GNSS-TECでみる地震：地震前異常と地震時擾乱
Earthquake studies with GNSS-TEC: Preseismic anomalies and coseismic disturbances

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An increasing number of Global Navigation Satellite System (GNSS) receivers continuously operating worldwide, makes it possible to observe changes in the ionospheric total electron content (TEC) associated with earthquakes, e.g. preseismic anomalies 10-40 minutes before earthquakes with Mw8 or more (e.g. Heki & Enomoto, 2015; He & Heki, 2017) , and coseismic ionospheric disturbances ~10 minutes after earthquakes by acoustic disturbances (e.g. Cahyadi & Heki, 2015). In this work, I compile as many past examples of both phenomena as possible, and explore general laws lying behind these two kinds of phenomena.

The TEC anomalies immediately before large earthquakes was found first for the 2011 Mw9.0 Tohoku-oki earthquake (Heki, 2011; Heki & Enomoto, 2013). It occurred as the TEC enhancement starting ~40 min before the mainshock. Later, similar TEC enhancements were found to have occurred before all the earthquakes in this century with Mw 8.2 or more and for smaller earthquakes with very high background absolute vertical TEC (VTEC) , say over 50 TECU (He & Heki, 2017). Their precursor times range from ~15 minutes for Mw8 earthquakes and ~40 minutes for Mw9 earthquakes, and seem to scale with the length of the fault. The strength of the anomalies, expressed as the VTEC rate increases, depended both on the background VTEC and Mw. Recently, He & Heki (2016) pointed out that both positive and negative preseismic TEC anomalies emerged before 3 large earthquakes in Chile, i.e. the 2010 Maule, the 2014 Iquique, and the 2015 Illapel earthquakes. For the last earthquake, He & Heki (2018), using 3D tomography technique, showed that the positive and negative anomalies started simultaneously at altitudes of ~200 km and ~400 km, respectively, suggesting the downward drift of electrons as the response to positive electric charges on the ground (Kelley et al., 2017).

The first phase of the coseismic ionospheric disturbance appear ~10 minutes after earthquakes with Mw7 or more as a result of upward propagation of infrasound excited by vertical crustal movements. They propagate with the sound speed (0.8-1.0 km/sec) at the F region of ionosphere. Their amplitudes relative to absolute VTEC increases by two orders of magnitude for the Mw increase of three, with significant negative deviation of the strike-slip earthquakes from this scaling law (Cahyadi & Heki, 2015). For earthquakes with Mw8 or more, we often observe two different TEC disturbances propagating with different speeds, i.e. the fast phase travelling by ~4 km/sec caused by the Rayleigh surface wave, and the slow phase propagating ~0.3 km/sec caused by the internal gravity wave.

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キーワード：GNSS-TEC、電離圏擾乱、地震
Keywords: GNSS-TEC, ionospheric disturbance, earthquake

