The "Standard Model" of Preseismic TEC Anomalies

Kosuke Heki email: heki@sci.hokudai.ac.jp
Dept. Earth Planet. Sci., Hokkaido Univ., N10 W8, Kita-ku, Sapporo, Hokkaido 060-0810, Japan

An increasing number of Global Navigation Satellite System (GNSS), e.g. Global Positioning System (GPS), receivers continuously operating worldwide, makes it possible to observe changes in the ionospheric total electron content (TEC) immediately before large earthquakes. Heki (2011 GRL) discovered the TEC enhancement starting ~40 min before the 2011 M_w9.0 Tohoku-oki earthquake (Fig.1). Later, similar TEC changes were found to have occurred before most the earthquakes in this century with $M_w \geq 8.2$ (Heki & Enomoto, 2015 JGR) and for $M_w \leq 8$ earthquakes with very high background absolute vertical TEC (VTEC) (He & Heki, 2017 JGR). Examples in Fig. 2 shows that the leading time ranges from ~12 minutes for the M_w7.5 earthquake to ~40 minutes for M_w9 earthquake, and that the cumulative VTEC increases relative to their background range from <1% to >10 %. Here I propose a series of physical processes responsible for these anomalies, as the "standard model" of preseismic TEC anomalies.

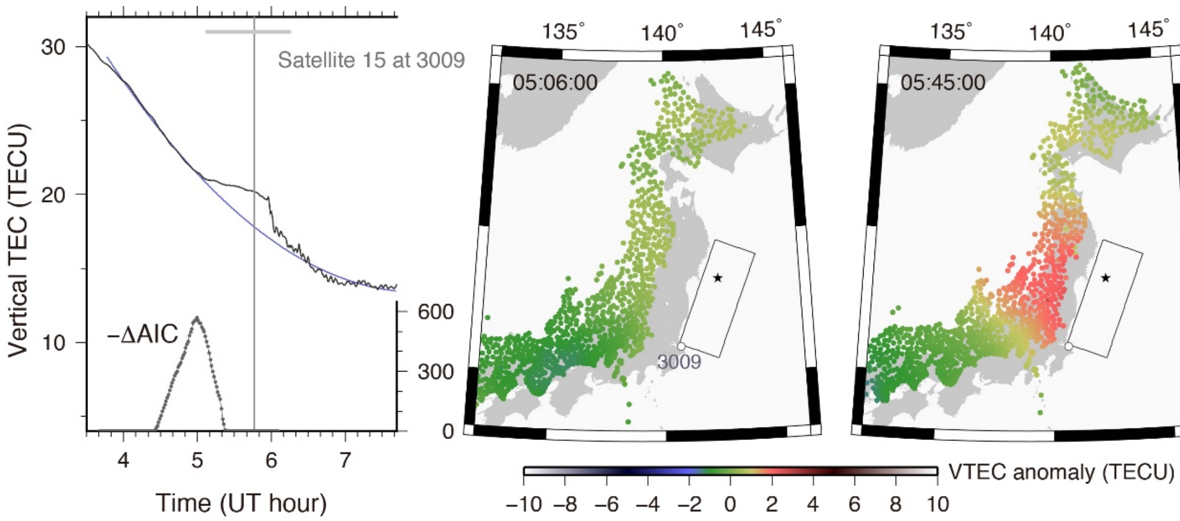

Fig.1 (left) Vertical TEC changes before and after the 2011 Tohoku-oki earthquakes of M_w9.0 observed with GPS satellite 15 at the 3009 GNSS station (see middle panel for position). The significance of positive bending is expressed as -ΔAIC (Heki & Enomoto, 2015 JGR). Departure from the reference curve at two epochs, 40 minutes (middle) and immediately before (right) the earthquake (Heki, 2011 GRL), plotted at the ground projections of the line-of-sight penetration points with a thin layer at 300 km altitude, show positive anomalies appearing near the ruptured fault (shown as the rectangle together with the epicenter).

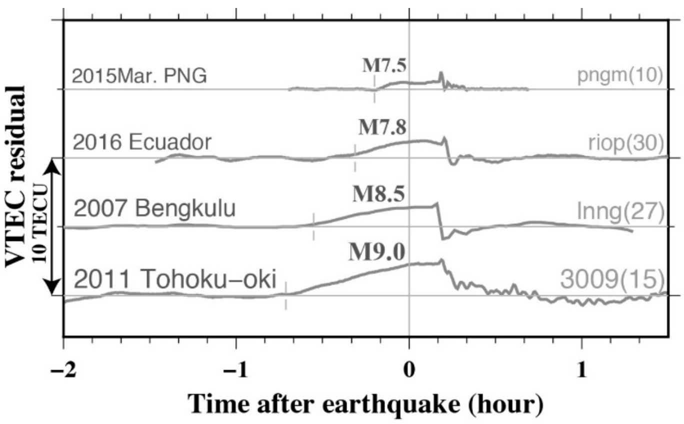

Fig.2 Vertical TEC anomalies (departure from reference curves) before and after four earthquakes of M_w7.5, 7.8, 8.5, and 9.0 observed with GNSS (He & Heki, 2017). They are characterized by gradual preseismic increase and postseismic decay overprinted with short-term acoustic disturbances starting ~10 minutes after earthquakes. Larger earthquakes show longer leading times as well as larger positive anomalies. Station names and GPS satellite numbers are shown to the right of the curves.

He & Heki (2016 GRL; 2018 JGR) showed that both positive and negative TEC anomalies emerged before the 2015 Illapel earthquakes, Chile, and demonstrated that the epicenter, the positive and negative electron density anomalies lined up along the geomagnetic field. We also found the simultaneous appearance of positive VTEC anomalies at the geomagnetic conjugate point (northern Australia) ~40 minute before the 2011 Tohoku-oki earthquake. These findings suggest the penetration of electric fields into the ionosphere in response to positive electric charges on the Earth's surface and consequent ***E***x***B*** drifts of electrons (Kelley et al., 2017 JGR). Origin of the electric charges is not known, but I consider positive holes, mobilized by micro-cracks and micro-dislocations in highly stressed rocks (numerous papers by F. Freund), is a possibility.

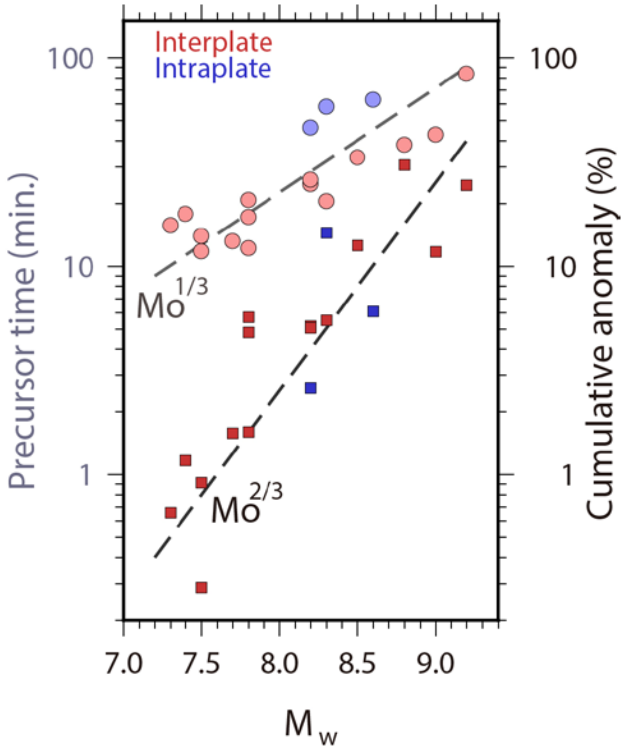

Fig.3 Relationship between the earthquake M_w and precursor times in minutes (circles) and cumulative anomalies immediately before earthquakes normalized by the background VTEC (squares), for 18 earthquakes of M_w7.3-9.2 (He & Heki, 2017 JGR). Three intraplate earthquakes have longer precursor times (blue circles). These two quantities are roughly proportional to the length ($Mo^{1/3}$) and area ($Mo^{2/3}$) of faults, respectively. Three intraplate earthquakes shown in blue have slightly longer leading time, but their anomalies do not show systematic deviation from the majority.

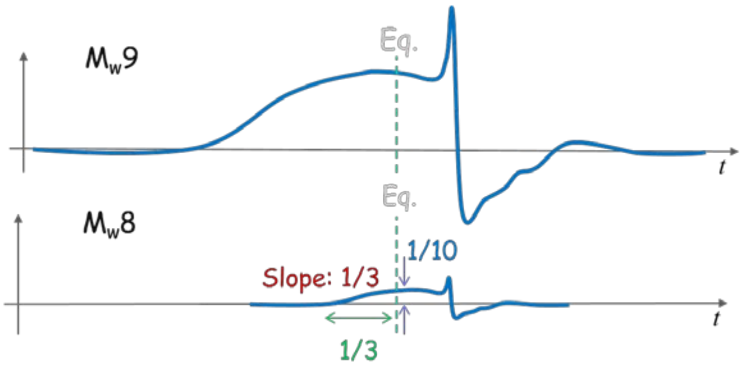

Fig.4 Comparison of VTEC anomalies immediately before M_w9 and M_w8 earthquakes. The anomalies at the time of the latter earthquake, normalized by background VTEC, is 1/10, while its leading time and average slope are 1/3 of the former.

In Fig.3, I plot the precursor times (minutes) and cumulative VTEC anomalies normalized by background VTEC (%) as functions of moment magnitudes of 18 earthquakes that showed immediate preseismic TEC anomalies (He & Heki, 2017). The precursor times seem to scale with the fault length (proportional to $Mo^{1/3}$), suggesting that a certain weakening process invades the fault at a fixed velocity of ~100 meters per second (100 km in 15 minutes) immediately before earthquakes. On the other hand, final size of the anomaly appears to scale with the fault area (proportional to $Mo^{2/3}$). These two scaling laws require that the slope of the VTEC change is proportional to $Mo^{1/3}$, i.e. it also scales with the fault length (Fig.4). These laws are realized if an invasion process, which weakens the fault, sweeps the fault from one end of the rectangle toward the other end and the mobile electric charges are generated at the invasion front. The VTEC curves are convex upward, suggesting the increasing decay of electric charges as they accumulate on the Earth's surface. This standard model suggests that earthquakes occur immediately after the completion of the process, although such processes may occur more frequently than earthquakes and many of those may end without earthquakes.