a local ionosonde and found that the critical frequency of the F2-peak, foF2, significantly decreased a few days prior to most of the $M \geq 6.0$ and $M \geq 5.0$ earthquakes in the Taiwan area during 1994 - 1999.

Recently, scientists have found an apparent reduction in GPS TEC a few days prior to some strong earthquakes (selected, e.g., Calais and Minster 1995; Liu et al. 2001, 2002, 2004). Case studies are carried out in this work to investigate pre-earthquake ionospheric anomalies by TEC during the Sulawesi earthquakes of 1993 - 2002, and the very powerful Sumatra-Andaman earthquake of 26 December 2004. Analyses of the observed data allow us to find seismo-ionospheric signatures prior to the earthquakes.

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2. INSTRUMENTATION AND DATA ANALYSIS

The ionospheric GPS TEC derived by using dual frequency measurements of three ground-based GPS stations, Sampali (3.62°N, 98.71°E), Bako (6.49°S, 106.85°E), and Parepare (3.98°S, 119.65°E) during the $M \geq 5.9$ Sulawesi earthquakes of 1993 - 2002, and the Sumatra-Andaman earthquake of 26 December 2004 are examined.

The GPS consist of 24 satellites, evenly distributed in 6 orbital planes around the globe at an altitude ~ 20200 km. Each satellite transmits signals on two frequencies ($f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz) with two different codes, P1 (or C/A) and P2 and two different carrier phases, L1 and L2. Since the ionosphere is a dispersive medium, the speed of propagation of the electro-magnetic waves transmitted by the GPS satellites depend on the frequency of radio waves. The carrier phase advance and group delay of GPS transmitted radio waves in the ionosphere is proportional to electron content integrated along the propagation path. One can derive TEC by comparing the phase delays of the L1 and L2 signals. Since the ionosphere is a dispersive medium, it is possible to evaluate the ionospheric effect by measuring modulations on carrier phases and phase codes recorded by dual-frequency receivers (Sardon et al. 1994; Leick 1995; Liu et al. 1996). From recorded broadcast ephemeris and a given sub-ionospheric height of 325 km, the slant TEC along the ray path can be converted into the vertical TEC (VTEC) at its associated longitude and latitude (Tsai and Liu 1999) every 30 s.

To identify abnormal signals and to avoid effects around or after the earthquake date, we compute the median \tilde{X} of the previous 15-day VTECs and the associated inter-quartile range (IQR), to construct an upper boundary, $\tilde{X} + \text{IQR}$, and lower boundary, $\tilde{X} - \text{IQR}$, at a certain local time. Under the assumption of a normal distribution with mean μ and stan-

dard deviation σ for the VTEC, the expected value of \tilde{X} and IQR are μ and 1.34σ , respectively. If an observed VTEC falls out of either the associated lower or upper boundary, we declare with a confidence level of about 80 - 85% that a lower or upper abnormal signal is detected.

3. RESULTS AND INTERPRETATION

3.1. The Sulawesi Earthquake during 1993 - 2002

Among 11 Sulawesi earthquakes recorded during 1993 - 2002, the biggest and most destructive earthquake struck Northern Sulawesi (1.10°N, 123.57°E), Indonesia at 0421 UT on 4 May 2000 with magnitude M_w 7.6 and depth 26 km (see Table 1 and Fig. 1). Figures 2 a and 3a illustrate anomalous decreases in GPS TEC at Parepare on April 28, 29, and May 2; i.e., 2, 5, and 6 days, respectively, before the earthquake. We find the intercept between the TEC slant and thin shell ionosphere at 325 km altitude to determine the location of the vertical TEC (latitude, longitude). The vertical axis is automatically the VTEC-Latitude. The time difference, delta_T , between the VTEC longitude, VTEC_long , and the receiver longitude, RECE_long , are further computed by $(\text{VTEC_long} - \text{RECE_long}) / 15$ degree. Thus, the VTEC located in the east (west) side of the receiver is ahead (behind) of the receiver observational time. Note that one hour is equivalent to 15 degrees in longitude. Therefore, the horizontal axis, $\text{Time} = \text{UT} + \text{delta_T}$ for each VTEC. In this computation, we use satellites with elevation angles smaller than about 20 degrees. The vertical and horizontal resolutions are 0.01 degrees and 30 seconds, respectively.

In order to clarify those anomalies, we further compare the TEC variations observed by the Parepare GPS receiver and those by the Sampali GPS receiver, which is located on Sumatra Island far away from the epicenter (see Fig. 4).

Table 1. The parameters of $M \geq 5.9$ Sulawesi earthquakes during 1993 - 2002 with identified Seismo-Ionospheric TEC precursors.

YY	MM	DD	hh	mm	sec	latitude	longitude	depth (km)	M	precursor
1993	12	09	04	32	20	0.49	125.99	25	6.9	D-3
1995	05	19	21	30	06	-1.21	120.50	26	5.9	D-4
1996	01	01	08	05	11	-0.73	119.93	24	7.5	D-7, D-6, D-3
1996	07	16	10	07	37	-1.02	120.25	33	6.6	D-5
1996	07	22	14	19	36	1.00	120.45	33	7.0	D-4, D-3
1997	09	28	01	38	29	-3.78	119.73	33	5.9	D-2
1997	11	25	12	14	34	1.24	122.54	24	7.0	D-4, D-2
1998	05	21	05	34	26	0.21	119.58	33	6.6	D-3
2000	05	04	04	21	16	-1.11	123.57	26	7.6	D-6, D-5, D-2
2001	10	19	03	28	44	-4.10	123.90	33	7.5	D-7, D-5
2002	08	15	05	30	26	-1.19	121.33	10	6.2	D-2

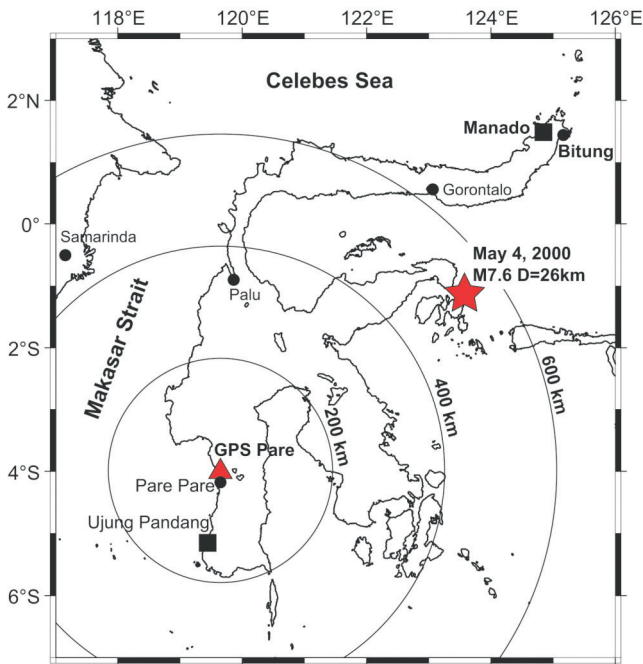


Fig. 1. The location of the GPS receiver and the epicenter of the Northern Sulawesi Earthquake on 4 May 2000. The star and triangle symbols denote the epicenter and Parepare GPS receiver, respectively.

Figures 2 and 3 reveal that the anomalies do not appear in TEC variations observed by the Sampali GPS receiver. Using a similar approach, we identify the seismo-ionospheric TEC precursors or decreases of the Sulawesi earthquakes during 1993 - 2002. Table 1 lists the occurrence time, location, depth, and magnitude of the $M \geq 5.9$ Sulawesi earthquakes during 1993 - 2002 (from USGS catalog; <http://earthquake.usgs.gov>) as well as the days on which the associated precursors appeared. Here, the earthquakes are within an epicentral distance less than 500 km from Parepare. The last column in Table 1 indicates the date before each earthquake when the TEC precursors appeared; for example, D-2 means 2 days before the earthquake. Note that each earthquake generally has at least one precursor day while the large earthquakes ($M \geq 7.0$) can yield two or three precursor days.

3.2. The Sumatra-Andaman Earthquake of 26 December 2004

The Sumatra-Andaman earthquake of 26 December 2004, was the fourth largest earthquake in the world since 1900 and is the largest since the 1964 Prince William Sound,

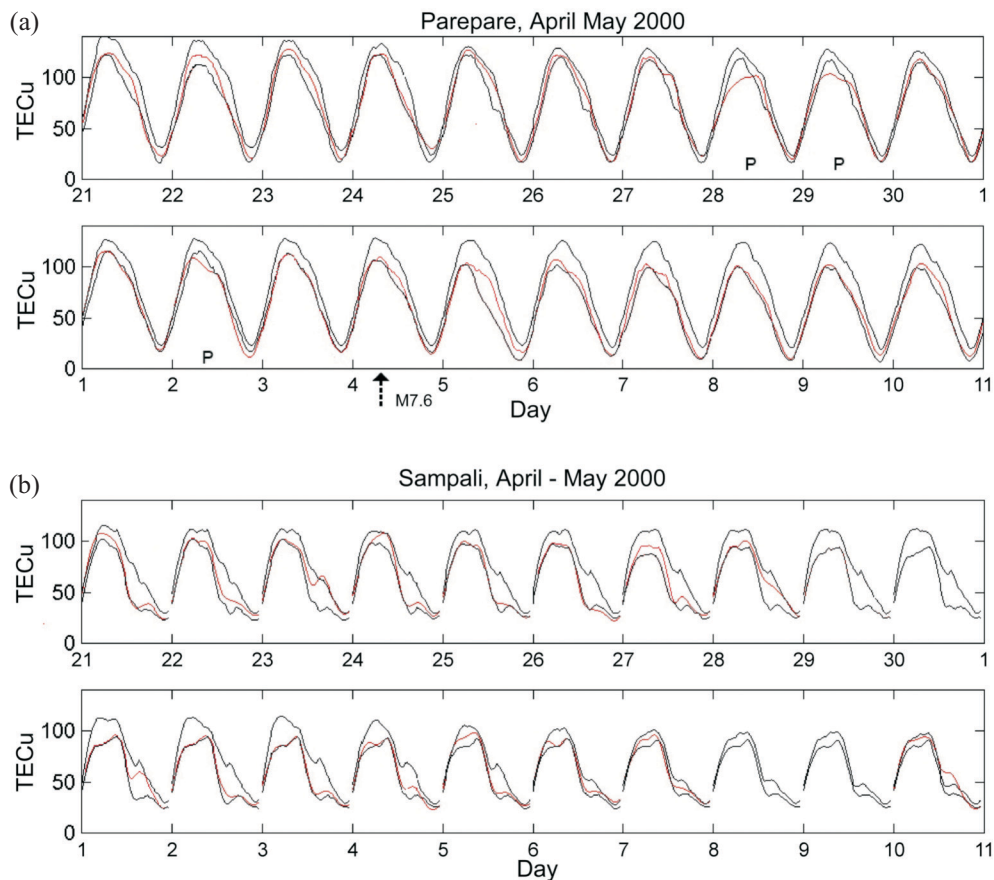


Fig. 2. The variation of VTEC observed by: (a) Parepare and (b) Sampali GPS receivers during the period of 21 April - 10 May 2000. No data observation at Sampali on 29 - 30 April and 8 - 9 May 2000. The red, solid curves and the P character denote the observed VTEC, upper/lower bounds and detected seismo-ionospheric anomalies, respectively.

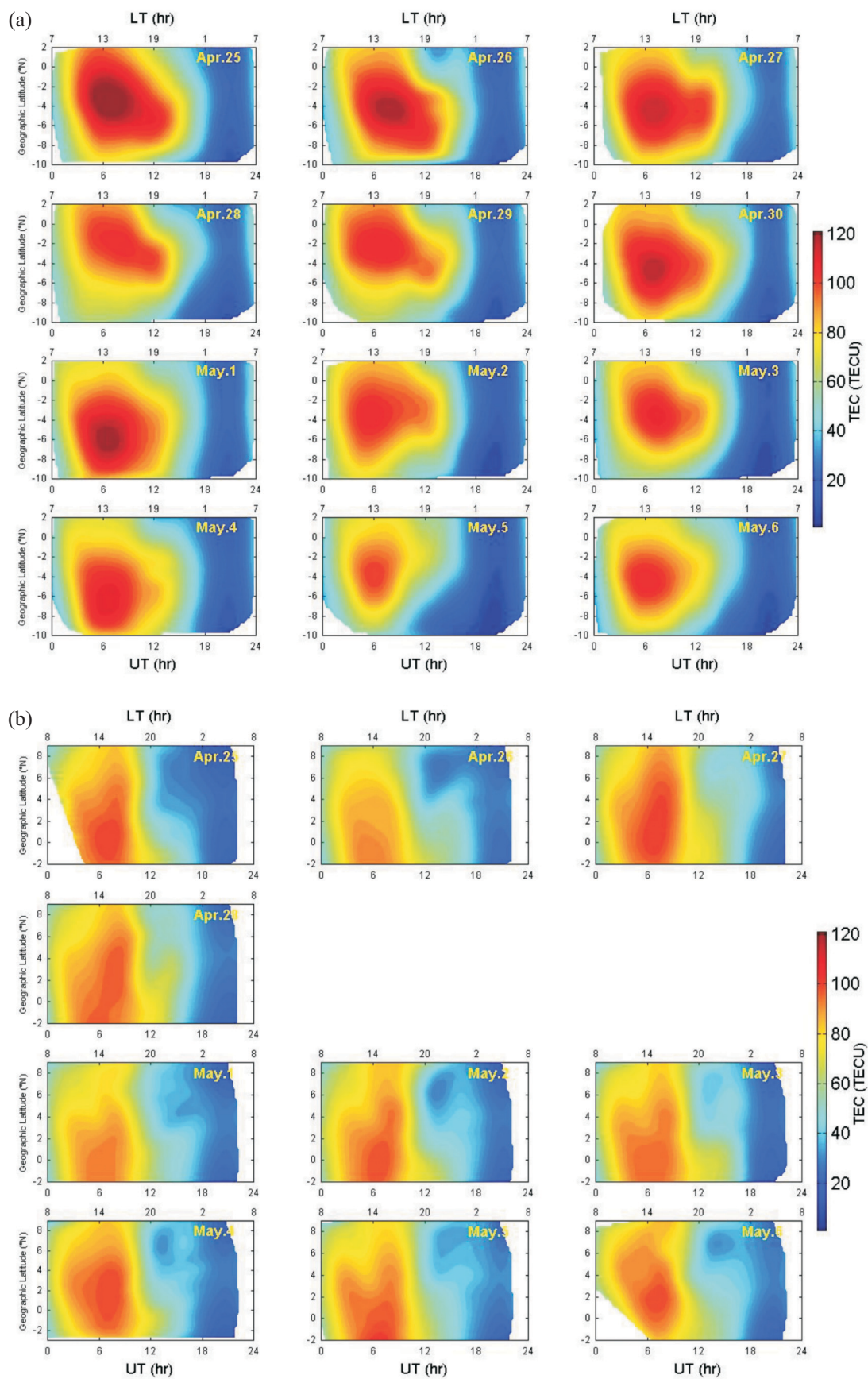


Fig. 3. Contour charts of VTEC observed by: (a) Parepare and (b) Sampali GPS receivers during the period of 21 April - 10 May 2000. No data observation at Sampali on 29 - 30 April and 8 - 9 May 2000.

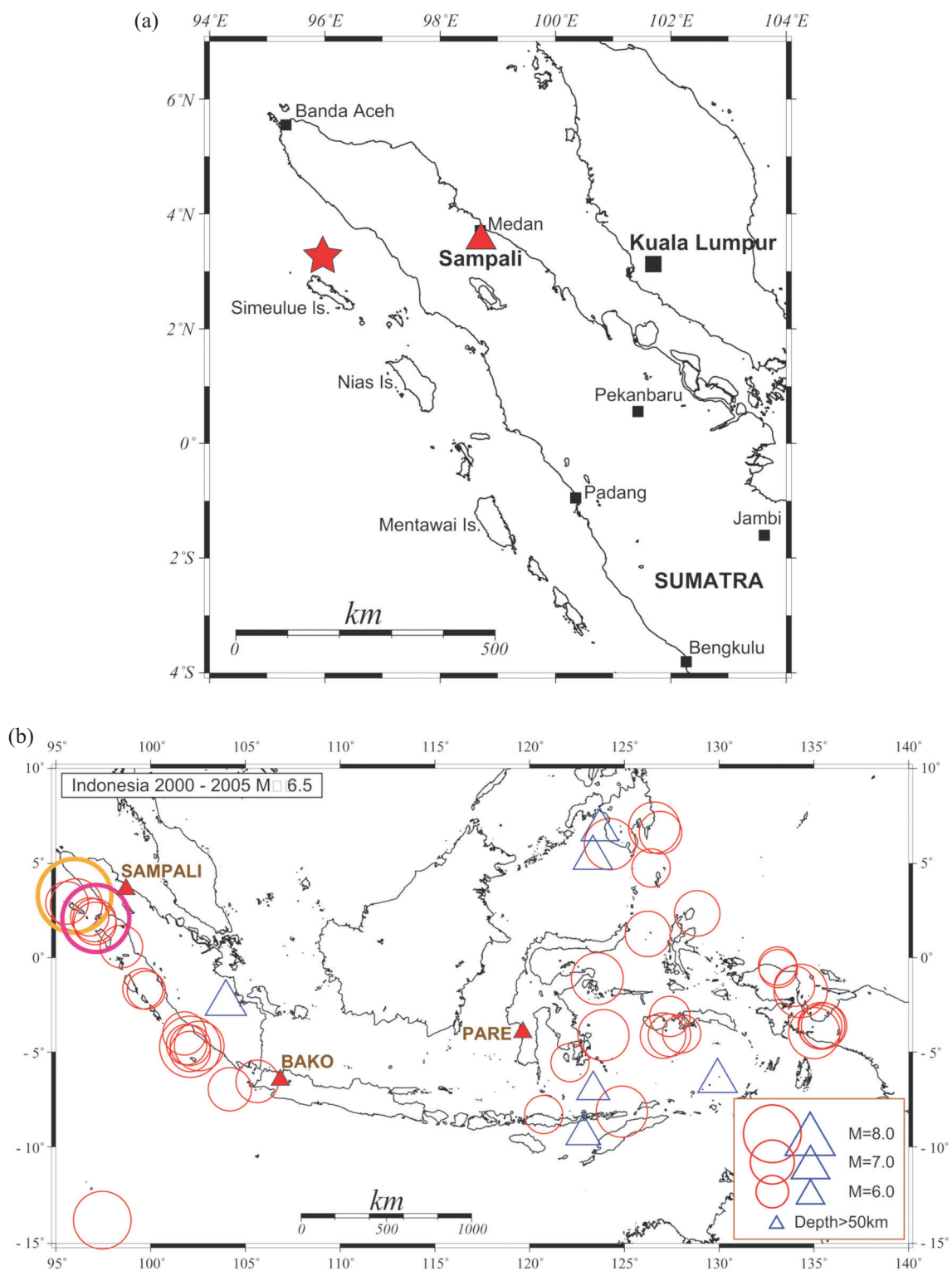


Fig. 4. The location of the GPS receiver and the epicenter of the Sumatra-Andaman Earthquake on 26 December 2004. (a) The star and triangle symbols denote the epicenter and Sampali GPS receiver, respectively. (b) The triangle symbols denote the epicenter and GPS receivers at Sampali, Bako, and Parepare and seismicity map of Indonesia, 2000 - 2005 ($M > 6.5$).

Alaskan earthquake. It occurred off the west coast of Northern Sumatra (3.30°N , 95.96°E) near Banda Aceh, Indonesia at 0058 UT 26 December 2004 with magnitude M 9.3 and

30 km depth (see Fig. 4). It can be seen that anomalous decreases in TEC at Sampali appear on December 14, 15, 19, and 21 (see Figs. 5a, 6a). Figure 6 is plotted in the same man-

ner as Fig. 3. By contrast, the anomalies on December 19 and 21, 5 and 7 days before the earthquake, might be anomalies of the Sumatra-Andaman earthquake. Since a geomagnetic storm's sudden commencement (SSC) on December 11, the anomalies appearing on December 14 and 15 could be geomagnetic storm related phenomena. To verify all this, we further compare TEC variations observed by the Sampali GPS receiver and the Bako GPS receiver, which are located about 1600 km from the epicenter (see Figs. 5, 6). It is surprising to find that the Bako GPS receiver also detected an anomaly on December 21. This reflects the power of the 2004 Sumatra-Andaman earthquake being so great that its associated preparation area was huge.

4. DISCUSSION AND CONCLUSION

We have investigated pre-earthquake ionospheric anomalies using GPS TEC data for Sulawesi earthquakes from 1993 - 2002, and the Sumatra-Andaman earthquake on 26 December 2004. The results show that anomalous decreases in GPS TEC occurred within 2 - 7 days before these earthquakes; an observation which generally agrees with previous observations in Taiwan (Liu et al. 2001, 2002,

2004). Hobara and Parrot (2005) demonstrate one clear example of such an anomaly in association with the 1968 powerful Hachinohe earthquake (M 8.3) in Japan, and confirm that a region of disturbed TEC was detected up to about 1500 km from their particular event. Our results show very close similarities in comparison to their work in that the precursory anomalies associated with the very powerful Sumatra-Andaman earthquake (M 9.3) extend to about 1600 km away from the epicenter. This scale seems to be smaller than that expected from an empirical formula by Dobrovolsky et al. (1979).

Many coupling mechanisms between the lithosphere, atmosphere, and ionosphere, dirty plasma diffusion, atmospheric gravity waves, and vertical electric fields generated during earthquake preparation periods have been proposed to explain seismo-ionospheric anomalies. Molchanov and Hayakawa (1998) have reported that the effect of gravity waves turbulence leading to ionospheric perturbation based on the observation of VLF (very low frequency) subionospheric signals. These gravity waves are considered to be generated by gas release from the crust above the earthquake preparation region (Pulinets et al. 1994). Freund (2000) finds that mobile positive holes can be activated in the crust

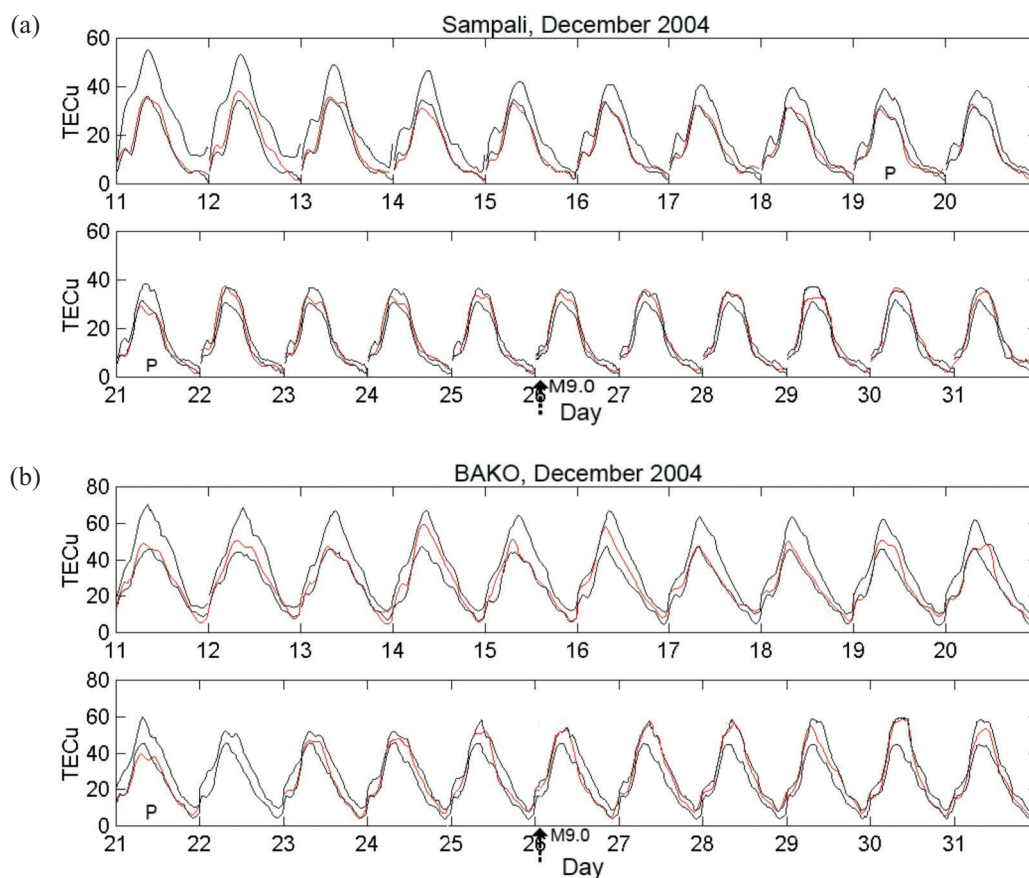


Fig. 5. The variation of VTEC observed by: (a) Sampali and (b) Bako GPS receivers during the period of 21 April - 10 May 2000. No data observation at Bako on 22 December 2004. The red, solid curves and the P character denote the observed VTEC, upper/lower bounds and detected seismo-ionospheric anomalies, respectively.

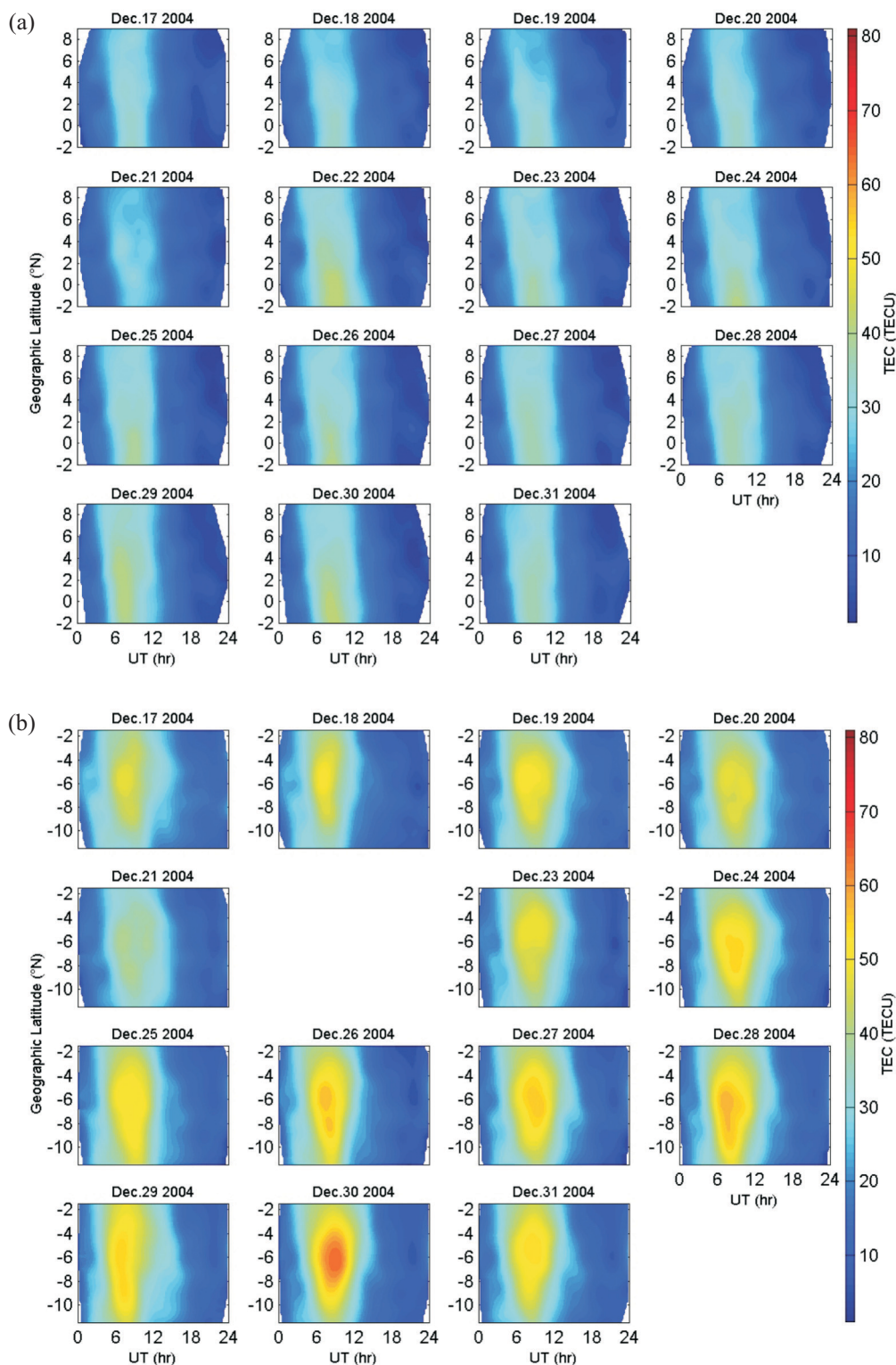


Fig. 6. Contour charts of VTEC observed by: (a) Sampali and (b) Bako GPS receivers during the period of 17 - 31 December 2004. No data observation at Bako on 22 December 2004.

by microfractures during the dilatancy stage of earthquake preparation and outflow from these holes generates high electric fields at the earth's surface. The most promising phenomena relating to seismo-ionospheric anomalies is due

to mechanical stresses in porous rocks prior to an earthquake's onset causing electrical charges to flow up toward the earth's surface. This leads to electric fields that can penetrate the earth's surface up into the ionosphere and modify its

dynamics and electron density distribution. This phenomena was also shown by Pulinets et al. (2000) and Pulinets and Boyarchuk (2004). Nowadays, more than a thousand ground-based GPS receivers are available worldwide. Studies, such as this one, provide an excellent opportunity to search for and validate the existence of possible seismo-ionospheric anomalies all over the world. The results of this paper suggest that TEC variations are apparent and can be employed to monitor the seismo-ionospheric signatures of Indonesia.

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