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Variations of ionospheric total electron content during the Chi-Chi earthquake

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Abstract. On 20 September 1999 UT (21 September in local time, LT) a large earthquake Mw=7.7 struck central Taiwan near the small town of Chi-Chi. The greatest plasma frequency in the ionosphere, foF_2, observed by the Chung-Li ionosonde (25.0°N, 121.2°E) reveals three clear precursors at 1, 3, and 4 days prior to the earthquake. This paper examines the ionospheric total electron content (TEC) observed by a network of the global positioning system (GPS) receivers in Taiwan area. It is found that variations in foF_2 and overhead TEC recorded at Chung-Li have a similar tendency. Combining the data of the network of 13 GPS receivers, time, and spatial variations of TEC prior to the Chi-Chi earthquake are examined. Results show that the equatorial anomaly crest moves equatorward and its TEC value significantly decreases 1, 3, and 4 days before the earthquake. A comparison between the disturbed and reference (previous 15-day median) days confirms that TEC decreases significantly around the epicenter in the afternoons of these days. Finally, possible mechanisms are proposed and discussed.

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 [*Calais and Minster*, 1995; *Liu et al.*,1996].

Recently, *Liu et al.* [2000] using the Chung-Li ionosonde (25.0°N, 121.2°E) studied seismo-ionospheric signatures prior to M≥6.0 Taiwan earthquakes and found the ionospheric electron density between 1200 and 1700 local time, LT (universal time UT= LT-0800 hr) significantly decreased within 6 days before these earthquakes. Based on the statistical results, they observed the seismo-ionospheric signatures on 1, 3, and 4 days before the Chi-Chi earthquake with M=7.3 (Mw=7.7), which occurred at 0147 LT, 21 September 1999, in the middle of Taiwan. However, the Chung-Li ionosonde simply provided time variations of the ionospheric electron density above the observating station.

To simultaneously monitor a large area of the ionosphere, the GPS is ideal to be employed. The system consists of 24 satellites, evenly distributed in 6 orbital planes around the globe at an altitude of about 20,200 km. Each 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 carrier phases and phase codes recorded by dual-frequency receivers [*Leick*, 1995; *Sardon et al.*, 1994; *Liu et al.*, 1996]. From recorded broadcast ephemeris and given sub-ionospheric height of 325 km, the slant TEC along the ray path can be converted into the vertical TEC at its associated longitude and latitude (*cf. Tsai and Liu* [1999]).

In this paper, to have a better understanding of the time and spatial variations of the ionospheric signatures prior to the Chi-Chi earthquake, data recorded by a network of 13 ground-based GPS receivers in Taiwan are employed to derive TEC. The simultaneously deduced overhead GPS TEC at Chung-Li is compared with and validated by the ionospheric electron density observed by the collated ionosonde. Later, combining all the data recorded by the GPS network, the diurnal latitude-time-TEC (LTT) plots and instant latitude-longitude-TEC (LLT) maps at a certain time are constructed. Finally, based on the time and spatial variations in the plots and maps, possible mechanisms resulting in the significant decreases of the ionospheric electron density prior to the Chi-Chi earthquake are discussed.

2. Observation

Fig. 1 illustrates the locations of the Chung-Li ionosonde, the GPS network, and the epicenter of the Chi-Chi earthquake. The ionosonde observes the ionosphere within a horizontal region of a radius 500 km from Chung-Li, while the GPS network monitors an area of 20°-30°N and 115°-125°E. Therefore, two observations simultaneously cover the ionospheric volume above the epicenter. UT is adopted by GPS, while LT is useful for examining the signatures during earthquakes. To coordinate the GPS and seismo-ionospheric observations, the figures adopt both UT and LT. For simplicity, the number of days prior to the earthquake is based on LT. Fig. 2 displays the ionospheric electron density NmF_2 and TEC currently derived from the ionosonde and the GPS network at Chung-Li. The relation between the plasma frequency foF_2 and the electron density NmF_2 at the F peak can be expressed as $NmF_2 = foF_2/80.3$ (for details see *Budden* [1990]), where NmF_2 is in electron/m^3 and foF_2 in Hz. Meanwhile, the TEC is in TEC unit, TECu (1TECu= 10^{16} electron/m^2). It can be seen that two measurements yield similar tendencies within 6 days prior to the earthquake. The correlation coefficient 0.953 indicates TEC and

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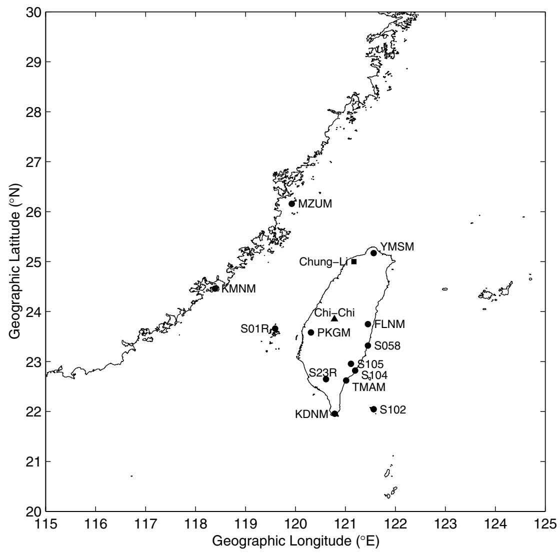

Figure 1. Locations of the Chung-Li ionosonde (filled square), 13 GPS receivers (filled circle), and the Chi-Chi epicenter filled triangle).

NmF_2 to be highly correlated, and confirms that TEC can be used to detect the seismo-ionospheric precursors. It can be seen from Fig. 2 that the significant TEC decreases between 1200 and 1700 LT (0400 and 0900 UT) occurred on 17 and 18 September 1999 (4 and 3 days before the Chi-Chi earthquake) but slight reduction appeared on 20 September (1 day before). Note that the Chi-Chi earthquake occurred at 0147 LT on 21 (at 1747 UT on 20) September 1999.

The GPS network of 13 receivers, and therefore for a full GPS constellation, 65-130 TECs can be derived every 30 seconds (5-10 each ground site). Accordingly, such a network can ultimately be capable of making a "snapshot" of LLT distribution in Taiwan area, thereby constructing TEC maps every 30 seconds. Combining the daily data from the network, we obtain an LTT plot, which describes the diurnal variation of TEC at various latitudes. Fig. 3 illustrates the LTT plots within 6 days prior to the earthquake. It is clear that the daytime TEC on 1, 3, and 4 days before the earthquake severely decreases and the associated crest of the equatorial anomaly moves southward (equatorward). Simply taking 15, 16, and 19 September as quick references, we found the crests on 17 and 18 September (4 and 3 days before the earthquake) to be about 50% less than their normal value, which has a good agreement with that of the NmF_2 reported by *Liu et al.* [2000].

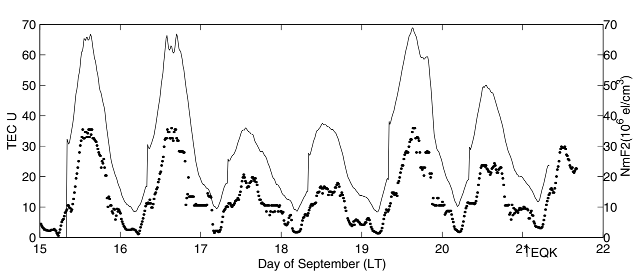

Figure 2. TEC and *NmF2* variations at Chung-Li observed within 6 days before the Chi-Chi earthquake.

To develop a suitable reference, we collect the corresponding hourly LLT maps 1-15 days before the earthquake onset and identify the median value of the 15 maps for each grid to construct a reference map. The top row in Fig. 4 shows the constructed reference LLT maps at 1200, 1400, and 1600 LT. The 2nd, 3rd, and bottom rows are the differential LLT maps, which are the recorded LLT maps subtracted from the associated references on 17, 18, and 20 September 1999 (4, 3, and 1 day(s) before the earthquake), respectively. It is found that TEC on 4 and 3 days before the Chi-Chi earthquake onset decrease significantly. Note that the most

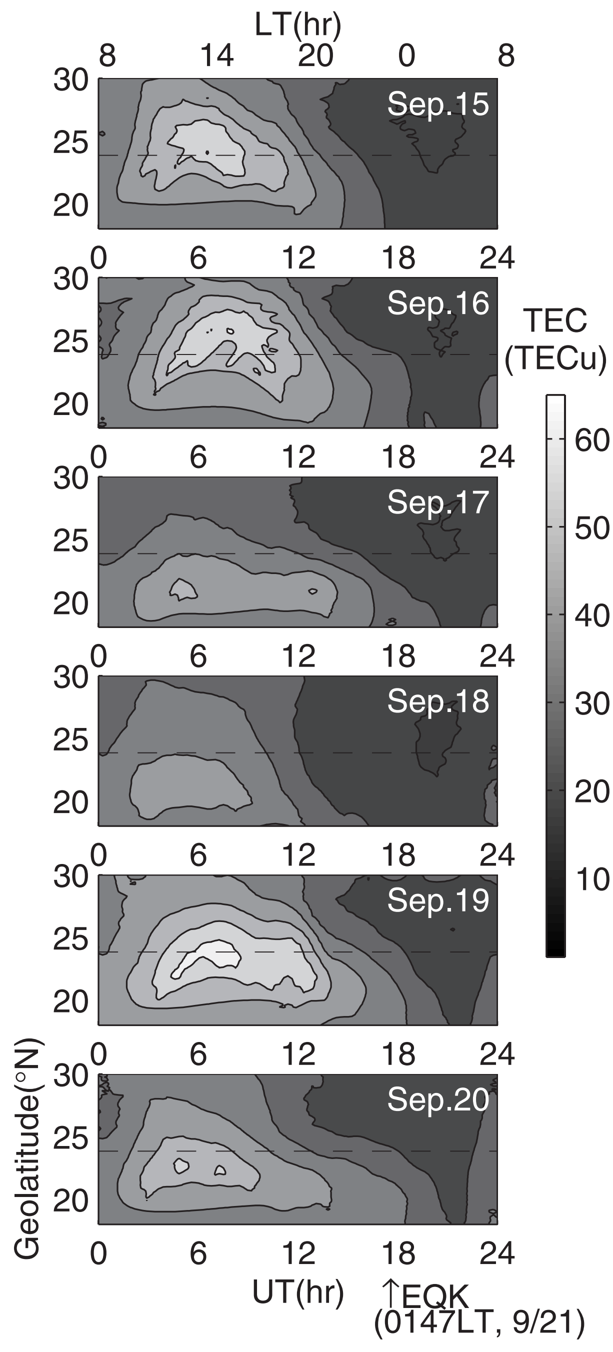

Figure 3. The latitude-time-TEC plots obtained from the Taiwan GPS network within 6 days before the Chi-Chi earthquake. The dashed line denotes the latitude of the Chi-Chi epicenter.

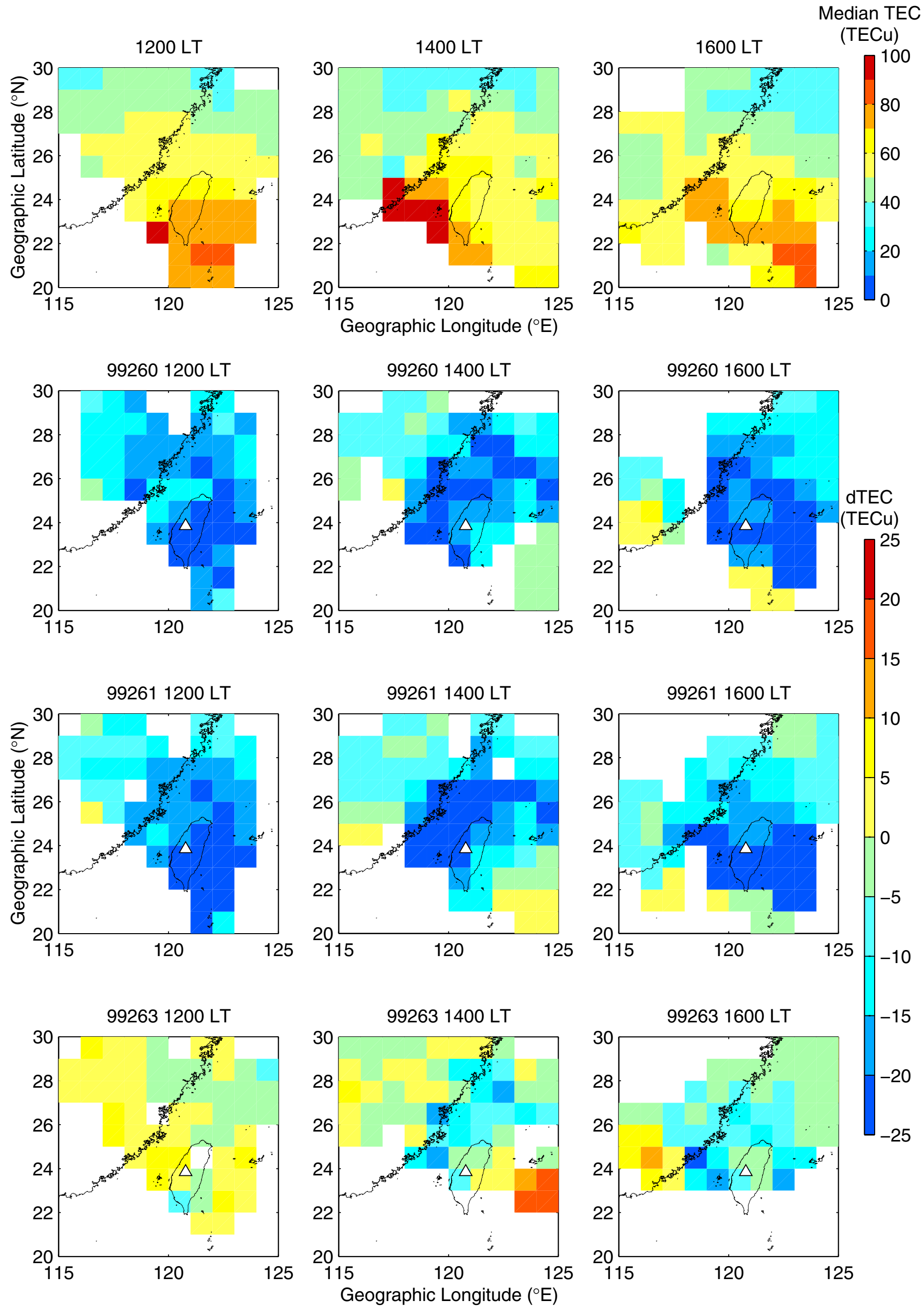

Figure 4. The reference and differential TEC maps prior to the Chi-Chi earthquake. The top row shows median maps of 1-15 days before the earthquake. The 2nd, 3rd, and bottom rows are differential TEC maps obtained on 17, 18, and 20 September 1999, respectively.

severe decreasing region in each map appears about a radius of 100-200 km from the epicenter. The bottom row displays TEC to be moderately decreased around the epicenter on 20 September 1999 (1 day before the earthquake).

3. Discussion and Conclusion

Liu et al. [2000] analyzed the ionospheric foF_2 recorded at Chung-Li and found NmF_2 reduced about 51% from its normal value between 1200-1700 LT, 3 and 4 days before the Chi-Chi earthquake. Results show that two measurements of NmF_2 and GPS TEC have similar tendencies and highly correlated. Therefore, the GPS TEC can be employed to detect the seismo-ionospheric signatures. The LTT plots and LLT maps indicate that the variations of NmF_2 and TEC at Chung-Li are functions of the magnitude and location of the equatorial anomaly crest.

It has been well known by scientists that near the geomagnetic equator, where the magnetic field is horizontal, the plasma movement resulting from an imposed eastward electric field 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 details see *Ratcliffe* [1974]). Notice that Taiwan is right under the north side of the equatorial anomaly region. Fig. 3 and the top row in Fig. 4 illustrate the time and spatial TEC variations of the anomaly region, respectively. Two figures show that during the three seismo-ionospheric days the anomaly crest moves toward the equator and the TEC value of the crest decreases significantly. *Freund* [1999] found that mobile positive holes can be activated in the crust by microfractures during the dilatancy stage of earthquake preparation [*Bolt*, 1988] and diffusion and outflow of these holes generate high electric fields at the earth surface. *Pulinets and Benson* [1999] and *Kim and Hegai* [1999] showed that a strong vertical electric field on the earth surface could penetrate into the ionosphere and modify its dynamics and electron density distribution prior to the earthquake onset. Based on these studies, *Liu et al.* [2000] then suggested that the perturbations in NmF_2 before the Chi-Chi earthquake were mainly attributed by the vertical electric field generated in forthcoming earthquake's epicentral zone.

Note that it needs a tremendous amount of energy to diminish the imposed eastward electric filed existed daily in the equatorial F region, and then reduce the value and motion of the TEC crest. *Liu et al.* [1999] show that the disturbed dynamo [*Blanc and Richmond,* 1980] and/or equatorward neutral wind occurring 12 to 36 hours after a major geomagnetic storm onset could result in the equatorward motion and TEC reduction of the crest. Since the *Kp* and *Dst* indices showed that 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, the ionospheric perturbations appeared on 17, 18, and 20 are unlikely the storms related. Although the generating processes are not understood, an equatorward neutral wind in the mid-latitude (or anomaly region) ionosphere seems to be one of the best candidates, which can easily blow the plasma particles traveling along to the magnetic field lines, to decrease the crest TEC value and directly push the anomaly crest toward the equator. Meanwhile, in the mid-latitude, the equatorward neutral wind in the lower ionosphere could generate a westward dynamo electric field, which mirrors to the equatorial F region and then partially cancels the imposed eastward electric filed existed daily, and result in the TEC decrease and the equatorward motion of the anomaly crest. Nevertheless, Figures 3 and 4 suggest that the existence of a vertical electric filed and/or an equatorward neutral wind to partially cancel and/or reduce the daily imposed eastward electric filed are essential.

There are about global distribution of thousands of ground-based GPS sites, which provides an excellent chance to monitor ionospheric perturbations before and after earthquake onset all over the world. The results from the Taiwan GPS network demonstrate that TEC variations are sensible enough and can be employed to detect the seismo-ionospheric signatures. The equatorward motions and significant TEC decreases of the equatorial anomaly crest suggest that an upward electric field near the epicenter and/or the equatorward neutral wind in the ionosphere play important roles.

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