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# A statistical investigation of preearthquake ionospheric anomaly

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[1] Empirical evidence of the preearthquake ionospheric anomalies (PEIAs) is reported by statistically investigating the relationship between variations of the plasma frequency at the ionospheric F2 peak *foF*2 and 184 earthquakes with magnitude M $\geq$ 5.0 during 1994–1999 in the Taiwan area. The PEIA, defined as the abnormal decrease more than about 25% in the ionospheric *foF*2 during the afternoon period, 1200–1800 LT, significantly occurs within 5 days before the earthquakes. Moreover, the odds of earthquakes with PEIA increase with the earthquake magnitude but decrease with the distance from the epicenter to the ionosonde station. These results indicate that the PEIA is energy related.

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## 1. Introduction

[2] Large earthquakes are often preceded or accompanied by signals of different nature: electric, electromagnetic, or luminous, although seismic waves are the most obvious manifestation [*Bolt*, 1999; *Freund*, 2000]. Recently, seismoionospheric phenomena have received considerable discussions [*Hayakawa and Molchanov*, 2002; *Liu et al.*, 2004]. Of special interests are seismoionospheric anomalies, which appear either a few days to weeks before large earthquakes or around the earthquake time. For example, *Liu et al.* [2000, 2001] observed anomalous reductions of the plasma frequency at the peak of the ionospheric F2 region *foF*2 and of the ionospheric total electron content (TEC) around the epicenter 1, 3, and 4 days before the Chi-Chi earthquake (occurred on 21 September 1999 in local time, $M_w$7.6). However, most of the studies focus only on certain special or limited earthquakes.

[3] The island of Taiwan is located in the activity 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. The high occurrence rate of the earthquakes provides an excellent chance to statistically examine how the ionospheric anomaly is related to the earthquakes. This paper investigates the relationship between variations in the *foF*2 and 184 magnitude M $\geq$ 5.0 earthquakes occurred in 170 days during 1994–1999 in the Taiwan area (Figure 1). Note that the earthquakes under study are all within a distance of 500 km to the Chung-Li ionosonde station.

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## 2. Definition of Abnormal Signal

[4] To detect abnormal signals of the *foF*2 variations with 15-min time resolution, a quartile-based process is performed. Note that the recurrence time of the M $\geq$ 5.0 earthquakes during 1991–1993 is 14.2 days. Therefore to find the references for background, we compute the median of every successive 15 days of *foF*2 at each 15-min time point from 1994 to 1999. The deviation between the observed *foF*2 on the 16th day and its pervious 15-day based median is then computed. To provide the information about the deviation, we also compute the first (or lower) and the third (or upper) quartiles, denoted by LQ and UQ, respectively. Let $\widetilde{X}$ and IQR(=UQ−LQ) be the median and the associated interquartile range. Note that under the assumption of a normal distribution with mean $\mu$ and standard deviation $\sigma$ for the *foF*2, the expected value of $\widetilde{X}$ and IQR are $\mu$ and 1.34$\sigma$, respectively [*Klotz and Johnson*, 1983]. Therefore the probability of a new *foF*2 in the interval ($\widetilde{X}$ − SIQR, $\widetilde{X}$ + SIQR) is approximately 50%, where SIQR is the semi-interquartile range as a half of IQR. The running medians together with the associated SIQRs then provide references for the *foF*2 variations on the 16th day. Thus when an observed *foF*2 on the 16th day is greater or smaller than its pervious 15-day based median by one SIQR, we declare an upper or lower abnormal *foF*2 signal.

[5] If the *foF*2 variations are seismosensitive, the probability of observing the abnormal signals before earthquakes should be significant. A study reveals that significant *foF*2 reductions often appear 1 day prior to M $\geq$ 6.0 earthquakes [*Liu et al.*, 2000]. To see if this is the case for M $\geq$ 5.0 earthquakes under study, we compute the numbers of upper and lower abnormal *foF*2 signals detected for the entire 6 years and find the associated background diurnal percentages. We also calculate the diurnal percentages of the upper and lower abnormal *foF*2 signals identified 1 day prior to all the 170 M $\geq$ 5.0 earthquake days. A comparison between the two sets of percentages shows that for the upper abnormal signals, the percentages of 1 day before the earthquakes are generally smaller than the associated background percentages (Figure 2a). Therefore it is difficult to

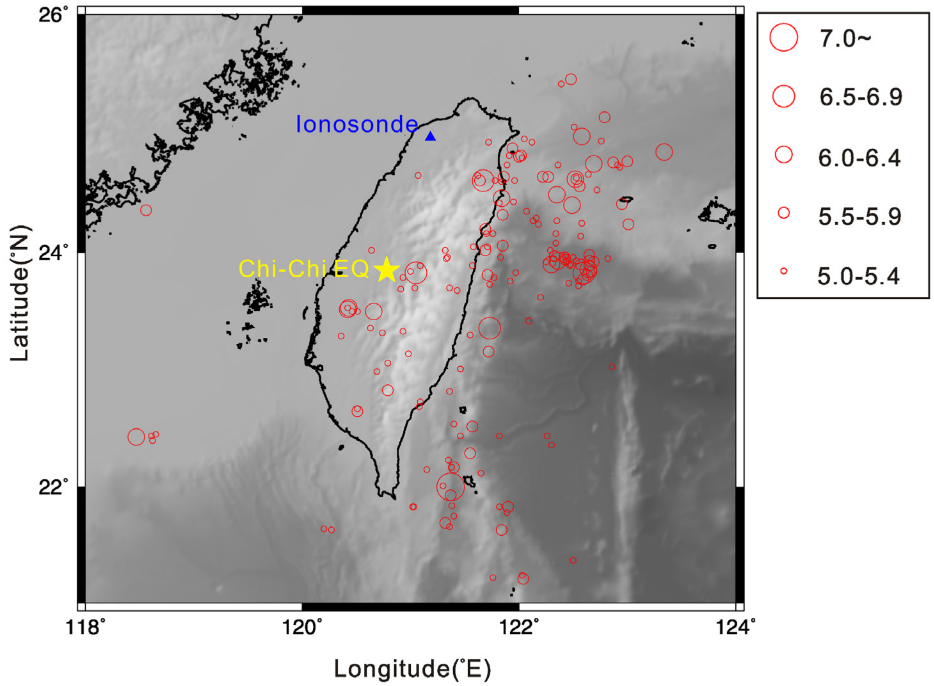


**Figure 1.** Locations of the ionosonde, the Chi-Chi earthquake, and the 184 M $\geq$ 5.0 earthquakes during 1994–1999. The ionosonde (triangular), Chi-Chi earthquake (star), and the M $\geq$ 5.0 earthquakes (circles) are denoted. The ionosonde located at Chung-Li (25.0°N, 121.2°E) Taiwan.

isolate the 1-day-before signals from the upper abnormal. However, the lower abnormal signals observed 1 day before the earthquakes yield greater percentages between 1200 and 1800 LT (local time) than the corresponding background percentages (Figure 2b). Moreover, we compute at each 15-min time point 1 day prior to the 170 M $\geq$ 5.0 earthquake days, the median of the observed *foF*2, the median of the associated reference medians, and the medians of the associated upper and lower bounds, respectively. The feature of the four median curves (Figure 2c) confirms again that the *foF*2 (depression) anomaly appears clearly between 1200 and 1800 LT 1 day before the earthquakes. To avoid short duration anomalies caused by transit geophysical effects, however, we define the *foF*2 anomaly day to be the day with continuous at least 2 hours (nine data points) lower abnormal signals during 1200–1800 LT.

## 3. Lead Time

[6] The next step is to examine if the lower *foF*2 anomaly occurs other days before the earthquakes. There are, in total, 416 anomalous days with the lower abnormal *foF*2 signals between 1200 and 1800 LT during the 6-year study period (Figure 3a). The standardized phi coefficients [*Conover*, 1999], or Z values, are employed to examine quantitatively the association between the occurrences of earthquakes and anomalous days at some time lags. The null hypothesis of independence is rejected at significance level about 0.01 if the Z value is beyond ±2.575 (see Figure 3b). Results show that the Z values are significant only for 1 and 5 days prior to the M $\geq$ 5.0 earthquakes. However, at latitudes such as Taiwan, the ionospheric *foF*2 could be depressed about a few hours to 2 days after geomagnetic storms [*Davies*, 1990]. In this study, we define a major storm day by a sudden storm commencement (SSC) day together with geomagnetic indices kp $\geq$ 6 and Dst $\geq$ 60 nT (see http://spaceweather.com/glossary/geostorm.html). During our study period, there are 117 ionospheric anomalies occurred within 1–2 days after the major storm days which are possibly caused by the geomagnetic storms. Among them, there are eight such ionospheric anomalies followed by M $\geq$ 5.0 earthquakes within 5 days. After removing the 109(=117–8) storm-related but earthquake irrelevant anomalies, we have 307 possible seismorelated anomalies. The occurrences of the 307 seismoionospheric anomalies and the 184 M $\geq$ 5.0 earthquakes during 1994–1999 in Taiwan (Figure 3a) illustrate that in certain time windows with fewer earthquakes the anomalies seem to appear less frequently. The standardized phi coefficients between the occurrences of earthquakes and 307 anomalous days (Figure 3b) further shows that the 1–5 day lead time is significant at level 0.01 when the geomagnetic storm related anomalies were taken out. Thereby, the anomalies appearing 1–5 days before the 184 M $\geq$ 5.0 earthquakes are referred to be the preearthquake-ionospheric anomalies (PEIAs).

## 4. Discussion and Conclusion

[7] Finally, our attempt is to understand the relationship between the occurrence of the PEIAs and the parameters of the related earthquakes. Note that most of the earthquakes in the Taiwan area occurred in depth less than 40 km [*Wang and Shin*, 1998]. To avoid possible confounded aftershock effects of the Chi-Chi earthquake, we simply focus on the

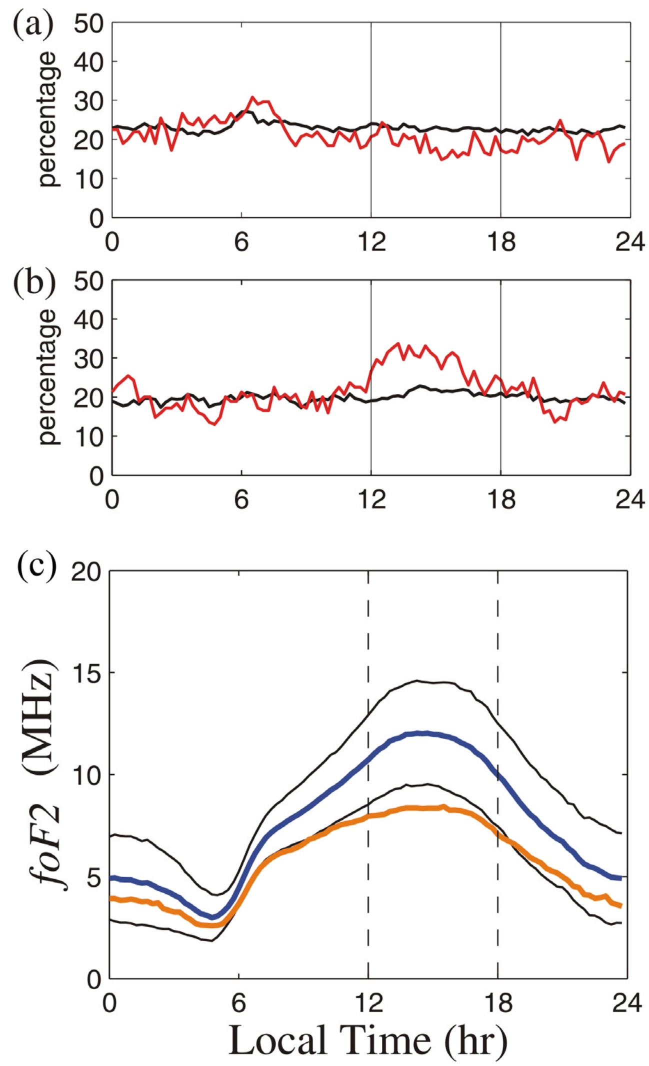


**Figure 2.** Percentages of the upper and lower abnormal signals detected the entire 6 years and 1 day before the $M \geq 5.0$ earthquakes during 1994–1999. The black and red curves denote the percentages of the entire 6 years and 1 day before the 170 earthquake days, respectively. (a) Percentage comparisons of the upper abnormal signals. (b) Percentage comparisons of the lower abnormal signals. (c) To visualize the shape of the lower abnormal signals, the median curve of the *foF*2 observed 1 day before the 170 earthquake days (heavy orange curve), together with median curves of their associated medians (heavy purple curve), upper, and lower (thin blue curves) bounds are plotted.

shallow earthquakes with the focal depth less than 40 km occurred in 93 days during 1 January 1994 to 21 September 1999.

[8] To find the earthquakes with certain magnitudes that are more likely to experience the PEIA, the odds of every 30 earthquakes sliding by 1 with the PEIA are computed from small to large magnitude. Results show the larger the earthquake, the better chance for the earthquake to be recognized by the PEIA (Figure 4a). However, only the $M \geq 5.4$ earthquakes have a significant chance to have the PEIA. In addition, the distance between the epicenter of each earthquake and the ionosonde station is computed. Again, the odds of every 30 earthquakes sliding by 1 with the PEIA are calculated from short to long distance. Results illustrate that the earthquakes within a distance of about 150 km to the ionosonde station have a significant chance to experience the PEIA (Figure 4b). In fact, all the 13 $M \geq 5.4$ shallow earthquakes occurred within the distance of 150 km have the PEIAs.

[9] Moreover, on the basis of the 93 earthquake days, the fitted logistic regression models [*Hosmer and Lemeshow*, 1989] for the logarithm of the odds of the earthquakes with the PEIA against the corresponding magnitude and distance, respectively, are

$$\log\{p/(1-p)\} = -6.96 + 1.50M$$

and

$$\log\{p/(1-p)\} = 29281.84/d^2,$$

where p is the probability that a shallow earthquake experiences the PEIA, M is the magnitude of the

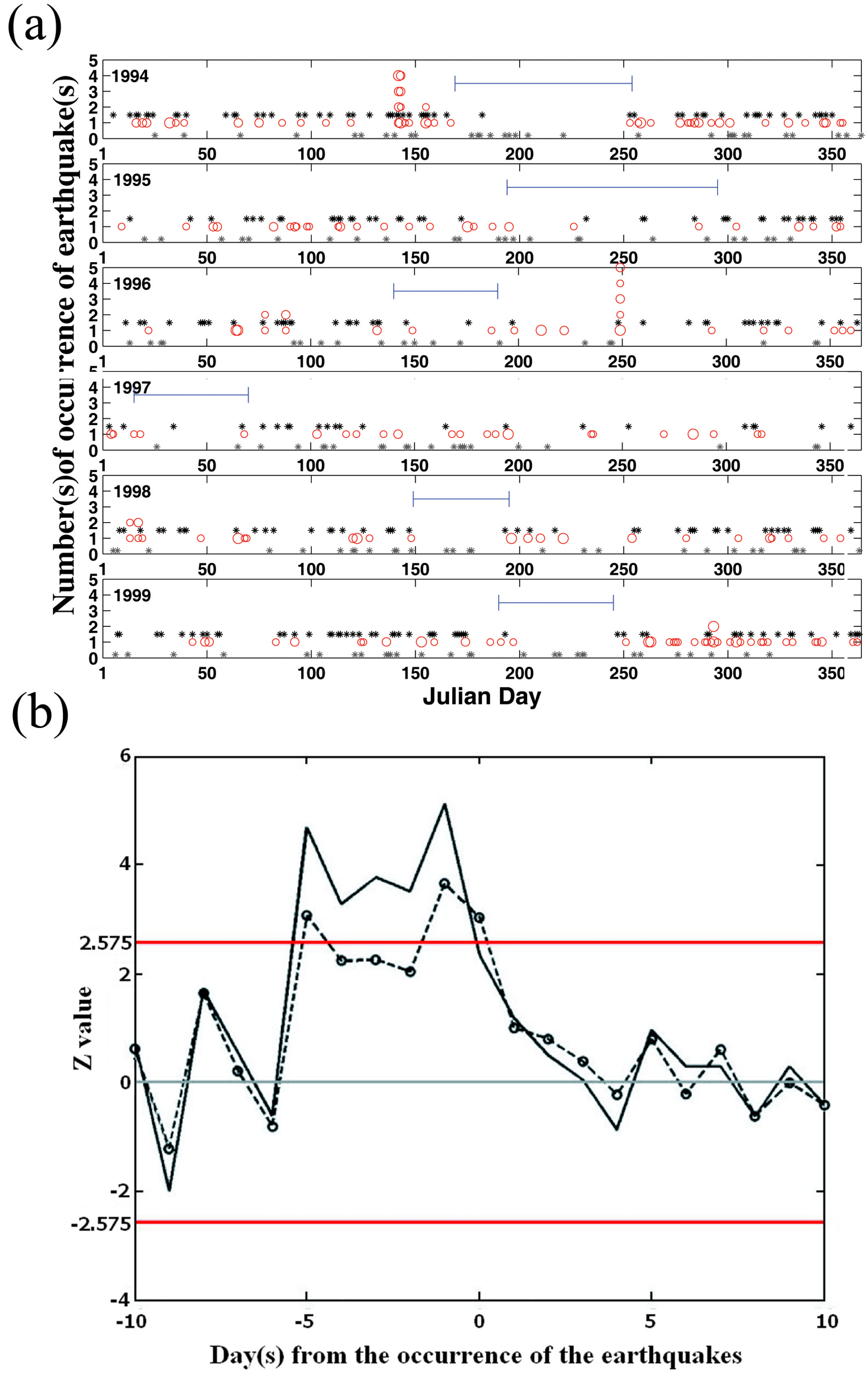


**Figure 3.** The ionospheric anomalies and M $\geq$ 5.0 earthquakes occurred in the Taiwan area during 1994–1999. (a) The compilation of ionospheric anomalies and earthquakes. The asterisks denote the 416 *foF*2-anomalous days (gray asterisk shows the 109 storm-related anomalies; black asterisk shows the 307 seismorelated anomalies), and red circles represent the184 M $\geq$ 5.0 earthquakes, respectively. The seismorelated anomalies and earthquakes simultaneously appear less frequently in some time windows (blue segmented lines). (b) Z values for the association between the 170 M $\geq$ 5.0 earthquakes and all the 416 ionospheric anomalies (dashed line) and the 307 seismorelated anomalies (solid line). The red lines at ±2.575 denote the rejection bounds at significance level 0.01.

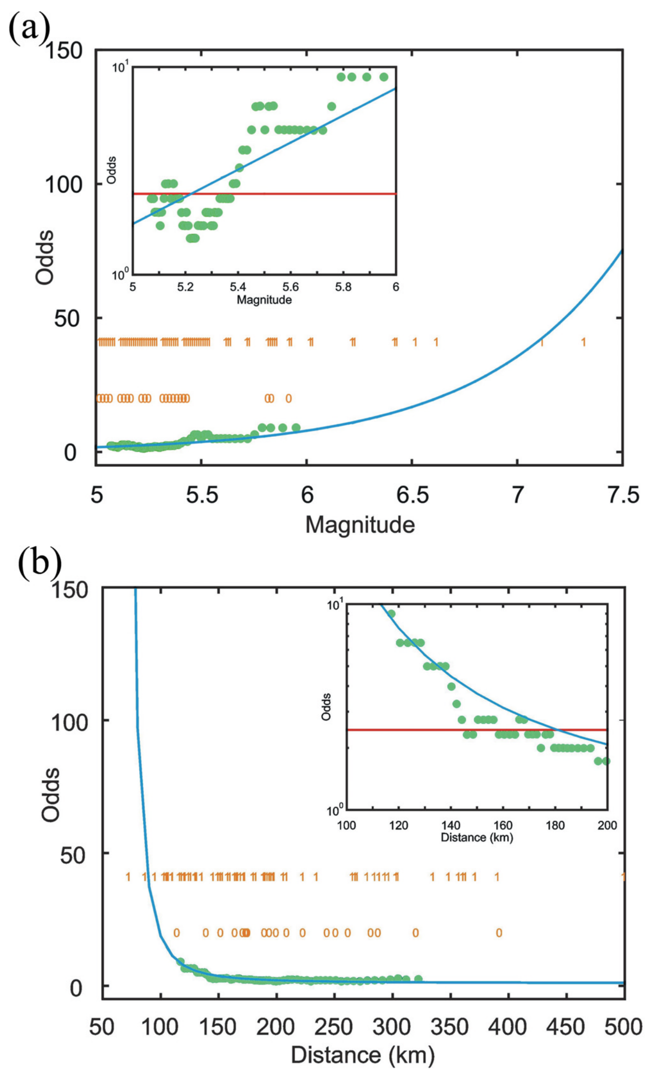


**Figure 4.** Odds of the shallow earthquakes with the PEIAs against the magnitude and distance. Zero and one (orange numbers) represent an earthquake with and without the associated PEIAs, respectively. (a) Odds (green dots) versus the related mean magnitude and the fitted logistic curve (blue curves) against magnitude. (b) Odds versus the related mean distance and the fitted logistic curve against the distance. The magnified plots in the two figures are presented in a semilog manner. The red lines in the two plots denote the rejection value of odds as 2.5 under significance level of 0.01.

corresponding earthquake, and d is the associated distance in kilometers between the earthquake epicenter and the ionosonde station. The fitted curves presented in Figures 4a and 4b indicate that the log-odds is a linear function of the earthquake magnitude with a positive slope of 1.5 but inversely proportional to the square of the distance. These findings demonstrate that the PEIA is related to the energy with a point geometry released from the associated earthquake [*Båth*, 1966; *Lay and Wallace*, 1995].

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