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Preseismic ionospheric electron enhancements revisited

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[1] Possible enhancement of ionospheric Total Electron Content (TEC) immediately before the 2011 Tohoku-oki earthquake (M_w9.0) has been reported by Heki (2011). Critical responses to it often come in two stages; they first doubt the enhancement itself and attribute it to an artifact. Second (when they accept the enhancement), they doubt the significance of the enhancement among natural variability of space weather origin. For example, Kamogawa and Kakinami (2013) attributed the enhancement to an artifact falsely detected by the combined effect of the highly variable TEC under active geomagnetic condition and the occurrence of a tsunamigenic ionospheric hole. Here we closely examine the time series of vertical TEC before and after the 2011 Tohoku-oki earthquake. We first demonstrate that the tsunami did not make an ionospheric hole, and next confirm the reality of the enhancement using data of two other sensors, ionosonde and magnetometers. The amplitude of the preseismic TEC enhancement is within the natural variability, and its snapshot resembles to large-scale traveling ionospheric disturbances. However, distinction could be made by examining their propagation properties. Similar TEC anomalies occurred before all the M ≥ 8.5 earthquakes in this century, suggesting their seismic origin.

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1. Introduction

[2] Global Positioning System (GPS) receivers provide useful information on ionospheric disturbances in terms of changes in Total Electron Content (TEC), number of electrons integrated along the line of sight (LOS). The dense network of permanent GPS tracking stations in Japan, GEONET (GNSS Earth Observation Network), enabled in-depth studies of the ionospheric disturbances by the 11 March 2011 Tohoku-oki earthquake (M_w9.0) and its tsunami. Early papers report, e.g., fast arrival of acoustic waves at ionospheric heights [*Astafyeva et al.*, 2011], concentric wavefront by internal gravity waves [*Tsugawa et al.*, 2011], excitation of atmospheric modes [*Saito et al.*, 2011; *Rolland et al.*, 2011], and numerical simulations of these disturbances [*Matsumura et al.*, 2011]. While the majority discusses ionospheric responses to various atmospheric waves excited by the vertical movement of the ground and the sea surface, *Heki* [2011] reported possible TEC enhancement starting ~40 min before the earthquake. Later, *Cahyadi and Heki* [2013, Coseismic ionospheric disturbance of the 2012 North Sumatra earthquakes, large intraplate strike-slip events, submitted to *Journal of Geophysical Research*, 2013] suggested that all the earthquakes with M_w of 8.5 or more in this century are preceded by similar preseismic TEC anomalies (except the 2005 Nias earthquake, M_w8.6, whose TEC data are disrupted by plasma bubbles).

[3] Such preseismic TEC enhancements, however, have not been widely accepted in scientific communities. As a typical critical response, they often doubt the existence of the TEC enhancement itself. *Heki* [2011] drew the reference curves by fitting cubic polynomials to vertical TEC excluding ~1 h period, e.g., from 40 min before the earthquake to 20 min after the earthquake. However, the period to be excluded (anomalous period) is not known a priori. At a first glance, only TEC drops starting when acoustic wave disturbed the *F* region are clear (it takes ~10 min for acoustic waves to reach the *F* region of the ionosphere). Then two scenarios are possible, i.e., (1) slow preseismic enhancement and its rapid recovery (Figure 1a) [*Heki*, 2011], or (2) rapid formation of an ionospheric "hole", and its slow recovery (Figure 1b) [*Kakinami et al.*, 2012]. If (2) is the case, defining the reference curve by inappropriately excluding the preseismic period would result in a spurious preseismic enhancement.

[4] *Kakinami et al.* [2012] considered that the TEC drop after the earthquake is a phenomenon irrelevant to precursory changes, and named it a tsunamigenic ionospheric hole. Typical tsunamis of interplate thrust earthquakes start with the upheaval of sea surface, followed by the subsidence 5–10 min later. They proposed a qualitative model that atmospheric waves excited by the downgoing sea surface carry ionospheric electrons down and promote their recombination with positive ions. Based on this concept, *Kamogawa and Kakinami* [2013] did numerical experiments for daily TEC time series to demonstrate that false precursors appear by postulating such holes ~10 min after the earthquake (as we show with the red dashed

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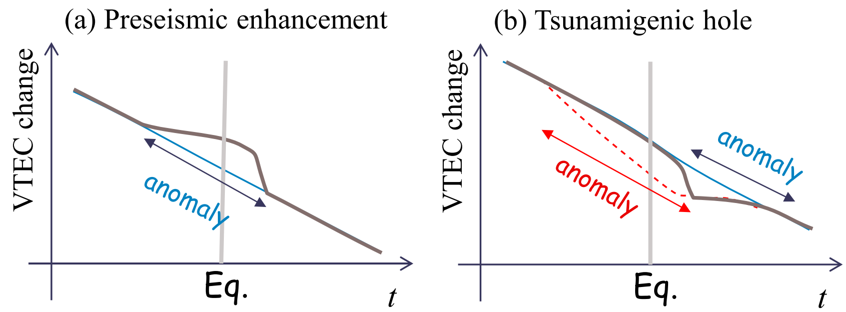

Figure 1. Two concepts to explain Total Electron Content (TEC) drops occurring ~10 min after the earthquake, i.e., (a) slow preseismic TEC enhancement and its recovery [*Heki*, 2011] and (b) tsunamigenic hole formation and its slow recovery [*Kakinami et al.*, 2012]. Curves in light blue are the reference, and anomaly is defined as the departure from the reference curves. The two scenarios agree with the existence of the TEC drop ~10 min after the earthquake. However, the scenario (b) considers that there were no preseismic anomalies and the spurious preseismic anomaly would emerge if we define the reference curve inappropriately (dashed curve in red).

curve in Figure 1b), and concluded that the preseismic TEC enhancement did not occur. Recently, *Astafyeva et al.* [2013] hypothesized that the TEC drops represent the negative phase of the "N waves". In spite of different interpretation, *Kamogawa and Kakinami* [2013] and *Astafyeva et al.* [2013] are based on the common idea that the TEC drops are irrelevant to precursors.

[5] The present paper is partially meant to be the rebuttal to *Kamogawa and Kakinami* [2013]. We will use vertical TEC (VTEC) time series on 11 March 2011 throughout this study instead of slant TEC (STEC) used in *Heki* [2011]. In section 2, we examine if the tsunami really made an ionospheric hole. In section 3, we compare the VTEC time series with data by other sensors looking for support to the preseismic TEC enhancement. In section 4, we discuss the significance of the preseismic TEC changes of the 2011 Tohoku-oki earthquake under high geomagnetic activity. Finally, we discuss the implication of GPS-TEC observations for future earthquake prediction in section 5.

2. Does a Tsunami Make an Ionospheric Hole?

2.1. From STEC to VTEC

[6] A factor to hamper intuitive recognition of anomalous behaviors of the TEC time series obtained by GPS is the existence of apparent U-shaped changes. Because GPS satellites move in the sky, changing incident angle of LOS to the ionosphere causes apparent variation of STEC. Such changes can be removed by converting STEC to VTEC. Let Z be the incident angle (we usually approximate the ionosphere as a thin layer at 300 km height), then STEC $\times$ cos$Z$ is the VTEC. We can calculate Z from satellite orbital information.

[7] To perform the conversion, we need to isolate STEC from the ionospheric (geometry-free) linear combination (often called L4) of the two L-band carrier phases, L1 and L2. L4 includes integer ambiguities intrinsic to phase measurements and interfrequency biases (IFB) specific to transmitter (satellite) and receiver (GPS station) hardware. The first component (ambiguities) can be obtained by comparing L4 with the ionospheric combinations of the unambiguous pseudorange (code) measurements. For the Japanese GPS data, daily values of both receiver-specific IFB and satellite-specific IFB, estimated together with ionospheric models, are available online from Electronic Navigation Research Institute (ENRI) [*Sakai*, 2005]. We used them to isolate STEC from L4. Although the IFBs have some dependence on receiver temperatures [*Coster et al.*, 2013], they remain nearly constant over days. Hence, there is no technical problem in the real-time conversion from L4 to VTEC.

[8] Figure 2 compares STEC and VTEC time series of three satellite-station pairs shown in the original article by *Heki* [2011]. Although their STEC signatures are very different, the VTEC behaves fairly similarly to each other (plot biases are given in Figure 2b to separate the curves for visual clarity). The remaining difference stems from different ionospheric penetration points (IPP). For example, because LOS to Satellite 27 has IPP in the southern sky during the first few hours, its VTEC shows somewhat higher values. IPP of Satellite 15 moves northward and then southward, resulting in a positive quadratic component which adds a gentle downward-convex curvature to the VTEC variation. Satellite 27 data before 4 UT and Satellite 26 data after 7 UT are fairly noisy because the satellite elevations are lower than 15°. These parts should be excluded from further scientific discussions (also these parts represent ionosphere very far from the epicenter, see subionospheric point (SIP) tracks in Figure 2c).

[9] In Figure 2b, we can see that preseismic VTEC increases did start ~40 min before the main shock (i.e., ~5 UT), and VTEC decreased to the original level after acoustic disturbances ~10 min after the earthquake. The VTEC curves obviously favor the "preseismic enhancement and recovery" scenario (Figure 1a) rather than the "tsunamigenic hole formation" scenario (Figure 1b).

[10] *Heki* [2011] also pointed out that negative TEC anomalies are seen with GPS stations distant from the epicenter (see e.g., Figure A4 of *Heki* [2011] for the distribution of negative anomalies). In Figure S1, we show that VTEC of distant stations exhibit preseismic decreases. This suggests that the preseismic TEC enhancement may be a result of transportation rather than net increase of electrons.

2.2. Numerical Experiments

[11] In addition to the intuitive pattern recognition, we perform a simple numerical experiment. We will use the VTEC

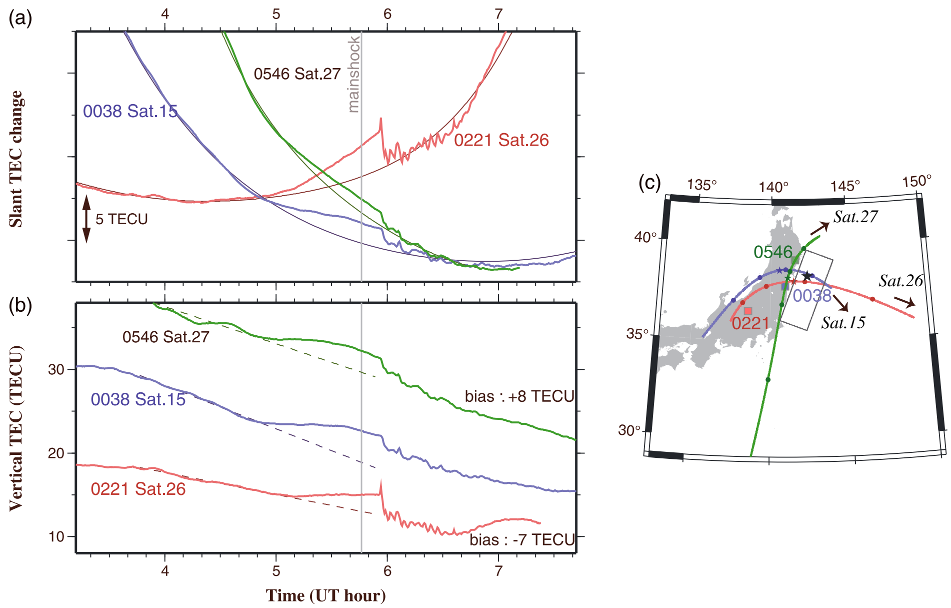

Figure 2. Time series of (a) slant TEC (STEC) changes and (b) vertical TEC (VTEC) of Satellites 15 (blue), 26 (red), and 27 (green) observed at 0038, 0221, and 0546, respectively. The reference smooth curves in Figure 2a were obtained following *Heki* [2011]. In the VTEC plot, the portions 1–2 h before the main shock were modeled with lines and extrapolated to the earthquake occurrence time (dashed lines in b). Subionospheric point (SIP) trajectories of the three satellites are plotted using the same color in Figure 2c. Stars on the SIP tracks show SIP positions at 5.77 UT (main shock time), and circles on the SIP tracks are 1 h time marks. The rectangle and the black star show the approximate fault area and the epicenter of the 2011 Tohoku-oki earthquake.

time series of Satellite 26 which have relatively long linearly changing portions before the earthquake. We modeled the 3 h period encompassing the earthquake using four lines connected with three breaks (Figure 3a). Period A is assumed to represent background steady decrease of afternoon VTEC. Periods B and C correspond to the preseismic increase and coseismic decrease, respectively. Here we compare the integrated changes during B and C relative to the trend during A. If they are comparable, the extension of Period A reaches the C–D junction (as shown by broken lines in Figure 3a), i.e., there is no net VTEC decrease.

[12] The results in Figure 3c suggest that the two quantities are identical within errors. Hence, the coseismic decrease is interpreted as the recovery from the preseismic increase. Because the tsunami did not create a hole in an active sense, the word “tsunamigenic ionospheric hole” might be misleading. The process hypothesized by *Kakinami et al.* [2012] may have worked in a short timescale, i.e., downgoing sea surface resulted in the decrease of ionospheric electrons. However, it is not a stand-alone phenomenon but a part of a longer process. We conclude that the artifact claim for the 2011 Tohoku-oki and the 2010 Maule cases by *Kamogawa and Kakinami* [2013] is not substantiated because it is based on the existence of the tsunamigenic ionospheric hole without preseismic changes.

[13] VTEC in Period D shows wavy postseismic behaviors. Some stations (e.g., 0572) show increase while other stations (e.g., 0265) do not. The positive VTEC anomalies around the end of the Period D correspond to the crest of a concentric wavefront around the “ionospheric” epicenter. The geographical distribution of these anomalies at this time epoch (i.e., 06:25 UT) is available in the Figure 2f of *Tsugawa et al.* [2011].

3. Do Other Sensors Show Preseismic Changes?

3.1. Three Sensors in the Same Time Window

[14] If the preseismic TEC anomaly involved transportation of electric charges in the ground and/or ionosphere, it should have accompanied electric currents and consequent changes in the geomagnetic field. *Utada et al.* [2011] showed coseismic and postseismic geomagnetic field changes of the 2011 Tohoku-oki earthquake and its tsunami. Although they did not pay attention to changes before the earthquake, *Enomoto* [2012] pointed out that the geomagnetic anomalies of several nT associated with the 2011 Tohoku-oki earthquake were observable at stations in NE Japan. In fact, geomagnetic declination in *Utada et al.* [2011] showed gradual changes up to 1 arc minute starting ~40 min before the earthquake. We downloaded geomagnetic data archive from Japan Meteorological Agency (JMA), and plot the declination change at Kakioka (KAK), Kanto, relative to Kanoya (KNY) in Kyushu, in Figure 4.

[15] Ionosonde observations are done at four stations in Japan, in which Kokubunji, west of Tokyo, is the nearest to the 2011 Tohoku-oki rupture area. Peak plasma frequencies at Kokubunji are available from the World Data Center for Ionosphere (WDC) (wdc.nict.go.jp). The F2 peak plasma frequency (foF2) remained high over the few days before the 2011 Tohoku-oki earthquake, but did not show significant changes immediately before and after the earthquake. However, the critical frequency at the sporadic-E (Es) layer (foEs) showed sudden appearance of the reflection at 5:30 UT, and it lasted until 6:15 UT (Figure 4). The Es occurrence is controlled by neutral wind shear rather than space weather

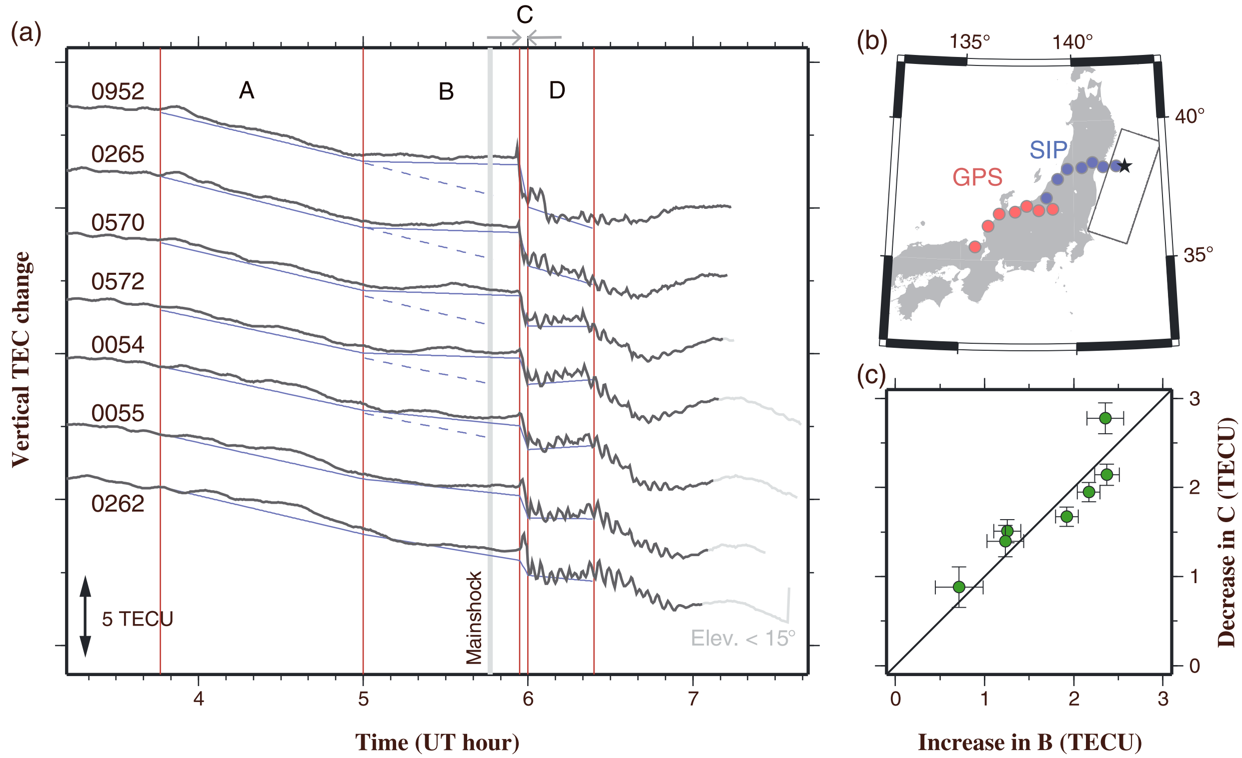

Figure 3. (a) Satellite 26 VTEC time series at seven GPS stations with various focal distances. Parts shown with light gray indicate the data obtained with satellite elevations lower than 15°. We divided ~3 h period from 3.77 UT (2 h before the earthquake) to 6.4 UT (~40 min after the earthquake) into four portions representing (A) normal background, (B) precursory enhancement, (C) coseismic drop, and (D) postseismic period, and fit lines with three breaks. In Figure 3b, we show GPS stations and their SIP at 5:46 UT. Their preseismic increases (increase during B relative to the trend in A) are compared with the decrease during C (error bars show 1σ) (c).

[e.g., *Whitehead*, 1989], and there were no enhanced Es activities at this time. The foEs at 5:30 implies only moderate increase of electron density in the *E* region, but it is the highest in this week (days 067–073) (Figure S2). Similar discussion on the foF2 and foEs behaviors is to be found in *Carter et al*. [2013].

[16] Figure 4 compares the time series of the two new observables in addition to VTEC (Satellite 15 at 3009). Both of the VTEC and the declination residual show moderate anomalies starting ~40 min before the 2011 Tohoku-oki earthquake, and disappear after the earthquake. Although the foEs time resolution is 15 min, its first appearance at 5:30 UT is consistent with the other two. As a whole, Figure 4 would give a certain support to the reality of the preseismic TEC enhancement.

[17] The foEs data suggested the electron density increase in the *E* region rather than the *F* region. This is consistent with the electron density profile above the Tohoku District (position shown in Figure 4b) from the COSMIC-2 (Constellation Observing System for Meteorology, Ionosphere, and Climate) GPS radio occultation measurements at 5:50 UT (4 min after the earthquake). The actual profile shown in *Astafyeva et al.* [2011] indicates that electrons in the *E* region were approximately three times as dense as the IRI-2007 model [*Bilitza and Reinisch*, 2008] while little anomalies are seen in the *F* region. The electron density increase in the *E* region may better explain the TEC decrease after the acoustic disturbance (called "tsunamigenic ionospheric hole" by them), i.e., the recombination process proposed by *Kakinami et al.* [2012] may work more efficiently for lower altitude electrons.

3.2. Geomagnetic Declination

[18] Geomagnetic data at seven observatories are available on the web, i.e., four Japan Meteorological Agency (JMA) stations at Memanbetsu (MMB), Hokkaido, Kakioka (KAK), Kanto, Kanoya (KNY), Kyushu, and Chichijima (CBI), the Bonin Islands, and three Geospatial Information Authority of Japan (GSI) stations at Esashi (ESA) and Mizusawsa (MIZ), Tohoku, and Kanozan (KNZ), Kanto. In Figure 5, we show time series of the geomagnetic declination at six stations with respect to KNY. On the earthquake day (Figure 5b), stations close to the epicenter showed preseismic declination changes. The anomalies at ESA, MIZ, KAK, and KNZ seem to have started simultaneously at ~40 min before the earthquake, the same onset time as the VTEC anomaly. Such an anomaly is not seen at CBI, and is vague at MMB. Preseismic anomalies are not clear in other components (e.g., intensity of horizontal and vertical components, see Figure S3), suggesting that the disturbing field was dominantly east-west.

4. Is the Preseismic TEC Change Significant?

[19] We do not claim that any of the VTEC, geomagnetic declination, and foEs exceeded normal variability under

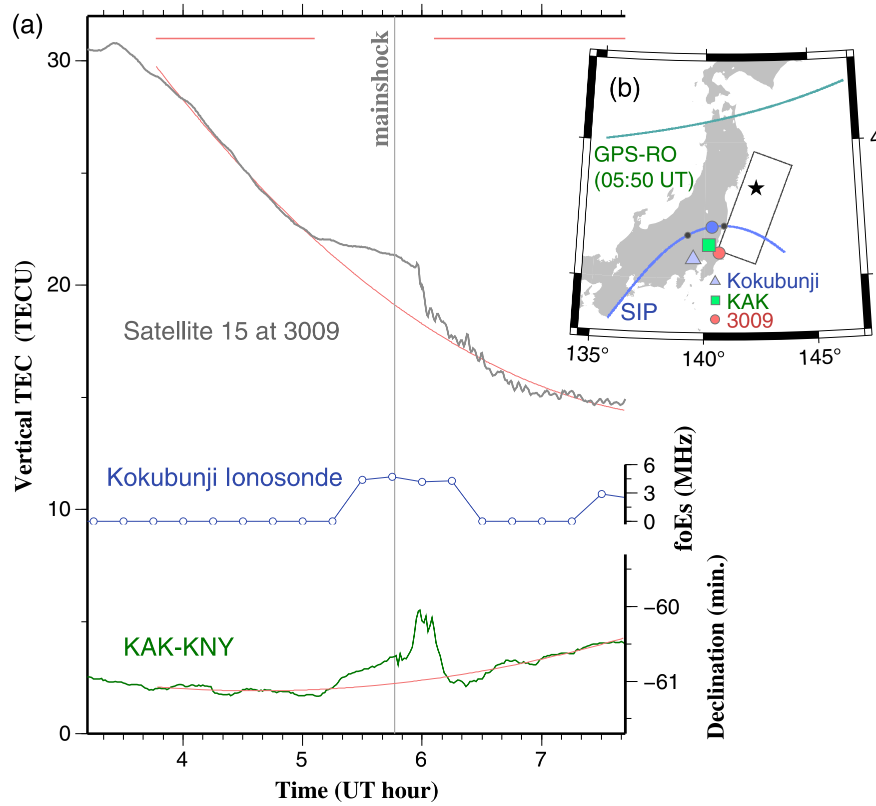

Figure 4. (a) Comparison of signals by the three sensors, VTEC by Satellite 15 at the station 3009 (gray curve), *E* layer critical frequency (foEs) from the ionosonde at Kokubunji (blue curve), and the geomagnetic field declination at Kakioka (KAK), Kanto, relative to Kanoya (KNY), Kyushu (green curve). The anomalies show up simultaneously ~40 min before the 2011 Tohoku-oki earthquake. Reference quadratic curves for VTEC and the geomagnetic declination have been drawn by fitting the part shown by horizontal lines at the top. Positions of the observatories are shown in Figure 4b. Black dots on the SIP trajectory show the positions at 5 and 6 UT. The dark green curve in Figure 4b shows the ionospheric penetration point (IPP) track of the GPS Radio Occultation measurement at 5:50 UT shown in *Astafyeva et al*. [2011].

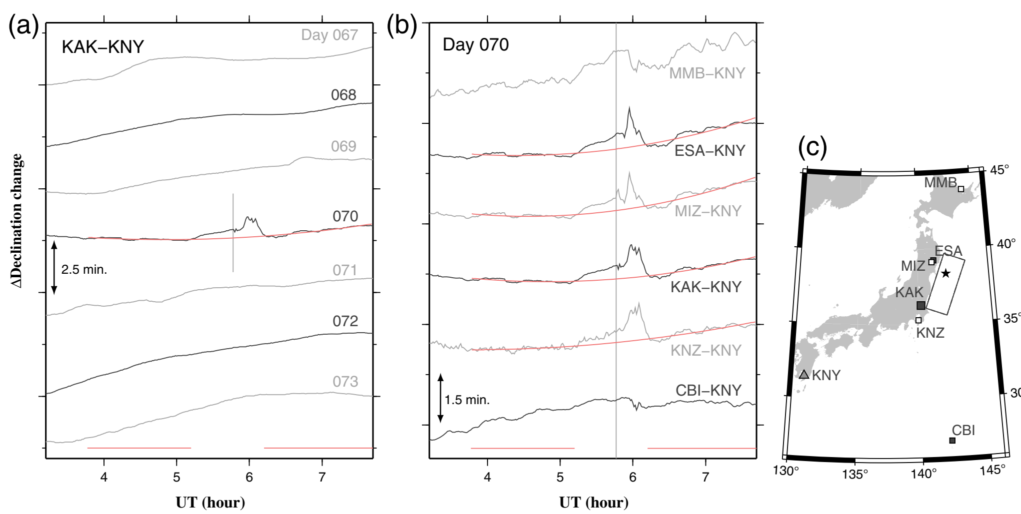

Figure 5. (a) Geomagnetic declination at Kakioka (KAK) relative to Kanoya (KNY) over the 7 day period encompassing the earthquake day (070). In Figure 5b, the declination changes relative to KNY of six geomagnetic observatories in Japan (c) on the earthquake day are shown. Model fitting with quadratic functions, similar to Figure 4, has been done for the data on the earthquake day (red curves). Positive anomalies are seen to have started ~40 min before the 2011 Tohoku-oki earthquake for stations in the Tohoku and the Kanto District. Vertical lines in Figures 5a and 5b indicate the earthquake occurrence time.

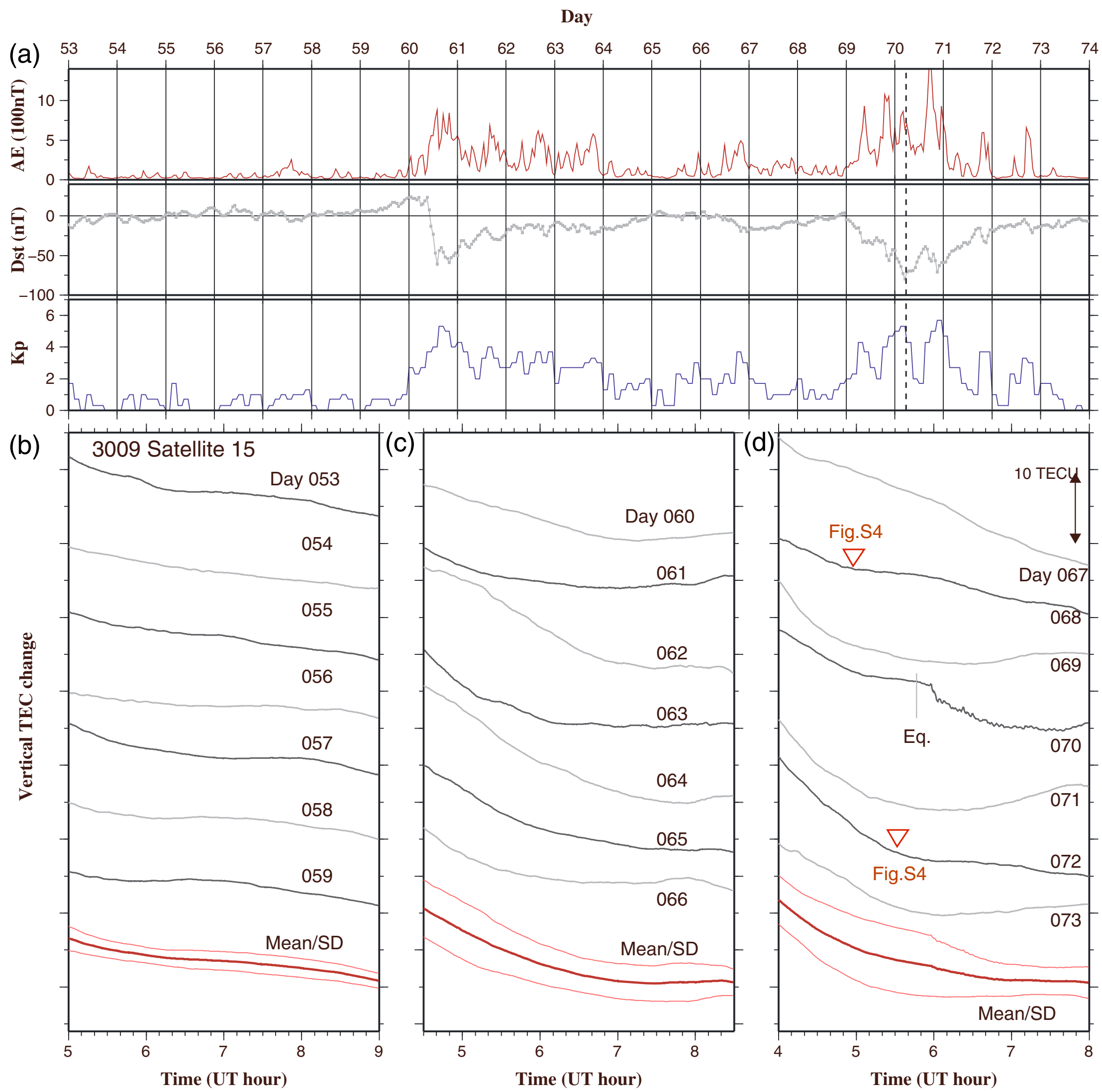

Figure 6. Auroral electrojet (AE), and Dst/Kp indices over the 3 week period from day 053 to day 073 in 2011 show (a) high geomagnetic activity in the second and the third weeks. The VTEC time series at the GPS station 3009 with Satellite 15 over 4 h period show (b) gentle afternoon decrease in the first week, but (c,d) complicated behaviors arise in the next two weeks. The two rather sharp bends on the days 068 and 072 are shown to be LSTID origin in Figure S4. The weekly mean VTEC and 1σ standard deviations are given at the bottom.

active geomagnetic conditions. Indeed, space weather directly influences these quantities. On the other hand, an earthquake is a phenomenon to release lithospheric stress, and could influence the upper atmosphere and geomagnetism only indirectly. The 2011 Tohoku-oki earthquake was an unprecedented M9-class earthquake with recurrence interval exceeding five centuries. However, one should never expect this earthquake to produce "unprecedented" anomalies in the ionosphere and geomagnetic fields.

[20] Figure 6a shows the auroral electrojet (AE) index and the geomagnetic activity indices Kp and Dst over three weeks from day 053 (22 February) to 074 (15 March). Geomagnetic condition was calm only in the first week, and the second/third weeks include lots of minor disturbances including the geomagnetic storm on 1 March (day 060). Relatively strong geomagnetic disturbance took place also on the day of the earthquake (day 070); Dst reached minimum shortly before the earthquake and the AE index showed related substorm activities. As pointed out by *Carter et al.* [2013], the ionosphere is likely to be highly variable before and after the earthquake, making it difficult to identify preseismic anomalies confidently.

[21] Figures 6b–d show VTEC of Satellite 15 at 3009 over this period. The 4 h time window was shifted by 0.5 h per week because GPS satellites rise ~4 min earlier every day. VTEC variability faithfully reflects geomagnetic activities, i.e., it shows simple decreases during the first week while its day-to-day variability is two- or threefold in the last two weeks. The preseismic anomaly in question (day 070) may exceed the natural variability of the quiet week, but the natural variability of the later weeks overwhelms the anomaly.

[22] A number of small VTEC disturbances during the weeks 2 and 3 are understood as the passages of small amplitude LSTIDs (large-scale traveling ionospheric disturbance)

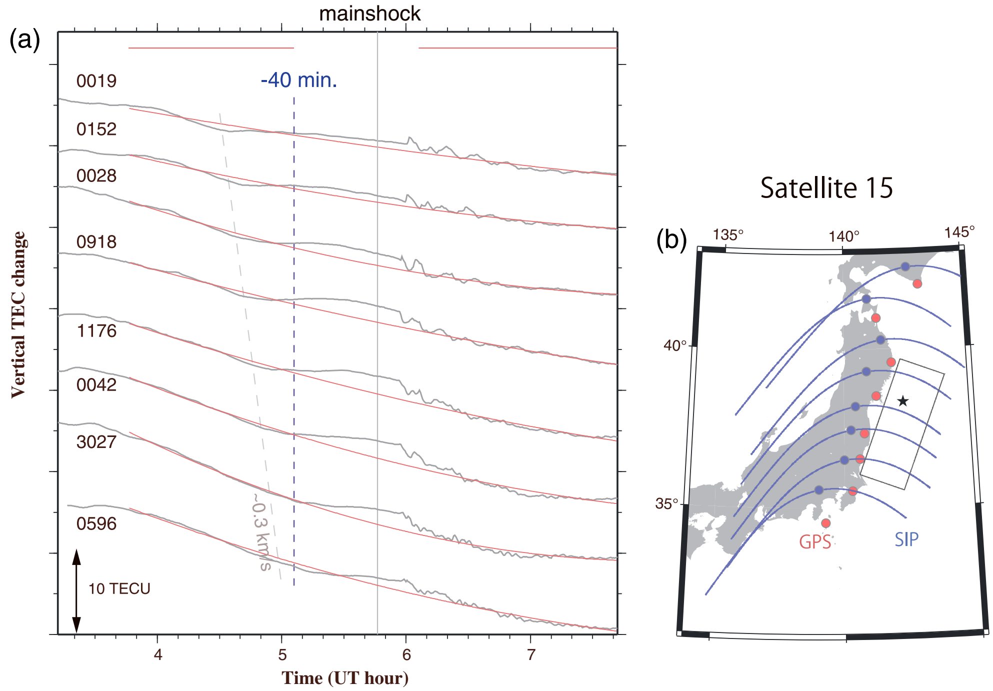

Figure 7. (a) VTEC time series by Satellite 15 at eight GPS stations shown in Figure 7b. Reference curves in red were drawn by fitting the parts shown by the horizontal red lines at the top using quadratic functions. SIP trajectories are shown by blue curves in Figure 7b. A positive VTEC anomaly seems to have started simultaneously ~40 min before the earthquake (vertical broken line). In addition to that, a small negative anomaly, possibly a small-amplitude LSTID, propagates from north to south by ~0.3 km/s.

propagating southward from the auroral oval as atmospheric gravity waves. In Figure 7, we show VTEC time series by Satellite 15 at eight coastal GPS stations from Hokkaido to the Kanto District with approximate separation of ~200 km. There, we can identify two kinds of VTEC disturbances, the first one is a small negative anomaly appearing around ~4.5 UT at the northernmost station, and the second one is the possible precursory enhancement. The second one is stationary and appears to have started simultaneously ~40 min before the earthquake. The first one, on the other hand, traveled southward with an approximate speed of 0.3 km/s. In Figure S4, we show that two small-scale irregularities seen on days 068 and 072 (Figure 6d) are also LSTIDs propagating southward. The geomagnetic declination residual time series at KAK over seven consecutive days (Figure 5a) show that it also suffers from natural variability due to space weather.

5. Discussion and Conclusion

5.1. Repeatability for Past $M_w \geq 8.5$ Earthquakes

[23] In section 2, we demonstrated that the VTEC data before and after the 2011 Tohoku-oki earthquake do not support the tsunamigenic ionospheric hole hypothesis (Figure 1b) [*Kakinami et al.*, 2012], but favored the preseismic increase and recovery scenario (Figure 1a). In section 3, we showed that two additional sensors, ionosonde and magnetometer, showed simultaneous anomalies. Considering these points, we concluded that the ionospheric electron enhancement did start ~40 min before the earthquake. In section 4, however, we showed that this earthquake occurred during a period of high geomagnetic activity, and the observed preseismic anomalies did not exceed nonseismic natural variability. There we showed that the preseismic changes could be distinguished from LSTID by monitoring their propagation. Nevertheless, it would be fair to say that we cannot prove this particular preseismic TEC enhancement to be an earthquake precursor.

[24] Acoustic waves excited by coseismic vertical crustal movements disturb the ionosphere ~10 min after earthquakes. Such coseismic ionospheric disturbances have been detected by GPS networks for >20 earthquakes [e.g., *Astafyeva et al.*, 2013; Cahyadi and Heki, submitted, 2013]. Although their amplitudes are less than nonseismic natural variability in most cases, their existence has never been questioned. That is because (1) they have spatial and temporal correlation with earthquakes (e.g., the spatial pattern of wavefront, delayed emergence with a time lag of ~10 min), and (2) its physical mechanisms are understood. As for the preseismic TEC enhancement, its physical mechanism is yet to be clarified, but it certainly has characteristics to suggest its earthquake origin, i.e., high repeatability for large earthquakes.

[25] From the VTEC time series before and after the 2011 Tohoku-oki earthquake, we found that earthquake-related ionospheric disturbances start ~40 min before the earthquake and end shortly after the acoustic disturbance. Let us assume that this emergence time window is common for other large earthquakes, i.e., we could isolate earthquake-related TEC signals by fitting reference curves to VTEC using a polynomial (degree 1–3 depending on the arc lengths and TEC variability) excluding the 1 h period (from −40 min to +20 min relative to earthquakes). Then, all the earthquakes in the 21st century with $M_w \geq 8.5$ (six in total) show similar preseismic TEC enhancements. *Heki* [2011] showed it for the 2004 Sumatra-Andaman

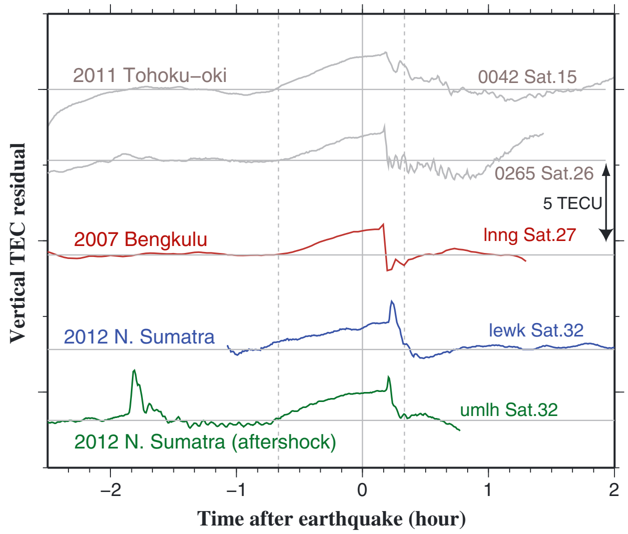

Figure 8. VTEC residuals from reference polynomials estimated excluding the period between the two broken lines (from −40 to +20 min) for the 2011 Tohoku-oki earthquake and three other earthquakes, i.e., the 2007 Bengkulu earthquake (M_w8.5), 2012 North Sumatra earthquake (M_w8.6), and its largest aftershock (M_w8.2) that occurred ~2 h later. Polynomial degrees are 2, 1, 3, 3, 2 from top to bottom. See *Cahyadi and Heki* [2013, also submitted, 2013] for the details of the data of the 2007 and 2012 earthquakes. The GPS station names and the satellite numbers are shown to the right. A strong positive anomaly seen in the bottom curve about −1.8 h is the coseismic ionospheric disturbance of the main shock.

(M_w9.2) and 2010 Maule (M_w8.8) earthquakes as well as for the 2011 Tohoku-oki earthquake (M_w9.0). Later, we found it for the 2007 Bengkulu earthquake (M_w8.5) and the 2012 M_w8.6 strike-slip earthquake (including its M_w8.2 aftershock) off the Indian Ocean coast of Northern Sumatra [*Cahyadi and Heki*, 2013, also submitted, 2013]. So far, only one exception is the 2005 Nias earthquake (M_w8.6), for which daily repeating plasma bubble activities hid all earthquake-related TEC signatures [*Cahyadi and Heki*, 2013].

[26] After all, the problem will be a matter of probability. In Figure 8, we compare the VTEC residuals of the 2011 earthquake with those for the three earthquakes not covered in the first paper [*Heki*, 2011], the 2007 Bengkulu earthquake [*Cahyadi and Heki*, 2013], the 2012 North Sumatra earthquake, and its largest aftershock (M_w8.2) that occurred ~2 h later (Cahyadi and Heki, submitted, 2013). There, the reference curves were defined by fitting the VTEC before and after the earthquake excluding 1 h period using degree 1–3 polynomials. They show striking similarities, steady growth after the onset ~40 min before earthquakes and quick recovery after acoustic disturbances. In order to rule out the seismic origin of these anomalies, we will have to attribute all these similar anomalies to space weather. To us, this seems very unlikely.

[27] Let us assume a certain probability that similar TEC enhancements appear immediately before $M_w \geq 8.5$ earthquakes by chance (i.e., the probability that an LSTID happen to pass over the rupture area immediately before an earthquake by chance). Even if this probability is as large as one third, the probability that the same anomalies occur for all the five $M_w \geq 8.5$ earthquakes (those in 2004, 2007, 2010, 2011, 2012) is $(1/3)^5$, i.e., <0.5%. Geomagnetic activities were fairly calm before and after the 2007 and 2010 earthquakes, and the actual possibility would be much smaller than one third. This is why we think that the TEC enhancements observed before $M_w \geq 8.5$ earthquakes are their precursors in spite of their amplitudes smaller than nonseismic natural variability.

[28] By the way, we have studied ionospheric disturbances of five $8.5 > M_w \geq 8.0$ events with regional GPS networks available. We found immediate preseismic TEC anomalies for the two, i.e., the 1994 Hokkaido-Toho-Oki earthquake (M_w8.3) [*Heki*, 2011] and the largest aftershock of the 2012 North Sumatra earthquake (M_w8.2) (Cahyadi and Heki, submitted, 2013), but not for the other three (the 2003 Tokachi-oki, the 2006 Kuril thrust, and the 2007 Kuril outer rise earthquakes). There have been no preseismic TEC anomalies found so far for earthquakes with M_w below 8.

5.2. Implication for Earthquake Prediction

[29] Here we discuss if the preseismic TEC enhancement satisfies the four requirements in the "guideline for submission of earthquake precursor candidates" by *Wyss* [1991]. The validation criteria require that the observed anomaly (a) should have a relation to stress, strain, or some mechanism leading to earthquakes, (b) should be simultaneously observed on more than one instruments, or at more than one site, and (c) the amplitude of the anomaly should bear a relation to the distance from the eventual main shock, and (d) the ratio of the size (in space and time) of the dangerous zone to the total region monitored shall be discussed to evaluate the usefulness.

[30] The TEC enhancement would clear (b)–(d), but (a) remains unclear. The multisensor observations indicate that the phenomenon that started ~40 min before the earthquake should accompany (1) TEC enhancement (and possibly decrease in the area relatively far from the epicenter, see Figure S1), (2) electron density increase in the *E* region of the ionosphere, (3) geomagnetic declination changes, and (4) quick disappearance after acoustic disturbances. They would certainly narrow the candidates of the physical processes. *Enomoto* [2012] proposed coupled interaction of earthquake nucleation with deep earth gases, and induced electric currents in the seawater and magnetic field in ionosphere as a possible mechanism for seismo-electromagnetic precursors including the TEC enhancement.

[31] Feasibility of the practical earthquake prediction by monitoring TEC is not clear. Rapid recognition of arrivals of LSTID that propagated from the auroral oval would be crucial to distinguish preseismic TEC disturbances out of nonseismic disturbances during high geomagnetic activity. Once its physical mechanism is identified, the most appropriate sensors should be sought in addition to GPS-TEC toward operational earthquake prediction in the future.

5.3. Conclusions

[32] This study can be concluded as follows,

[33] 1. VTEC plot is useful to intuitively understand what is happening in the ionosphere.

[34] 2. The 2011 Tohoku-oki earthquake tsunami did not cause net decrease of TEC.

[35] 3. VTEC, geomagnetic declination, and foEs started to change simultaneously ~40 min before the 2011 Tohoku-oki earthquake.

[36] 4. Observed preseismic anomalies do not exceed natural variability under high geomagnetic activity. Typical nonseismic variations are small amplitude LSTIDs and could be distinguished by detecting their southward propagation.

[37] 5. Repeatability of the TEC enhancement immediately before $M_w \geq 8.5$ earthquakes suggests its seismic origin.

[38] 6. Further investigation of its physical mechanism should be pursued.

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