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A study on the TEC perturbations prior to the Rei-Li, Chi-Chi and Chia-Yi earthquakes

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Abstract: Three large earthquakes struck central Taiwan near the towns of Rei-Li on 17 July 1998, Chi-Chi on 20 (21 for local time) September 1999 and Chia-Yi on 22 October 1999, respectively. These earthquakes severely damaged structures heavily changed landforms and disturbed geophysical environments. In this paper, a procedure is introduced to derive the ionospheric total electron content (TEC) from data recorded by a network of the Global Positioning System (GPS) in Taiwan. Based on the network data, the latitude-time-TEC (LTT) plots prior to the three earthquakes are constructed. The plots show that during 1-4 days prior to the three earthquake onsets, the TEC values decrease and the anomaly crests move toward the equator.

1. Introduction

Many scientists have 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 have a better estimation on earthquake hazard, a large amount and broad distribution of GPS stations 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). Calais and Minster (1995) showed GPS detection of ionospheric TEC perturbations following the January 17, 1994, Northirdge Earthquake. Recently, Liu et al. (2000a; 2000b) using the ionosonde at Chung-Li station (25.0° N, 121.2° E) and the Taiwan GPS network observed significant decreases of the ionospheric electron density, foF2, and TEC, 3 and 4 days before the Chi-Chi Earthquake. Liu et al. (1996) show that the foF2 and TEC generally yield similar tendencies. In this paper, we adopt the method developed by Liu et al [1996] to examine the TEC variations during the three severest earthquakes striking central

Taiwan near the towns of Rei-Li on 17 July 1998, Chi-Chi on 20 (21 for local time) September 1999 and Chia-Yi on 22 October 1999, respectively (for detail see Table 1). To validate the current method, the simultaneously deduced overhead TEC and the foF2 observed at Chung-Li during the three earthquakes are compared and examined. Later, combining all the data recorded by the GPS network, the latitude-time-TEC (LTT) plots prior to the three earthquakes are constructed. Finally, based on these plots, possible mechanisms resulting in the significant decreases of the ionospheric electron density prior to strong earthquakes are proposed.

Table 1. The Parameters of Rei-Li, Chi-Chi, and Chia-Yi Earthquakes from Identified foF2 Precursors.

YY	MM	DD	hh	mm	sec	latitude	longitude	depth (km)	M	precursor
98	07	17	04	51	15.0	23.503	120.662	2.8	6.2	D-3
99	09	20	17	47	12.6	23.850	120.780	8.0	7.3	D-4, D-3, D-1
99	10	22	02	18	56.9	23.52	120.42	16.6	6.4	D-1,D-3

Note that the time is in UT (UT=LT-8hr)

2. Methodology

To simultaneously observe larger area of the ionosphere, the global positioning system (GPS) is ideal to be employed. The space segment of the GPS consists of a conetellation of 24 operating satellites in six circular orbits 20,200 km above the Earth at an inclination angle of 55° with a 12-hr period. The satellite transmits two frequencies of signals (f_1=1575.42 MHz and f_2=1227.60 MHz). Since the ionosphere is a dispersive medium, scientists are able to evaluate the ionospheric effect with measurement of the modulations on the carrier (codes) and the carrier phases recorded by dual-frequency receivers [*Leick*, 1995; *Sardón et al.*, 1994; *Liu et al.*, 1996]. From recorded broadcast ephemeris and given sub-ionospheric height (325 km in the current paper), the slant TEC along the ray path can be converted into the vertical TEC at its associated longitude and latitude.

The propagation of the GPS signals is affected by both environment and instrument. Therefore, GPS pseudorange $p^i_{k,j}$ and carrier phase $L^i_{k,j}$ for frequencies 1 and 2, in range units, can be expressed as follows:

$$P^i_{1,j} = s^i_{0,j} + d^i_{ion,1,j} + d^i_{trop,j} + c(\tau^i - \tau_j) + d^i_{q,1} + d_{q,1,j} + d^i_{res,j} \quad (1a)$$

$$P^i_{2,j} = s^i_{0,j} + d^i_{ion,2,j} + d^i_{trop,j} + c(\tau^i - \tau_j) + d^i_{q,2} + d_{q,2,j} + d^i_{res,j} \quad (1b)$$

$$L^i_{1,j} = \lambda_1 \phi^i_{1,j} = s^i_{0,j} - d^i_{ion,1,j} + d^i_{trop,j} + c(\tau^i - \tau_j) - \lambda_1 b^i_{1,j} \tag{1c}$$

$$L^i_{2,j} = \lambda_2 \phi^i_{2,j} = s^i_{0,j} - d^i_{ion,2,j} + d^i_{trop,j} + c(\tau^i - \tau_j) - \lambda_2 b^i_{2,j} \tag{1d}$$

The superscript i and subscript j represent the satellite and ground-based GPS receivers, respectively,

s_0, the true distance between the receiver and satellite;

d_{ion}, d_{trop}, the ionospheric and tropospheric effects;

c, the speed of light in free space;

τ, the satellite or receiver clock offset;

d_q, the instrumental bias of the satellite or receiver;

d_{res}, other bias;

λ, the carrier wavelength;

ϕ, the total carrier phase between the receiver and satellite, and

b, the cycle slips of the carrier phase.

The ionosphere acts as a dispersive medium for the GPS signals, but the troposphere is nondispersive. As such the tropospheric effect in the carrier phase and pseudorange can be removed by subtracting (1a) from (1b) and (1c) from (1d), respectively. According to the Appleton formula (for an example see Budden, 1985) the phase refractive index n in the ionosphere is a function of the radiowave frequency, electron concentration (or plasma frequency), collision frequency and geomagnetic field strength (or gyrofrequency). In fact, however the GPS radiowave and plasma frequencies are much greater than the other two. Hence, the ionospheric effect in terms of the total electron content along a line-of-sight, TEC* in electron/m2, between ground receiver Rx and the satellite Tx can be written as:

$$d_{ion} = s' - s_0 = \int_{Rx}^{Tx} (n_g - 1) dl = \frac{40.3}{f^2} \int_{Rx}^{Tx} N \, dl = \frac{40.3}{f^2} TEC^* \tag{2}$$

where s' is the virtual distance between the receiver and satellite, N is the electron concentration in electron/m^3, and f represents radiowave frequency in Hz. The l-axis stands for the satellite-to-receiver direction. Combining (1) and (2) yields:

$$TEC^* = \frac{1}{40.3} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \left(P^i_{2,j} - P^i_{1,j} - k^i - k_j \right), \text{ and} \tag{3}$$

$$TEC^* = \frac{1}{40.3} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \left(\lambda_1 \phi^i_{2,j} - \lambda_2 \phi^i_{2,j} + A^i_j \right) \tag{4}$$

where $k^i = d^i_{q,2} - d^i_{q,1}$, $k_j = d_{q,2,j} - d_{q,1,j}$, and

$$A_j^i = \left(P_{2,j}^i - P_{1,j}^i\right) + \left(\lambda_2\phi_{2,j}^i - \lambda_1\phi_{1,j}^i\right) - \left(k^i - k_j\right) \quad (5)$$

Wilson et al. (1992) and Sardon et al. (1994) found k^i to be about 2-3 nanoseconds which is as small as $8\text{x}10^{16}$ electron/m^2. Nevertheless, two tables given by Wilson et al. (1992) and Sardon et al. (1994) were employed to redeem the bias of k^i. Tsai (1995) studied k_j and found that the value of k_j of a GPS receiver is nearly a constant. Ezquer et al. (1992) indicated that the TEC during 0400-0500LT usually yields the smallest value. For simplicity, we can arbitrarily assign a k_j value, which results in the TEC during 0400-0500LT to be about 5 TECu (1 TECu = $1\text{x}10^{16}$ electron/m^2). Liu et al. (1996) evaluated the error percent of the daytime TEC caused by the simplification to be less than 5%. Although (3) can solely and directly derive the TEC, due to the length of the pseudo code, the precision of the TEC* is relatively low. The alternative way is to combine (3) and (4) to obtain the least-square-fit value of $A^i{}_j$, and then to utilize (4) to attain greater precision of the *TEC**.

As a satellite passes from the horizon to zenith, the *TEC** can be obtained. However, scientists have found that it is useful to mathematically adjust the *TEC** to the TEC observed at the subionospheric point which is referred to as the vertical total electron content, VTEC:

$$VTEC = TEC^* \, S(e). \quad (6)$$

In (6), S(e) is the slant function given by Sover and Fanselow (1987):

$$S(e) = \frac{\sqrt{R^2\sin^2 e - R^2 + (R + h_1)^2} - \sqrt{R^2\sin^2 e - R^2 + (R + h_2)^2}}{h_1 - h_2} \quad (7)$$

where e is the satellite elevation, h_1 and h_2 are the lower and upper heights of the ionosphere, respectively and R is the mean radius of the Earth. It should be noted that the function $S(e)$ basically depends on the height of the mean layer of the ionosphere, $h_m = (h_1 + h_2)/2$. Davies [1990] indicated that h_m could lie between 300 and 450 km, while Holfmann-Wellenhof et al. [1992] considered it should be limited between 300 and 400 km. For simplicity, Sardon et al. (1994) assumed the h_m to be 355 km. Based on the results in Wu (1992), the present authors find the h_m in the Taiwan area during 1993 and 1994 to be about 325 km. Assuming there to be a network of 8 ground receivers and a full GPS constellation, 40-64 VTECs can be derived simultaneously (5-8 each ground site). Accordingly, such a network can ultimately be capable of making a "snapshot" of the longitudinal/latitudinal VTEC distribution in the Taiwan area, thereby constructing the TEC map. To further derive the time variation TEC along a certain longitude, we simply convert the differential longitude, the certain longitude subtracting from the VTEC longitude, into the differential time by 1hr/15°. To assign a correct time for each observed VTEC, we need to add the time at the certain longitude with the associated differential time.

3. Observations

Figure 1 illustrates the locations of the Chung-Li ionosonde, the GPS receivers, and the epicenters of the three strong earthquakes. The ionosonde observes the ionosphere within a horizontal region of a radius 500 km from Chung-Li, 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 three epicenters. Figure 2 displays the ionospheric electron density *NmF2* and *VTEC* currently derived from the ionosonde and the GPS network at Chung-Li. The relation between the plasma frequency *foF2* and the plasma density *NmF2* at the *F*-peak can be expressed as (for detail see Budden, 1990)

$$NmF2 = (foF2)^2 / 80.3 \qquad (8)$$

Where *NmF2* is in electron/m^3 *and foF2* in Hz*.* It can be seen that during the three earthquake periods, the two measurements yield nearly identical tendencies, except during 17 and 22 October 1999. Note that the sudden drops in the VTEC were caused by no data recorded from six out of the eight GPS receivers. Nevertheless, the general agreement between the two observations suggests that the TEC can be used to detect the seismo-ionospheric precursors. It can be seen that the significant *VTEC* decreases occurred on 14 July 1998, three days before the Rei-Li earthquake and on 17 (18) September 2000, 4 (3) days before the Chi-Chi earthquake while *VTEC* decreases occurred between 0400 and 0900 UT on 19 (21) October 2000, 3 (1) days before the Chia-Yi earthquake.

The Taiwan GPS network consists of 8 ground-based receivers, and therefore for a full GPS constellation, 40-64 TECs can be derived simultaneously (5-8 each ground site). Accordingly, such a network can ultimately be capable making of an LTT plot observing the diurnal TEC variation in various latitudes. Figure 4 illustrates the LTT plots seven days prior to each earthquake. It is clear that the daytime TEC values on those anomaly days severely decrease and the crest of the equatorial anomaly moves southward (equatorward).

4. Discussion and conclusion

An existing procedure is introduced to derive the TEC from the Taiwan GPS network. It is found the anomaly decreases in TEC appear 1-4 days prior to the three earthquake onsets. Liu et al. [2000] analyzed the ionospheric *foF2* recorded at Chung-Li and found 4 (3) days before the Chi-Chi earthquake the *F*-peak electron density *NmF2* between 1200-1700 LT reduced about 51% from its normal value. Chuo et al. [2000] studied the ionospheric *foF2* recorded during the Chia-Yi earthquake and observed about 44% *NmF2* decreases on 3 (1) days before the earthquake. Chuo et al. [2000] further estimated the *F2*-peak electron density *NmF2* reductions 3 days prior the Rei-Li earthquake to be about 30%. The seismo-ionospheric signatures observed by the three radar (Chung-Li ionosonde) studies agree with the anomalies in the GPS TEC presented in Table 1. The similar result was obtained for *foF2* latitudinal variations obtained from Intercosmos-19 topside sounding data while satellite passed across the equatorial anomaly one day before the near equator earthquake in comparison with the passes over the same place for undisturbed days. The satellite data were supported by the data of latitudinal chain of ionospheric stations [Pulinets et al., 2000]. In the case considered the equatorial anomaly crest completely disappeared. Since the *foF2* and *VTEC* are two very different physical quantities derived form two completely different techniques (on the base of the echo mechanism and sounding frequency viewpoints), the significant decreased features in the two quantities concurrently appeared 1-4 days before the three earthquakes could be considered the possible earthquake precursors.

It has been well known by the ionospheric scientists that near the geomagnetic equator, where the magnetic filed is horizontal, the movement resulting from an imposed eastward electric filed is vertical; it is upward during the day and, when combined with preferential diffusion along the direction of the geomagnetic filed, produce enhanced concentration at the places on each side of the equator. This interesting phenomenon has been called the "equatorial anomaly" (for detail see, Ratcliffe, 1974). Figure 3 shows the variations of the north side of the equatorial anomaly region with the GPS *VTEC*. It can be seen that during the precursory days the TEC value decreases and the anomaly crest move toward the equator. It is the TEC reduction together with the crest equatorward motion result in the significant electron density decreases previously observed by the ionosonde at Chung-Li.

In conclusion, the TEC derived from the Taiwan GPS network have been employed to detect earthquake precursors. The anomalies simultaneously appearing in the previous *foF2* and the current GPS TEC prior to the Rei-Li, Chi-Chi, and Chia-Yi earthquakes that suggest the seismo-ionospheric signatures to be sensible enough to be detected.

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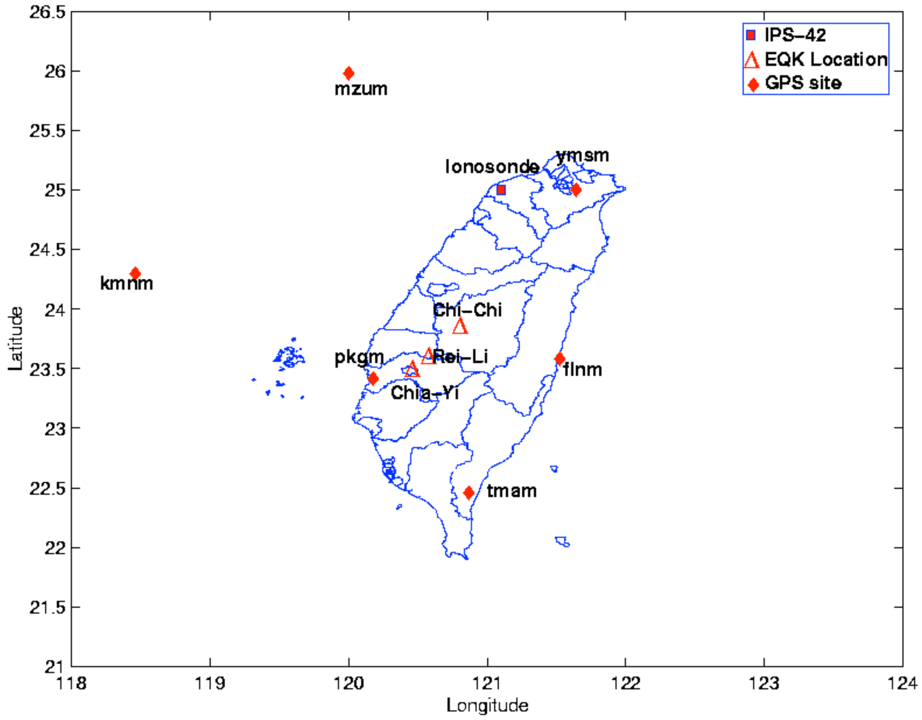

Figure 1. The locations of earthquakes , ionosonde, and GPS sites

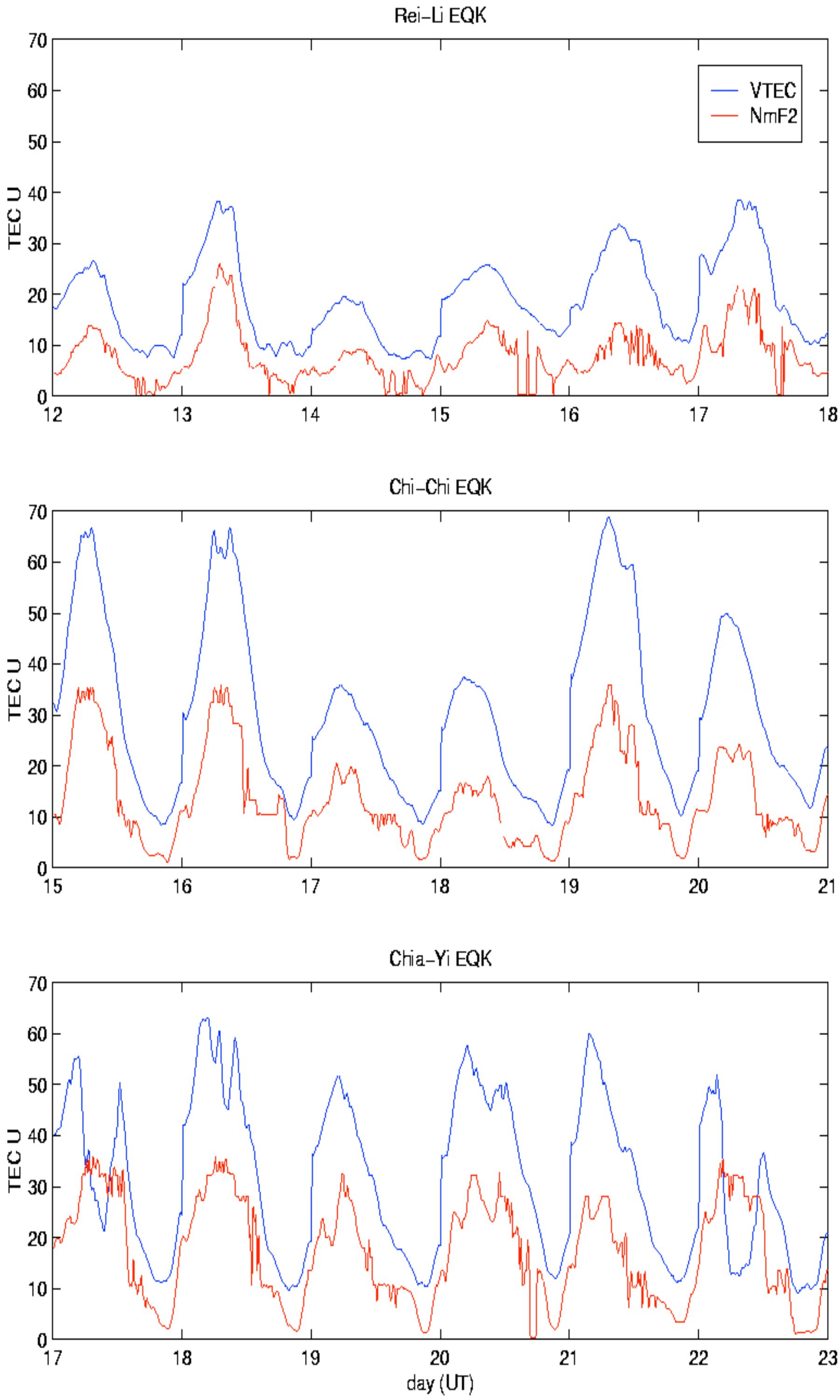

Figure 2. The TEC and NmF2 variations during the Rei-Li, Chi-Chi, and Chia-Yi earthquakes.

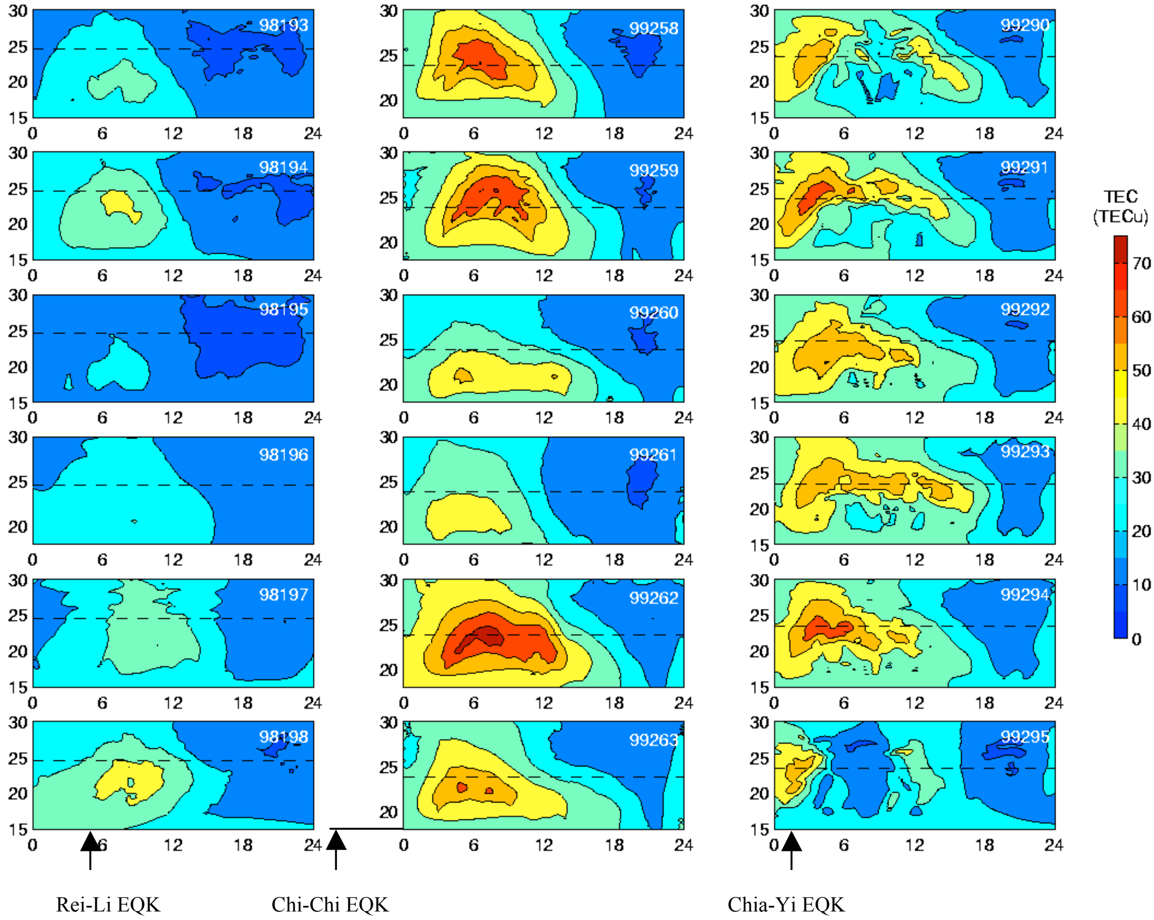

Figure 3. The latitude-time-TEC plots during the three earthquakes. The onset Julian days for Rei-Li, Chi-Chi, and Chia-Yi earthquakes are 198 (17 July) 1998, 262 (20 September) 1999, and 295 (22 October) 1999, respectively.