Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake

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[1] The 2011 March 11 Tohoku-Oki earthquake (M_w9.0) caused vast damages to the country. Large events beneath dense observation networks could bring breakthroughs to seismology and geodynamics, and here I report one such finding. The Japanese dense network of Global Positioning System (GPS) detected clear precursory positive anomaly of ionospheric total electron content (TEC) around the focal region. It started ~40 minutes before the earthquake and reached nearly ten percent of the background TEC. It lasted until atmospheric waves arrived at the ionosphere. Similar preseismic TEC anomalies, with amplitudes dependent on magnitudes, were seen in the 2010 Chile earthquake (M_w8.8), and possibly in the 2004 Sumatra-Andaman (M_w9.2) and the 1994 Hokkaido-Toho-Oki (M_w8.3) earthquakes, but not in smaller earthquakes. **Citation:** Heki, K. (2011), Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake, *Geophys. Res. Lett.*, *38*, L17312, doi:10.1029/2011GL047908.

1. Introduction

[2] Various kinds of earthquake precursors have been reported so far [*Rikitake*, 1976]. Among others, electromagnetic phenomena have been explored worldwide, e.g., electric currents in the ground [*Uyeda and Kamogawa*, 2008], propagation anomaly of VLF [*Molchanov and Hayakawa*, 1998] and VHF [*Moriya et al.*, 2010] radio waves. They are based on measurements by purpose-built instruments at discrete observing points. Hence it has been difficult to verify their spatial correlation with earthquakes. Spatial coverage could be improved by satellite observations [*Němec et al.*, 2008], but it is difficult to monitor the region of future earthquakes continuously.

[3] The 2011 March 11 (05:46UT) Tohoku-Oki earthquake ruptured the plate boundary ~450 km in length and ~200 km in width along the Japan Trench where the Pacific Plate subducts beneath NE Japan (Figure 1). GEONET (GPS Earth Observation Network) is composed of >1000 continuous GPS stations. It has been yielding useful crustal deformation data since its launch in 1994 [*Heki*, 2007], and already revealed coseismic and early postseismic crustal movements of the Tohoku-Oki earthquake [*Ozawa et al.*, 2011]. GEONET offers continuous measurements of nearly two-dimensional crustal movements of the country. Although it could detect mm level precursory crustal deformation of earthquakes, there have been no such reports to date. GPS can also measure TEC, ionospheric electron contents integrated along line-of-sights, by using the phase differences between the two L-band carrier waves. Here I focus on the two-dimensional TEC distribution above Japan and its behavior immediately before the 2011 Tohoku-Oki earthquake.

2. TEC Changes in the 2011 Tohoku Earthquake

[4] A popular seismological target of GPS-TEC studies has been coseismic ionospheric disturbances (CID) caused by various atmospheric waves generated by earthquakes [*Calais and Minster*, 1995]. They include direct acoustic waves excited by vertical crustal movements [*Heki et al.*, 2006], Rayleigh surface waves [*Rolland et al.*, 2011a], and internal gravity waves [*Occhipinti et al.*, 2008]. Figure 1a shows the TEC behavior before and after the earthquake seen from a GPS station in NE Japan. At the time of earthquake (5:46UT), eight GPS satellites were visible there (Figure 1b). CIDs are clearly seen with satellites 5, 15, 26, 27, 28 as the irregular TEC changes caused by acoustic waves ~10 minutes after the earthquake, and with satellites 18 and 22 as the oscillatory variations caused by internal gravity waves 40–80 minutes after the earthquake [*Rolland et al.*, 2011b]. I try to isolate non-oscillatory TEC anomalies immediately before the earthquake, which are not readily visible in Figure 1a.

[5] Figure 2 shows slant TEC changes over ~5 hours period observed at five GPS stations with the satellite 15. The TEC shows gentle curvature due to satellite elevation changes. I employ the data analysis procedure used for the detection of ballistic missile signatures in TEC [*Ozeki and Heki*, 2010] (see auxiliary material).[1] In addition to CID, transient positive anomaly of TEC is seen to start ~40 minutes before the earthquake. Figure 2b shows trajectories of sub-ionospheric points (SIP) assuming a thin layer at 300 km altitude. The TEC anomaly is larger for the SIP closer to the epicenter, and reaches ~4 TECU (1 TECU is 10^{16} electrons/m^2). On the other hand, slight negative TEC anomaly is seen at GPS stations with SIP distant from the epicenter. These anomalies disappear and TEC returns to normal after CID arrivals.

[6] Figure 3 shows three snapshots of the geographical distribution of such TEC anomalies. There are little anomalies 1 hour before the earthquake (Figure 3a). Positive anomalies have already emerged in NE Japan 20 minutes before the earthquake (Figure 3b), and become larger toward the earthquake occurrence time (Figure 3c). Slight negative changes of TEC are also seen in SW Japan. The maximum positive anomaly of vertical TEC is ~2.3 TECU, which corresponds to ~8% of the background value (~27 TECU according to the global ionospheric map [*Mannucci et al.*, 1998] of this day). The latitudinal extent of the positive

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047908.

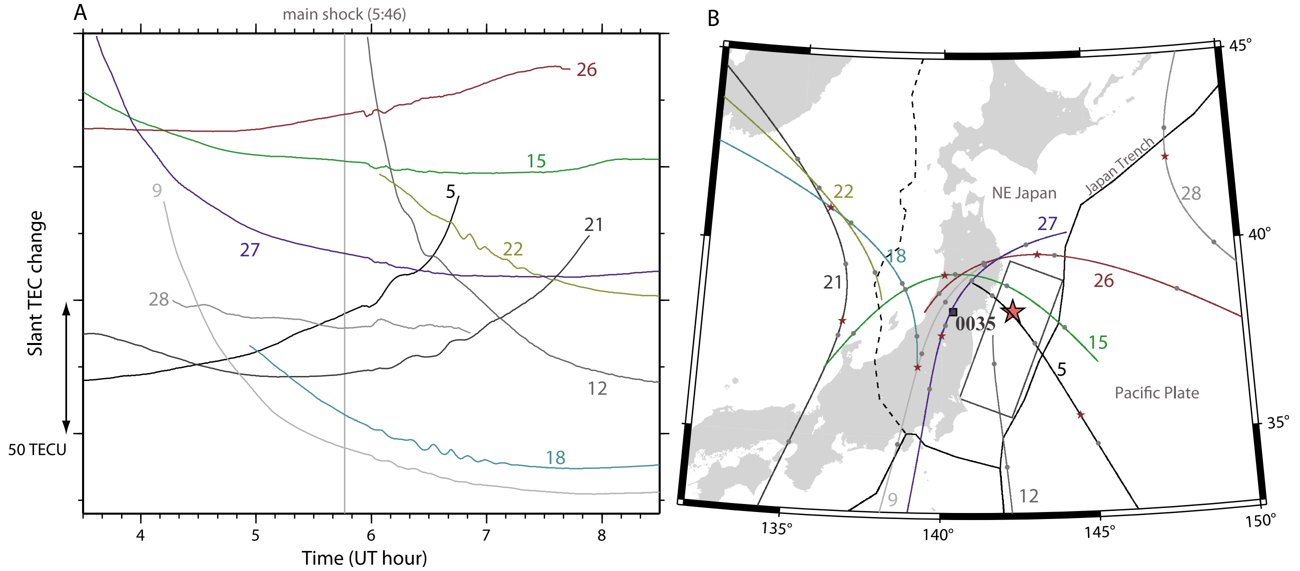

Figure 1. (a) Time series 3.5–8.5 UT of slant TEC changes observed at 0035 (black square in Figure 1b) with ten GPS satellites. Because each satellite-receiver pair has a different measurement bias, only their temporal changes are meaningful. CIDs are seen in almost all satellites after the main shock at 5:46. (b) Trajectories of SIP for the satellites shown in Figure 1a. On the trajectories, small red stars are SIP at 5:46 and small dots are hourly time marks. The rectangle shows the approximate rupture zone of this earthquake. The large red star shows the epicenter.

TEC anomaly approximately overlaps with the ruptured fault segments. Similar figures to Figures 2 and 3 were drawn using three other satellites 27, 26, 9, and are shown in Figures S1, S3, and S5 and Figures S2, S4, and S6, respectively. The spatial extent and amplitudes of the positive anomalies seems to vary slightly from satellite to satellite. This would reflect the three-dimensional nature of the electron density change which is projected onto a thin layer at 300 km altitude in drawing these figures.

[7] Global ionospheric maps (GIM) calculated from worldwide GPS stations have spatial resolution of 2.5/5 degrees in latitude/longitude [*Mannucci et al.*, 1998]. I downloaded the model (codg0700.11i) from University of Berne (ftp.unibe.ch), and added the slant TEC calculated for 0038/Sat.15 using this GIM to Figure 2a. Because the GPS station Mizusawa (mizu in Figure 2b), only ~200 km from the epicenter, is used in deriving the GIM, the synthesized curve also shows preseismic TEC enhancement although short wavelength components are lost due to its low spatial resolution.

3. Discussion

3.1. Past Earthquakes

[8] In order to find out if such TEC anomalies commonly precede earthquakes, I analyzed GPS data of the two recent M9 class earthquakes, the 2010 Central Chile (Maule) earthquake (M_w8.8) [*Moreno et al.*, 2010] and the M_w9.2 2004 Sumatra-Andaman earthquake [*Banerjee et al.*, 2005]. Raw data files of Argentine continuous GPS stations on Feb. 27, 2010, have been downloaded from www.ign.gob.ar, and analyzed to see the TEC changes before the Chile earthquake. The TEC time series obtained with the satellite 17, sensitive to ionosphere close to the rupture area, show similar enhancement starting ~50 minutes before the earthquake and recovery after the CID arrival (Figures 4 and S9). The anomaly is 3–4 TECU in slant TEC, somewhat smaller than the 2011 Tohoku earthquake.

[9] CIDs of the 2004 Sumatra-Andaman earthquake have been analyzed using GPS stations in Indonesia and Thailand [*Heki et al.*, 2006]. SIP of the satellite 20 from Phuket (phkt) is very close to the epicenter, and the slant TEC time series there is found to show temporary increase exceeding 5 TECU lasting ~90 minutes (Figures 4 and S10). Although spatial coverage of GPS data in these two earthquakes is not sufficient, preseismic positive TEC anomaly appears to have accompanied these earthquakes.

[10] In order to see if TEC enhancement occurs before smaller earthquakes, I analyzed GPS-TEC data of several largest earthquakes in time and region covered by GEONET. In the M_w8.3 1994 Hokkaido-Toho-Oki earthquake [*Tsuji et al.*, 1995], the satellite 20 showed similar positive TEC anomaly starting ~60 minutes before the earthquake (Figures 4 and S11). Although significant, the amount of anomaly is much smaller than those of the three M9 class earthquakes (Figure 4). The 2003 Tokachi-Oki earthquake (M_w8.0) showed clear CID [*Heki and Ping*, 2005]. This earthquake, together with a few other M7-8 class earthquakes with clear CIDs, did not show significant preseismic TEC anomalies (Figure S12). Figure 4b summarizes the magnitude dependence of the vertical TEC enhancement immediately before the earthquake.

3.2. Models

[11] There are no conclusive models for the preseismic electron enhancement. Here I give a few clues for future searches of the model. The smaller anomalies for the satellites 9/27 than 15/26 (auxiliary material) would be explained if ionospheric F-layer electrons are assumed to have moved down along the geomagnetic field. For example, we would see the positive TEC anomaly similar to the observation if

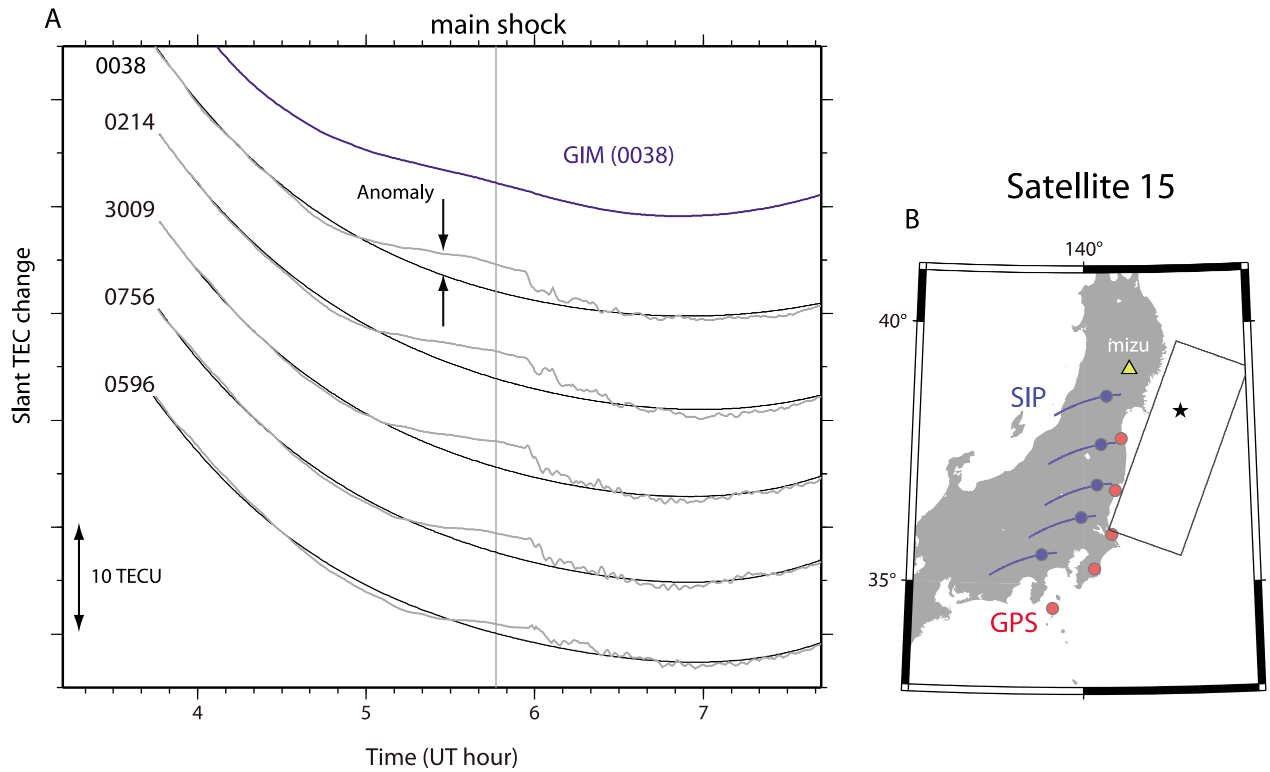

Figure 2. (a) Slant TEC change time series taken at five GPS stations with the satellite 15. Temporary positive TEC anomalies started ~40 minutes before the earthquake and disappeared after CID passages. Black smooth curves are the models (see auxiliary material), and anomalies are defined as the departure from the model curves. Slant TEC changes calculated using GIM for site 0038 is shown as the blue curve. (b) Positions of the fives GPS stations (red dots) and their 5:00–6:00UT SIP trajectories (blue dots indicate 5:46). The northernmost point is 0038. Then follow 0214, 3009, 0756 and 0596 southward.

electrons within a layer of 20 km thickness at 350 km height moved down to 300 km.

[12] Electromagnetic earthquake precursors have been often attributed to positively charged aerosols [*Tributsch*, 1978]. Several hypotheses have been proposed for their sources. For example, experiments demonstrated that stresses mobilize positive holes in igneous rocks [*Takeuchi et al.*, 2006]. Alpha decay of radon released from the crust can also ionize the atmosphere. They may change the electric resistivity of the lower atmosphere, which could disturb the

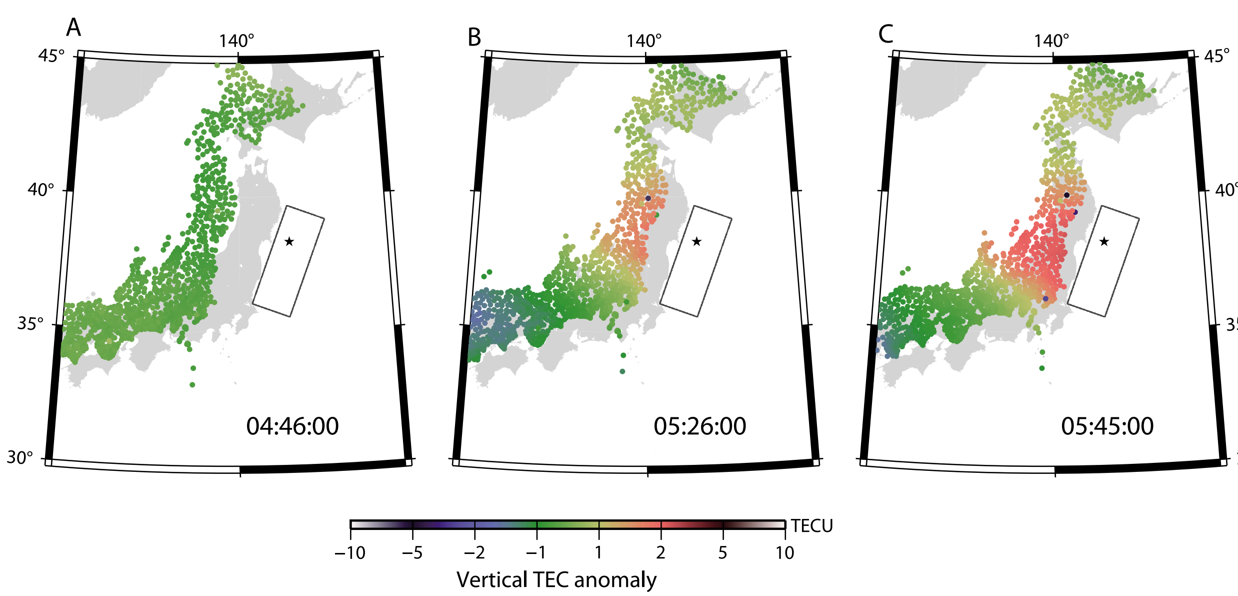

Figure 3. Vertical TEC anomalies at three time epochs, (a) 1 hour, (b) 20 minutes, and (c) 1 minute before the earthquake, observed at GEONET stations with the satellite 15. Positive anomalies (red color) are seen to grow near the focal region.

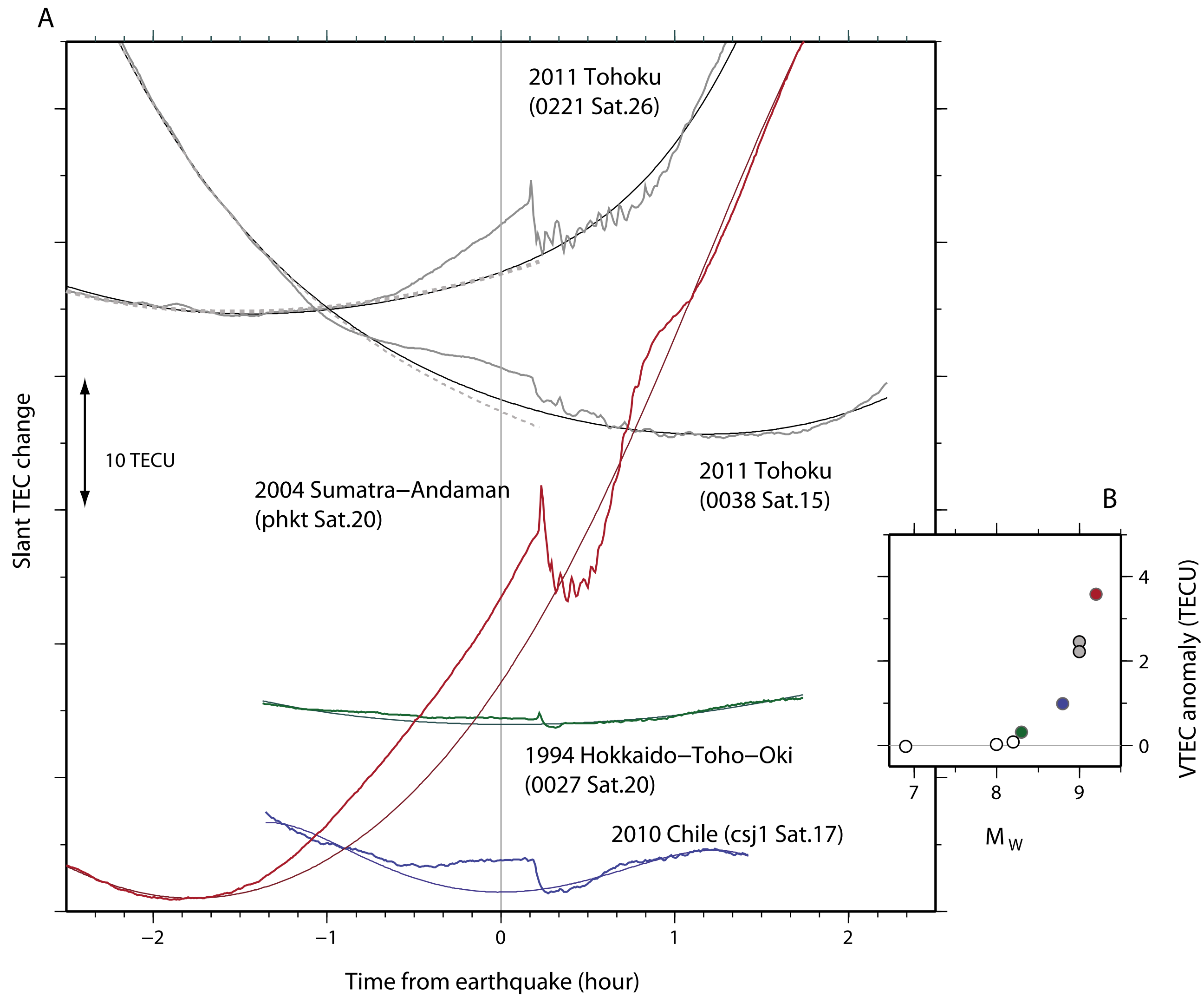

Figure 4. (a) Slant TEC changes and their models in the 2011 Tohoku earthquake, the 2004 Sumatra-Andaman earthquake, the 1994 Hokkaido-Toho-Oki earthquake, and the 2010 Chile (Maule) earthquake. The horizontal axis shows the time from earthquakes. Dashed curves in gray for the top two time series show the models derived with data prior to the possible onset of the precursor (before 5.2 UT) and extrapolated to 5.2–6.0 UT. (b) Vertical TEC anomalies immediately before the earthquakes as a function of their moment magnitudes. Colors correspond to those in Figure 4a. In addition to the five data from four earthquakes in Figure 4a, three smaller earthquakes (Figure S12) are included (white circles).

global electric circuit and redistribute ionospheric electrons [*Pulinets and Ouzounov*, 2011].

[13] The disappearance of the enhanced TEC after the passage of CID would be understood as the mixing of ionosphere by acoustic waves. The amplitude of acoustic waves grows in the light upper atmosphere, e.g., a few parts of 0.1 mm/s vertical velocity at the ground level is amplified to >100 m/s at the F layer height [*Rolland et al.*, 2011a]. Such high-speed oscillations with periods of ~4.5 minute (atmospheric fundamental mode) would effectively homogenize the electron density irregularities formed before earthquakes.

[14] One may consider that the TEC decrease associated with CID caused apparent preseismic TEC enhancement as an artifact. I demonstrate this is not the case in Figures 4 and S3. I extrapolated the TEC model fitted for the period before 5.2 UT (i.e., before the precursor appeared) to the later period (gray dashed curves in Figure 4, and red curves in Figure S3). The observed TEC keeps deviating positively from the extrapolated curves during the ~40 minutes period before the earthquake and CID brings them back to normal (i.e., it canceled out the anomalous preseismic enhancement by stirring the F layer). This is also confirmed by comparing the short-term TEC changing rates ~30 minutes before the earthquake between regions near the epicenter and those farther away (Figure S7). Figure S5 also shows an example of preseismic TEC enhancement without coseismic decrease.

4. Conclusions

[15] Here I present an objectively testable scientific hypothesis that M9 class earthquakes are immediately preceded by positive TEC anomalies of magnitude-dependent amplitude lasting for an hour or so. Because the raw data files are available on the web, one can reproduce the results reported here. It is also easy to apply the method to other earthquakes. The possible precursor reported here is different

qualitatively from past examples in three points, (1) obvious temporal correlation (immediately before earthquakes), (2) obvious spatial correlation (occurring around the focal area), and (3) clear magnitude dependence (Figure 4b). The claim that earthquakes are inherently unpredictable [e.g., *Geller et al.*, 1997] might not be true at least for M9 class earthquakes.

[16] A few points need to be cleared before the preseismic TEC enhancement can be used for short-term prediction of a large earthquake. A vital question is how often similar local TEC enhancement of non-earthquake origins occur. In Figure S8, I compare the five hours slant TEC time series of the satellite 15 observed at 3009 from Jan. 1 to Apr. 30, 2011. They were all modeled with degree-3 polynomials. The precursory anomaly of the Tohoku-Oki earthquake was the largest of all. The second and the third largest anomalies (days 061 and 094) were found to have traveled southward suggesting their space weather origin (Figures S8e and S8f). In order to discriminate such disturbances and preseismic TEC enhancements in real time, we may need to monitor TEC outside the Japanese Islands.

[17] A rather technical issue is the separation of the real TEC changes from apparent changes due to satellite movements in the sky. At the moment, we need an arc of 1–2 hours or more to accurately separate satellite-specific biases from temporal changes of TEC. The situation will be improved by including Quasi-Zenith Satellite System (see qzss.jaxa.jp for detail). They are supposed to stay near zenith and will enable real time observations of vertical TEC changes.

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