Seismo-ionospheric signatures prior to M≥6.0 Taiwan earthquakes

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Abstract. This paper examines variations of the greatest plasma frequency in the ionosphere, foF2, recorded by the Chung-Li ionosonde (25.0° N, 121.1° E) before M≥6.0 earthquakes during 1994-1999. The 15-day running median and the associated inter-quartile range are utilized as the reference and the upper or lower bounds to monitor the ionospheric foF2 variations for finding seismo-ionospheric signatures (precursors) of the earthquakes. It is found that precursors, in the form of the recorded foF2 falling below its associated lower bound around 1200-1700 LT, appear 1-6 days prior to these earthquakes. On September 20, 1999 UT (September 21, Taiwan local time) a large Mw=7.7 earthquake struck central Taiwan near the small town of Chi-Chi. We analyzed the foF2 and found three clear precursors 1, 3, and 4 days prior to the Chi-Chi earthquake.

Introduction

Electromagnetic phenomena associated with seismic activity have been extensively discussed (see papers listed in Hayakawa and Fujinawa, 1994; Puilnets, 1998; Molchanov and Hayakawa, 1998; Hayakawa, 1999; Freund, 1999). Of special interest are short-term electromagnetic variations that appear either as precursory effects from a few days to a few weeks before an earthquake or as an effect around the earthquake date. Note that most previous studies have been done only for specific strong earthquakes. Moreover, the precursory effect studies even employed the electromagnetic data which across the earthquakes under consideration.

Chen et al. [1999] indicated that in this way, the precursor could be confounded with the effects around or after the earthquake date. To avoid the after effect, they considered the average reoccurrence interval of earthquakes and constructed a monitoring technique based on robust statistics by comparing the greatest plasma frequency foF2 (for example see, Davies, 1990) in the ionosphere with its previous 15-day based foF2 median to explore the seismic-ionospheric perturbations (earthquake precursor). They then show that at about 95% confidence level, the foF2 recorded at a certain time on the 16[th] day X_{16} would be between the lower and upper bounds, namely, $\widetilde{X}$ -IQR and $\widetilde{X}$ +IQR, where $\widetilde{X}$ is the median value and IQR is the associated inter-quartile range between the upper and lower quartiles of the previous 15-day foF2. Notice that the monthly median, and upper and lower quartiles are standard parameters in ionosonde data books of the International Union of Radio Science (URSI).

In this paper, the technique developed by Chen et al. [1999] is applied to examine the variations in ionospheric foF2 before M≥6.0 earthquakes of 1994-1999 to find the precursors of these earthquakes. Later, the foF2 perturbations prior to the Chi-Chi earthquake with M=7.3 (Mw=7.7), which occurred at 0147 LT (UT = LT – 8 hr), 21 September 1999, in the middle of Taiwan, are investigated. Finally, the possible precursor mechanism is proposed and discussed.

Observation

An IPS-42 ionosonde located at Chung-Li (25.0° N, 121.1° E) has been routinely recording ionograms every 15 minutes to observe the ionosphere in Taiwan area. Table 1 lists the occurrence time, location, depth, and magnitude as well as the appearing day (before the earthquake) of the associated precursors of the M≥6.0 earthquakes within a radical distance of 400 km from the Chung-Li Ionospheric Station during January 1994 - September 1999 (see Figure 1). It can be seen that the Chi-Chi earthquake is the one with the largest magnitude. The foF2 recorded 0-20 days prior to each earthquake are analyzed using the technique of Chen et al. [1999] to identify the precursors. The last column in Table 1 indicates the date before each earthquake when the foF2 precursors appeared: D-6, for example, means 6 days before the earthquake. Note that one earthquake generally had one precursor, while the Chi-Chi earthquake yielded three precursors. In the following, we first examine the precursors of the M≥6.0 earthquakes occurred in 1994-1998 (see Figure 2), and then compare them with those of the Chi-Chi earthquake.

Figures 2a and 2b respectively illustrate the foF2 recorded on the disturbed days and the associated 15-day running medians of the M≥6.0 earthquakes occurred in 1994-1998 listed in Table 1. Figure 2c reveals the deviations of the recorded foF2 from its associated median. The recorded foF2 are much less than their associated median during 1200-1800LT. Based on Chen et al. [1999], the recorded foF2 exceeding their associated upper or lower bounds are considered to be the anomalous and the strength of the anomalous can be defined as the exceeding value. Therefore, the positive (negative) quantities corresponding to the exceeding values at which the recorded foF2 are greater (less) than their associated upper (lower) bounds, respectively. Figure 2d presents the anomaly strengths (dots) together with the upper (lower) anomaly counts shown by a blue (red) line, respectively. It can be seen from Figure 2d that the lower anomaly counts during 1200-1800 LT are larger than the greatest value of the upper anomaly counts at 0715 LT. To avoid the dusk effect, we therefore consider that the precursor

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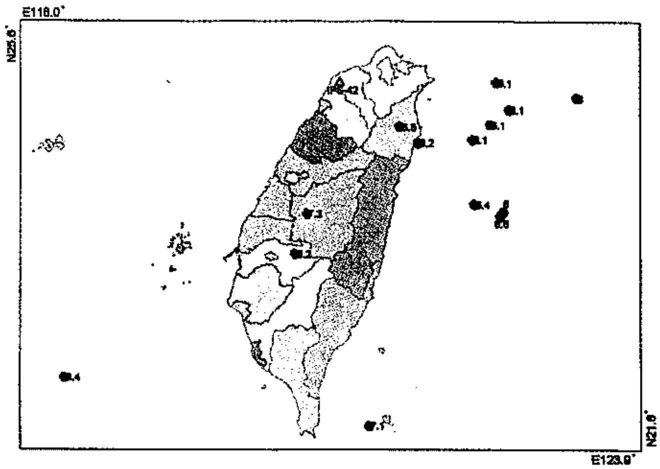

Figure 1. Locations of the ionosonde and the M ≥ 6.0 earthquakes around Taiwan area during January 1994 - September 1999.

is the recorded foF2 less than their associated lower bounds between 1200-1700 LT.

The Chi-Chi earthquake with M=7.3 (Mw=7.7) occurred at 0147 LT (1747 UT) on 21 (20) September 1999, in central Taiwan. The earthquake epicenter was located at 23.85° N, 120.78° E geographic (see Figure 1) with a depth of 8.0 km. To clearly isolate the earthquake precursor from the other geophysical signals such as geomagnetic storms, the geomagnetic indices Kp and Dst are examined. Note that the Kp index monitors the planetary activity on a worldwide scale while the Dst index records the equatorial ring current variations (Mayaud, 1980). Figure 3 illustrates the geomagnetic condition that was relatively quiet in September 1999, except 1-3 days after two sudden storm commencements (SSCs) on 12 and 22 September, respectively. Since the 9/12 storm happened long before and the 9/22 one occurred after the Chi-Chi earthquake, any precursors should not be contaminated by the two storms.

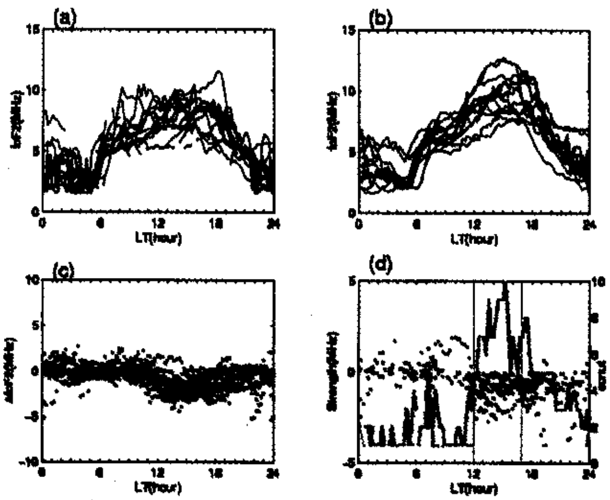

Figure 2. The perturbed foF2 (a), the associated running median (b), the perturbed foF2 deviated from their associated median (c), and the strength and the count of the anomalies/precursors of the $M^3$6 earthquakes (d), during 1994-1998.

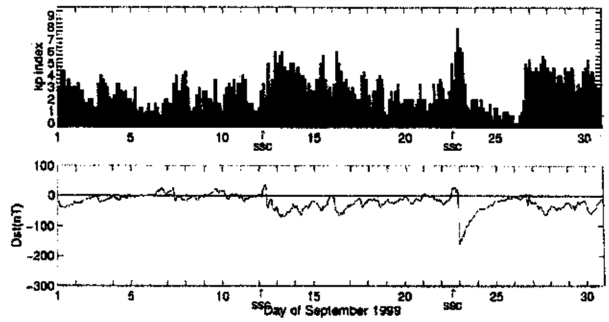

Figure 3. Variations of the geomagnetic indices Kp and Dst in September 1999. The horizontal axis represents the day of September 1999 in a UT coordinate and the SSC denotes the sudden storm commencement.

Figure 4a displays an overview of the ionospheric foF2 variations in September 1999 obtained by applying the technique of Chen et al. [1999]. The red, blue, and black lines denote the recorded foF2, 15-day median, and lower/upper bounds, respectively. Figure 4b illustrates the strengths of the lower anomalies (green line) or the precursory signals (black shaded region), for September 1999. Note that the precursory signals have been defined to be the lower anomalies occurring between 1200 and 1700 LT. Some strong anomalies, which appeared around midnight on 6, 9, 14, 15, 25, and 26 September, were due to the occurrences of the spread F, which made the foF2 very difficult scaled (also see spiky fluctuations of the red line shown in Figure 4a). Meanwhile, the short lasting precursory signals that appeared on 6, 8, and 9 could be related to an M5.4 earthquake (depth=5.2 km, 22.44°N, 121.82°E) that occurred at 2218 LT on 10 September 1999. A weak signal appeared on 14 September that could have been either an early precursor of the Chi-Chi earthquake or a fluctuation perturbed by the magnetic storm of which SSC occurred on 12 September. It is found that three clear precursors appeared on 17, 18, and 20 September.

Discussion and Conclusion

Chen et al. [1999] analyzed the foF2 associated with M≥5.0 earthquakes during 1994-1997. They found that the chance of observing a precursor within five days before an M≥5.0 earthquake was about 73.8%, and usually one precursor would be registered for each earthquake. Table 1 shows that the chances of observing a precursor within one day (D-1) and three days (D-1 - D-3) prior to an M≥6.0 earthquake are 50% (7/14) and 85.7% (12/14), respectively, and all precursor are observed within six days before the M≥6.0 earthquakes. Moreover, three precursors were observed 1, 3, and 4 (D-1, D-3, and D-4) days before the Chi-Chi earthquake. By comparing the results shown in Figures 2d and 4b, it can be seen that the strengths of the two larger precursors, which appear on 17 and 18 September, of the Chi-Chi earthquake are stronger than those observed for the other M≥6.0 earthquakes that occurred of the last five years. Therefore, it may be expected that stronger earthquakes not only have a higher chance of observing their precursors but also yield larger precursors.

Freund [1999] shows that mobile positive holes can be activated in the crust by microfractures during the dilatancy

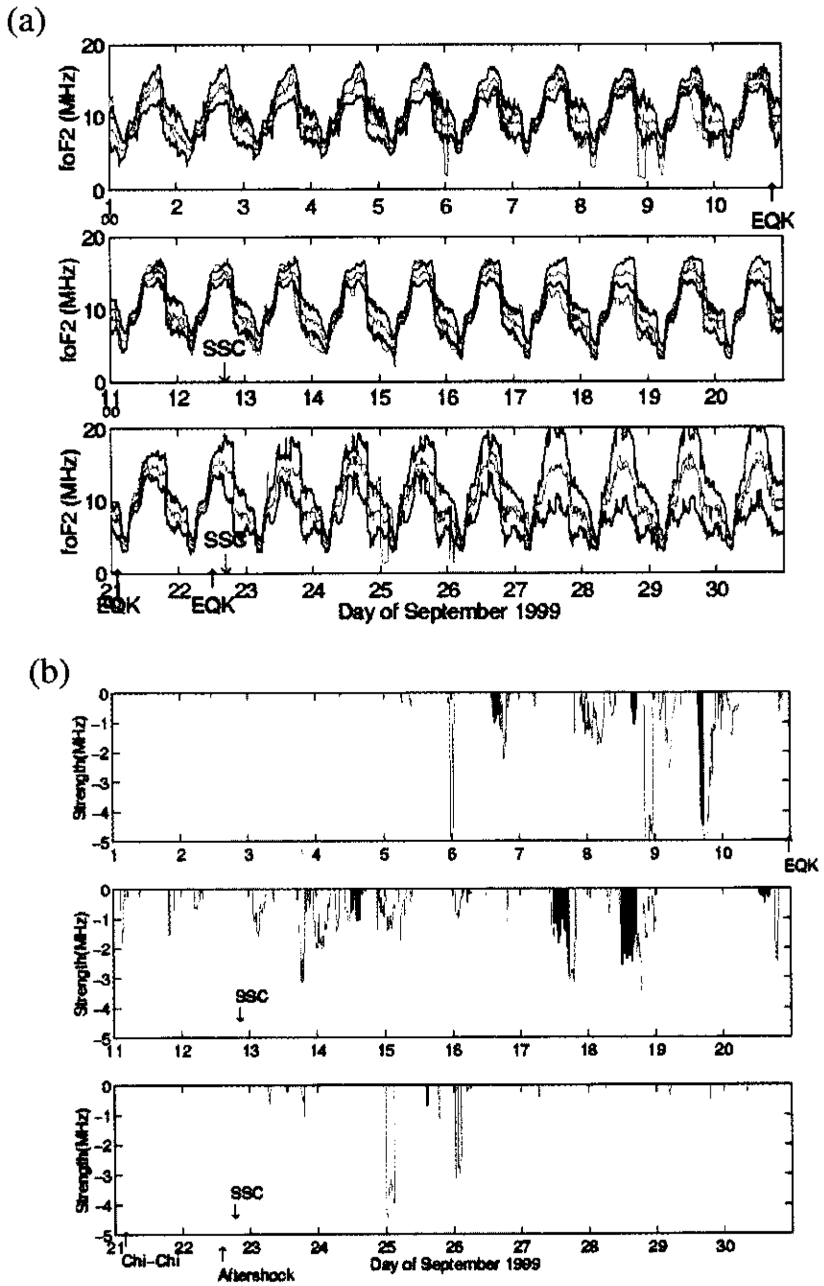

Figure 4. Observations, associated medians, and upper and lower bounds of the foF2 (a); and the strengths of the lower anomalies and the precursors (b) in September 1999. The EQK denotes the occurrence of an earthquake.

stage of earthquake preparation [Bolt, 1988] and diffusion and outflow of these holes generate high electric fields at the earth surface. Puilnets and Benson [1999] analyzing topside sounder data showed that strong vertical atmospheric electric field significantly affects the electron density in the ionosphere. Kim and Hegai [1999] theoretically studied the changes in the F2 region caused by the vertical electric filed generated in forthcoming earthquake's epicentral zone and found that the horizontal distribution of ionospheric electron density was appreciably perturbed in a non-uniform manner over the area size of about 400 km. They also evaluated the electron density being perturbed about +/- 10%. Figures 4a and 4b demonstrate at about 1400LT on D-4/D-3 days of the Chi-Chi earthquake that the perturbed foF2 and the associated running medians are about 10.5 MHz and 15.0 MHz, respectively. Since the plasma density is proportional to the square of its frequency (for example see, Davies, 1990) the perturbed electron density is about -51.1%. If the perturbation of electron density was caused by the vertical electric fields, the latter prior to the Chi-Chi earthquake were significant.

In conclusion, we applied a technique with 95% confidence intervals on the foF2 variations to search for the precursors of M≥6.0 earthquakes of 1994-1999. Results show that all the earthquake precursors are detected within six days before the earthquakes. Moreover, the strength and number of precursors suggest that the energy leakage of the Chi-Chi earthquake during its preparation period is significant.

Table 1. The parameters of M≥6.0 earthquakes from 1994~1999 with identified foF2 Precursors.

YY	MM	DD	hh	mm	sec	latitude	longitude	depth (km)	M	precursor
94	02	01	22	44	27.7	24.747	122.693	115.6	6.1	D-6
94	05	23	15	16	58.8	23.863	122.636	5.5	6.0	D-1
94	05	24	04	00	40.5	23.827	122.603	4.4	6.6	D-1
94	06	05	01	09	30.1	24.462	121.838	5.3	6.2	D-1
94	09	16	06	20	15.6	22.426	118.467	19.1	6.4	D-3
95	06	25	06	59	7.1	24.606	121.669	39.9	6.5	D-3
96	03	05	14	52	27.1	23.930	122.362	6.0	6.4	D-1
96	07	29	20	20	53.5	24.489	122.347	65.7	6.1	D-2
96	09	05	23	42	7.9	22.000	121.367	14.8	7.1	D-1
97	07	15	11	05	33.4	24.622	122.516	86.6	6.1	D-1
97	10	11	18	24	25.7	24.981	122.576	146.4	6.1	D-2
98	07	17	04	51	15.0	23.503	120.662	2.8	6.2	D-3
98	08	11	02	07	49.8	24.851	123.335	116.3	6.0	D-4
99	09	21	01	47	12.6	23.850	120.780	8.0	7.3	D-4, D-3, D-1

Note: Earthquake parameters are based on the Central Weather Bureau's catalog.

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