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The anomalies in the *foEs* prior to $M \geq 6.0$ Taiwan earthquakes

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In this paper, the greatest electron density (or plasma frequency) of the ionospheric sporadic *E* layer, *foEs*, 1–5 days observed by the Chung-Li ionosonde (25.0°N, 121.1°E) prior to $M \geq 6.0$ Taiwan earthquakes during 1994~1999 are examined to understand the ionospheric irregularities in the lower ionosphere. A comparison between the day-to-day variability and perturbations of the *foEs* before $M \geq 6.0$ Taiwan earthquakes shows that the seismo-ionospheric signatures in *foEs* mainly appear during the sunrise and sunset periods. The significant frequency increase in the *foEs* anomaly indicates that in the lower ionosphere, the electron density and irregularity during the terminator time periods enhance within 5 days before strong earthquakes.

1. Introduction

It has been suggested that prior to strong earthquakes the plasma density in the lower ionosphere could be significantly disturbed. Many scientists have observed the seismo-ionospheric variations in the greatest plasma frequency of the sporadic *E* layer, *foEs*, (see the papers listed in Hayakawa, 1999). However, those papers mainly focus on individual case studies (Papagiannis, 1972; Pierce, 1976; Hayakawa and Fujinawa, 1994; Hayakawa *et al.*, 1996; Ondoh and Hayakawa, 1999). In this paper, the *foEs* recorded by the Chung-Li ionosonde (25.0°N, 121.1°E) before strong Taiwan earthquakes are examined. Figure 1 illustrates the ionosonde location. We first study the day-to-day behavior of the *foEs* and compare that with the *foEs* appeared 1–5 days prior to the $M \geq 6.0$ Taiwan earthquakes during 1994–1999. Later, four severe earthquakes are isolated for further detailed investigations. Finally, the anomalies in the *foEs* observed in this study are compared with previous results.

2. Observation

The ionosonde at Chung-Li (25.0°N, 121.1°E) has been routinely operated recording ionograms every 15 minutes to observe the ionosphere in Taiwan area. For a typical/vertical sounding, an ionogram displays the variation of 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 (Davies, 1990). Figure 2 shows an ionogram recorded three days before the 21 September 1999 Chi-Chi earthquake in which the *foEs* and the virtual height are about 10.3 MHz and 110 km, respectively. To detect the *foEs* anomaly, we adopt the analysis method developed by Liu *et al.* (2000) and take the previous 15-day running median and associated inter-quartile range to construct the reference and upper/lower bounds. The inter-quartile range is the quantity between the upper and lower quartiles, which are the medians of the upper and lower halves, respectively. The lower and upper bounds are defined to be the inter-quartile range adding to and subtracting from the running median. Chen *et al.* (1999) shows that about 95% confidence level, the recorded quantity certain time would be between the lower and upper bounds.

The examined quantity in this paper is the *foEs* appearing 1–5 days before strong earthquakes. Table 1 lists the seismic catalog of $M \geq 6.0$ earthquakes registered in Taiwan area during 1994–1999 while Fig. 1 shows locations of the earthquakes. Figures 3a–b respectively show the *foEs* anomalies and their associated medians of these earthquakes. It can be seen that the *foEs* anomalies are much greater than their associated medians during the sunrise and sunset periods. Meanwhile, we survey the magnetic indices *Kp* and *Dst* before these earthquakes and find that the magnetic conditions within 1–5 days before the earthquakes are relatively quiet. Consequently, the anomalously large *foEs* values are not solar-terrestrial disturbance related. Therefore, they could be the seismo-ionospheric features appearing before the strong earthquakes.

To have a better understanding of the *foEs* signatures, four strong well-known earthquakes listed in Table 1 are isolated and investigated for further investigation. Figures 4a–d show the *foEs* variations before $M = 7.1$ earthquake occurred at eastern of Tai-Tone on 6 September 1996; and at Rei-Li, $M = 6.2$, 17 July 1998; Chi-Chi, $M = 7.3$, 21 September 1999; and Chia-Yi, $M = 6.4$, 22 October 1999, respectively. The thin curves from up and down respectively display the upper bound, the median, and lower bound, while the heavy curve is the observed *foEs*. It can be seen that 2 pulse-like signatures occurred on 1 and 2 days before the Tai-Tone and on 1 and 4 days before the Rei-Li earthquakes but only 1 signature occurred on 3 days before the Chi-Chi and the Chia-Yi earthquakes.

Table 1. The parameters of $M \geq 6.0$ earthquakes from 1994 to 1999.

YY	MM	DD	hh	mm	sec	Longitude	Latitude	Depth (km)	Distance (km)	Magnitude
1994	02	02	06	44	27.7	24.747	122.693	115.6	170	6.1
1994	05	23	23	16	58.8	23.863	122.636	5.5	199	6.0
1994	05	24	12	00	40.5	23.827	122.603	4.4	198	6.6
1994	06	05	09	09	30.1	24.462	121.838	5.3	100	6.2
1994	09	16	14	20	15.6	22.426	118.467	19.3	360	6.4
1995	06	25	14	59	7.1	24.606	121.669	39.9	78	6.5
1996	03	05	22	52	27.1	23.930	122.362	6.0	285	6.4
1996	07	30	04	20	53.5	24.489	122.347	65.7	144	6.1
1996[a]	09	06	07	42	7.9	22.000	121.367	14.8	302	7.1
1997	07	15	19	05	33.4	24.622	122.516	86.6	156	6.1
1997	10	12	02	24	25.7	24.981	122.576	146.4	158	6.1
1998	05	04	07	30	16.6	22.200	125.630	61.3	541	7.0
1998[b]	07	17	12	51	15.0	23.503	120.662	2.8	154	6.2
1998	08	11	10	07	49.8	24.851	123.335	116.3	234	6.0
1999[c]	09	21	01	17	12.6	23.850	120.780	8.0	117	7.3
1999[d]	10	22	10	18	56.9	23.520	120.420	16.6	159	6.4

[a]The Tai-Tone earthquake, [b]the Rei-Li earthquake, [c]the Chi-Chi earthquake, [d]the Chia-Yi earthquake.

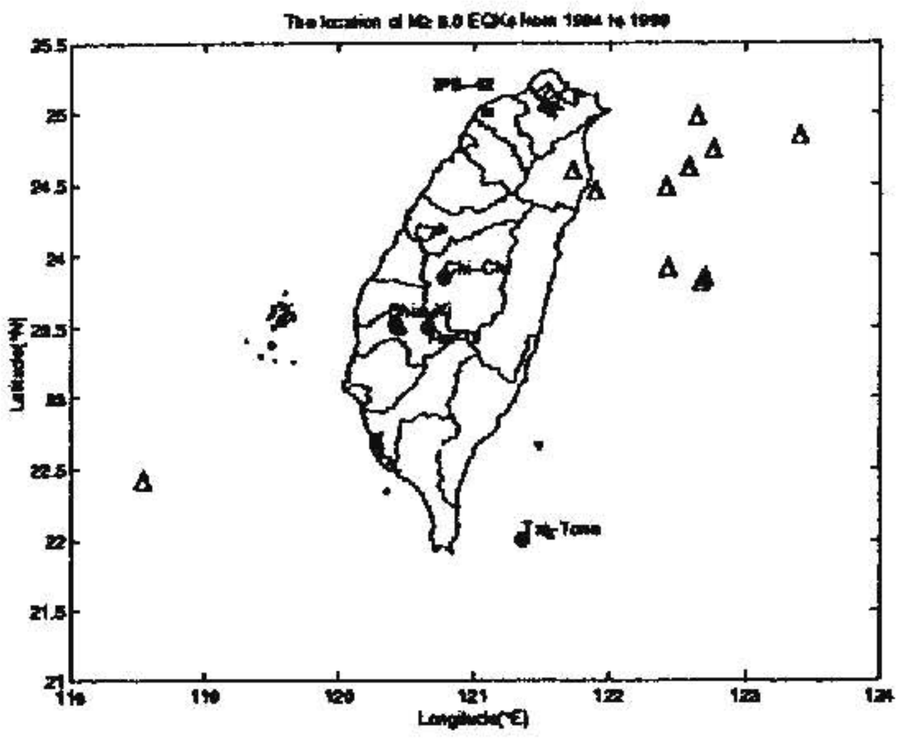

Fig. 1. The locations of Ionosode and $M \geq 6.0$ earthquakes during 1994–1999.

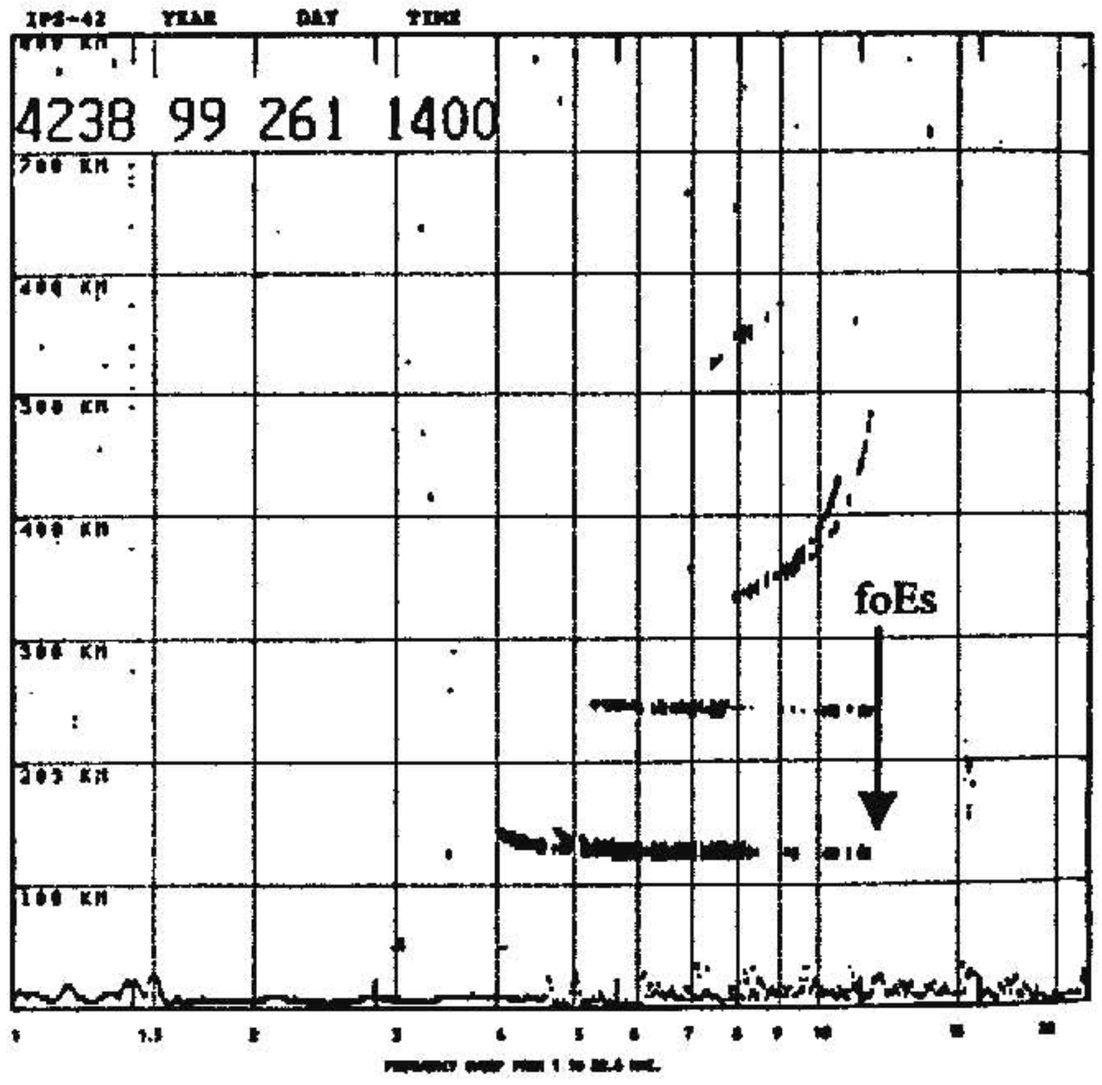

Fig. 2. An ionogram recorded at the Chung-Li ionosonde at 1400LT on 18 September 1999.

3. Discussion and Conclusion

Ondoh and Hayakawa (1999) studied anomalous occurrence of the *Es* layer before 17 January 1995, Kobe earthquake. Their figure 1 displays that the *foEs* are greater than their associated monthly median around the sunrise and sunset periods on 14 and 15 January 1995. Hayakawa (2000) studies electromagnetic phenomena associated with earthquakes. His figure 1 illustrates a surprising result on the significant change in terminator time shifts before the 17 January 1995, Kobe earthquake that the morning terminator time shifts to early hours and the evening one to later hours, on 14 and 15 January 1995. It is found that the occurrence days of the clear terminator time shift observed by Hayakawa (2000) agree with those of anomalous occurrence of the *Es* layers, reported by Ondoh and Hayakawa (1999). It has been well known that the lower ionosphere, such as the *E*- or *F*1-region, is the photochemical dominant. Therefore, due to lack of the solar X-ray/EUV radiation and the collision effect the ionospheric electron density before sunrise and after sunset usually is much smaller than that during daytime. However, when the *Es* layer appears, the electron density in the lower ionosphere increases. Due to the increased electron density during the sunrise and sunset periods, the morning and evening terminators detected by Hayakawa (2000) shift earlier and later, respectively. Finally, the previous observations and current results suggest that the seismo-ionospheric signatures in the lower ionosphere is the *foEs* increasing significantly during the sunrise and sunset periods 1–5 days before strong earthquakes.

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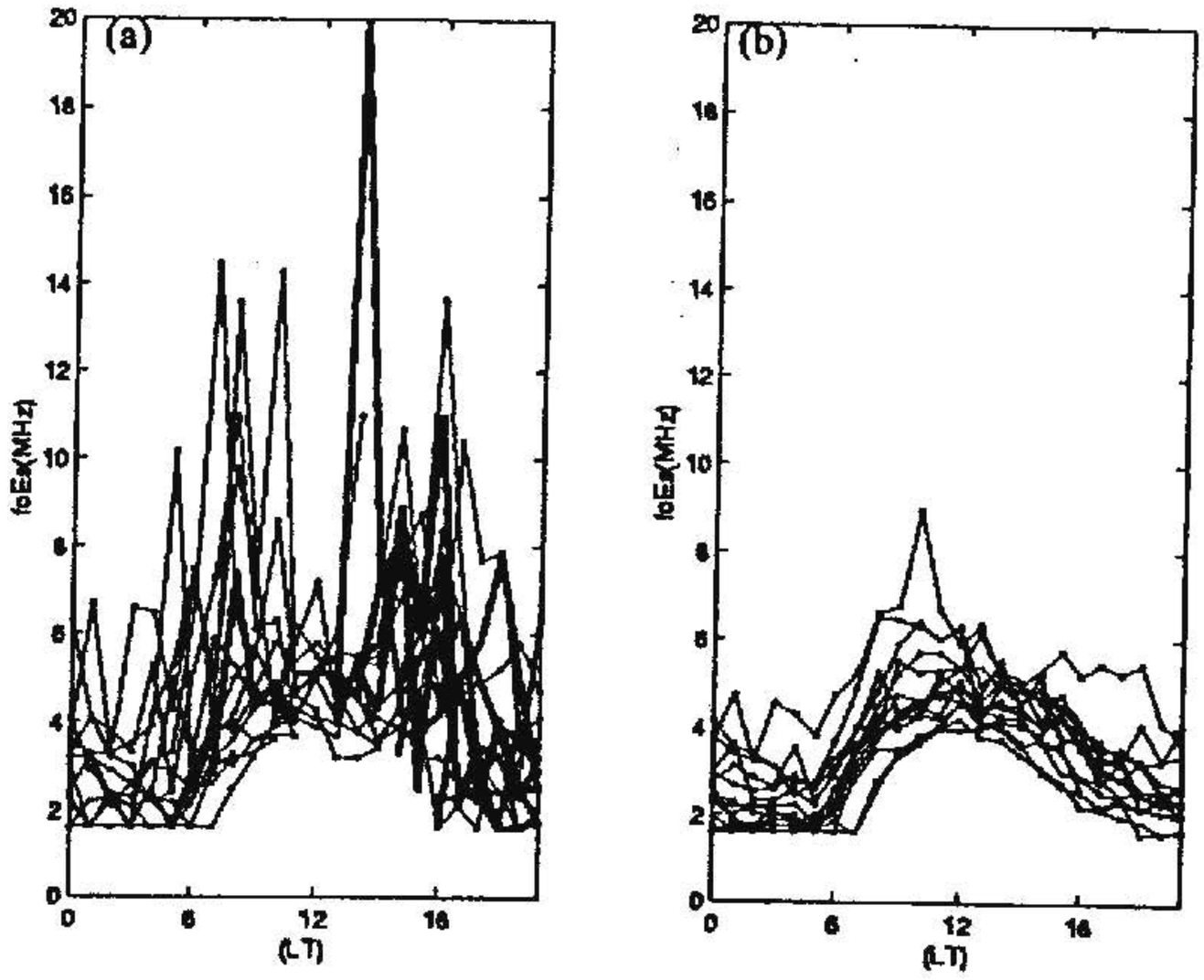

Fig. 3. The *foEs* diurnal variations observed on the disturbed (a) and, (b) the associated running median days.

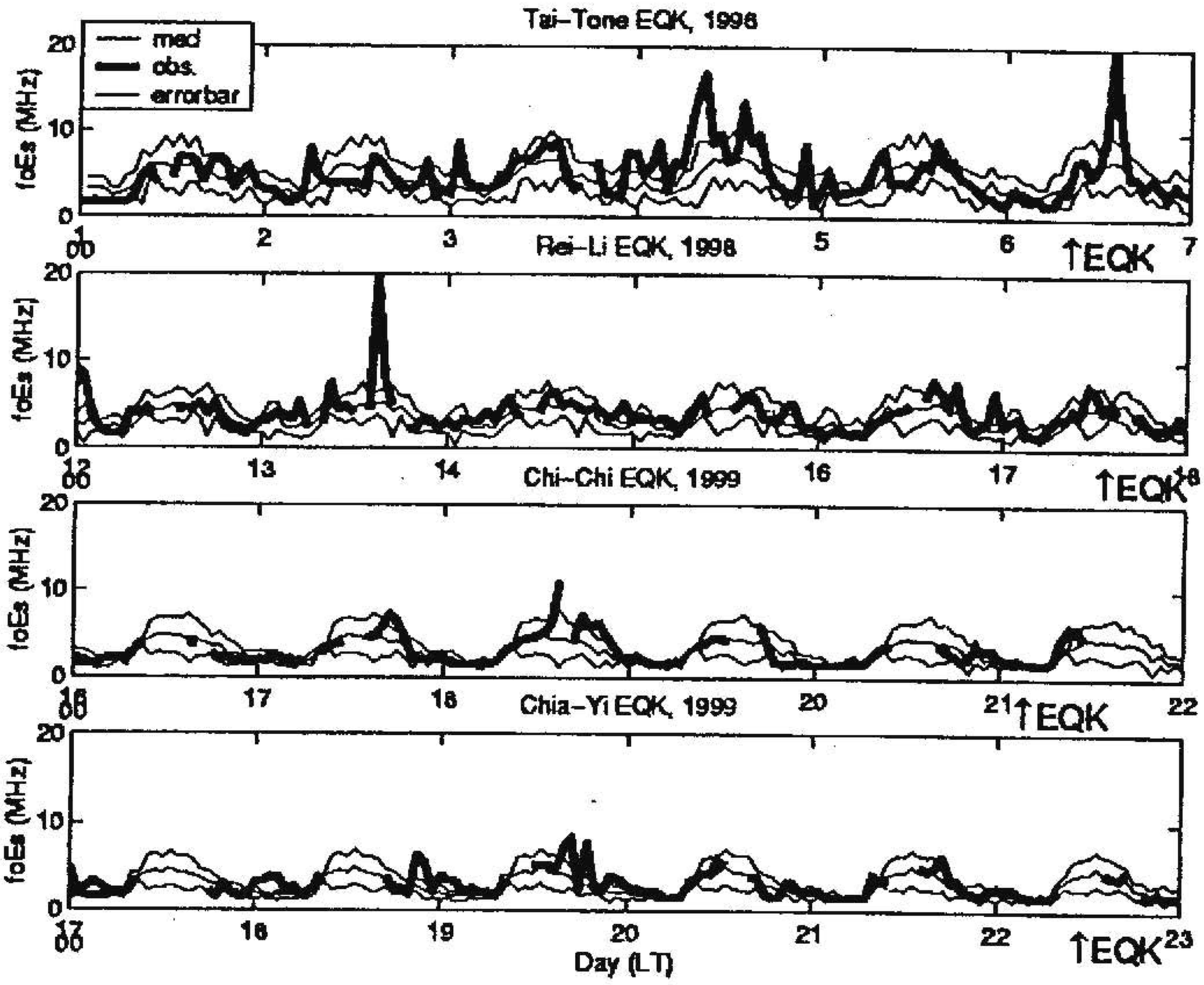

Fig. 4. Observations, associated medians, and upper and lower bounds of *foEs*, (a) the Tai-Tone earthquake (M7.1, 6 September 1996), (b) the Rei-Li earthquake (M6.2, 17 July 1998), (c) the Chi-Chi earthquake (M7.3, 21 September 1999), (d) the Chia-Yi earthquake (M6.4, 22 October 1999).

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