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Ionospheric foF2 and TEC Anomalous Days Associated with M ≥ 5.0 Earthquakes in Taiwan during 1997-1999

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ABSTRACT

In this paper, we examine variations in the critical frequency foF2 recorded by an ionosonde, and the total electron content (TEC) derived from a network of 5 ground-based receivers of the global positioning system (GPS), as well as occurrences of 144 M ≥ 5.0 earthquakes in Taiwan during 1997 - 1999. Results show that the foF2 and TEC yield similar tendencies, and often concurrently register pronounced decrease anomalies 4 days before the earthquakes. A detailed investigation of anomalies appearing before and after the earthquakes confirms significant decreases in the foF2 and TEC to be the pre-earthquake anomalies.

(Key words: Ionosphere, Ionosonde, Global positioning system, GPS, Total electron content, TEC, Earthquake)

1. INTRODUCTION

Electromagnetic phenomena associated with seismic activities have been extensively discussed (e.g., Hayakawa and Fujinawa 1994; Hayakawa 1999; Hayakawa 2000; Hayakawa and Molchanov 2002). 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) examined the ionospheric plasma frequency (or electron density) recorded by a local ionosonde and found that the critical frequency of the F2-peak, foF2, significantly decreased 1-6 days prior to most of the 14 M ≥ 6.0 earthquakes in the

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Taiwan area during 1994-1999.

Recently seismologists carried out investigations on the Earth's surface deformation rates by using the Global Positioning System (GPS) [see the papers listed in Calais and Amarjargal (2000)]. To obtain a better estimate of earthquake hazard, a large amount and broad distribution of ground-based GPS receivers recording for longer periods of time are usually needed. While observing Earth's surface deformation, a network of GPS receivers can be employed to monitor the ionospheric total electron content (TEC) (Liu et al. 1996). Liu et al. (2001) analyzed the measurements of the Taiwan GPS network and reported significant decreases in the TEC on the 3rd and 4th days before the Chi-Chi earthquake. Liu et al. (2004) further examined the GPS TEC during all of the 20 M ≥ 6.0 earthquakes in the Taiwan area from September 1999 to December 2002. They found that anomalous decreases in the GPS TEC often appeared 1-5 days before the earthquakes.

Due to events of the foF2 and GPS TEC anomalies examined by Liu et al. (2000, 2004) being very limited and covering different time periods, it is difficult to cross compare the two observations. In this paper, we investigate foF2 and TEC anomalies and 144 M ≥ 5.0 earthquakes which occurred in 86 days in the Taiwan area during the 3-year period of 1997 - 1999. Notice that large earthquakes are usually followed by large aftershocks. To avoid confounded effects due to possible aftershocks, we also remove data after the Chi-Chi earthquake and simply examine the association between the anomalies and 63 M ≥ 5.0 earthquakes (occurred in 61 earthquake days) between 1 January 1997 and 21 September 1999 (the 2.7-year period).

2. OBSERVATIONS AND ANALYSES

Most of our knowledge of the ionosphere comes from remote sensing by radio waves. The conventional equipment for measuring the virtual height of the ionosphere is a sweep frequency (usually range from 1-20 MHz) pulsed radar device termed an ionosonde (Hunscucker 1991). The measurement of the frequency vs. the virtual height of the ionosphere obtained by an ionosonde is called an ionogram. For a vertical sounding, an ionogram displays the variation of the virtual height of reflection with frequency, where the virtual height is equivalent to the product of one-half the time-of-flight of the transmitted radio wave and the speed of light c. Usually there are two traces O- and X-mode appearing on an ionogram. Based on the magneto-ionic theory (for detail see, Budden 1985), the plasma frequency is equal to the vertically reflected O-mode frequency. The greatest frequency on an O-mode trace is considered to be the critical (or penetration) frequency of the ionospheric F2 region, which is termed foF2. In this paper, we examine the foF2 (in MHz) recorded every 15-minute by an ionosonde at Chung-Li (25.0°N, 121.0°E) during 1997 - 1999 (Fig. 1).

On the other hand, owing to a dispersive medium of the ionosphere, scientists can derive the TEC from the signals recorded by ground-based GPS receivers every 30 sec. (Sardon et al. 1994; Leick 1995; Liu et al 1996). The slant total electron content, $STEC$, along ray path l between a GPS satellite, Tx, and a ground-based receiver, Rx, can be written as:

$$STEC = \int_{Rx}^{Tx} N dl = \frac{f^2}{40.3}\int_{Rx}^{Tx}(n^{-1}-1)dl = \frac{f^2}{40.3}\int_{Rx}^{Tx}\left[\left(\sqrt{\left(1-\frac{f_N^2}{f^2}\right)}\right)^{-1} - 1\right]dl\ , \quad (1)$$

where N is the electron density in el/m^3, n denotes the refractive index, and f and f_N represent radio wave and plasma frequency in Hz, respectively. The l-axis stands for the receiver-to-satellite direction. From recorded broadcast ephemeris (GPS satellite parameters) and given local sub-ionospheric heights, the *STEC* can be converted into the vertical total electron content *VTEC* at its associated longitude and latitude (Tsai and Liu 1999). Both *STEC* and *VTEC* are in TECu (1 TECu = 10^{16} el/m^2). For simplicity, the *VTEC* is denoted TEC hereafter. The TEC is derived every 30-sec. but simply recorded 15-min. by a network of five ground-based receivers in Taiwan during 1997 - 1999 (Fig. 1).

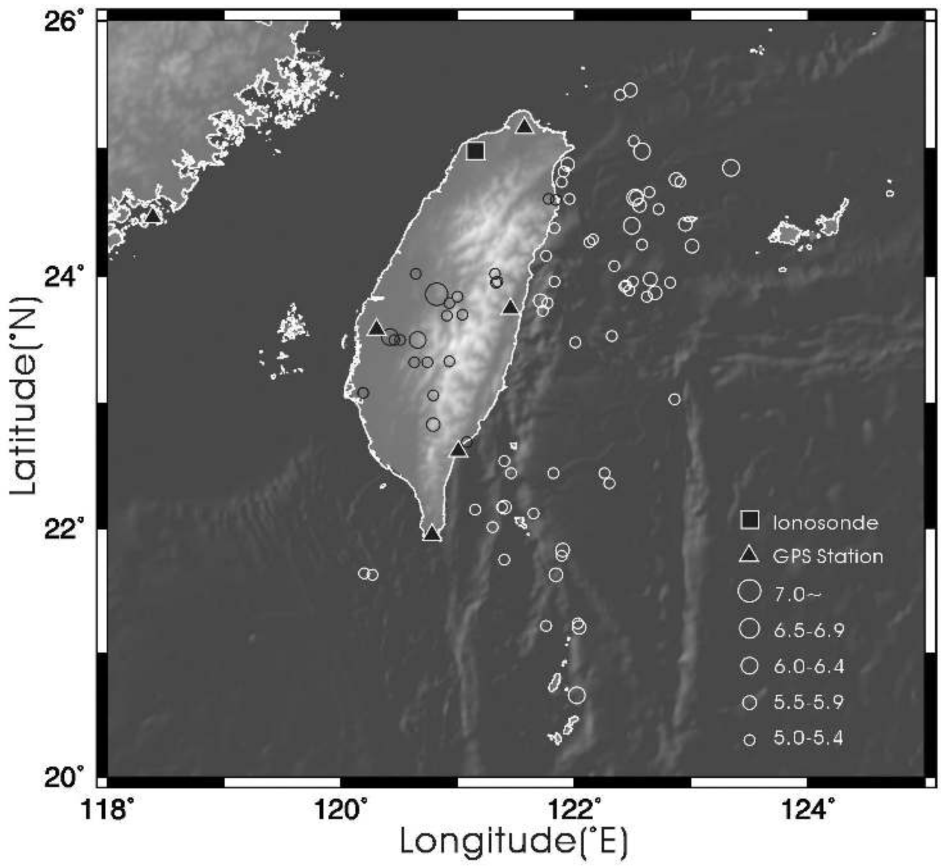

Fig. 1. Locations of the Chung-Li ionosonde, the GPS receivers, and the epicenters of the 144 M ≥ 5.0 earthquakes during 1997 - 1999.

Figure 1 illustrates the locations of the Chung-Li ionosonde, the GPS receivers, and the epicenters of the 144 M ≥ 5.0 earthquakes during 1997 - 1999. The ionosonde observes the ionosphere within a horizontal region of a radius 500 km from Chung-Li (25.0°N, 121.0°E), while the GPS network covers an area of 15° - 30°N and 110° - 130°E. Therefore, the two observations simultaneously monitor the ionospheric volume above the epicenters.

Taiwan is located the seismic zones around the Rim of the Pacific Ocean and therefore earthquakes frequently occur. For instance, the recurrence interval of an M ≥ 5.0 earthquake during 1991-1999 generally lies between 13 and 15 days. To identify abnormal signals, we compute in this paper the median $\tilde{X}$ (50%) of the previous 15-day foF2 (or TEC) and the associated upper-quartile (75%) and lower-quartile (25%) to be the reference, the upper bound and lower bound at a certain local time (LT), respectively. If an observed foF2 (or TEC) falls out of either the associated lower or upper bound, we then declare a lower or upper abnormal signal being detected.

3. RESULTS AND INTERPRETATIONS

Figures 2a and b show distributions of the inter-event time of the 86 M ≥ 5.0 earthquake days during the 3-year period and the 61 M ≥ 5.0 earthquake days during the 2.7-year period, respectively. Figures 2a and b indicate that the M ≥ 5.0 earthquakes during the 3-year period are clustered particularly in 1-2 days and the clustering effect is basically owing to the Chi-Chi earthquake. However, both figures show that the successive earthquakes occur most probably 6 days apart.

To see if the foF2 and TEC anomalies are related each other, Fig. 3a illustrates, for the Chi-Chi earthquake, in particular, that the two observations simultaneously register lower abnormal signals on 6, 8, 9, 14, 17, and 18 September 1999 (Figs. 3b, c). The significant decreases of foF2 and TEC on the 4th and the 3rd days before the Chi-Chi earthquake agree with Liu et al. (2000, 2001). To investigate if the significant foF2 and TEC decreases appear several days prior to the M ≥ 5.0 earthquakes, the numbers of the upper and lower abnormal foF2 (or TEC) signals detected everyday for the entire 3-year period are stacked to calculate the diurnal background percentages. Meanwhile, the same stacking process is performed, respectively, for the upper and lower abnormal foF2 (or TEC) signals identified a certain day prior to all the 86 M ≥ 5.0 earthquake days for obtaining the associated diurnal percentages. A comparison between the two sets of percentages shows that the percentages of the upper abnormal signals on the 4th day, for example, before the earthquakes are generally smaller than the background ones in the entire 3-year period (Figs. 4a, c). Therefore, it is difficult to isolate the seismo-related signals from the upper abnormal. However, the lower abnormal signals observed on the 4th day before the earthquakes yield greater percentages than those detected everyday in the 3-year period (Figs. 4b, d). This confirms significant decreases in the foF2 and TEC as potential pre-earthquake anomalies. A similar comparison is also carried out for the 2.7-year period. It is clear that after removing the period after the Chi-Chi earthquake, the percentages of the upper abnormal signals on the 4th day before the earthquakes are even smaller than the background ones (Figs. 5a, c), while the lower abnormal signals yield much greater percentages on the 4th day before the earthquakes than do in the background (Figs. 5b, d).

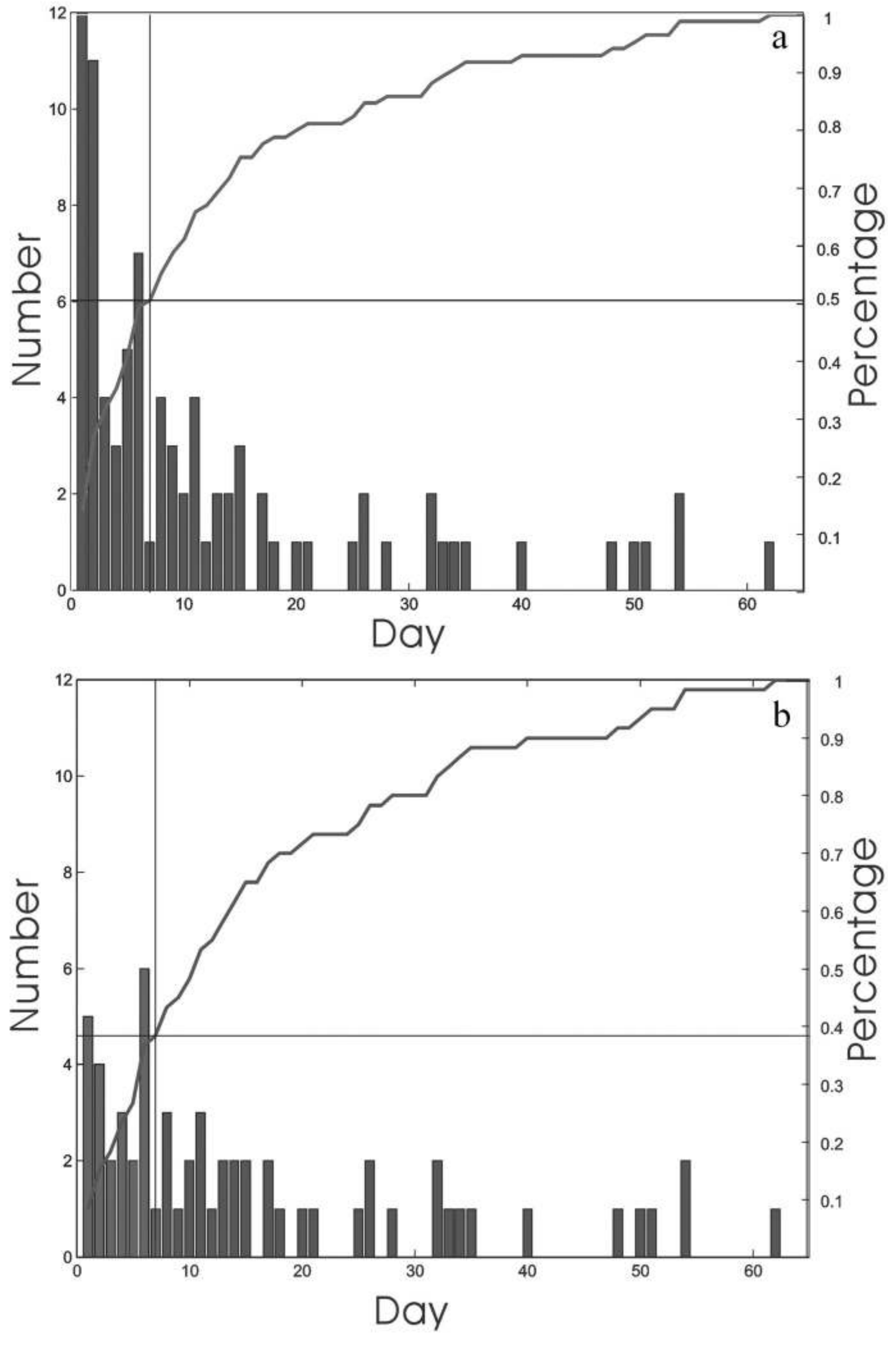

Fig. 2. The inter event time of the M ≥ 5.0 earthquakes. (a) 1997/1/1-1999/12/31, and (b) 1997/1/1-1997/9/21. The curves denote the cumulative percentages of the earthquakes.

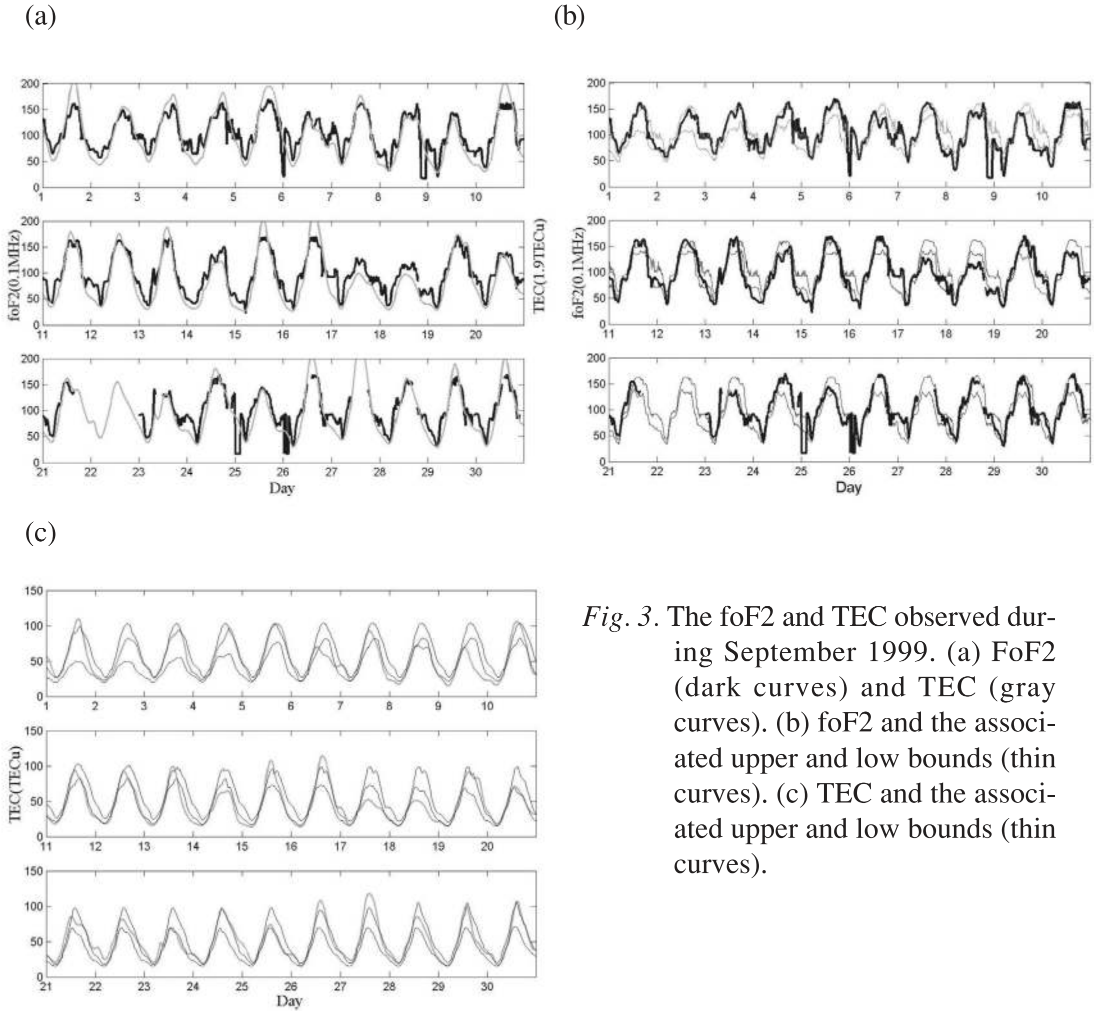

Fig. 3. The foF2 and TEC observed during September 1999. (a) FoF2 (dark curves) and TEC (gray curves). (b) foF2 and the associated upper and low bounds (thin curves). (c) TEC and the associated upper and low bounds (thin curves).

Comparing to the background percentages in the 3-year or 2.7-year period, we compute the summations of the percentages on a certain day before or after the earthquake days under study that exceed the corresponding background ones. Figures 6a and b (6c, d) present the summations of the respective upper and lower foF2 (or TEC) over-background percentages during the 3-year period, and Figs. 7a and b (7c, d) show the related summations of over-background percentages for the 2.7-year period. It is clear that, for both the foF2 and TEC, the summations for the lower abnormal percentages before the earthquakes are greater than those after, but the summations for the upper abnormal percentages do not show the tendency. In fact, for the upper and lower abnormal percentages in foF2 (TEC) in the 3-year period, the ratios of the summations 1-7 before to those 1-7 after the earthquakes are 0.5 and 1.7 (0.4 and 2.0), respectively. Moreover, for the 2.7-year period, the corresponding ratios of the foF2 (TEC) are 0.4 and 2.3 (0.3 and 2.5), respectively. These ratios once again confirm that the lower abnormal foF2 (TEC) has a higher chance to appear 1-7 days prior to the earthquakes.

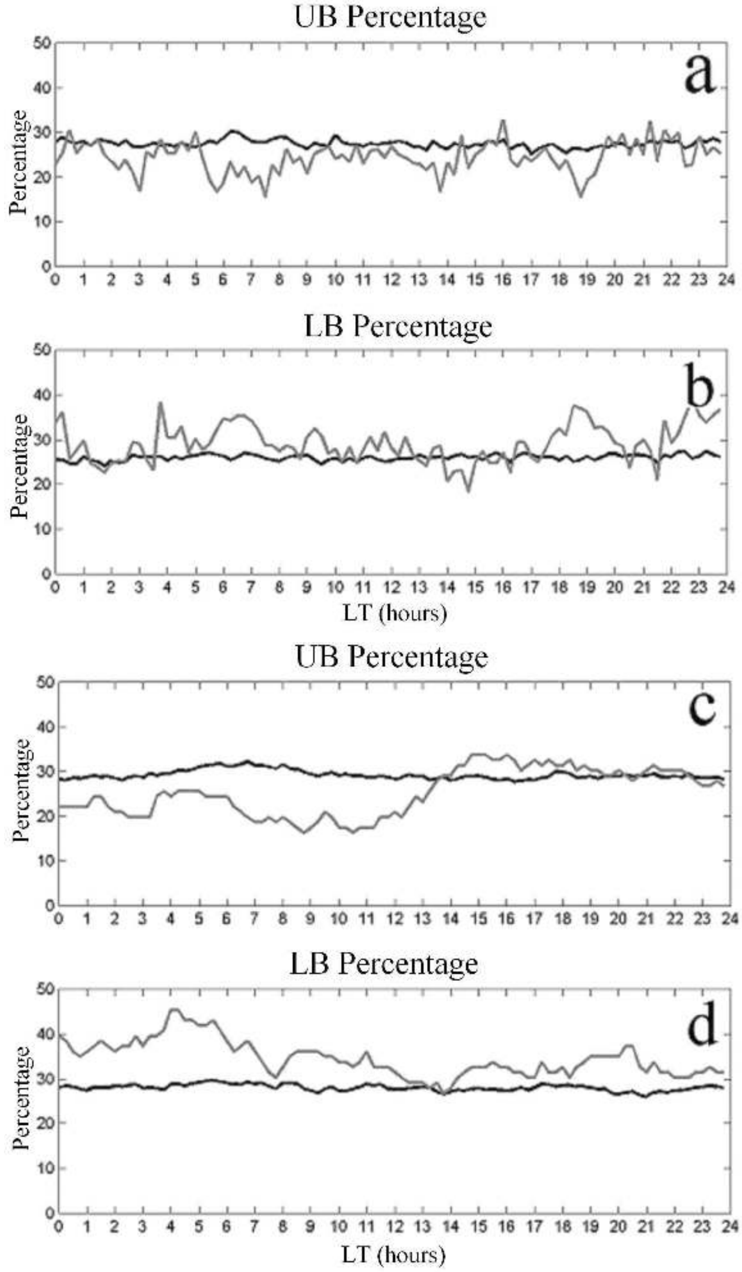

Fig. 4. The percentages of upper and lower anomalies in foF2 and GPS TEC appear everyday and the 4th days before the earthquakes during 1997-1999. The dark and gray curves denote everyday and the 4th day, respectively. (a) The foF2 upper anomalies, (b) the foF2 lower anomalies, (c) the TEC upper anomalies, and (d) the TEC lower anomalies.

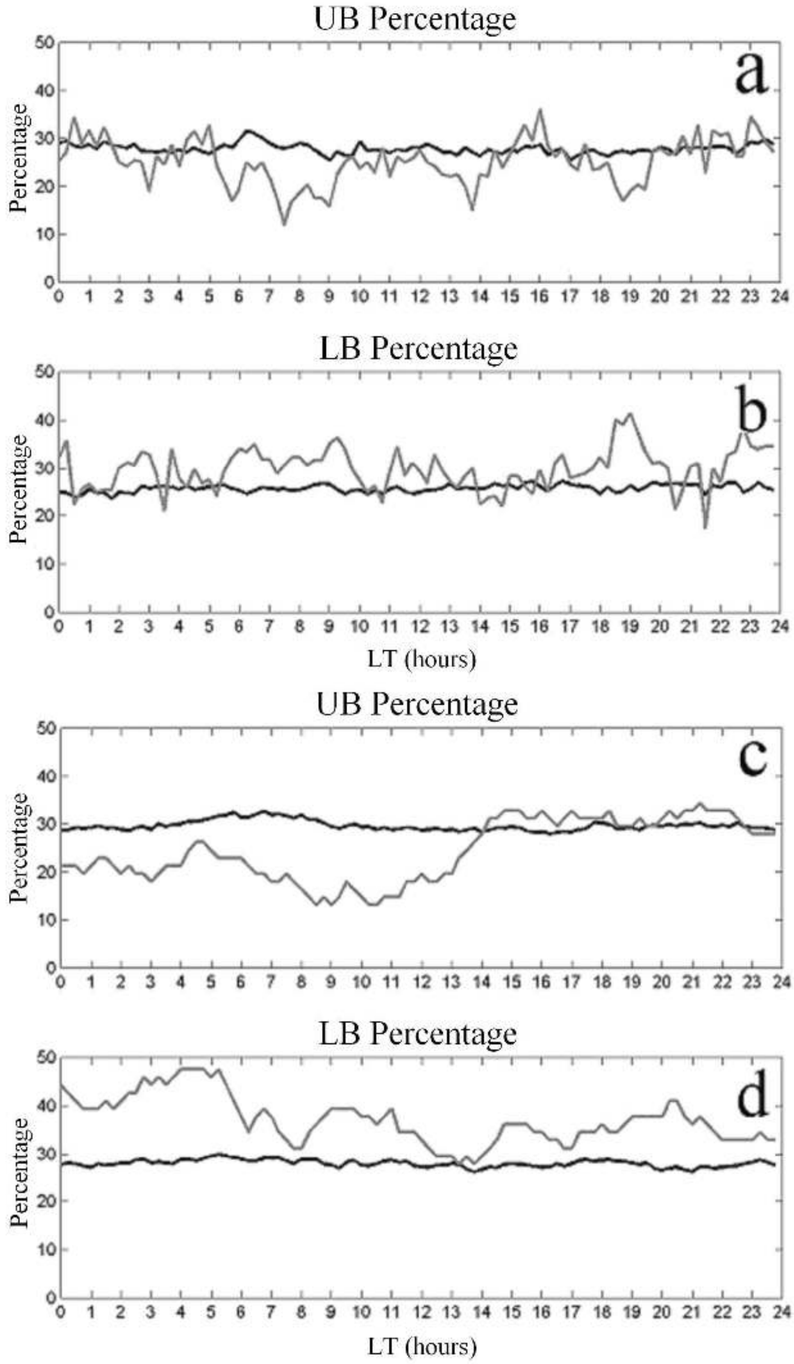

Fig. 5. Similar to Fig. 4 but during 1997/1/1 - 1999/9/21.

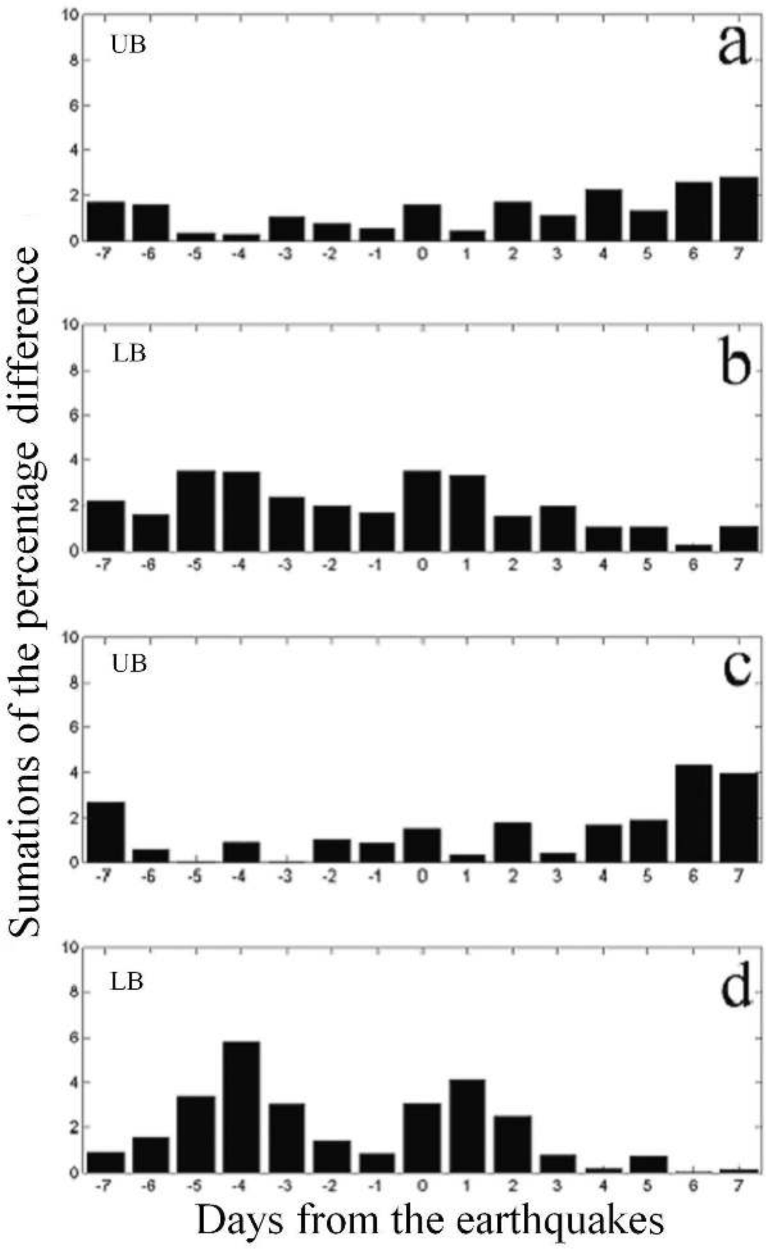

Fig. 6. Figure 6. The summations of the respective upper and lower foF2 or TEC over-background percentages during 1997 - 1999. (a) The foF2 upper anomalies, (b) the foF2 lower anomalies, (c) the TEC upper anomalies, and (d) the TEC lower anomalies.

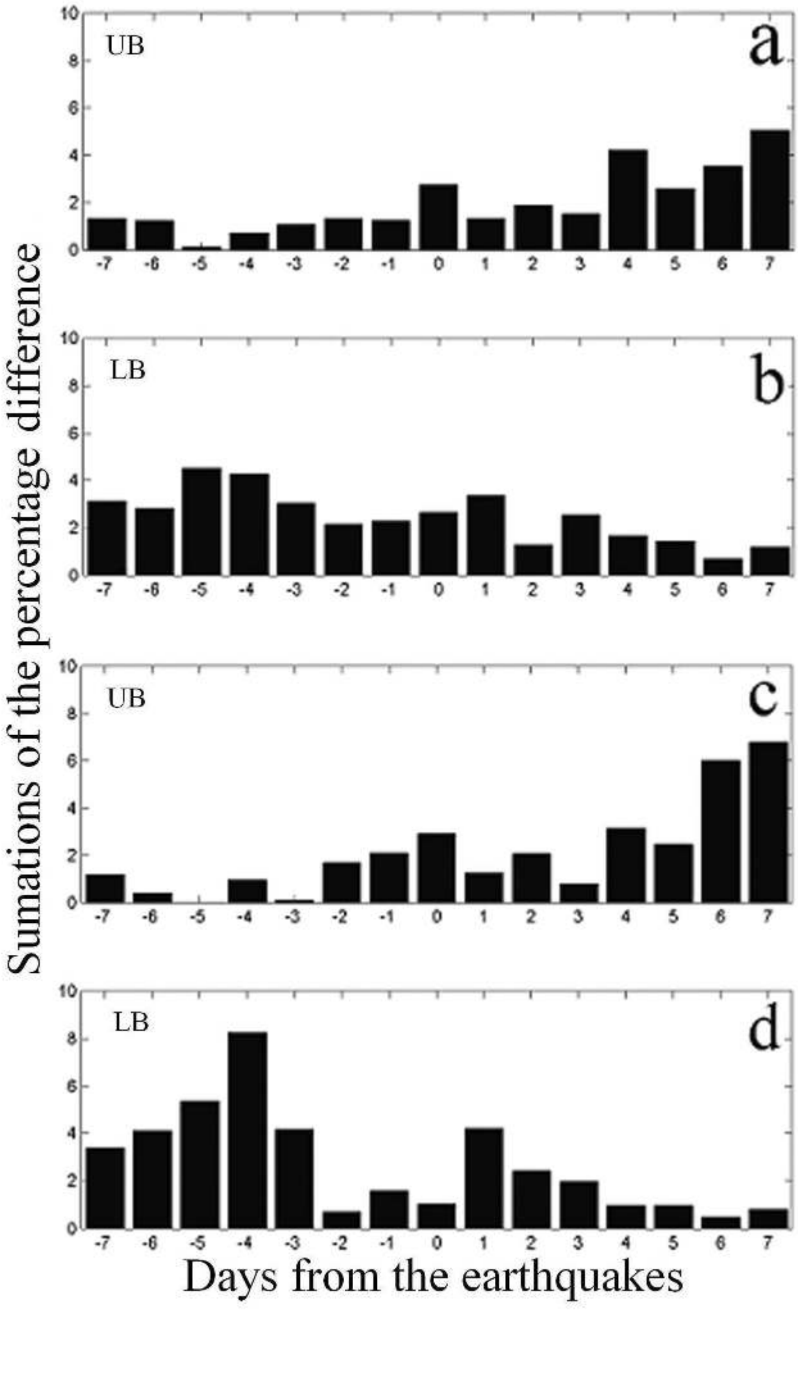

Fig. 7. Similar to Fig. 6 but during 1997/1/1 - 1999/9/21.

4. DISCUSSIONS AND CONCLUSIONS

Liu et al. (2000, 2004) studied the association between ionospheric electron density variations and M ≥ 6.0 earthquakes in the Taiwan area, and found the significant foF2 and TEC decreases appearing most likely 1 - 6 days before the earthquakes. To have a better view of the anomalies, we compare the percentages of the anomalies appearing around the earthquake days with the associated background ones. Notice that Liu et al. (2000) reported that the decrease anomalies in the foF2 before M ≥ 6.0 earthquakes often appeared during the afternoon period, while Liu et al. (2004) found that the TEC decrease anomalies usually occurred between dusk and pre-midnight. However, Figs. 4b, 4d, 5b, and 5d in this paper show that, for M ≥ 5.0 earthquakes under study, chances of detecting the decrease anomalies in foF2 and TEC seem not to be a function of local time.

Liu et al. (2004) examined the decrease anomalies appearing 15 days before and after the 20 M ≥ 6.0 earthquakes occurring in1999 - 2002. However, for M ≥ 5.0 earthquakes, the study of the inter-event time suggests that to minimize the confounded effect, the suitable period should be about 5 days before and after the earthquake. Figures 6 and 7 and the associated ratios in this paper demonstrate that the decrease anomalies most likely appear 3 - 5 days before the M ≥ 5.0 earthquakes. In fact, more enhanced signatures appear in the 2.7-year period than in the 3-year period. This suggests a mask effect on the pre-earthquake anomaly owing to basically the inclusive of possible Chi-Chi aftershocks.

Liu et al. (2000) reported the foF2 decrease anomalies most likely appearing 1 day before the 14 M ≥ 6.0 earthquakes during January 1994 - September 1999, while Liu et al. (2004) found the GPS TEC anomalies often occurring on the 2nd days before the 20 M ≥ 6.0 earthquakes during September 1999 - December 2002. However, this paper shows that the greatest chances of observing the decrease anomalies of the foF2 and TEC occur on the 4th days before the M ≥ 5.0 earthquakes under study. Although possible causal mechanisms are not fully understood (Bolt 1999; Freund 2000; Kim and Hegai 1999), we found that the lead time of anomalies to the M ≥ 6.0 earthquakes tends to be shorter than that to the M ≥ 5.0 earthquakes.

Figure 3a depicts variations of the foF2 to be more fluctuated than those of the TEC. The fluctuated foF2 are possibly caused by the ionospheric absorption, blanking/screen effects from the ionospheric sporadic, Es, layer, short wave fadeout, etc (Davies 1990). Despite the shortcomings, an ionosonde monitors the vertical distribution in electron density right above. Unlike the foF2 derived from a single ionosonde, the TEC is obtained from multiple GPS signals recorded by a network of ground-based receivers. Notice that the interpolation process could smooth the TEC data. On the other hand, the multiple GPS data provide scientists the TEC distributions in the latitudinal and longitudinal direction, which are useful for further understanding the spatial structure of the observed anomalies (Liu et al. 2001). Nevertheless, this study confirms that the foF2 and TEC decrease anomalies tend to proceed the M ≥ 5.0 earthquakes by about 3 - 5 days in Taiwan during 1997 - 1999. These results, somehow, shed light on a future study for extensive investigation of seismo-ionospheric precursors of Taiwan earthquakes.

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