Observations and simulations of seismoionospheric GPS total electron content anomalies before the 12 January 2010 *M*7 Haiti earthquake

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[1] In this paper, the total electron content (TEC) of the global ionosphere map (GIM) is used to detect seismoionospheric anomalies associated with the 12 January 2010 *M*7 Haiti earthquake, and an ionospheric model is applied to simulate the detected anomalies. The GIM temporal variation shows that the TEC over the epicenter significantly enhances on 11 January 2010, 1 day before the earthquake. The latitude-time-TEC (LTT) plots reveal three anomalies: (1) the northern crest of equatorial ionization anomaly (EIA) moves poleward, (2) the TECs at the epicenter and its conjugate increase, and (3) the TECs at two dense bands in the midlatitude ionosphere of 35°N and 60°S further enhance. The spatial analysis demonstrates that the TEC enhancement anomaly appears specifically and persistently in a small region of the northern epicenter area. The simulation well reproduces the three GIM TEC anomalies, which indicate that the dynamoelectric field of the ionospheric plasma fountain might have been perturbed by seismoelectric signals generated around the epicenter during the earthquake preparation period.

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1. Introduction

[2] Recently, seismoionospheric anomalies before large earthquakes have been intensively studied [*Pulinets and Boyarchuk*, 2004; *Kamogawa*, 2006; *Rishbeth*, 2006]. Although preearthquake ionospheric anomalies could appear almost in any local time period, *Liu et al.* [2000, 2001, 2004, 2006, 2009, 2010a] find that the ionospheric electron density or total electron content (TEC) over a forthcoming epicenter region tends to significantly decrease or increase in the afternoon and/or evening period 1–6 days before the earthquake occurrence. They propose that seismoelectromagnetic environments could be modified around the epicenter, where the generated seismoelectric fields might penetrate into the ionosphere and perturb the TEC within it during the earthquake preparation period. Meanwhile, *Zhao et al.* [2008], *Liu et al.* [2009], and *Pulinets and Ouzounov* [2010] report that the ionospheric GPS TEC enhancement and/or reduction anomalies appear above the epicenter and its magnetic conjugate point simultaneously 3–6 days before the 12 May 2008 *M*7.9 Wenchuan earthquake. The simultaneous features above the epicenter and its conjugate latitude indicate that the seismo-generated electric field can map from the epicenter along the Earth's magnetic field line to the conjugate ionosphere and possibly disturb the daily dynamoelectric field in between. The disturbed dynamoelectric field near the magnetic equator further affects the **E** × **B** drift and the equatorial plasma fountain resulting in modification of the location and magnitude of the equatorial ionization anomaly (EIA) [*Liu et al.*, 2010b]. *Liu et al.* [2009] report that when the TEC enhancement (reduction) anomaly appears 3 (6) days before the Wenchuan earthquake, the EIA crests move poleward (equatorward) and the associated strengths increase (decrease) accordingly.

[3] An earthquake with magnitude of *M*7 occurred at the Haiti region (18.5°N, 72.5°W) with 13 km depth at 21:53 UTC (16:53 LT) on 12 January 2010 (http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2010rja6.php). In this paper, the GPS TEC of the global ionosphere map ((GIM) ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex) published at the Center for Orbit Determination in Europe (CODE) [cf. *Schaer*, 1999] is employed to find seismoionospheric anomalies associated with the Haiti earthquake, while an ionospheric model is for the first time used to simulate the seismoionospheric GPS TEC anomalies. We

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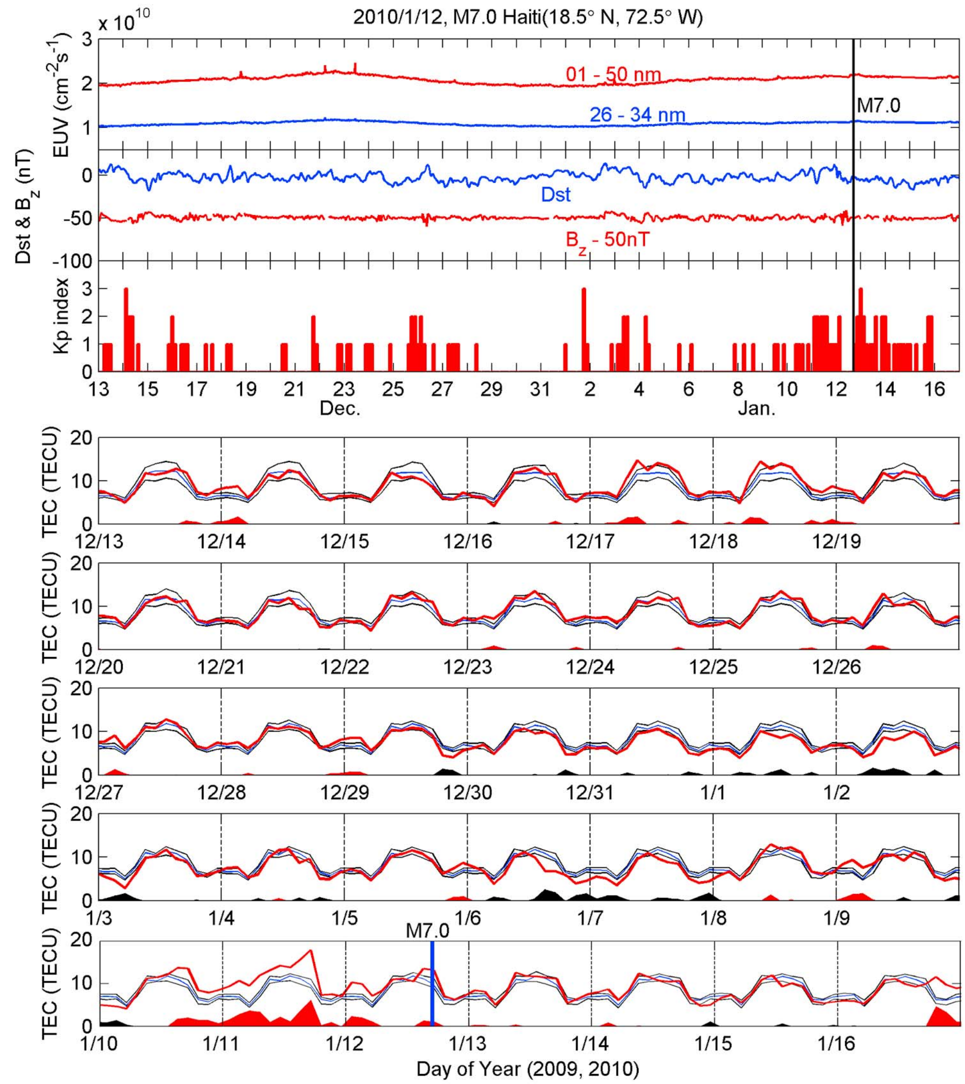

Figure 1. A time series of the solar radiation, IMF Bz component, and the Dst and Kp geomagnetic index as well as the GPS TEC right above the Haiti epicenter extracted from the GIM during 13 December 2009 to 16 January 2010. The solar radiation of 26–34 nm and 01–50 nm EUV is from SOHO/SEM. Note that the IMF Bz is offset by −50 nT. The *M*7 Haiti earthquake occurred at 1653 LT on 12 January 2010. The red, blue, and two black curves denote the GIM TEC, associated median, and upper/lower bound (UB/LB), respectively. The LB and UB are constructed by the 1–30 previous days' moving median (M), lower quartile (LQ), and upper quartile (UQ). Here, LB = M − 1.5(M − LQ) and UB = M + 1.5(UQ − M). Red and black shaded areas denote differences of O–UB and LB–O, respectively, where O is observed GPS TEC.

cross compare the GIM TEC with the simulation to have better understanding of causal mechanisms of the seismoionospheric anomalies and the lithosphere-ionosphere coupling before the Haiti earthquake.

2. GIM TEC

[4] The solar EUV radiation, the z component of interplanetary magnetic field (IMF) Bz, and the geomagnetic Dst and Kp index indicate that the space weather and geomagnetic activity are relatively quiet during 13 December 2009 to 16 January 2010, 30 days before to 4 days after the 12 January 2010 *M*7 Haiti earthquake (Figure 1). The GIM TEC maps with 2 h time resolution covering ±87.5°N latitude and ±180°E longitude ranges with spatial resolutions of 2.5° and 5°, respectively, are utilized in this study. Each map consists of 5040 (= 70 × 72) grid points. Figure 1 displays that time series of the GPS TECs above the Haiti epicenter isolated from the GIM maps increase pronouncedly and significantly during the entire day of 11 January 2010 (1 day before the earthquake), especially around 2100 UT (1600 LT). The anomalous TEC enhancement, exceeding the associated upper bound, persistently appears from 1500 LT

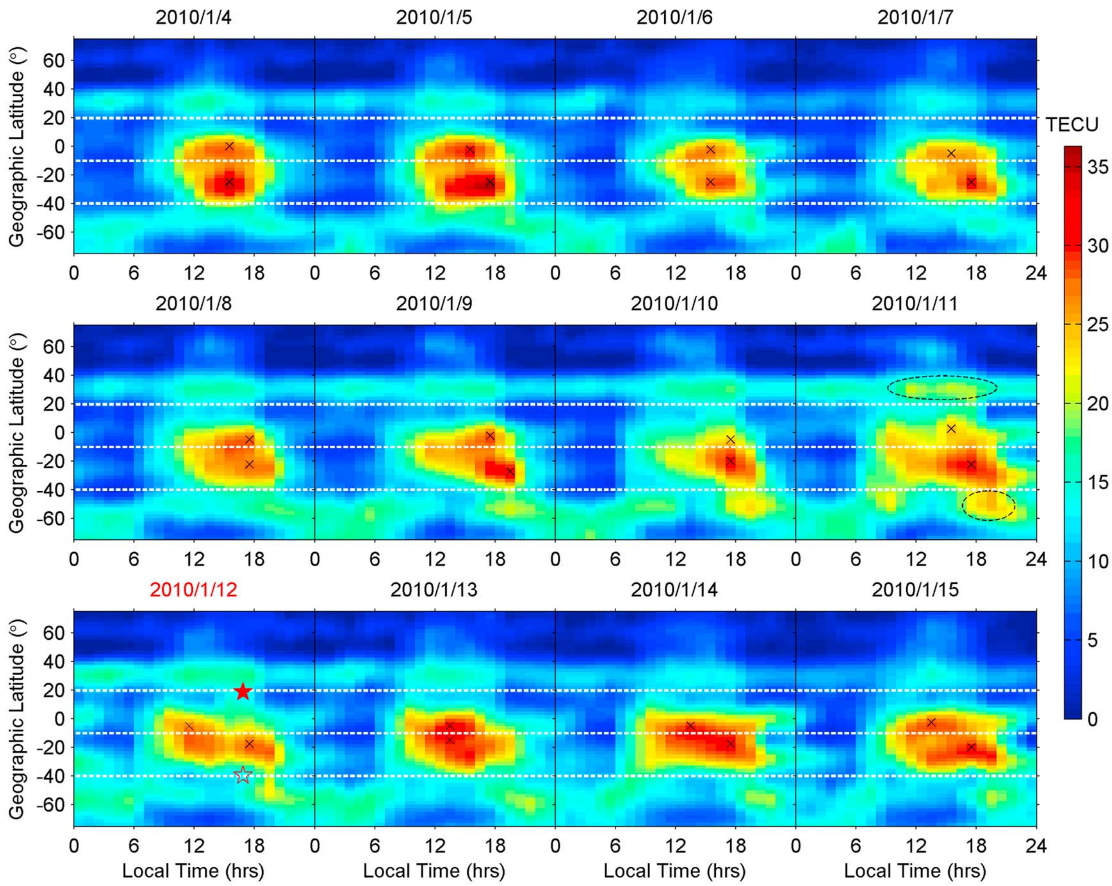

Figure 2. The latitude-time-TEC plots extracted from the GIM during 4–15 January 2010. The cross symbols denote the EIA crests. The solid and open start symbols are the epicenter and corresponding conjugate point of the Haiti earthquake, respectively. The three dashed white lines from the top to down denote magnetic latitudes of the epicenter, magnetic equator, and conjugate point, respectively. The dashed ellipses are the most anomalous enhancements among the same latitudes and local times during 4–15 January 2010.

on 10 January to 2200 LT on 11 January and from 0000 LT to 0700 LT on 12 January, indicating that the duration of the anomalous enhancement is about 31 h (or 40 h, except at 2300 LT 11 January). Figure 2 illustrates the latitude-time-TEC (LTT) plots along the 72.5°W longitude extracted from the GIM between 8 days before and 3 days after the earthquake (4–15 January 2010). It can be seen that the two EIA crests significantly move poleward, while the TECs of the two midlatitude dense strips on 35°N/60°S and those of the epicenter/conjugate point reach their maximum values of the study period on 11 January 2010. These three anomalous features suggest the dynamoelectric field being disturbed and enhanced significantly.

[5] It has been reported that seismoionospheric TEC (or electron density) anomalies often repeatedly and persistently appear near the epicenters for 8 to 12 h on the anomalous days before large earthquakes [*Liu et al.*, 2000, 2004, 2006, 2009, 2010a, 2010b]. To see if the TEC enhancement anomalies specifically appear in the earthquake region for a long duration or simply randomly occur worldwide on 11 January 2010, a spatial analysis is conducted. Figure 3 displays that the location of the 30 day (13 December 2009 to 11 January 2010) extreme enhancement (maximum) at each grid point repeatedly appears at various time points on the local day of 11 January 2010 in the Haiti area. The extreme maximum grids with 1, 2, 3, and more repeating time points (times) occur worldwide, whereas those with 4, 5, 6, and more repeating times appear mainly in the epicenter, the magnetic conjugate areas, and high latitudes of the northern hemisphere. It can be seen that the extreme maximum grids repeating up to 7–8 and even more times occur mainly around the epicenter and the conjugate point. The extreme maximum grids with 9–10 and more repeats appear in a relative large area of the epicenter. Finally, the extreme maximums appearing specifically in a small area around the epicenter repeat up to 11 times and even the entire day (i.e., 12 times) of 11 January 2010 (the GIM with 2 h time resolution; 12 time points of a day). Therefore the extreme maximums appearing around the conjugate point is 2/3 (= 8/12) of the anomalous day, while the extreme

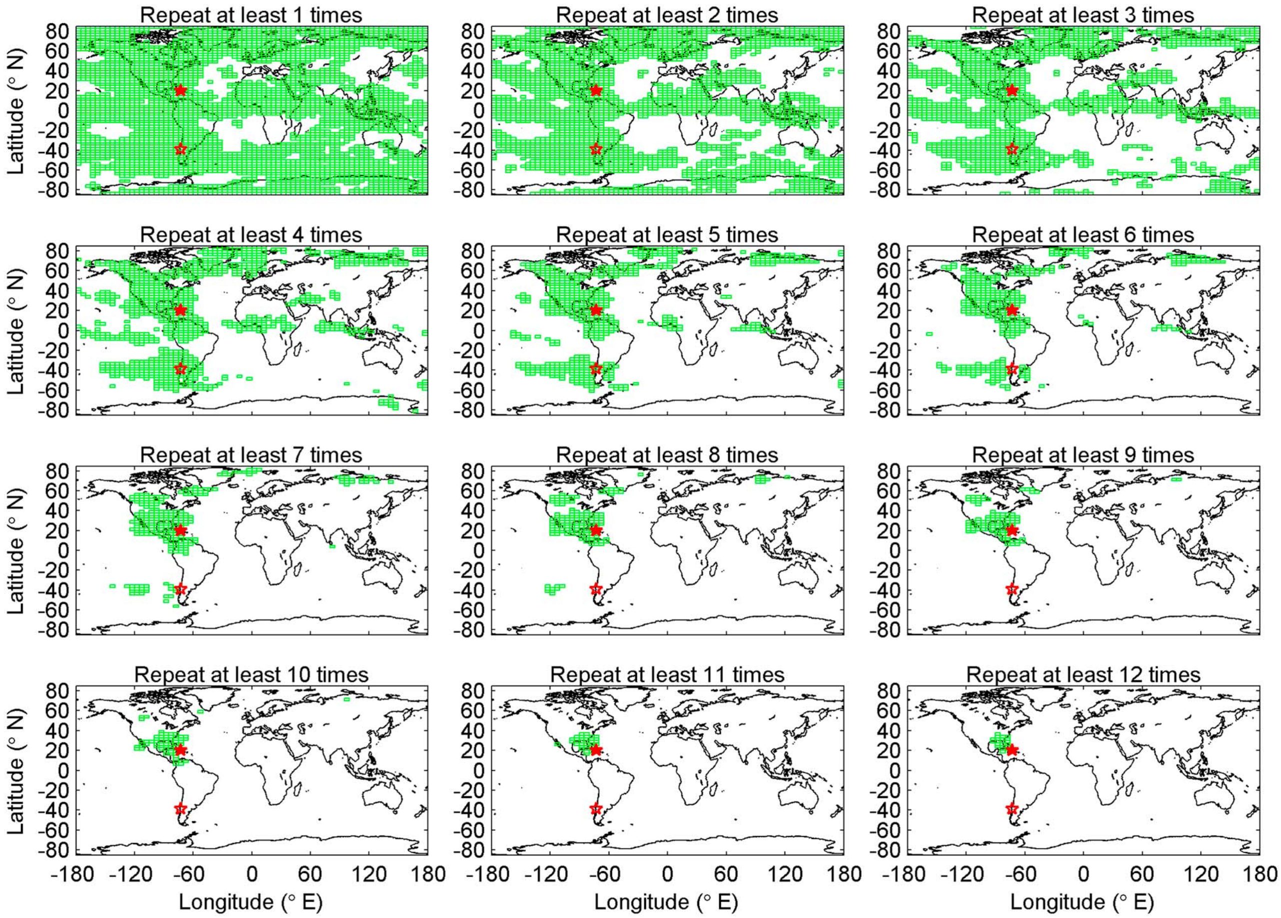

Figure 3. Locations of the 30 day extreme enhancement (maximum) repeatedly appear at various time points on the local day of 11 January 2010 in Haiti. The number of the repeat time point is noted on top of each panel. The solid and open start symbols denote the epicenter and its conjugate point.

enhancement persistently locating the epicenter for the entire day of 11 January. The long-persisting anomalies on 11 January indicate that these anomalies are most likely related to the 12 January 2010 *M*7 Haiti earthquake.

3. Numerical Simulation

[6] We simulate the ionosphere before the Haiti earthquake by using the Theoretical Ionospheric Model of the Earth in Institute of Geology and Geophysics, Chinese Academy of Sciences (TIME IGGCAS) [*Yue et al.*, 2008]. The model solves the 2-D coupled equations of the mass continuity, momentum, and energy for three dominant ions O^+, H^+ and He^+. It also calculates values of concentrations of three minor ions N_2^+, O_2^+ and NO^+ in the E and *F* region under the assumption of photochemical equilibrium. The neutral temperature and density are taken from the NRLMSIS-00 model [*Picone et al.*, 2002], and the NO concentration is calculated from an empirical model developed by *Titheridge* [1997]. The neutral winds are supplied by the HWM-93 model [*Hedin et al.*, 1996]. The photoelectron heating effect is similar to that of *Millward et al.* [1996]. At low altitudes (below 300 km), the photoelectron heat is distributed locally. At higher altitudes (above 300 km), the photoelectron heat comes from local and also from sources in the other hemisphere.

[7] On the basis of *Dobrovolsky et al.* [1979], the earthquake preparation area on the ground can be estimated by $R = 10^{0.43M}$, where R is the radius of the preparation zone and M is the earthquake magnitude. For the M = 7.0 Haiti earthquake, we obtain R = 1023 km (about ±10 degrees in the latitudinal direction from the epicenter), which is considered as the seismo-electromagnetic area. We therefore model by modifying the east-west electric field along the magnetic field lines in the meridian plane of 72.5°W in a form of Gaussian distribution with a half-peak strength radius of about 5 degrees in the latitudinal direction centering at 18.5°N (i.e., the epicenter latitude), which can cover the seismo-electromagnetic latitude (Figure 4a). Figure 4b illustrates variations of the unperturbed (background) dynamoelectric E field and the seismo-perturbed one. Here we perturb the model by increasing the eastward dynamo E field to simulate the anomalous GIM TEC enhancement.

[8] Figure 5a illustrates the GIM TEC on 11 January, while Figure 5b depicts simulated TECs of the TIME

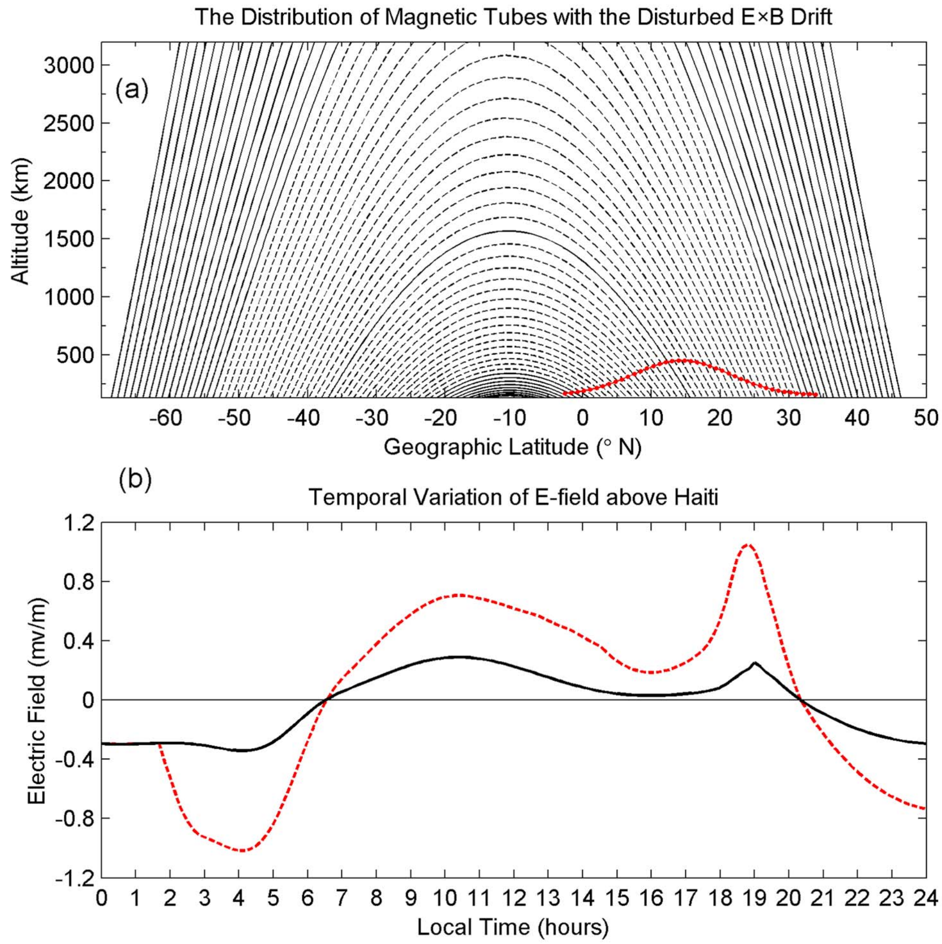

Figure 4. A sketch of the seismoelectric signal mapping and variations of the dynamoelectric fields. (a) The solid and dashed lines denote the unperturbed and seismo-perturbed electric fields map along the Earth's magnetic field lines, where the red dotted curve is the perturbed amplitude in a Gaussian distribution centering at the epicenter latitude. (b) The time variation of the dynamoelectric E field right above the Haiti epicenter. The solid and dashed curves denote the background E_0 and positive perturbed $E = E_0 + \Delta E$ dynamoelectric fields. To simulate the observed GPS TEC, ΔE is amplified by various factor k at different local times: $\Delta E = kE_0$, where k = 2, 3, 4, and 2 at 02–13 LT, 13–14 LT, 14–19 LT, and 19–24 LT, respectively, and is smoothed with a 1 h moving window.

IGGCAS model with the eastward perturbation ΔE (Figure 4b). It can be seen that the model well reproduces the two EIA features but not clearly the feature of the two midlatitude dense strips. We further compute the median of the TEC for each grid at the associated time point during 1–30 days before the earthquake (13 December 2009 to 11 January 2010) and calculate the unperturbed condition as the GIM and simulation references, respectively. To find the seismoionospheric signatures, we calculate the differences between the GIM/simulated TEC on 11 January 2010 and their associated references. Figure 5c reveals the difference between the GIM and its associated reference indicating that the TEC at the epicenter and conjugate latitudes significantly enhances (except the conjugate latitudes during 13–15 LT) and reduces at magnetic equator during 11–17 LT. Similar to the GIM difference, the increased perturbation results in TEC enhancements clearly appearing in the epicenter and conjugate latitudes (Figure 5d). Note that the simulations fail to reproduce the reduction feature at the conjugate latitude during 13–15 LT and at the equator at 11–17 LT as shown in Figure 5c. Although the feature of the two enhancement stripes is not reproduced by the model, the eastward perturbation ΔE results in the slight TEC increases around the two-stripe latitudes, 35°N and 60°S (Figure 5d).

4. Discussion and Conclusion

[9] The solar EUV radiations, IMF, Kp index, and Dst index are rather stable and quiet 1–30 days before the earthquake (Figure 1) which suggests that the anomalous TEC enhancement around the epicenter 1 day before the

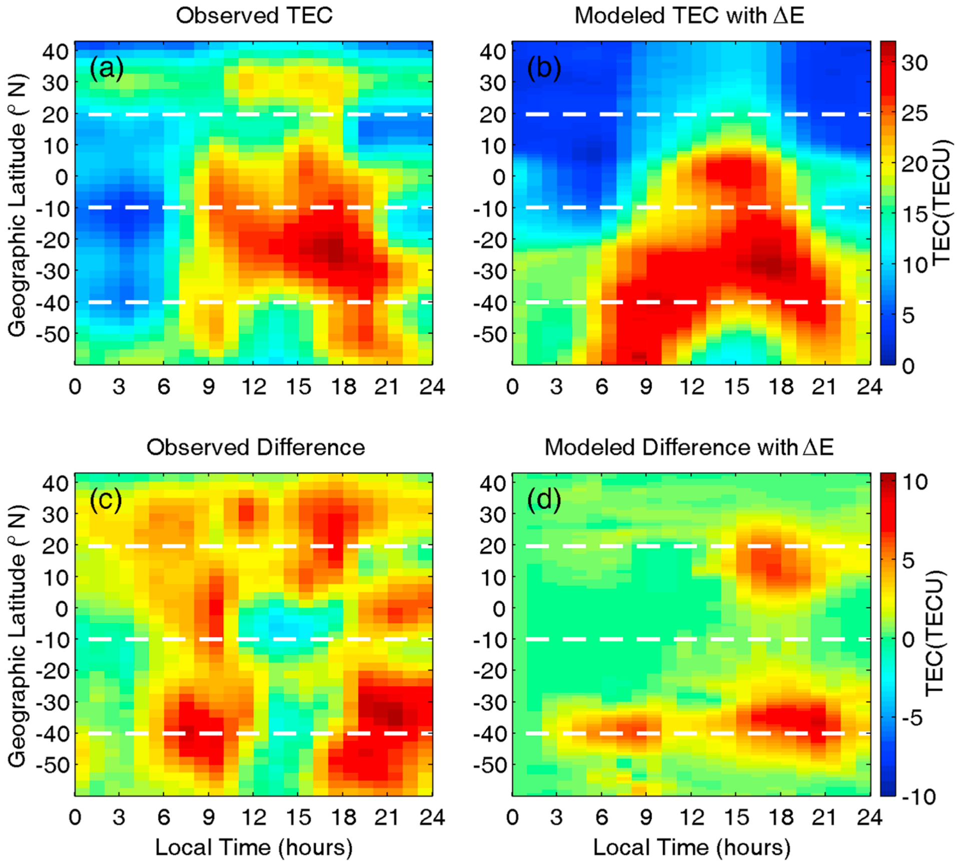

Figure 5. The GIM and the simulation TEC along the earthquake longitude on 11 January 2010. The TEC of (a) the GIM and (b) the simulation with the ΔE perturbation. The TEC differences between (c) the GIM and its associated 30 day median as well as (d) the ΔE perturbed and unperturbed simulations.

earthquake is unlikely related to space weather changes and/or magnetic activities. To find the chance of such a long-duration enhancement appearing around the epicenter area, we examine the TECs over the Haiti epicenter extracted from the GIM and derived by 3 neatest local ground-based GPS receiving stations, SCUB, BYSP, and MIPR, (ftp://garner.ucsd.edu/pub/rinex/2010/) during a 5 year period of 2005–2009. It is found that the durations of the GIM TEC anomalous enhancement are all less than 20 h, while those of the 3-station lasting up to 24 h appear on 3 days, 16 February 2005, 06 January 2008, and 11 May 2009. We find the magnetic conditions of the first 2 days are relatively disturbed, while the last one is quite. Although an *M*5.0 earthquake coincidently occurs at 19.00°N, 65.50°W, where is not far from the Haiti epicenter (18.5°N, 72.5°W), on 20 May 2009 which is 9 days after the third enhancement anomaly appearing, it is difficult to confirm whether these two are associated or not. There are 1826 days (= 365 × 5 + 1) in the 5 year period of 2005–2009. Even assume the third anomaly being not related to the *M*5.0 earthquake, the chance of the anomaly on 11 January 2010 not associated with the Haiti earthquake is 5.5×10^{-4} (= 1/1826) which is very small. In fact, no enhancement anomaly at the Haiti epicenter lasts longer than 24 h, except the one on 11 January 2010 lasting for more than 31 h, during the 5 year period.

[10] Anomalous regions of seismoionospheric electron density and/or TEC before earthquakes usually are very large [see *Pulinets and Boyarchuk*, 2004; *Liu et al.*, 2010a]. Figure 3 shows that the anomalous region of the Haiti earthquake indeed is very large even with 8–10 repeats. It can be seen that the extremely anomalous enhancements with 12 repeats become smaller and specifically appear within a region of 20° latitude ×30° longitude (19 grids) in northwest of the epicenter. Since planetary waves and tides generally induce much larger-scale signatures and are often featured by dual polarities/phases of reduction and enhancement or troughs and multipeaks, the long-persisting anomalous TEC enhancement fixed near the epicenter without the above mentioned feature is unlikely caused by the waves and/or tides. The gravity waves, although might induce rather small and/or localized signatures, they usually do not last for a long time with a single polarity or phase. Therefore, the anomalous TEC enhancement is unlikely resulted from gravity waves either.

[11] On the basis of *Dobrovolsky et al.* [1979], the preparation radius of the *M*7 Haiti earthquake is 1023 km (about 10° in latitude and longitude). *Kelly* [2009] indicates that

scale sizes greater than a few kilometers in the lower ionosphere can map unattenuated to *F* region heights. Figure 3 shows that the anomaly is about thousands kilometers and exists around the epicenter more than 24 h persistently. It might be that the seismoelectric fields with thousand kilometer size generated around the epicenter efficiently/persistently map and penetrate into the ionosphere, and then disturb the electron density within it, which enables the GIM registering the TEC anomalies before the Haiti earthquake.

[12] It is interesting to find the two enhancement stripes constantly appearing at about 30°N and 50/60°S during 4–15 January 2010 (Figure 2). To see if the two stripes are real and whether the GIM data are accurate enough for searching the seismoionospheric anomalies, we reproduce the LTT plot similar to Figure 2 by using measurements of 21 ground-based GPS receivers (data retrieved from ftp://garner.ucsd.edu/pub/rinex/2010/) along the Haiti earthquake longitude (Appendix A). It is found that the LTT plots from the GIM and the 21 GPS receivers are nearly identical, which confirms the two enhanced stripes to be real. In fact, the two enhanced stripes are signatures of the "midlatitude nighttime electron density enhancement" observed by using ionosondes, incoherent scatter radars, satellites, etc. (see papers listed in the work by *Luan et al.* [2008]). The observations and related simulations of the midlatitude nighttime electron density enhancement show that the diurnal and seasonal variations as well as the neutral winds and $\mathbf{E} \times \mathbf{B}$ plasma fountain are essential. *Mikhailov et al.* [2000] find that the nighttime midlatitude electron density is proportional to the $\mathbf{E} \times \mathbf{B}$ plasma fountain. Although the features of the two enhancement stripes are not reproduced by the model (Figure 5b), the slight TEC increases in latitudes of the two stripes can be observed (Figure 5d). The agreement between the GIM and simulation explains that the seismo-generated electric signals perturbs and increases the eastward dynamo electric field, which causes the further increases of the two enhancement stripes on 11 January 2010.

[13] The prominent feature before the Haiti earthquake obtained by the simulation is the simultaneous TEC enhancements at the epicenter and its conjugate latitudes (Figure 5d). The GIM and simulated TECs over the epicenter and the conjugate point simultaneously and significantly increase 1 day before the Haiti earthquake (Figures 2 and 5) which are similar to the TEC enhancement anomalies appearing day 3 before the Wenchuan earthquake [*Zhao et al.*, 2008; *Liu et al.*, 2009; *Pulinets and Ouzounov*, 2010]. The agreement of the simultaneous features in the GIM and simulations demonstrate that the seismo-generated electric field mapping from the epicenter along the Earth's magnetic field line to the conjugate ionosphere is essential.

[14] *Liu et al.* [2009] observe that the EIA crests move poleward (equatorward) when the TECs at the epicenter/conjugate point simultaneously/anomalously enhance (reduce) few days before the Wenchuan earthquake. *Liu et al.* [2010b] statistically examine ionospheric EIA crest motions and 150 $M \geqq 5.0$ earthquakes in the Taiwan area during 2001–2007. They suggest that a stronger eastward dynamo electric field results in a greater plasma fountain which upward raises the plasma to the higher altitude and then downward diffuses along magnetic field lines to the higher latitudes (i.e., the poleward EIA motion) [*Bramley and Young*, 1968; *Sterling et al.*, 1969; *Ratcliffe*, 1972; *Anderson*, 1973; *Tsai et al.*, 2001; *Chen et al.*, 2008]. The poleward motion of the northern EIA crest (Figure 2) and the agreement of the EIA locations between the GIM and the simulation (Figures 5a and 5c) indicate that the seismo-generated electric field maps along the Earth's magnetic field line disturbing/increasing the dynamo electric field. Nevertheless, the GIM and the model results again show that the daily dynamoelectric field is perturbed and enhanced on 11 January 2010.

[15] Figure 3 demonstrates that the 30 day extreme TEC enhancements repeatedly and constantly appear near the epicenter on the entire day of 11 January 2010. Note that the occurrence chance of each grid on each day of the 30 day period is 0.033 (= 1 day/30 day). If the persistence of the entire day (24 h; 12 time points) is considered, the appearance chance of the Haiti anomaly appearing specifically around the epicenter is 1.6×10^{-18} (= 0.033^{12}). The small probability suggests that the enhancement anomalies appear around the epicenter on 11 January 2010 being very likely associated with the Haiti earthquake.

[16] Although the mapping process and the perturbation factor are not fully understood, the model simulations successfully reproduce the main features of the enhancements in the epicenter area, and partly, except the reduction at 13–15 LT, at the conjugate point (Figures 5c and 5d). It can be seen that the simulated variations at the epicenter and the conjugate point are generally in phase, which indicates that the electric fields are well mapped along the Earth's magnetic field lines between the two locations. Therefore, the discrepancy between the GIM and simulation during 13–15 LT might result from a poor mapping efficiency due to a shielding effect of the extreme dense of the TEC enhancements over the epicenter and the EIA crests (see Figures 1 and 2).

[17] In conclusion, the temporal TEC variation over the epicenter indicates the preseismic anomaly being the significant enhancement of the ionospheric TEC on 1 day before the 2010 *M*7 Haiti earthquake. The localization and the persistence of the 30 day extreme suggest that the enhancement anomaly on 11 January 2010 is highly related to the Haiti earthquake. The spatial distribution of the extreme might be useful to locate a possible forthcoming earthquake. The agreement between the GIM and simulation reveals that the seismoelectric environment around the epicenter has been changed, which perturbs the daily dynamoelectric field and fountain effect in the equator, low-latitude and midlatitude ionosphere during the earthquake preparation period.

Appendix A

[18] Measurements of a chain of 21 ground-based GPS receiving stations (Figure A1) (ftp://garner.ucsd.edu/pub/rinex/2010/) are used to produce latitude-time-TEC (LTT) plots along the Haiti earthquake longitude 72.5°W during 4–15 January 2010 (Figure A2). The LTT plot is derived based on the technique described by *Liu et al.* [1996].

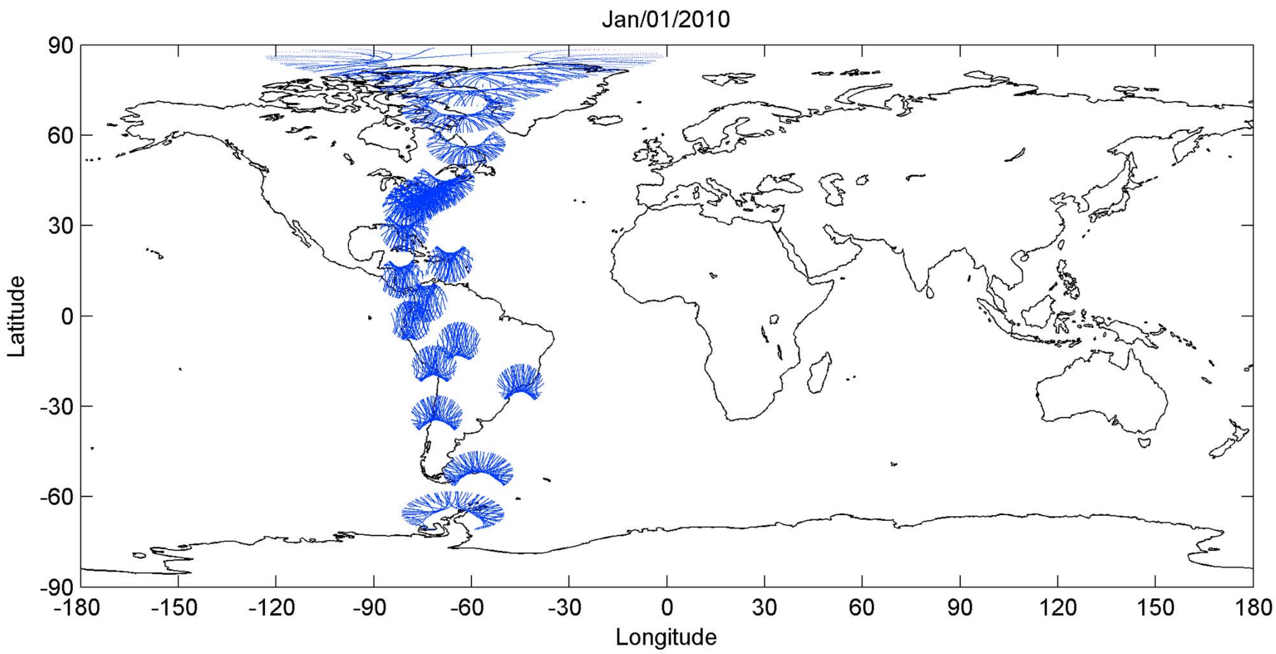

Figure A1. A chain of 21 ground-based GPS receiving stations along the Haiti earthquake longitude 72.5°W is used to produce LTT plots.

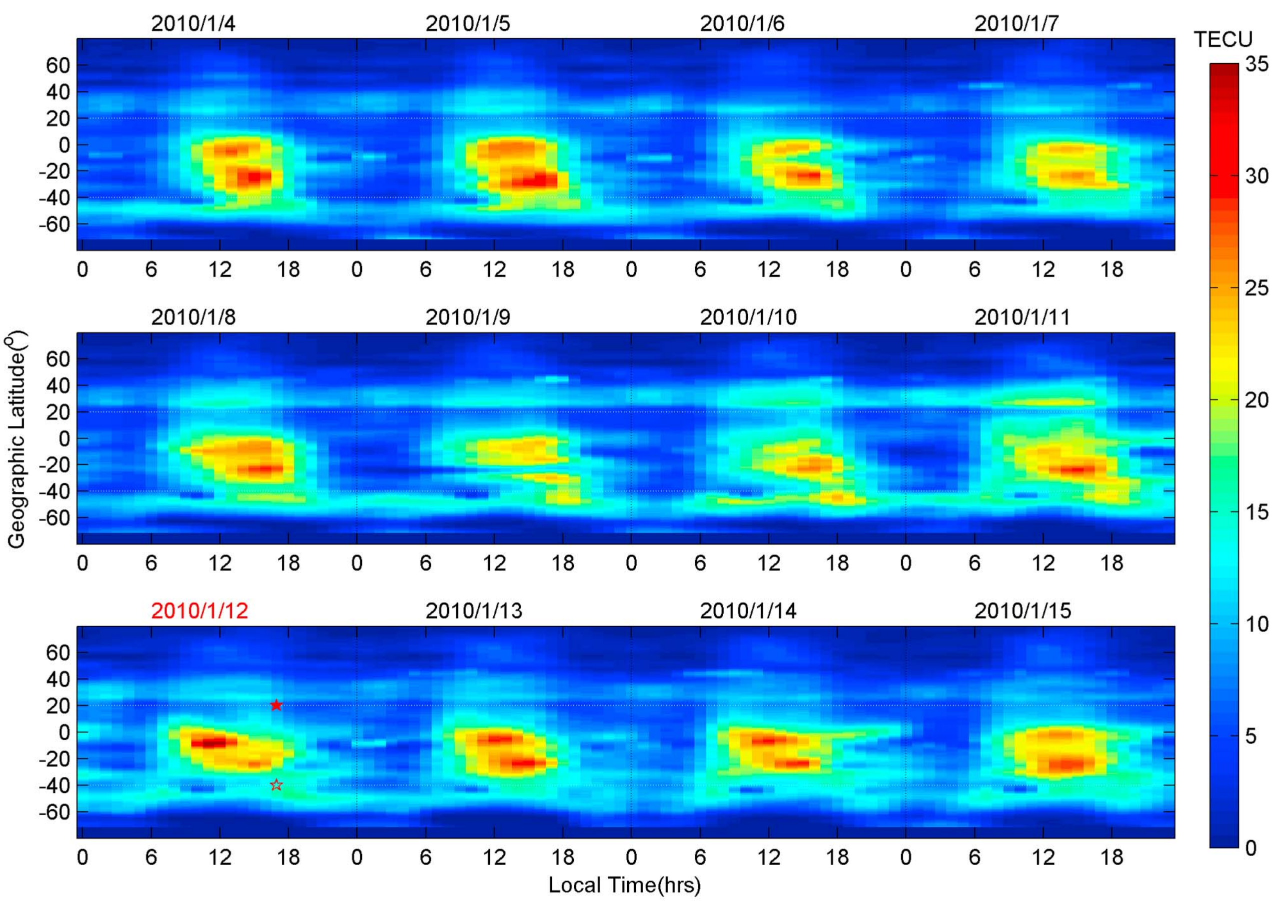

Figure A2. Similar to Figure 2, it shows LLT plots during 4–15 January 2010. It can be seen that the LLT plots constructed by the GIM (Figure 1) and by the 21-station chain (Figure A2) have good agreements.

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