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A statistical study of ionospheric earthquake precursors monitored by using equatorial ionization anomaly of GPS TEC in Taiwan during 2001–2007

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ABSTRACT

In this paper, we examine pre-earthquake ionospheric anomalies by the total electron content (TEC) derived from a ground-based receiver of the global positioning system (GPS). A network of eight GPS receivers is used to construct daily latitude-time-TEC (LTT) plots to monitor the crest of equatorial ionization anomaly (EIA) in the Taiwan area. Three parameters of the strength, location, and formation time of the EIA crest are extracted. A 15-day running medians of the three parameters and the associated upper and lower quartiles are utilized as the references for identifying abnormal signals for all of the 150 $M \geqq 5.0$ earthquakes in the Taiwan area during 2001–2007. Results show that the EIA crest significantly moves equatorward (poleward) and appears in an earlier (later) time of the afternoon period a few days before (after) the earthquakes along the Taiwan longitude. The two parameters of the EIA crest location and occurrence time can be employed to detect ionospheric earthquake precursors. The results further imply that atmospheric electric fields generated around the epicenter of a forthcoming earthquake during the preparation period are essential.

1. Introduction

The Island of Taiwan is located in the active boundary between the Philippine Sea plate and Eurasian plate, and therefore a large number of earthquakes often occur in a rather small region during a relatively short time period. For example, there are 150 $M \geqq 5.0$ earthquakes in Taiwan during 2001–2007, and therefore the average recurrence is about 15 ($14.6 = (365 \times 6 + 1)/150$) days. The high occurrence rate of the earthquakes provides an excellent chance to statistically examine how the ionospheric anomaly is related to the earthquakes. On the other hand, near the magnetic equator, where the magnetic field **B** is horizontal, the movement (**E** × **B** plasma drift or flow) resulting from a dynamo eastward electric field **E** generated by the atmospheric tides is upward during the day, which is termed "plasma fountain". The raised plasma then diffuses down along the geomagnetic field to produce enhanced plasma (or electron) density at places, ±12°N geomagnetic, on each side of the equator and decreased density at the equator itself (for detail see Ratcliffe, 1972). The interesting enhancement phenomenon has been called the equatorial ionization anomaly (EIA). Taiwan lies between 10°N and 14°N geomagnetic (21°N and 25°N, geographic), which is located right under the ionospheric EIA of the northern hemisphere along the about 170°E geomagnetic longitude (121°E, geographic). Thus, the upper atmospheric (or ionospheric) electric field is essential to the plasma fountain and the EIA.

To simultaneously observe large area of the ionosphere, data recorded by a network of ground-based receivers of global positioning system (GPS) is ideally used. Recently, the total electron content (TEC) at a certain point (24°N, 120°E) of the central Taiwan area derived from ground-based GPS receivers has been used to monitor variations of the ionosphere associated with earthquakes in Taiwan (Liu et al., 2001, 2002, 2004a,b, 2008). Based on the temporal variations, they find that the ionospheric GPS TEC over a forthcoming earthquake region significantly decreases in the afternoon and/or evening period of 1–5 days before the earthquake occurrence. Meanwhile, Liu et al. (2001) conduct simultaneously temporal and spatial observations and find that when the GPS TEC significantly decreases in the central Taiwan area, the associated EIA crest moves equatorward remarkably on 4 and 3 days before the 20 (21 for local time) September 1999 M7.3 (Mw7.6) Chi-Chi earthquake. Liu et al. (2002) further examine the temporal and spatial variations in the GPS TEC during three large (M6.2, M7.3, and M6.4) earthquakes respectively struck central Taiwan near

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the town of Rei-Li on 17 July 1998, Chi-Chi on 20 September 1999, and Chia-Yi on 22 October 1999, and also observe a similar correlation that the GPS TEC of the central Taiwan area decreases and concurrently the EIA crest moves toward the equator 1–4 days prior to these three earthquakes. These correlations indicate that the EIA of the ionospheric GPS TEC might be alternative observables to have better understandings on the pre-earthquake anomalies. In this paper, the EIA crest of the TEC observed by a network of eight ground-based GPS receivers and 150 $M \geqq 5.0$ earthquakes in the Taiwan area during 2001–2007 are examined. Three parameters of the strength (i.e. GPS TEC value), location, and formation time of the EIA crest during the 26 December 2006 M7.0 Pingtung doublet are first served as an example, and then anomalous variations of the three parameters associated with the 150 earthquakes of the entire observation period are statistically investigated and discussed.

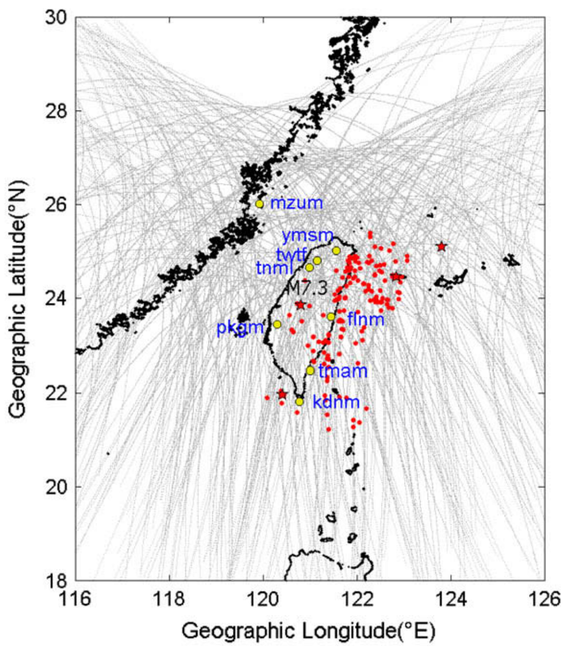

Fig. 1. Coverage of eight ground-based GPS receivers and locations of the 150 $M \geqq 5.0$ earthquakes. The gray curves and yellow dots denote the traces or foot prints of subionospheric points around altitude 325 km and location of the GPS receivers, respectively. Red dots and stars are the $7.0 > M \geqq 5.0$ and $M \geqq 7.0$ earthquakes in 2001–2007, respectively (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

2. Observation and analysis

Fig. 1 illustrates the geographic locations of the network of eight ground-based GPS receivers and the 150 $M \geqq 5.0$ earthquakes in Taiwan during 2001–2007. We utilize all the GPS network data to construct a daily latitude-time-TEC (LTT) plot (Liu et al., 1996). Fig. 2 displays a time series of LTT plots of the GPS TEC observed along 120°E longitude and four earthquakes, M5.4, M7.0 × 2 (Pingtung doublet), M5.8, and M5.0, occurred in December 2006. It can be seen that the EIA crest on 5 and 4 days as well as 1 day before the December 23, 2006 M5.4 earthquake; 4 days and 1 day before December 26, 2006 M7.0 Pingtung doublet; as well as 5 and 2 days before December 27, 2006 M5.8 earthquake remarkably decreases and moves equatorward (i.e. toward the lower latitude). The daily values of the strength, latitude, and formation/appearance time of EIA crest are further isolated (Fig. 3). In order to avoid possible confounded effects from adjacent earthquakes (the average recurrence is about 15 days in Taiwan) and to identify anomalies in the three parameters during the earthquakes, we compute the median $\tilde{X}$ of the previous 15-day values, and their upper quartile (UQ) and lower quartile (LQ) as a reference. We then daily construct the upper bound $\tilde{X} + 1.5(\mathrm{UQ} - \tilde{X})$ and lower bound $\tilde{X} - 1.5(\tilde{X} - \mathrm{LQ})$ for each parameter. Under the assumption of a normal distribution with mean u and standard deviation σ for the parameter, the construct upper and low bounds are 1.34σ, respectively. If an observed

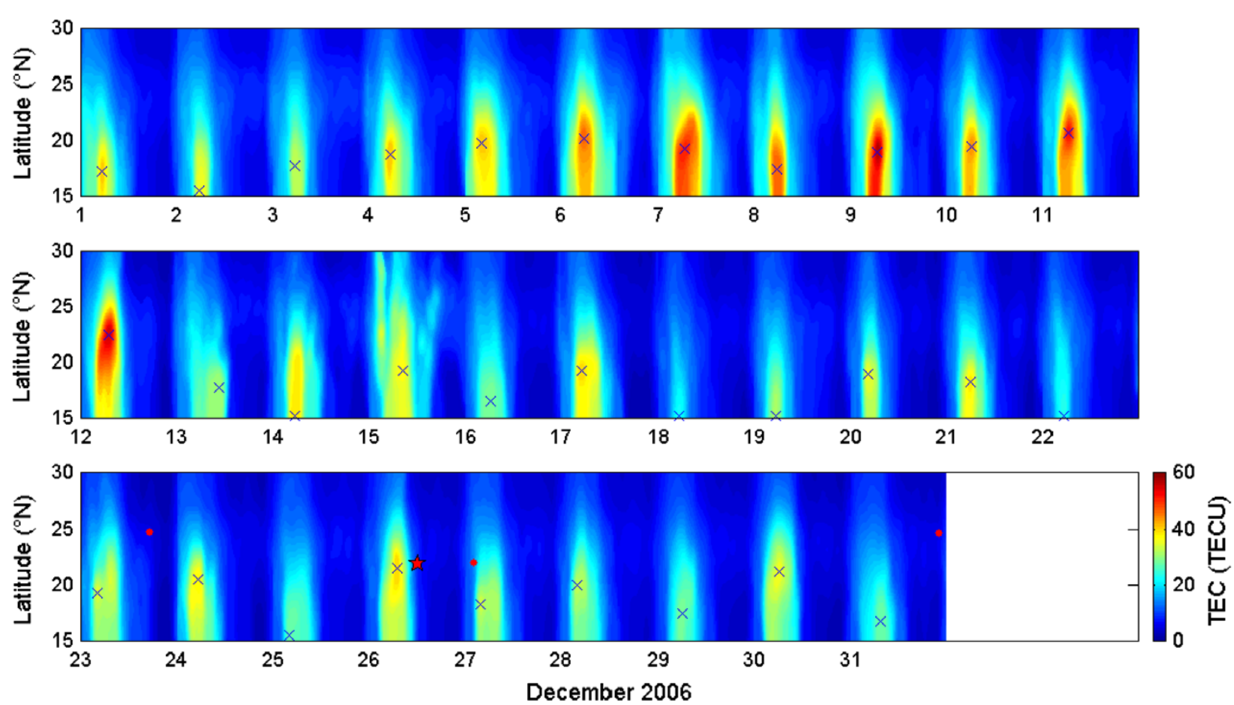

Fig. 2. Latitude, time, and TEC plots along 120°E longitude sector in December 2006. The dot/star and cross symbols denote the $M \geqq 5.0$ earthquake epicenters (M5.4 (122.3°E, 24.8°N) on 12/23, M7.0 × 2 (120.4°E, 22.0°N) on 12/26, M5.8 (120.4°E, 22.1°N) on 12/27, and M5.0 (122.6°E, 24.7°N) on 12/31) and EIA crests, respectively. 1TECU = 10^{16} electrons/m^2.

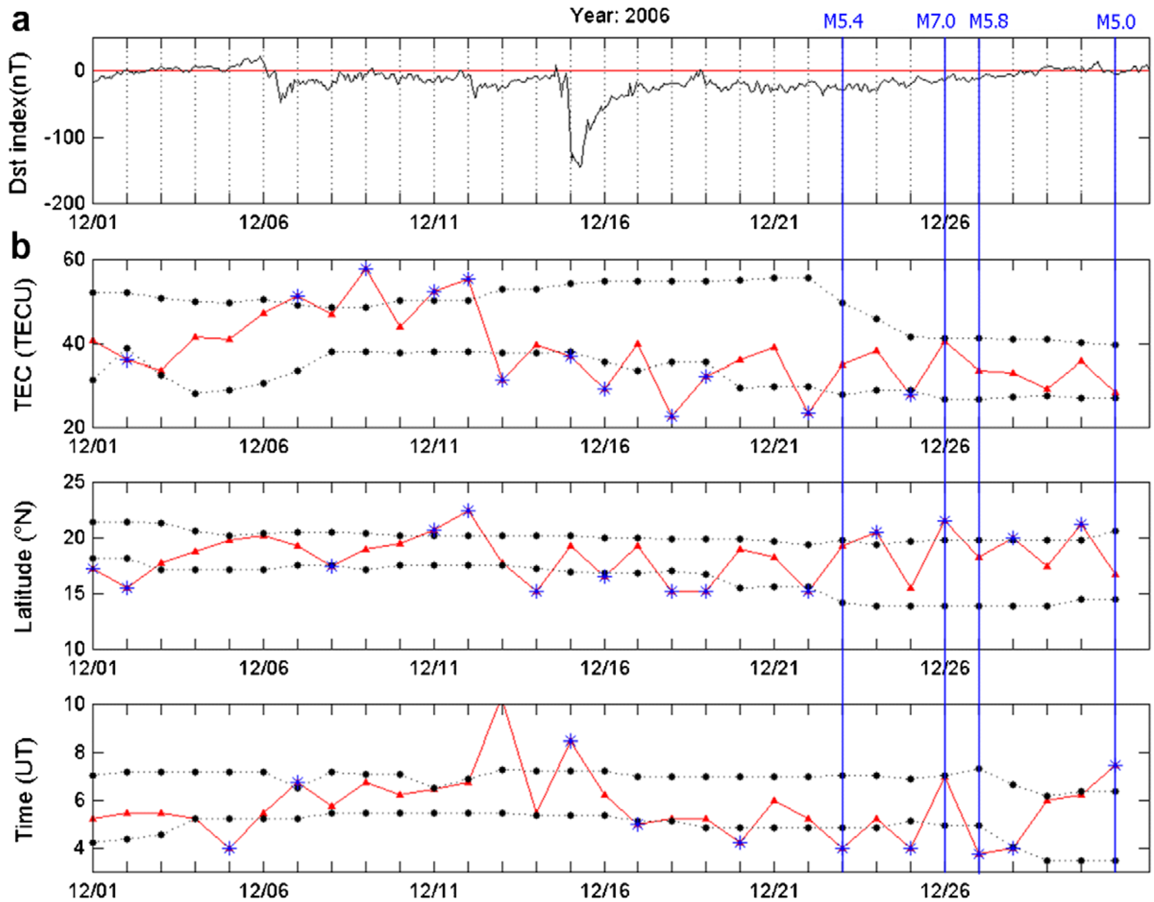

Fig. 3. Variations of geomagnetic Dst index and the three EIA parameters in December 2006. (a) Geomagnetic Dst index (top panel), and (b) the strength (2nd panel), location (3rd panel), and appearance time (bottom panel) of the ionospheric EIA crest. Red curves denote the daily variation of the three quantities and black dot curves are the associated previous 15-day running upper and lower bounds. Blue stars indicate that the observed parameters exceed the associated upper or lower bound. Blue line denotes the 4 $M \geqq 5.0$ earthquakes in December 2006 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

parameter falls outside of either the associated lower or upper bound, we declare with a confidence level of about 65–70% that a lower or upper abnormal signal is detected (Neter et al., 1988). Fig. 3 reveals that the EIA significantly decreases and moves equatorward on 1 day before the M5.4 earthquake; again decreases and moves equatorward on 4 days and 1 day before the Pingtung doublet; and decreases and however appears much earlier on 2 days before the M5.8 earthquake. Note that the crest seems often moving poleward after the M5.4 earthquake and Pingtung doublet. In general, the crest tends to decrease, move equatorward, and/or appear earlier 1–5 days before the four earthquakes.

To further understand seismo-anomalies of the three parameters, we statistically examine the EIA crest variations of the GPS TEC associated with the 150 $M \geqq 5.0$ earthquakes during 2001–2007. Note that if there is no seismo-related effect, the chance of observing anomalies before and after an earthquake should be approximately equivalent, both about 0.5. Therefore, a z-test is suitable to be employed testing whether the sampling proportion has changed from its normal level 0.5. The test concerning the proportion is based on the standardized test statistic (Neter et al., 1988),

$$z = \frac{p - 0.5}{\sqrt{\frac{0.5(1-0.5)}{n}}}$$

where n is a sample size. Under the 10% level of significance of the test, if $z \geqq 1.645$, p is then considered to be very different from the normal level 0.5, which means that appearances of the anomaly before and after the earthquakes are significantly different, and in turn, suggests existence of the earthquake anomaly.

Here, we first compare the number of anomalies within a certain day period before and after each earthquake. If the number before (after) an earthquake is greater than that its after (before), it counts as 1 (0), otherwise it is 0.5. We repeat the same process and calculate the p value which is the proportion of the number of anomalies before and after the 150 $M \geqq 5.0$ (also 48 $M \geqq 5.5$; 25 $M \geqq 6.0$) earthquakes for the day period. Thus, the calculated z-value exceeding +1.645 (−1.645) means the anomaly is significant within the certain day period before (after) the earthquakes.

Fig. 4 summarizes results of the z-values of the upper and lower anomalies in the three parameters for the day periods from 1 to 15. For the upper anomalies in the crest TEC strength, it is significant on 1–2 days after the $M \geqq 5.5$ earthquakes (Fig. 4a), and however, the lower anomaly is not notable (Fig. 4b). Fig. 4c illustrates that the upper anomalies in the latitude (i.e. toward-high-latitude or poleward motion) are out of the 10% level of significance of the test on 1–5 days and 9–14 days after the $M \geqq 5.0$ earthquakes. Fig. 4d illustrates the lower anomalies in the latitude (i.e. toward-low-latitude or equatorwar motion) that it is significant on 1–5 days before the $M \geqq 6.0$ earthquakes. It is clear that the upper anomalies in the time (i.e. late) are significant on 2–3, 6, 8–11, and 13 days after the $M \geqq 5.0$ earthquakes, and on 9–12 days after the $M \geqq 6.0$ earthquakes (Fig. 4e). Moreover, Fig. 4f displays that on 3–5 days before the $M \geqq 5.0$ earthquakes, the lower anomalies in the appearance time (i.e. early) are significant. In general, the EIA crest significantly decreases (increase), moves equatorward

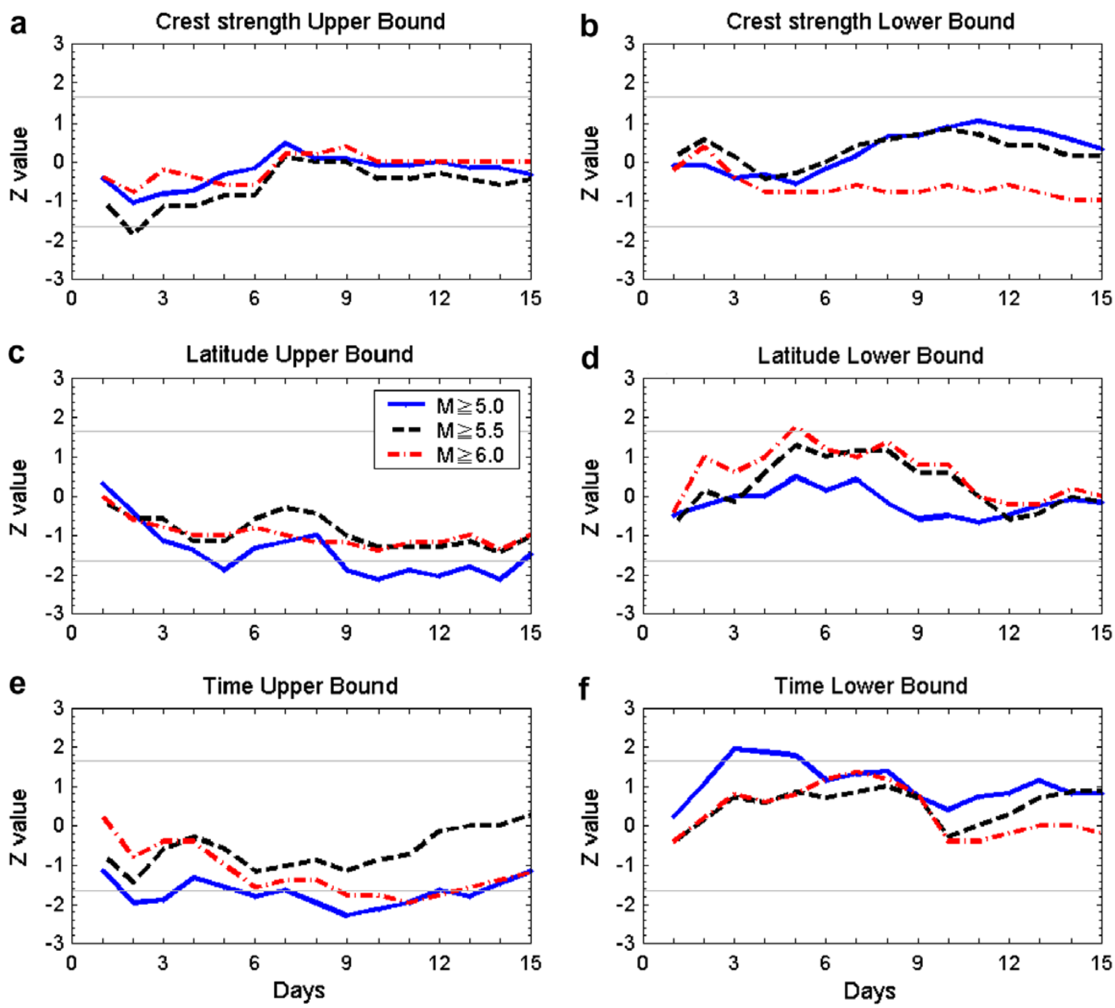

Fig. 4. The *z*-value of the three EIA parameters of the GPS TEC. The upper (a) and lower (b) anomalies of the strength, the upper (c) and lower (d) anomalies of the latitude, and the upper (e) and lower (f) anomalies of the appearance time of the ionospheric EIA crest. The blue, black dashed, and red dotted lines denote the 150 $M \geqq 5.0$, 48 $M \geqq 5.5$, and 25 $M \geqq 6.0$ earthquakes (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

(poleward), and appears early (late) few days before (after) the earthquakes.

3. Discussion and conclusion

In this paper, the appearance time of the EIA crest related to the earthquakes is for the first time studied. Fig. 4e and f prove that in general the EIA crest appears significantly early before but late after the earthquakes. Liu et al. (2001, 2002) report that 1–4 days before the 17 July 1998 M6.2 Rei-Li, the 20 September 1999 M7.3 Chi-Chi, and 22 October 1999 M6.4 Chia-Yi earthquakes, the ionospheric EIA crest of GPS TEC yields the equatorward tendency. Fig. 4d confirms that EIA crest significantly moves equatorward on 1–5 days before the earthquakes. Meanwhile, Liu et al. (2004a,b) statistically demonstrate that the GPS TEC at central Taiwan (24°N, 120°E) significantly decreases on 1–5 days before $M \geqq 5.0$ and/or $M \geqq 6.0$ earthquakes, while Fig. 4b by contrast shows that the EIA crest strength does not decrease significantly before the earthquakes. It has been known that a stronger eastward electric field results in a greater plasma fountain which upward raises the plasma to the higher altitude and then takes a longer time (i.e. a late appearance time for the EIA crest) downward diffusing to the higher latitude (i.e. the poleward EIA motion) (Bramley and Young, 1968; Sterling et al., 1969; Ratcliffe, 1972; Anderson, 1973; Tsai et al., 2001; Chen et al., 2008). The equatorward motion (Fig. 4d) and early appearance time (Fig. 4f) of the EIA crest indicate that the fountain electric field somehow becomes significantly weakened on 1–5 days before the earthquakes. It might be due to the weakened electric field that the EIA crest moves equatorward which in turn results in the GPS TEC significantly decreasing at the normal/typical location of the EIA crest in Taiwan (24°N, 13°N in geomagnetic) on 1–5 days before the $M \geqq 5.0$ and/or $M \geqq 6.0$ earthquakes reported by Liu et al. (2004a,b).

It is interesting to find whether the seismo electromagnetic signals generated during the preparation periods of the Taiwan earthquakes (21–25°N geographic; 10–14°N magnetic) could possibly disturb the daily plasma fountain electric field at the magnetic equator, where is about 1100–1540 km from the epicenters. Recently, ionospheric scientists (cf. Chen et al., 2008; Fang et al., 2008a,b) employ differences in the horizontal component of the magnetic field between at 7°N magnetic and that at the equator to estimate the electric field strength of plasma fountain around the magnetic equator. Based on these studies, the plasma fountain electric field should be within ±7°N magnetic. For the Taiwan longitude, 121°E, the northern boundary of the fountain electric field is be 18°N geographic. On the other hand, 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 M = 5–7, we obtain R = 140–1000 km. Fig. 1 reveals the earthquakes occurring 21–25°N (or 10–14°N, magnetic). Thus, the distances between the earthquakes and the northern boundary range from 3–7° in latitude which are about 330–770 km. Again, on the base of Dobrovolsky et al. (1979), the preparation area of the earthquakes with magnitude $M \geqq 5.9$ could overlap with the fountain electric field region. When the fountain electric fields are disturbed, the EIA crest moves equatorward which in turn cause seismo-ionospheric reduction anomalies of the GPS TEC in Taiwan. It is clear that a greater earthquake shall yield a larger overlapping area. Therefore, the larger the earthquake, the better chance observing the seismo-ionospheric anomalies which agrees the results reached by Liu et al. (2000, 2006, 2009). Although generation mechanisms of seismo electromagnetic signals are not well understood, the statistical results reveal that before the earthquakes, the weakened electric field causes the equatorward motion and early appearance time, and however does not significantly decrease the EIA crest strength (Fig. 4b). In conclusion, the EIA anomalies show the electric field of the plasma fountain in the ionosphere has been significantly disturbed and diminished, which in turn suggests that seismo-generated electromagnetic signals, especially electric fields, are essential during the earthquake preparation period.

Acknowledgements

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References

Anderson, D., 1973. A theoretical study of the ionospheric *F* region equatorial anomaly-II. Results in the American and Asian sectors. Planetary and Space Science 21, 421–442.

Bramley, E.N., Young, M., 1968. Winds and electromagnetic drifts in the equatorial F2 region. Journal of Atmospheric and Terrestrial Physics 30, 99–111.

Chen, C.H., Liu, J.Y., Yumoto, K., Lin, C.H., Fang, T.W., 2008. Equatorial ionization anomaly of total electron content and equatorial electrojet of ground-based geomagnetic field strength. Journal of Atmospheric and Solar-Terrestrial Physics 70, 2172–2183.

Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zones. Pure and Apply Geophysics 117, 1025–1044.

Fang, T.W., Richmond, A.D., Liu, J.Y., Maute, A., Lin, C.H., Chen, C.H., Harper, B., 2008a. Model simulation of the equatorial electrojet in the Peruvian and Philippine sectors. Journal of Atmospheric and Solar-Terrestrial Physics 70, 2203–2211.

Fang, T.W., Richmond, A.D., Liu, J.Y., Maute, A., 2008b. Wind dynamo effects on ground magnetic perturbations and vertical drifts. Journal of Geophysical Research 113, A11313. doi:10.1029/2008JA013513.

Liu, J.Y., Tsai, H.F., Jung, T.K., 1996. Total electron content obtained by using the global positioning system. Terrestrial Atmospheric and Oceanic Science 7, 107–117.

Liu, J.Y., Chen, Y.I., Pulinets, S.A., Tsai, Y.B., Chuo, Y.J., 2000. Seismo-ionospheric signatures prior to $M \geqslant 6.0$ Taiwan earthquakes. Geophysical Research Letters 27, 3113–3116.

Liu, J.Y., Chen, Y.I., Chuo, Y.J., Tsai, H.F., 2001. Variations of ionospheric total electron content during the Chi-Chi earthquake. Geophysical Research Letters 28, 1383–1386.

Liu, J.Y., Chuo, Y.J., Pulinets, S.A., Tsai, H.F., Xeng, X.P., 2002. A study on the TEC perturbations prior to the Rei-Li, Chi-Chi and Chia-Yi earthquakes. In: Hayakawa, M., Molchanov, O.A. (Eds.), Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. TERRAPUB, Tokyo, pp. 297–301.

Liu, J.Y., Chuo, Y.J., Shan, S.J., Tsai, Y.B., Chen, Y.I., Pulinets, S.A., Yu, S.B., 2004a. Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements. Annales Geophysicae 22, 1585–1593.

Liu, J.Y., Chen, Y.I., Jhung, H.K., Lin, Y.H., 2004b. Ionospheric foF2 and TEC anomalous days associated with $M \geqq 5.0$ earthquakes in Taiwan during 1997–1999. Terrestrial Atmospheric and Oceanic Science 15, 371–383.

Liu, J.Y., Chen, Y.I., Chuo, Y.J., Chen, C.S., 2006. A statistical investigation of pre-earthquake ionospheric anomaly. Journal of Geophysical Research 111, A05304. doi:10.1029/2005JA011333.

Liu, J.Y., Chen, S.W., Chen, Y.C., Yen, H.Y., Chang, C.P., Chang, W.Y., Tsai, L.C., Chen, C.H., Yang, W.H., 2008. Seismo-ionospheric precursors of the 26 December 2006 M7.0 Pingtung earthquake doublet. Terrestrial Atmospheric Oceanic Science 19, 751–759.

Liu, J.Y., Chen, Y.I., Chen, C.H., Liu, C.Y., Chen, C.Y., Nishihashi, M., Li, J.Z., Xia, Q., Oyama, K.I., Hattori, K., Lin, C.H., 2009. Seismo-ionospheric GPS TEC anomalies observed before the 12 May 2008 Mw7.9 Wenchuan earthquake. Journal of Geophysical Research 114, A04320. doi:10.1029/2008JA013698.

Neter, J., Wasserman, W., Whitmore, G.A., 1988. Applied Statistics, third ed. Allyn and Bacon, Inc.

Ratcliffe, J.A., 1972. An Introduction to the Ionosphere and Magnetosphere. Cambridge University Press, London.

Sterling, D.L., Hanson, W.B., Moffett, R.J., Baxter, R.G., 1969. Influence of electromagnetic drifts and neutral air winds on some features of the F2 region. Radio Science 4, 1005.

Tsai, H.F., Liu, J.Y., Tsai, W.H., Liu, C.H., Tseng, C.L., Wu, C.-C., 2001. Seasonal variations of the ionospheric total electron content in Asian equatorial anomaly regions. Geophysical Research Letters 106, 30363–30369.