Precursory TEC enhancement immediately before the 2011 Tohoku-Oki earthquake

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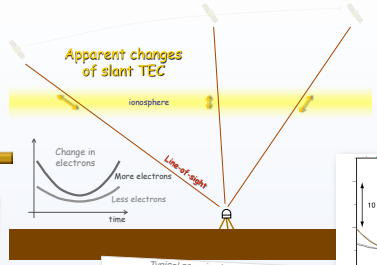
AGU FALL MEETING 2011 SAN FRANCISCO

U53D-0109

Abstract The Japanese dense network of Global Positioning System (GPS) detected preseismic enhancement of ionospheric total electron content (TEC) over the region within 200-300 km from the focal region. It started ~60-40 minutes before the 2011 March 11 NE Japan earthquake (M_w9.0) , and reached ~8 % of the background TEC. It lasted until atmospheric waves arrived at the ionosphere. Similar preseismic TEC anomalies, with amplitudes dependent on magnitudes, were seen in the 2010 Chile (M_w8.8), the 2004 Sumatra-Andaman (M_w9.2), the 2007 Bengkulu (M_w8.6), and the 1994 Hokkaido-Toho-Oki (M_w8.3) earthquakes, but not before earthquakes with M_w8 or less.

OBJECTIVE



TEC enhanced 60~40 min. before the Eq.

Vertical TEC enhancement of the 2011 Tohoku-Oki eq. was ~2 TECU, ~8 % of the background TEC. They lasted until seismic waves (CID) arrived at the ionosphere.

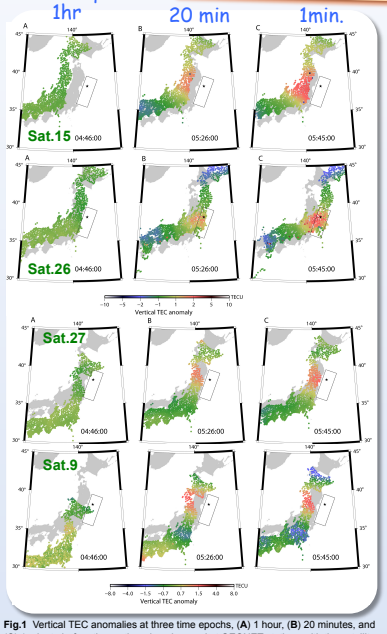


Fig.1 Vertical TEC anomalies at three time epochs, (**A**) 1 hour, (**B**) 20 minutes, and (**C**) 1 minute before the earthquake, observed at GEONET stations with the satellite 15, 26, 27, 9. Positive anomalies (red color) are seen to grow near the focal region of the 2011 Tohoku-Oki eq..

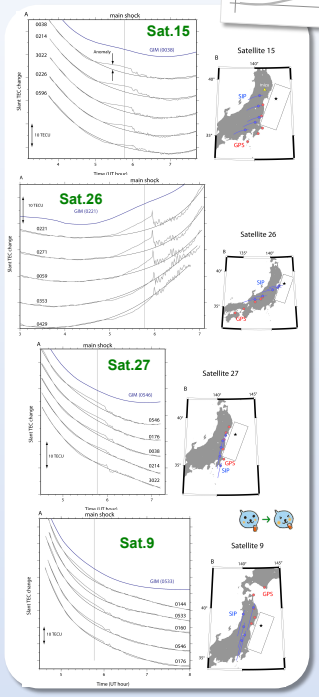
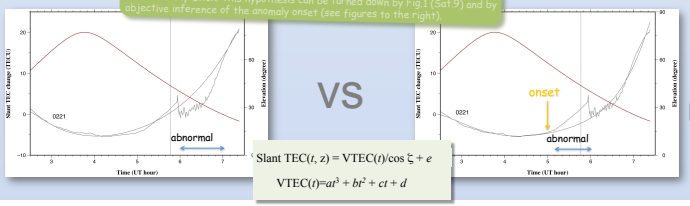


Fig.2 (**A**) Slant TEC change time series taken at five GPS stations with the satellites 15, 26, 27, 9. Temporary positive TEC anomalies started ~60-40 minutes before the earthquake and disappeared after CID passages. Black smooth curves are the models, and anomalies are defined as the departure from these models. Slant TEC changes calculated using GIM for site 0038 is shown as the blue curves. (**B**) Positions of the fives GPS stations (red dots) and their 5:00-6:00UT SIP trajectories (blue dots indicate 5:46).

Artifact hypothesis

One may consider preseismic enhancement an artifact originating from coseismic depletion. This hypothesis can be turned down by Fig.1 (Sat.9) and by objective inference of the anomaly onset (see figures to the right).



$$\text{Slant TEC}(t, z) = \text{VTEC}(t)/\cos\zeta + e$$

$$\text{VTEC}(t) = at^3 + bt^2 + ct + d$$

Objective inference of preseismic TEC breaks (anomaly onset)

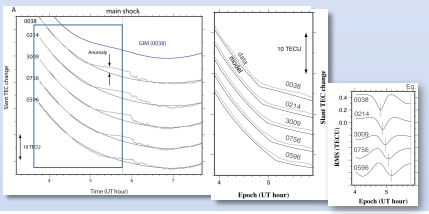
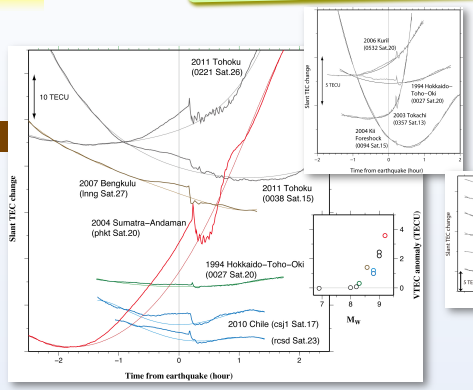


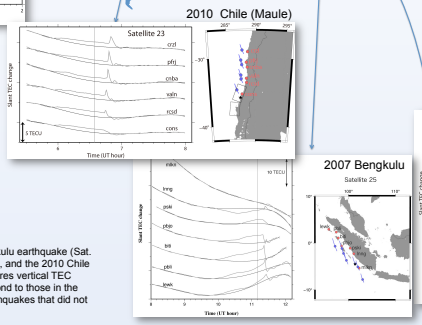
Fig.5 Preseismic changes were modeled with two lines connected to each other. We moved the break time and found the times giving smallest RMS. They correspond to the onset times of preseismic enhancement.

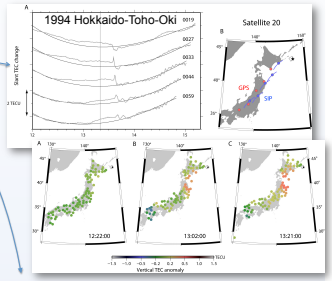
TEC enhancement always occur before large earthquakes

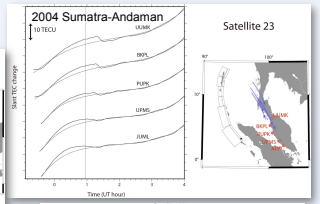
GPS data before and after the 2010 Maule, 2007 Bengkulu, 2004 Sumatra, and 1994 Shikotan earthquakes were studied. They (Mw >8.3) all showed similar preseismic TEC enhancement.

Malaysian and Chilean GPS data courtesy of C. Vigny, ENS (France)









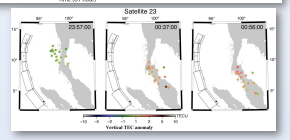


Fig.3 Slant TEC changes and their models in the 2011 Tohoku earthquake (Sat.26, 27), the 2007 Bengkulu earthquake (Sat. 27), the 2004 Sumatra-Andaman earthquake (Sat.20), the 1994 Hokkaido-Toho-Oki earthquake (Sat.20), and the 2010 Chile (Maule) earthquake (Sat.17, 23). The horizontal axis shows the time from earthquakes. The inset compares vertical TEC anomalies immediately before earthquakes as a function of the earthquake magnitudes. Colors correspond to those in the main figure. In addition to seven data from five earthquakes shown in the main figure, three smaller earthquakes that did not show preseismic TEC changes (see the small diagram on the top right) are included (white circles).

Fig.4 Slant TEC change time series observed at 5-7 GPS stations in Chile/Argentine (for 2010 Maule earthquake), SE Asia (for 2004 Sumatra-Andaman and 2007 Bengkulu earthquakes), and Japan (for 1994 Hokkaido-Toho-Oki earthquake). Black smooth curves are the models derived assuming vertical TEC changes according to cubic polynomials of time. To the right-hand sides, I show sub-ionospheric point (SIP) trajectories (blue dots indicate earthquake occurrences) plotted as blue curves. Preseismic electron enhancement seems to have started ~40-90 minutes before these earthquake as seen in the GPS stations close to the epicenters. Preseismic TEC enhancement was not clear for the 2005 Nias earthquake due to severe plasma bubble activities (not shown in poster).

Surface positive charges can influence TEC

Vertical **E** becomes radial and perpendicular to **B** in ionosphere, and **E** X **B** drift makes electrons on the western/eastern side of the charge go down/up.

From Kuo, C.L. et al., Ionosphere plasma bubbles and density variation induced by pre-earthquake rock currents and associated surface charges, *J. Geophys. Res., 116*, A10317, doi:10.1029/2011JA016628, 2011.

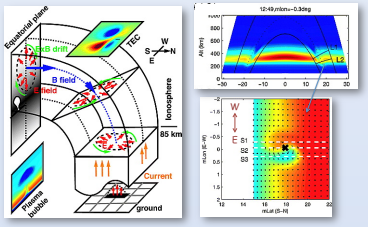
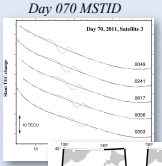


Fig.6 Electromagnetic precursors have been attributed often to positive charges on the ground (and positively charged aerosols) [*Tributsch, 1978*], and such charges may be generated as positive holes from stressed igneous rocks [*Takeuchi et al.*, 2006]]. *Kuo et al.* [2011] showed that surface charges due to rock current of 0.2-10 μA/m² could change daytime TEC by 2-25 %.

TEC changes of non-earthquake origins

TEC enhancement of solar-terrestrial origins often occurs. Here I show three examples, (1) solar flare, (2) MSTID, and (3) LSTID. Snapshots of LSTID resemble to preseismic TEC enhancements.

Day 070 MSTID



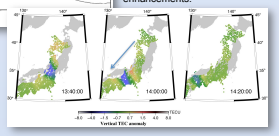
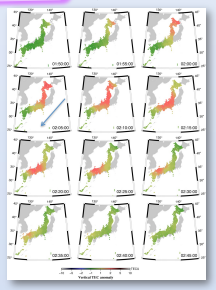


Fig. 7 Medium-scale and large-scale traveling ionospheric disturbances (MSTID and LSTID) propagate toward SW as fast as ~0.3 km/sec. Sudden increase of TEC (SiTEC) by solar flares occur over the whole hemisphere. These features enable us to distinguish these non-earthquake origin disturbances from preseismic TEC enhancements.

Day 094 LSTID



Day 046 Solar Flare