Title	Reply to comment by K. Heki and Y. Enomoto on " Preseismic ionospheric electron enhancements revisited "
Author(s)	Heki, Kosuke; Enomoto, Yuji
Citation	Journal of Geophysical Research: Space Physics, 119(7), 6016-6018 https://doi.org/10.1002/2014JA020223
Issue Date	2014-07
Doc URL	http://hdl.handle.net/2115/57801
Rights	Copyright 2014 American Geophysical Union.
Type	article
File Information	JGRsp_119_6016-.pdf

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

REPLY

10.1002/2014JA020223

This article is a reply to *Utada and Shimizu* [2014], doi:10.1002/2014JA020044.

Correspondence to:
K. Heki,
heki@mail.sci.hokudai.ac.jp

Citation:
Heki, K., and Y. Enomoto (2014), Reply to comment by K. Heki and Y. Enomoto on "Preseismic ionospheric electron enhancements revisited", *J. Geophys. Res. Space Physics*, *119*, doi:10.1002/2014JA020223.

Received 27 MAY 2014
Accepted 15 JUL 2014
Accepted article online 17 JUL 2014

Reply to comment by K. Heki and Y. Enomoto on "Preseismic ionospheric electron enhancements revisited"

Kosuke Heki[1] and Yuji Enomoto[2]

[1]Department of Natural History Sciences, Hokkaido University, Sapporo, Hokkaido, Japan, [2]SASTec, Shinshu University, Nagano-city, Nagano, Japan

Preseismic enhancement of ionospheric total electron content (TEC) was found to have started ~40 min before the 2011 Tohoku-oki earthquake from the dense network of Global Positioning System (GPS) receivers in Japan [*Heki*, 2011]. In response to *Kamogawa and Kakinami* [2013], who doubted the reality of the enhancement, *Heki and Enomoto* [2013] employed two approaches. The first one is to convert slant TEC to vertical TEC (VTEC), which is free from apparent TEC variations due to satellite movements. They showed that preseismic increases are comparable to postseismic drops; i.e., there were no net postseismic TEC decreases as claimed by *Kamogawa and Kakinami* [2013]. The other approach is to compare TEC changes with data from three different sensors, i.e., *E* region critical frequencies (f_oE_s), electron density profile by GPS radio occultation, and geomagnetic field data. *Heki and Enomoto* [2013] suggested that both f_oE_s at Kokubunji and geomagnetic declination at six stations in eastern Japan changed simultaneously with VTEC.

In this issue, *Utada and Shimizu* [2014] decomposed the geomagnetic declination anomalies into three parts, ΔD_1, ΔD_2, and ΔD_3, which roughly correspond to preseismic increase, coseismic increase, and subsequent drop, respectively, and investigated their spatial dependence. They showed that ΔD_2 and ΔD_3 are larger at points closer to the ruptured fault. Such "coseismic" changes actually occur with a time lag of ~7–8 min, reflecting the acoustic wave travel time to the ionosphere. We agree with *Utada and Shimizu* [2014] that ΔD_2 and ΔD_3 reflect acoustic disturbances in the ionosphere caused by coseismic vertical crustal movements. As for ΔD_1 (preseismic part), however, they showed that it gets larger in higher latitudes and concluded that it is not related to the 2011 Tohoku-oki earthquake.

In Figure 1, we show average declination anomalies over the 40 min period before the earthquake. They are shown as ΔD and correspond to ΔD_1 in *Utada and Shimizu* [2014]. Although they are simple differences from the reference station (Kanoya), they well reproduce the claim by *Utada and Shimizu* [2014] that ΔD_1 becomes larger in higher latitudes; i.e., Memanbetsu (MMB) (and possibly in Akaigawa) shows larger ΔD than southern stations. At the same time, the background natural variability is found to be the highest at MMB. It makes the excessive declination change at MMB within the level of such variability. We therefore do not think that the linear relationship between ΔD_1 and latitude was so significant, considering the variable noise level and limited spatial distribution of the northern stations (they used only two stations in Hokkaido, not farther than ~500 km from the fault).

It was also pointed out by *Utada and Shimizu* [2014] that $|\Delta D_3|$ (postseismic drop) exceeds $|\Delta D_2|$ (coseismic increase) in many stations, and they suggested that the postseismic anomaly may last longer than ~20 min, assumed by *Heki and Enomoto* [2013]. In Figure 1b, we modeled the geomagnetic declination time series at Kakioka using various ending times of the exclusion window. The fit kept good even if we extended the exclusion window to 1 h after the earthquake. The amount of preseismic increase changed less than 10%.

Utada and Shimizu [2014] also pointed out that ΔD_4, a disturbance caused by the geomagnetic storm on the same day, shows similar latitude dependence to ΔD_1. On such a day of high geomagnetic activity, we see numbers of large and small changes in TEC and geomagnetic fields like ΔD_4. Next we examine the behavior of VTEC during the same interval, 21:10–21:30 UT (Figure 2). We selected GPS Satellite 20, which was the highest elevation satellite at 21:30 UT. Figure 2a shows that there were no significant VTEC changes synchronized with the ΔD_4 episode. Although ΔD_1 and ΔD_4 may appear similar in latitude dependence, their relevance to TEC changes is different. Thus, even if ΔD_1 was of geomagnetic activity origin, it would not rule out the seismic origin of the TEC changes in question.

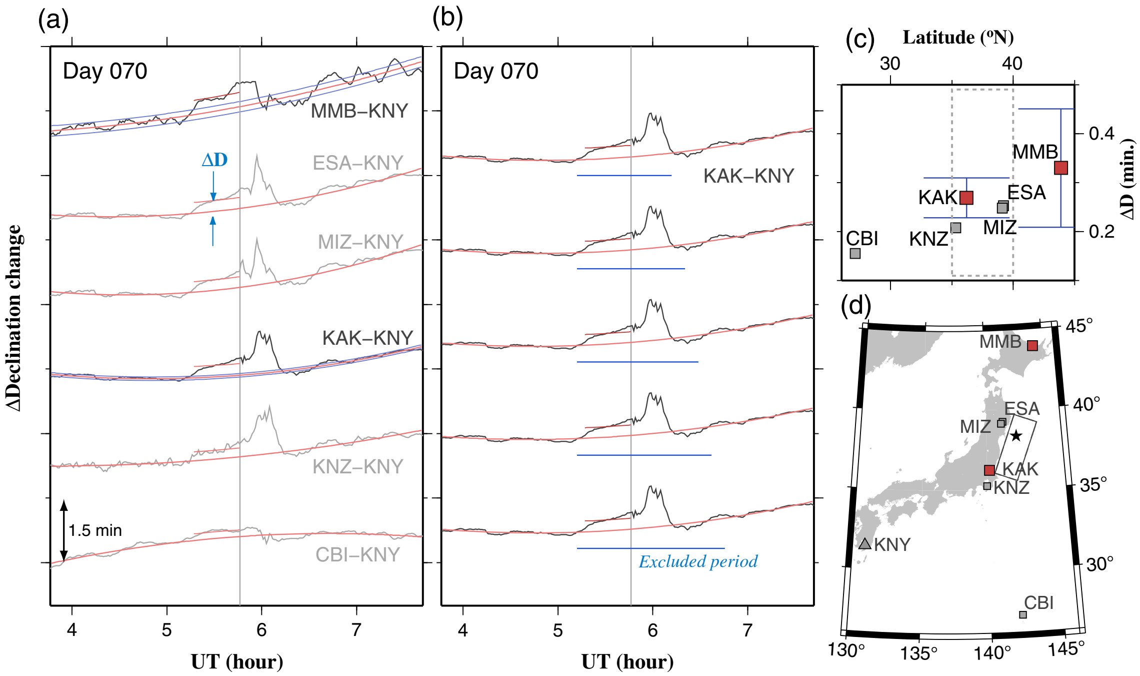

Figure 1. (a) Same as Figure 5a in *Heki and Enomoto* [2013]. Quadratic functions were fit (red curves) using the data over the period covering 2 h before and after the earthquake, excluding 1 h period (from 40 min before the earthquake to 20 min after the earthquake). The vertical line indicates the earthquake occurrence time (5:46 UT). (b) The ending time of the exclusion period (blue horizontal line) was changed from (top) 20 min to (bottom) 60 min progressively after the earthquake to show that the overall story does not depend on the exclusion window. (c) The average anomalies of the declination over the 40 min period before the earthquake (ΔD) are plotted against their latitudes. (d) Geomagnetic declination changes of six geomagnetic observatories in Japan relative to Kanoya (KNY), SW Japan, on the earthquake day (11 March 2011). The error bars for the two data (red squares in Figures 1c and 1d) in Figure 1c indicate the standard deviations of the postfit residuals of the MMB-KNY and Kakioka-KNY pairs, possibly reflecting the natural variability in the studied period. These standard deviations are also shown with thin blue curves in Figure 1a. The star and the rectangle in Figure 1d show the epicenter and the ruptured fault, respectively, of the 2011 Tohoku-oki earthquake.

Although we showed that TEC enhancements occurred before all earthquakes with $M_w \geq 8.5$ in this century [*Heki and Enomoto*, 2013], we were able to study geomagnetic field behaviors only before the 2011 Tohoku-oki earthquake. It is still an open question if preseismic TEC enhancements and geomagnetic field variation commonly occur simultaneously in the same area. In principle, geomagnetic variation reflects

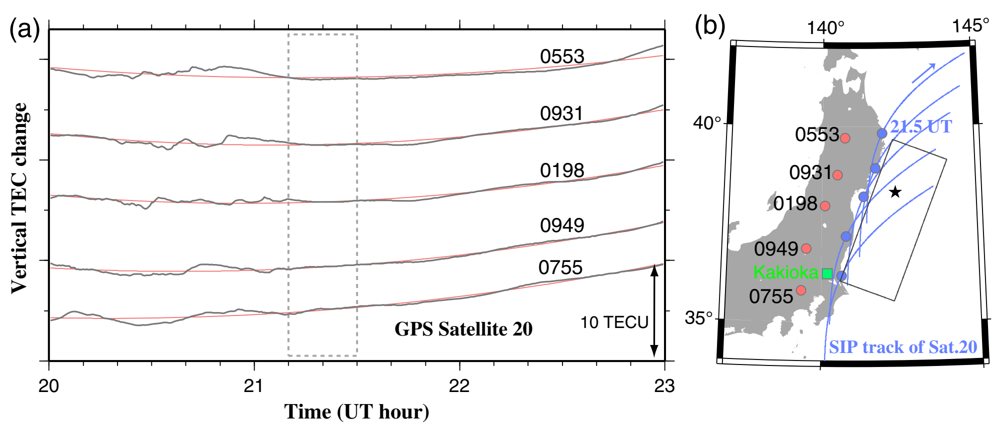

Figure 2. (a) Vertical TEC time series of GPS Satellite 20 in 20–23 UT, 11 March 2011. At around 21:30 UT, strong geomagnetic declination changes occurred (see Figure 2 of *Utada and Shimizu* [2014]), but the ionosphere above Kakioka did not show significant disturbances in VTEC. The square indicates the period in which *Utada and Shimizu* [2014] defined ΔD_4. (b) The red circles show the ground GPS stations, and the blue curves are the tracks of subionospheric points (SIP), ground projections of piercing points of line of sights with hypothetical thin ionosphere as high as 300 km (blue circles show SIP positions at 21:30 UT).

electric current (i.e., transportation of charges), while TEC anomaly reflects cumulative changes of the electron transportation. They would be correlated in space and time, but their distribution and timing would never be identical. We appreciate *Utada and Shimizu* [2014] for letting us realize this important issue which needs to be addressed by future observations.

Acknowledgments
The GPS data have been downloaded from the Geospatial Information Authority (GSI) of Japan (terras.gsi.go.jp). Geomagnetic data were obtained from GSI and Japan Meteorological Agency.

Alan Rodger thanks Philippe Lognonne and Seiya Uyeda for their assistance in evaluating this paper.

References

Heki, K. (2011), Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake, *Geophys. Res. Lett.*, *38*, L17312, doi:10.1029/2011GL047908.

Heki, K., and Y. Enomoto (2013), Preseismic ionospheric electron enhancements revisited, *J. Geophys. Res. Space Physics*, *118*, 6618–6626, doi:10.1002/jgra.50578.

Kamogawa, M., and Y. Kakinami (2013), Is an ionospheric electron enhancement preceding the 2011 Tohoku-oki earthquake a precursor?, *J. Geophys. Res. Space Physics*, *118*, 1–4, doi:10.1002/jgra.50118.

Utada, H., and H. Shimizu (2014), Comment on "Preseismic ionospheric electron enhancements revisited" by K. Heki and Y. Enomoto, *J. Geophys. Res. Space Physics*, doi:10.1002/2014JA020044.

