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# Anomalous ionospheric disturbances over South Korea prior to the 2011 Tohoku earthquake

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**Abstract**

An anomalous disturbance in ionospheric total electron content (TEC) variations was observed by a GPS network in South Korea and three GPS stations in Japan before the 2011 great Tohoku earthquake on March 11, 2011. We investigate the standard deviation time series of the vertical TEC variations for all ground receivers and two satellite pairs. Ionospheric disturbances occurred approximately 40–50 min prior to the earthquake and lasted for over one hour. We also investigate the STD time series of the TEC variations on 1–15 March 2011. A pattern of ionospheric disturbance starting ∼45 min (05:00 UT) before the earthquake was relatively different from those of other days. It is noted that there were precursory features in the near-field close to the epicenter. However, no significant disturbance was observed in the regions that were relatively far from the epicenter. These precursory features may be associated with an anomalous electric field generated by complex processes.


*Keywords:* Ionosphere; Earthquake; TEC; Disturbance

## 1. Introduction

Sudden ionospheric disturbances can be caused by numerous influences, such as solar flares, geomagnetic storms, and seismic events. Over the past two decades, many studies of ionospheric total electron content (TEC) variations associated with seismic signatures have been conducted with the global positioning system (GPS) (e.g. Heki and Ping, 2005; Otsuka et al., 2006; Choosakul et al., 2009).

An earthquake with a magnitude of 9.0 occurred offshore of Honshu, Japan (38.322°N, 142.369°E, depth 32 km), at 05:46:23 UT (universal time) on 11 March 2011. The ionospheric disturbances triggered by this large earthquake have also been analyzed by many investigators (Maruyama et al., 2011; Matsumura et al., 2011; Saito et al., 2011; Tsugawa et al., 2011; Tsai et al., 2011; Liu et al., 2011; Rolland et al., 2011). In particular, many scientists have attempted to find geophysical phenomena in the ionospheric precursors of earthquakes. Several studies have focused on significant correlation between seismic activities and unexpected anomalies in ionospheric TEC variations (Parrot et al., 1993; Pulinets et al., 2003). Hasbi et al. (2011) reported that both positive and negative ionospheric TEC anomalies were detected during periods ranging from a few hours to 6 days prior to the earthquakes. Most of the anomalies on the precursory reports appeared several days before the earthquakes. However, ionospheric slant TEC enhancement started ∼40 min prior to the 2011 Tohoku earthquake has been reported by Heki (2011). For the Tohoku earthquake, he detected a clear precursory positive anomaly in the TEC variations around the epicenter. The

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anomaly increased almost ten percent compared to the background slant TEC. Heki and Enomoto (2013) suggested that similar preseismic TEC anomalies dependent on magnitude were observed in the 2012 North Sumatra earthquake (Mw 8.5), and in the 2007 Bengkulu earthquake (Mw 8.6). However, no pre-seismic TEC anomalies were observed for all earthquakes with magnitudes below 8.0.

In contrast, there were controversial reports of the precursory TEC variations associated with the Tohoku earthquake. Kamogawa and Kakinami (2013) hypothesized that the slant TEC enhancement that occurred 40 min before the earthquake reported by Heki (2011) is an artifact due to the reference lines, assuming the occurrence of a tsunamigenic ionospheric hole (Kakinami et al., 2012). The authors suggested that the slant TEC enhancement was attributed to the depletion of TEC by the tsunami rather than precursory variations. Recently, Masci et al. (2015) examined the precursory TEC increase before the Tohoku earthquake reported by Heki (2011) and Heki and Enomoto (2013). They also concluded that the reported TEC increase prior the earthquake was normal and an artifact induced by the data fitting procedure. In addition, some published reports (Thomas et al., 2012; Astafyeva et al., 2013; Utada and Shimizu, 2014) have demonstrated that there is no significant correlation between the precursory TEC enhancement and seismic activity. The ionosphere is very sensitive to seismic effects. Special reviews associated with gas release and atmospheric heating prior to earthquakes were reported (Pulinets et al., 2007; Baragiola et al., 2011; Ouzounov et al., 2011).

The ground-based GPS network allows for the detection of anomalies in ionospheric TEC variations. Previous studies focused on the pre-seismic TEC enhancement above the epicenter of the 2011 Tohoku earthquake. In this paper, we investigate ionospheric disturbances in the TEC variations prior to the Tohoku earthquake using the Korean GPS network (KGN) data and three GPS stations in Japan.

## 2. Data and methods

To investigate ionospheric perturbations in the TEC time series obtained by GPS before the Tohoku earthquake, we used GPS data extracted from the KGN in South Korea. The sampling rate of the GPS data recorded by the KGN is 30 s. The estimation methods used to extract the TEC from the GPS signals have been described by several reviews (Klobuchar et al., 1994, 1996; Jakowski et al., 1999). To perform a TEC estimation, the carrier phase measurements are considered with the pseudorange (code) measurements. They are much more accurate than the code measurements, which have a large uncertainty due to a large amount of noise. They also require a resolution of phase ambiguity and consideration of infrequent cycle slips.

In general, the TEC is estimated with the so called geometry-free linear combination of two GPS signals (L1–L2). However, the TEC values extracted from different frequencies have an uncertainty because hardware biases from GPS satellite transmitters and receivers are included in the GPS signals. Hardware biases significantly affect the accuracy of the ionospheric TEC estimates (Coco et al., 1991; Sardon et al., 1994; Davies and Hartmann, 1997). Hardware biases for all GPS satellites and receivers are considered as constant values for each day.

To calculate the ionospheric TEC, we adopted the common model in which the ionosphere consists of a thin shell at a fixed height, usually 350 km. Slant TEC is a measure of the total electron content of the ionosphere along the ray path. It can be computed.

$$\mathrm{STEC} = \frac{1}{40.3}\left(\frac{f_1^2 \cdot f_2^2}{f_1^2 - f_2^2}\right)(P_2 - P_1 + D^s + D_r) \quad (1)$$

where $D^s = d_2^s - d_1^s$ and $D_r = d_{2r} - d_{1r}$ are the differential code bias (DCB) of the satellite and the receiver, respectively. It is well known that these biases significantly affect ionospheric TEC values (Ma and Maruyama, 2003; Choi et al., 2011). The DCB values were obtained with weighted least squares. In our study, these values are routinely calculated as daily constants.

To perform the conversion from STEC to vertical TEC (VTEC), we used a modified single layer mapping function as presented in Grejner-Brzezinska et al. (2004):

$$\mathrm{M}(\zeta) = 1/\cos(\zeta'), \quad \sin(\zeta') = \frac{R}{R+H}\sin(\alpha \cdot \zeta) \quad (2)$$

where $\zeta'$ is the zenith distance at the ionospheric pierce points (IPP), $R$ is the radius of Earth, $H$ is the ionospheric thin layer height ($\sim$350 km), $\alpha$ is the correction factor (0.9872).

Several visible GPS satellites above South Korea were observed at the time of the Tohoku earthquake. Fig. 1 shows IPP trajectories for two GPS satellites (PRN 18 and PRN 26). The IPP for the PRN 26 satellite moves toward the epicenter of the Tohoku earthquake across South Korea. They moves northward and then southward. The IPP of the PRN 18 satellite moves toward South Korea at the onset of the earthquake.

## 3. TEC disturbances

To perform a detailed analysis of the TEC disturbances before the earthquake, we produce a TEC time series at all of the KGN sites and apply the moving average filter which is an efficient method for the reduction of noise.

Fig. 2 shows the time series of the time-differenced vertical TEC (TECU/30 s) of the PRN 26 satellite measured at 48 GPS stations in South Korea. A VTEC time series is obtained by detrending the data and then estimating using a moving average filter with a time window of five minutes. We also consider the relative distance from the GPS stations to the epicenter. As shown in Fig. 2, the VTEC disturbances appear to be enhanced approximately 40–50 min