

## Stochastic evaluation of the pre-seismic total electron contents enhancement

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In this study, we tested the precursory enhancement in ionospheric total electron content (TEC) measured by GNSS before the 2011 Tohoku-Oki earthquake (Mw9.0).

The precursory enhancement of the ionospheric total electron content (TEC) within a few tens of minutes before large earthquakes has been reported by Heki [2011] and some Global Navigation Satellite System (GNSS) TEC observational studies. Heki [2011] extracted the TEC enhancement prior to the 2011 Tohoku-Oki Earthquake using a reference curve to model the slant TEC (STEC) time series, with the departure from the reference curve defining the TEC anomaly in the focal area. Since there were some criticisms to this method that the post-seismic depletion should affect the detection of the preseismic change, Heki and Enomoto [2015] introduced a method to detect a TEC enhancement based on Akaike's information criterion (AIC) without using reference curves. They reported that there were enhancements before five huge earthquakes. They evaluated the low occurrence rate of the phenomena using inter-seismic period to show that the observed pre-seismic enhancements are not the product of chance but the precursor of the earthquakes.

We followed their manner to verify how often the TEC enhancement occurs during the day time (12:00-17:00 local time) over two-month period including the Tohoku Oki earthquake using the same threshold with them. The average occurrence rate of the TEC positive breaks measured using all of the visible satellites is 0.65 times per hour with a 25° elevation mask angle. This is much larger than the occurrence rate of 0.08 times per hour reported in Heki and Enomoto [2015] using only one satellite (PRN15). We evaluated the probability of the case where the breaks are observed within 90 min before huge earthquakes assuming a Poisson process. The probability of observing  $n$  events during a time period when  $\mu$  events occur is expressed as follows:

$$f_n = \frac{\mu^n}{n!} e^{-\mu}. \quad (1)$$

The average rate is 0.98 times per 90 min ( $\mu = 0.98$ ) when a 25° elevation mask angle is assumed, and the probability of observing at least one event during the time period is  $1 - f_0 = 0.62$ . The 25° elevation mask angle that is adopted in this evaluation is not too small, as the pre-seismic breaks that were extracted by Heki and Enomoto [2015] included breaks at very low elevation angles, such as 15° for the 2012 Mw 8.6 North Sumatra Earthquake.

This 62% probability indicates that a pre-seismic positive TEC break is expected for 62 of 100 earthquakes. The reported pre-seismic positive TEC breaks for five of the eight great earthquakes analyzed in Heki and Enomoto [2015] is reasonable as the nature of TEC time series from this probabilistic viewpoint.

We cannot rule out the possibility that the pre-seismic VTEC changes before the great earthquakes reported by Heki and Enomoto [2015] are just a product of chance. They have underestimated the occurrence rate of the TEC enhancement because they did not consider the enhancement occurring

solely with the other satellites than PRN15.

Keywords: Ionosphere, Earthquake, Precursor

