NWRA NorthWest Research Associates – www.nwra.com

4118 148th Ave NE, Redmond, WA 98052 Tel: 425.556.9055 Fax: 425.556.9099

Award: USGS Earthquake Hazards Program, External Research Award G11AP20177

Title: Study of Ionospheric-Precursory Signals to Large Earthquakes

Affiliation: Northwest Research Associates, 4118 148th Ave., NE, Redmond, WA 98052, USA

Author: Jeremy N. Thomas

Contact info: 1-206-947-2678; jeremy@nwra.com

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Abstract:

Earthquakes are one of the most devastating natural phenomena on earth, causing high deaths tolls and large financial losses each year. Precursory signals would provide an advanced warning of these impending disasters, possibly saving countless lives. Unfortunately, the evidence for ionospheric-precursory events has yet to be carefully and rigorously analyzed.

For USGS Earthquake Hazards Program External Research Award G11AP20177, we examined reports of precursors prior to two earthquakes: Hector Mine, CA 1999 and Tohoku, Japan 2011. Pulinets et al. [2007] reported ionospheric anomalies prior to the 16 Oct. 1999 Hector Mine, California earthquake. Using Global Positioning System (GPS) data recorded near the epicenter of the earthquake, they identified anomalous precursory changes in the ionospheric total electron content (TEC). Whereas, in a separate analysis, Afraimovich et al. [2004] concluded that the TEC variations were controlled by geomagnetic activity instead of earthquake preparation processes. In a check of their results, we examined multiple TEC time series derived from GPS stations near the earthquake epicenter. We found that TEC anomalies are observed long before and after the Hector Mine earthquake. Moreover, no temporal relationship was found between these TEC anomalies and regional seismicity. Thus, in agreement with Afraimovich et al., we concluded that the anomaly reported by Pulinets et al. is not unique and is most likely unrelated to the Hector Mine earthquake. It could not be used as a part of reliable statistics-based earthquake prediction technique. As a second example, Heki [2011] reported TEC anomalies prior the 11 Mar. 2011 Tohoku, Japan earthquake. We also present an analysis, still ongoing, of this report.

An undergraduate student research assistant, Nicholas Rivera, played an active role in this project. He developed tools in MATLAB to process the TEC data, attended the AGU Fall Meeting to help present our poster, and was a coauthor on a article published in *Geophysical Research Letters* [Thomas et al., 2012]. Nicholas graduated from the Digipen Institute of Technology in Computer Engineering in May 2012 and plans to pursue a PhD in electrical engineering at the U. of Washington.

Results were disseminated through Meeting presentations and publication in refereed journals. Thomas and Rivera attended the AGU Fall Meeting in San Francisco, CA in December of 2011 and presented a poster “On the reported ionospheric precursors of the 1999 Hector Mine, CA and 2011 Tohoku, Japan earthquakes”. As indicated in the bibliography, one paper was published in *Geophysical Research Letters*, one is under review in *Natural Hazards and Earth System Sciences*, and three more manuscripts are in preparation.

Final Report:

1. Introduction

A direct correlation between earthquake activity and changes in ionospheric properties (such as conductivity and electron density) has been observed by numerous researchers [e.g. Calais and Minster, 1995; Otsuka et al., 2006]. However, ionospherc-precursory events to earthquakes, which occur well before the seismic activity, have yet to be verified or dismissed within the scientific community. Earthquakes are a major hazard to civilization, and predicting them would benefit most of the earth's inhabitants. However, we need to be responsible in pushing ahead on this frontier, making a full exploration of alternative, and more conventional, explanations of reported precursors.

Perturbations in ionospheric conductivity precursory to earthquakes have been reported by various researchers [e.g.; Davies et al., 1965; Datchenko et al., 1972; Chuo et al., 2002; Plotkin 2003; Krankowski et al., 2006; Hayakawa et al., 2006; Zakharenkova et al., 2006; Horie et al., 2007; Pulinets, 2007; Zhao et al., 2008; Liu et al., 2009; Heki, 2011]. Most of these studies involved changes in the ionospheric total electron content (TEC) derived from Global Positioning System (GPS) data. Other researchers observed ionospheric variations in ionosonde data, very low frequency (VLF) radio wave measurements [e.g. Horie et al., 2007], and satellite-borne in situ measurements such from the DEMETER satellite [e.g. Parrot et al., 2006]. There have been other studies that found no relationship between earthquakes and precursory ionospheric anomalies. One notable example is the work of Dautermann et al. [2007] that involved the analysis of two years of GPS TEC data in Southern California. They found no statistically significant correlation, temporally or spatially, between TEC perturbations and earthquakes, including the December 2003, M6.6 San Simeon and September 2004, M6.0 Parkfield earthquakes.

The purpose of this work was to conduct a critical examination of existing precursor reports, focusing on TEC observations derived from GPS data for the Hector Mine, CA 1999 and Tohoku, Japan 2011 earthquakes.

2. Analysis of reported Hector Mine earthquake precursor

Using Global Positioning System (GPS) data from sites near the 16 Oct. 1999 Hector Mine, California earthquake, Pulinets et al. [2007] identified anomalous changes in the ionospheric total electron content (TEC) starting one week prior to the earthquake. Pulinets [2007] suggested that precursory phenomena of this type could be useful for predicting earthquakes. On the other hand, and in a separate analysis, Afraimovich et al. [2004] concluded that TEC variations near the epicenter were controlled by solar and geomagnetic activity that were unrelated to the earthquake. In an investigation of these very different results, we examine TEC time series of long duration from GPS stations near and far from the epicenter of the Hector Mine earthquake, and long before and long after the earthquake. While we can reproduce the essential time series results of Pulinets et al., we find that the signal they identify as anomalous is not actually anomalous. Instead, it is just part of normal global-scale TEC variation. We conclude that the TEC anomaly reported by Pulinets et al. is unrelated to the Hector Mine earthquake.

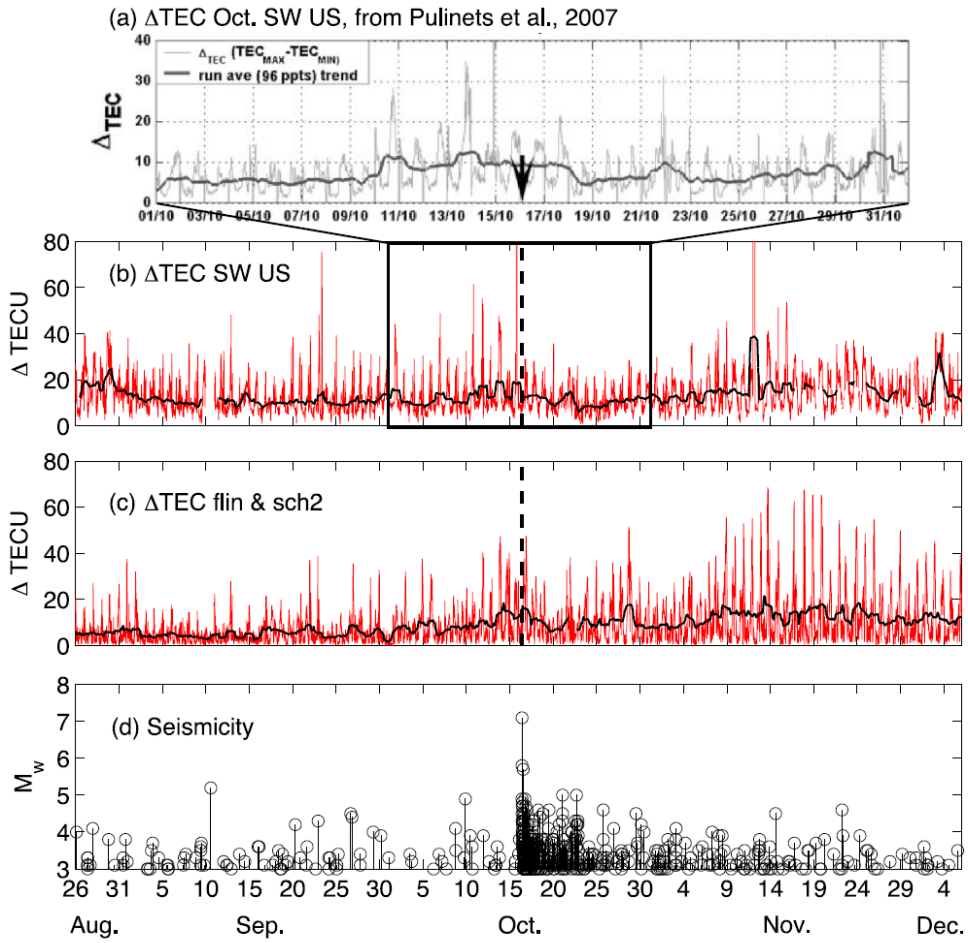

Figure 1: [Figure 1 and caption from Thomas et al., 2012]: (a) Ionospheric vertical total electron content (TEC) for Oct., 1999 reproduced from Pulinets et al. [2007, Figure 6, Courtesy of Advances in Space Research]: 10-min ΔTEC and 1-day running average for the set of GPS stations 1–13 in Table 1. (b, c, d) TEC and earthquake activity for 26 Aug. – 6 Dec. 1999: (b) 10-min DTEC (red) and 1-day running average (black) for the set of GPS stations 1–13 in Table 1. Oct. ΔTEC are within the rectangle. (c) shows 10-min ΔTEC (red) and 1-day running average (black) for the set of two stations flin and sch2. (d) magnitude (M_w) of earthquakes that occurred within 1200 km of the Hector Mine earthquake epicenter (black circles). Only Mw > 3 are included. The Hector Mine earthquake and subsequent aftershocks are seen starting on 16 Oct. The units for the TEC are known as TEC units (TECU), where 1 TECU = 10^{16} electrons/m².

We use TEC time series derived from 30-sec GPS data recorded at the same 13 stations that were used by Pulinets et al. [2007, Fig. 5] and which they assert provide coverage of the Hector Mine earthquake "preparation zone" within 1200 km of the earthquake epicenter. For controlled comparison, we also use data from two stations (flin and sch2) that are located in Canada very far from the earthquake region (2496 km and 4383 km, respectively). The 15 stations used are listed in Table 1. The duration of each TEC time series used here is approximately 3 months (26 Aug. – 6 Dec. 1999), considerably longer than the 1-month period of time considered by Pulinets et al. [2007, Fig. 6].

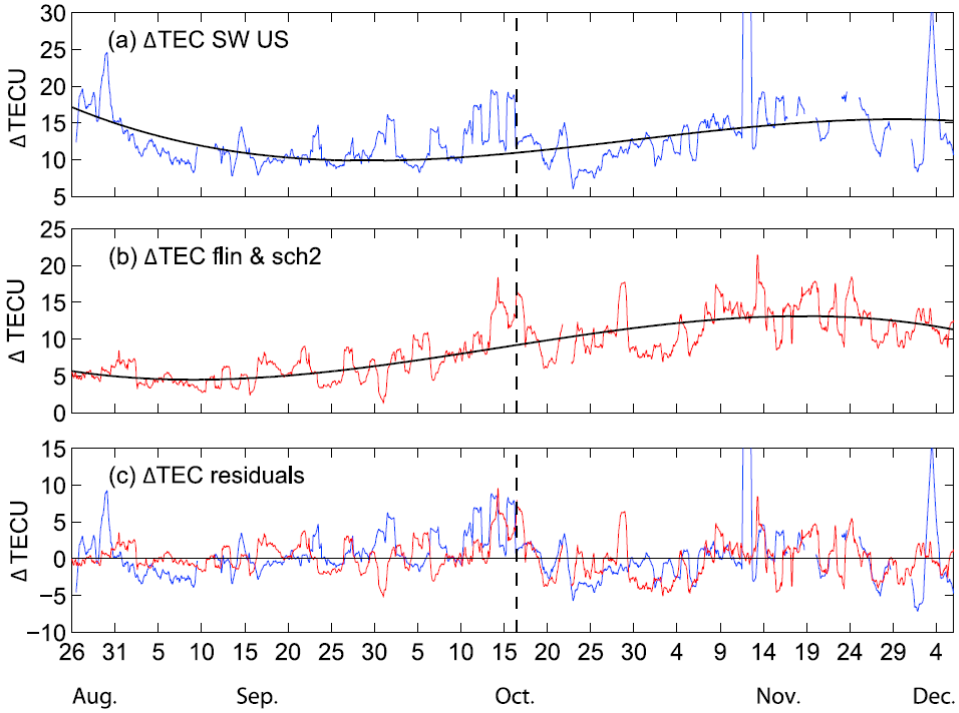

Figure 2: [Figure 2 and caption from Thomas et al., 2012]: TEC for 26 Aug. – 6 Dec. 1999: (a) 1-day running average ΔTEC (blue, same as in Figure 1b) and cubic least-squares fit curve (black) for the set of GPS stations 1–13 in Table 1. (b) 1-day running average ΔTEC (red, same as in Figure 1c) and cubic least-squares fit curve (black) for the set of two stations flin and sch2. (c) Residuals of cubic least-squares fit curves for GPS stations 1–13 (blue) and stations flin and sch2 (red).

We follow the data processing procedures of Pulinets et al. [2007]. Redundant TEC values from multiple and simultaneous GPS satellite transmissions are removed by choosing the TEC values with the lowest measurement uncertainty for a given epoch. The median measurement uncertainty of these non-redundant time series is about 0.12 TECU and has a small standard deviation (± 0.015 TECU) from station to station. We calculate the 10-min minimum-to-maximum range for each TEC time series, and then calculate what Pulinets et al. called the variability index ΔTEC, defined as the 10-min minimum-to-maximum range for TEC time series among a set of GPS stations. We calculated ΔTEC for the 13 stations in the earthquake "preparation zone". We also calculate ΔTEC for the two stations (flin and sch2) that are far from the epicenter.

To examine the ΔTEC time series in the broad context of seismicity in Southern California and Western North America, where earthquakes of small magnitude occur very frequently, we acquired a listing from the USGS National Earthquake Information Center of earthquakes having moment magnitude (M_w) greater than 3 that occurred within the Hector Mine earthquake "preparation zone" during 26 Aug. – 6 Dec. 1999.

It is important to recognize that we are able to reproduce the main TEC time series results of Pulinets et al. [2007] over the limited duration of time that they considered (the month of October). Fig.1b shows the 10-min ΔTEC time series (red curve) for stations in the southwest US, along with the 1-day running average ΔTEC (black curve), centered on the time of the Hector Mine earthquake. Compare our Fig. 1b with Pulinets et al. [2007, their Fig. 6], reproduced here in our

Fig.1a, where they also use a 1-day running average. In our analysis, ΔTEC increased on about 10 Oct. until just prior to the earthquake on 16 Oct. As shown in our Fig.1a, Pulinets et al. reported a similar increase that started on about 10 Oct., but ended on 18 Oct., a few days later than our processed observations. The magnitudes of the ΔTEC values (baseline near 12 TECU) in our analysis are slightly greater than those reported by Pulinets et al. (baseline near 8 TECU), which is not of consequence for our discussion here.

Where we differ from Pulinets et al. [2007] is in the interpretation of the TEC time series. In contrast to their presentation, ours gives a broader panoramic view of the ΔTEC time series. From this, we can see ΔTEC variation long before and long after the Hector Mine earthquake that is greater than or equal to the anomaly identified by Pulinets et al. For instance, during 26-31 Aug. and 12-16 Nov. we see ΔTEC (Fig. 1b) increases similar in magnitude and duration to the increase that occurred prior to the earthquake. Other signals having amplitudes similar to the seemingly anomalous signal identified by Pulinets et al. are apparently part of normal TEC variation. That these are independent of seismicity can be seen from Fig. 1d where we show the moment magnitude (M_w) of earthquakes that occurred within the vicinity of the Hector Mine earthquake epicenter (black circles). The main Hector Mine earthquake shock and subsequent aftershocks can be seen starting on 16 Oct. In examining Fig.1b,d, there appears to be no clear relationship between ΔTEC and the earthquake activity in the region.

To investigate whether the increase in ΔTEC on 10-16 Oct. was local to the earthquake, we next examine ΔTEC calculated from a set of two stations: flin and sch2 (2496 km and 4383 km from the earthquake, respectively). In Fig. 1c we present the 10-min ΔTEC (red) and 1-day running average (black) for these two stations. Although Fig. 1c includes only stations flin and sch2 that are far from the earthquake, Figs. 1b and 1c do show some agreement, especially for about 4 days prior to the earthquake where both show enhanced ΔTEC.

To better compare ΔTEC from stations near the earthquake with ΔTEC from distant stations, we need to remove longer-term ΔTEC trends from the time series. In Fig. 2a,b, we find the cubic least-squares fit (black curve) to the 1-day running average ΔTEC for (a) the 13 southwest US stations and (b) stations flin and sch2. These cubic fit curves characterize the longer-term (annual) trend of the ΔTEC time series. In Fig. 2c we show the residuals of these cubic fit curves, which are the ΔTEC time series with the longer-term trends removed. Both residual ΔTEC time series show enhancement prior to the earthquake and at other times within the 3-month period – evidence for a global mechanism likely related to solar-terrestrial interaction. We should point out that some variations are not well-correlated between the two residual time series, but might still be related to solar-terrestrial interaction. Since we are not accounting for the physics describing the ionospheric response to solar drivers, we do not, in general, expect a good correlation between these ΔTEC time series. Moreover, the ΔTEC index of Pulinets et al. [2007] was not designed to measure solar-terrestrial interaction. But the lack of a tidy correlation does not, therefore, mean that it is related to earthquakes. In summary, the observations presented in Figs. 1 and 2 show that global TEC variations occurred prior to the earthquake and at other times during the 3-month period.

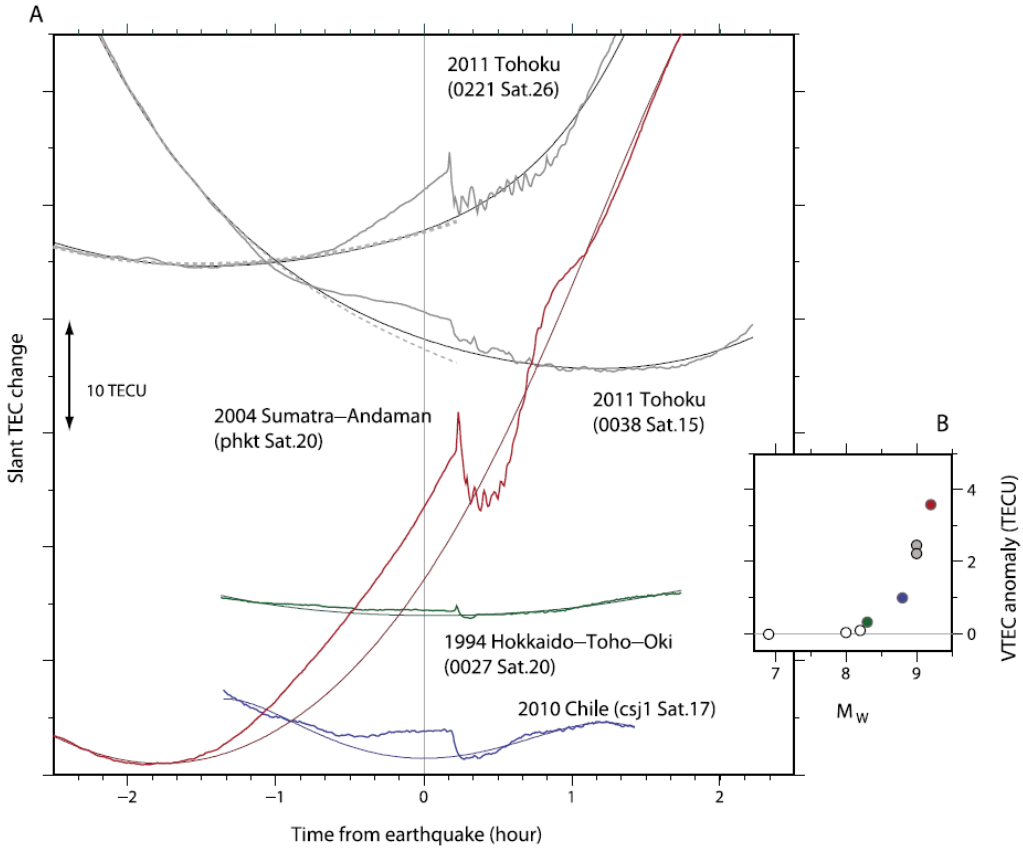

Figure 3: [Figure 4. and caption from Heki, 2011] (a) Slant TEC changes and their models in the 2011 Tohoku earthquake, the 2004 Sumatra-Andaman earthquake, the 1994 Hokkaido-Toho-Oki earthquake, and the 2010 Chile (Maule) earthquake. The horizontal axis shows the time from earthquakes. Dashed curves in gray for the top two time series show the models derived with data prior to the possible onset of the precursor (before 5.2 UT) and extrapolated to 5.2–6.0 UT. (b) Vertical TEC anomalies immediately before the earthquakes as a function of their moment magnitudes. Colors correspond to those in Figure 4a. In addition to the five data from four earthquakes in Figure 4a, three smaller earthquakes (Figure S12) are included (white circles).

We find that the signal identified by Pulinets et al. [2007] as anomalous and possibly related to the Hector Mine earthquake was not actually particularly anomalous. Similar signals occurred long before and long after the earthquake, and the specific signal of Pulinets et al. [2007] as precursory to the Hector Mine earthquake was actually global. Our results can be viewed in the wider context of earthquake prediction, a subject that remains enormously controversial [Jordan, 2006]. Moreover, some well-cited reports of magnetic precursory changes prior to large earthquakes have been shown to be due to instrument failure or global, solar-driven variability [Thomas et al., 2009a,b; Masci, 2010, 2011a,b]. Those works, and the results presented here for the ionospheric precursor result of Pulinets et al. [2007], demonstrate the need for controversial scientific claims to be scrutinized through independent hypothesis testing and the communication of results between scientific peers.

3. Analysis of reported Tohoku earthquake precursor

In September of 2011, a report was published in GRL of TEC changes prior to the Tohoku earthquake, as well as the Sumatra-Andaman (2004) and Maule, Chile (2010) earthquakes [Heki, K. (2011), Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake, *Geophys. Res. Lett.*, 38, L17312, doi:10.1029/2011GL047908].

This report has gained a lot of attention in both academic circles and the media: http://blogs.agu.org/geospace/2011/09/14/atmospheric-electrons/ http://www.earth-issues.com/tag/american-geophysical-union/ http://www.irishweatheronline.com/news/earth-science/geology/japanese-university-detects-atmospheric-precursor-to-2011-megaquake/42911.html

Figure 3 [Figure 4 and caption from Heki, 2011] shows slant TEC time series for the Sumatra-Andaman (2004), Maule, Chile (2010), and Tohoku, Japan earthquakes. Coseismic ionospheric disturbances (CID) caused by atmospheric waves generated by the earthquakes are seen. After applying a cubic-fit to the

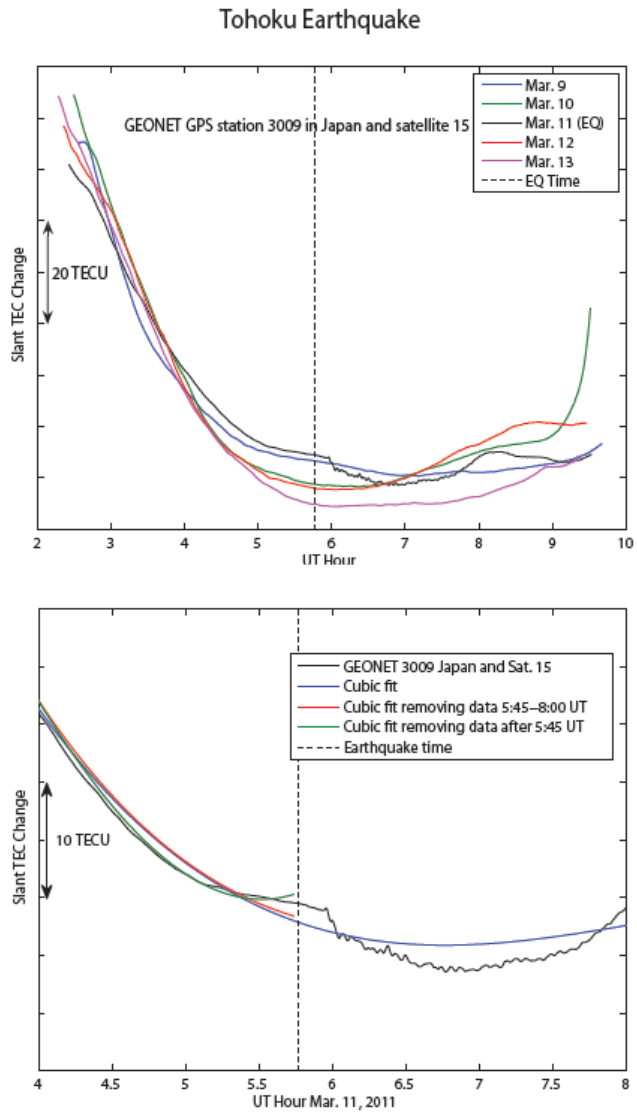

Figure 4: [From Thomas et al. 2011, AGU Fall Meeting Poster] (Top) Slant TEC for Mar. 9-13, 2011 for GEONET GPS station 3009 in Japan and satellite 15. The time of the earthquake (5:46 UT) on Mar. 11 is shown as the black vertical dashed line. A coseismic ionospheric disturbance is clearly seen on Mar. 11 (black curve) starting just after the earthquake. Heki 2011 reported that the enhancement of the slant TEC curve starting at 5:00 UT Mar. 11 is a possible precursor. The enhancement is comparable with the slant TEC for Mar. 9 (blue curve) that shows a similar trend from 5:00 - 5:50 UT. (Bottom) Slant TEC for Mar. 11, 2011 for GEONET GPS Station 3009 in Japan and satellite 15. Cubic least-squares fits to the slant TEC with and without the coseismic disturbance are shown. Reported precursory enhancement decreases when coseismic disturbance is removed from the fit.

slant TEC curves, anomalies of 3-5 TECU relative to the fit curve are observed about 50 min prior to the earthquakes.

Figure 4 shows our initial analysis of the reported Tohoku slant TEC precursor presented at the AGU fall Meeting in 2011. Our preliminary findings are: 1. Precursory slant TEC enhancement reported by Heki 2011 is not anomalous when compared with slant TEC curves from the same GPS stations and satellites for other days, especially Mar. 9. 2. Fitting of slant TEC with coseismic disturbance removed from time series decreases precursory enhancement. This work is not yet complete. The completion of this work has been proposed for a FY2013 Earthquakes Hazards External Award. If funded, we would analyze additional slant TEC time series from GPS stations both near and far from Japan for a duration of 2+ months to investigate whether the reported precursory enhancement was local to the earthquake.

4. Student Training

Undergraduate student Nicholas Rivera was my intern for this project. He developed tools in MATLAB to process the TEC data, attended the AGU Fall Meeting to help present our poster, and was a coauthor on the GRL [Thomas et al., 2012]. Nicholas graduated from the Digipen Institute of Technology in Computer Engineering in May 2012 and plans to pursue a PhD in electrical engineering at the U. of Washington.

5. Dissemination

Thomas and Rivera attended the AGU Fall Meeting in San Francisco, CA in December of 2011 and presented a poster "On the reported ionospheric precursors of the 1999 Hector Mine, CA and 2011 Tohoku, Japan earthquakes". As indicated in the bibliography below, one paper was published in GRL, one is under review in NHESS, and three more manuscripts are in preparation.

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1. Refereed Publications

- **Thomas, J. N.**, J. J. Love, A. Komjathy, O. P. Verkhoglyadova, M. Butala, and **N. Rivera** (2012), On the reported ionospheric precursor of the 1999 Hector Mine, California earthquake, *Geophys. Res. Lett.,* 39, L06302, doi:10.1029/2012GL051022.

- Love, J. J. and **J. N. Thomas,** Is solar-terrestrial triggering of earthquakes significant?, *Natural Hazards and Earth System Sciences*, Submitted and Under Review, June 2012.

- **Thomas, J. N.**, J. J. Love, **N. Rivera,** and J. Secan, On the reported ionospheric precursor of the 2011 Tohoku, Japan earthquake, *Geophys. Res. Lett.*, In Preparation.

- **Thomas, J. N.**, J. J. Love, and M. J. S. Johnston, Reply to Comment on "On the reported magnetic precursor of the 1989 Loma Prieta earthquake" by A.C. Fraser-Smith, P.R. McGill, and A. Bernardi, *Phys. Earth Planet. Inter.*, In Preparation.

- **Thomas, J. N.**, J. J. Love, and M. J. S. Johnston, Reply to Comment on "On the reported magnetic precursor of the 1989 Loma Prieta earthquake" by J.M.G. Glen, S.L. Klemperer, D.K. McPhee, *Phys. Earth Planet. Inter.*, In Preparation.

2. Conference Presentations

- **Thomas, J. N.**, J. J. Love, A. Komjathy, O. P. Verkhoglyadova, M. Butala, D. A. Galvan, and **N. Rivera**, On the reported ionospheric precursors of the 1999 Hector Mine, CA and 2011 Tohoku, Japan earthquakes, American Geophysical Union, Fall Meeting 2011, abstract #NH51A-1693.