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Michael C. Kelley is now Professor Emeritus, and Wesley E. Swartz is now retired.

Key Points:

- TEC fluctuations over distances of 500 km occurred simultaneously (i.e., tied to Earth, no traveling) 40 min before a Japanese earthquake
- GPS signatures imply electric fields mapping from ground to ionosphere, making uplifts/downdrafts similar to MSTIDs' (but with no motion)
- MSTIDs can be separately detected due to their horizontal movement through the ionosphere

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Apparent ionospheric total electron content variations prior to major earthquakes due to electric fields created by tectonic stresses

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Abstract Growing evidence for ionospheric signatures of impending earthquakes comes from electron content measurements along slanted paths from GPS satellites to multiple ground stations located up to 500 km away from the epicenters. These slant total electron content (STEC) measurements deviate from the classic U-shape pattern, starting about 40 min to over an hour before major earthquakes. Unlike other naturally occurring STEC fluctuations at midlatitudes, we show here that these earthquake-induced deviations are simultaneous over a wide geographical area and do not propagate, thereby indicating a ground-based origin. Prior to the 11 March 2011 Tohoku-Oki earthquake (M_w 9.0), the deviations were as much as 10% of the undisturbed STEC. We argue that such deviations must be due to an electric field-forced rise or fall of the main ionosphere with little change in the vertical electron density profile. Hence, "apparent" is used in the title. We show how stress-related underground electric fields penetrate to 80 km altitude (above which penetration to the main ionosphere easily occurs) with magnitudes high enough to create STEC variations comparable to those observed. Since many thousands of GPS receivers exist worldwide, our theory suggests the possibility of early warning systems that could provide 10 to 20 min notice prior to large earthquakes, after allowing time for signal processing. This theory for prequake-induced STEC fluctuations also explains the ground-based ULF magnetic field data acquired by Fraser-Smith et al. 40 min prior to the Loma Prieta earthquake.

1. Introduction

Many studies have purported to show precursors to earthquakes [e.g., *Parrot*, 1995, and references therein; *Geller*, 1997, *Pulinets and Ouzounov*, 2011]. Some reports were merely word of mouth, particularly those reporting severe distress of livestock and wild animals in the days before a major earthquake [*Tributsch*, 1982]. There is a healthy skepticism in the scientific community as to the veracity of such effects, although in one case, a major city in China was evacuated based on animal behavior [*Tributsch*, 1982]. Although one might reasonably expect seismic data to be a prime source of earthquake precursor information, this concept has not seemingly generated a consensus to date. For example, an immense controversy was triggered by *Varotsos and Lazaridou* [1991], who claimed some success in predicting earthquakes using seismic electrical signals that occurred up to 23 days before quakes. The critique of the Varotsos and Lazaridou work by *Mulargia and Gasperini* [1992] eventually led to 43 papers covering both sides in a special issue of *Geophysical Research Letters* (Volume 23, Issue 11 (1996)) without settling the issue.

Another notable controversy was spawned by *Campbell* [2009] and *Thomas et al.* [2009] following the *Fraser-Smith et al.* [1990] report of anomalous ULF (ultralow frequency) magnetic field variations beginning about an hour before the 1989 Loma Prieta earthquake in the San Francisco Bay area. However, further study by *Bernardi et al.* [1991] and *Culp et al.* [2007] supported the claim that a magnetic precursor was actually detected. The electromagnetic effect we discuss below is consistent with the Fraser-Smith et al. magnetic field results. *Utada et al.* [2011] and *Heki and Enomoto* [2013] showed precursor effects on the magnetic field declination. In addition, *Hayakawa et al.* [1997] reported a VLF signature for the Kobe event.

Our study of the timing of slant total electron content (STEC) events over a wide geographic area strengthens the precursor interpretation of the data published by *Heki* [2011] and *Heki and Enomoto* [2013, 2015]. *Heki and Enomoto* [2014] discussed the magnetic activity of the day and also reinforced their conclusions in their rebuttal of an alternative interpretation proposed by *Kamogawa and Kakinami* [2013]. Finally, *Liu et al.* [2001] and *Hayakawa and Schekotov* [2016] are examples of retrospective studies of the ionospheric effects of the Chi-Chi and Kobe events, respectively.

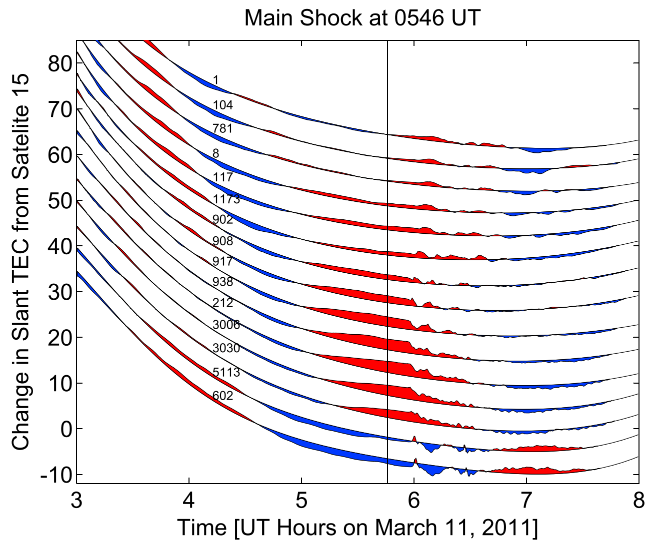

Figure 1. Slant TEC time series from 15 ground stations and Satellite 15. The ground station numbers are listed at the left, and the time of the quake is indicated by the vertical line. The red fills correspond to STEC enhancements and the blue fills to STEC depressions.

In this paper, we formulate a plausible mechanism that explains the STEC precursors that are simultaneous in time over 500 km, thereby providing an important key for future work in developing a predictive system.

2. Data Presentation

Figure 1 shows several STEC time series in a format similar to Figure 2 in the *Heki* [2011] article but uses data from different ground stations to more evenly cover a range of latitudes. Color shading has been added to emphasize times of STEC enhancement (red) or depression (blue). The data, plotted bottom to top, are from stations located at increasing latitudes with slowly increasing longitudes. The smooth black curves are the expected values of STEC without an earthquake and generally follow a U shape that corresponds to changes in the slant TEC with the changing satellite-to-ground path with minima near the points of closest approach for each satellite ground-station pair. The curves were generated by using the method described by *Heki* [2011]. The time of the earthquake is marked by a vertical line. The red areas, beginning shortly after 5 UT for stations 3030, 3006, 212, 938, 817, 908, 902, 1173, 117, and 8, are features of the growing values of STEC, similar to what Heki identified as earthquake precursor events. Data from Station 15 are plotted in Figure 2 for 10 days before and 2 days after the day of the event, which is in red on the plot. No enhancement like the one before the earthquake on day 70 is seen in the other days. Similar precursor deviations from the classic GPS/STEC U-shaped curves, beginning about 40 min to an hour before the 11 March 2011 Tohoku-Oki earthquake (M_w 9.0) at 0546 UT, were found in thousands of GPS satellite-to-ground-station pairs. Heki also reported precursor events from several other earthquakes and showed a clear correlation of the deviation magnitudes with the magnitudes of the quakes. Precursors were obvious only for quakes with $M_w > 8.2$, although the class 6 Napa earthquake was tentatively detected using this technique [*Kelley et al.*, 2014].

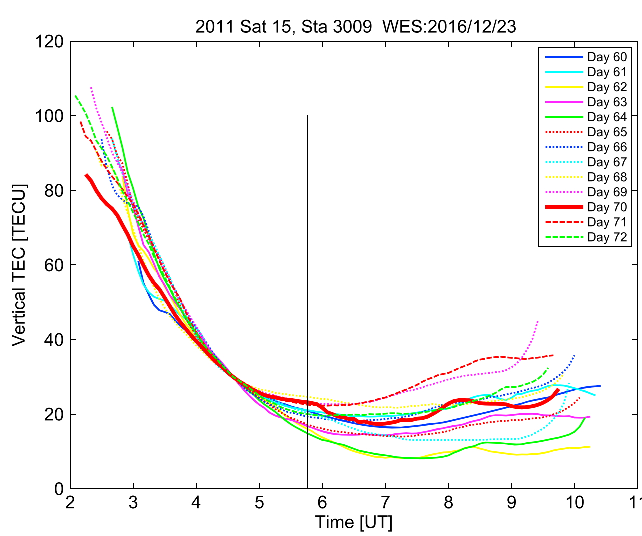

Figure 2. Slant TEC time series from ground station number 3009 and Satellite 15 for 13 consecutive days. Day number 70 is the day of the Tohoku-Oki earthquake.

Figure 3 shows latitude-versus-longitude tracks of the subionospheric points (SIP) of the same data used for Figure 1. The STEC variations are added by using the same color shading as in Figure 1. The area fractured by the earthquake is depicted in yellow, and the asterisks show the locations of the SIPs at the time of the quake. Noting that the SIPs move eastward in time, the largest enhancements prior to the earthquake were at latitudes of the fractured area, while the STEC at latitudes south of the fractured zone was depressed prior to the quake. Precursor studies have shown that they begin sooner for larger earthquakes.

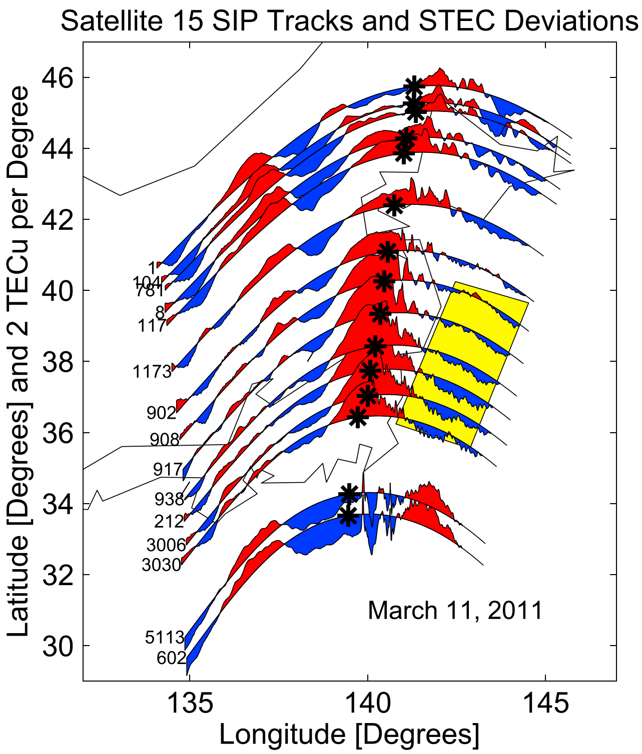

Figure 3. Ground tracks corresponding to the STEC time series of Figure 1 from Satellite 15. The black asterisks mark the SIP positions at the time of the earthquake, and the yellow area delineates the fractured region.

The STEC variations along the SIPs from Satellite 26 for the same ground stations used for Satellite 15 in Figures 1 and 3 are shown in Figure 4. Satellite 26 was east of Satellite 15 for the time period around the quake. While this figure also shows that STEC was enhanced at latitudes of the fractured region, it also shows that STEC was depressed at more northerly latitudes. When considered together, Figures 2 and 4 infer a significant east-west extent of the enhancements of STEC being coupled to the depressed values to the north and south of the fractured zone.

Figure 5 shows the STEC variations along the SIPs for Satellite 5 with the same ground stations used in the previous figures. We again see big STEC prequake enhancements at the latitudes of the fractured area. These three satellites provide wide coverage of the area around the location of the quake from over land to the west and over ocean to the east and southeast of the epicenter.

We do not believe that these STEC changes necessarily imply big changes in the vertical TEC and density profile at any given location, but rather a lifting or lowering of the ionospheric layer with respect to the satellite-to-ground-station paths, as explained in more detail in section 3. We used the term "apparent" in our title since we do not believe that the variations correspond to actual increases or decreases in the amount of plasma in the ionosphere, unlike other explanations in the literature. Large-scale, nontransport changes in the number of electrons in the main ionosphere that invoke enhanced production (e.g., from alpha particles as suggested by *Pulinets and Boyarchuk* [2004]) or recombination (via ion chemistry [e.g., see *Kelley*, 2009]) are very unlikely at midlatitudes. While gas release mechanisms could cause local plasma density changes [*Kelley et al.*, 2014], one would not expect them to be distributed quickly enough to trigger events simultaneously over a wide geographical area, as is actually shown here. A change in the height of the layer is supported by the study of *Maruyama et al.* [2011] using data from four ionosondes around the area of the Tohoku-Oki earthquake, only one of which was within 800 km of the epicenter. Although their study focused on how the ionosphere was disturbed after the quake, the Kokubunji station, 440 km from the epicenter, showed a rise of 27 km in the peak height of the F_2 layer 13 min after the main shock compared to the record just before the quake.

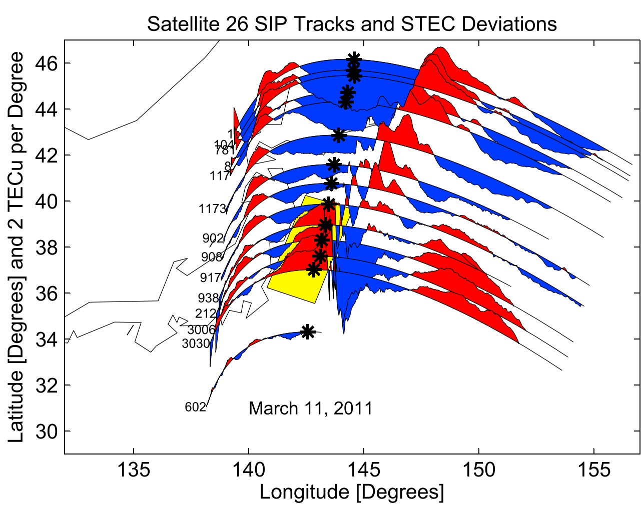

Figure 4. The same as for Figure 2 but for Satellite 26.

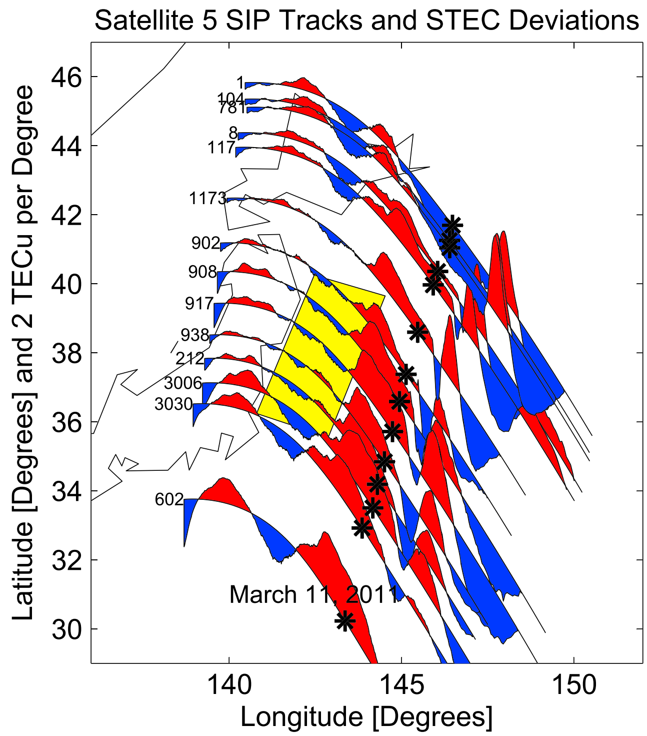

Figure 5. The same as for Figure 2 but for Satellite 5.

The key point here is that prior to these earthquakes, enhancements of STEC occur near the fracture area, whereas simultaneous decreases occur away from the fracture area. We address the implications of these precursors in section 3.

We have data from many more than the 15 ground stations used for Figures 1–5, but the clutter from displaying them all in one figure in those formats would mask important results. Instead, we show that the earthquake effects on the STEC are tied to the Earth and are not propagating. Figure 6 shows the onset times of enhancements occurring between 30 and 60 min before the quake. For this plot, we have chosen stations along the full length of Japan with a longitude window about the same line used in selecting stations for Figures 1–5 but widened by a factor of 10. There are 140 ground stations within this group. Many commencement times are seen to cluster between a narrow time interval of 45 to 50 min prior to the quake; i.e., they are nearly simultaneous over latitudes from 38° to 43°, corresponding to a distance of over 1700 km. For this to be a propagating effect happening in ±2.5 min, the propagation velocity would need to exceed 10 km/s. Hence, the use of the word "simultaneous" seems appropriate, and thus, the short time scale can only be explained by an electric field structure larger than Japan.

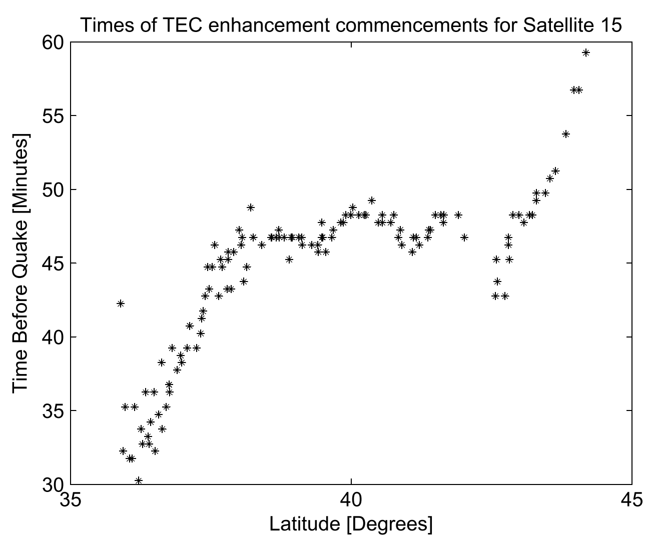

Figure 6. Plot of the time intervals between STEC enhancement commencements (i.e., transitions from blue to red) and the time of the Tohoku-Oki earthquake, showing near-simultaneous events for latitudes between 38° and 43°. One hundred forty stations were selected for this plot. The fact that this indicator occurs simultaneously over the length of Japan, in this case, shows that the STEC enhancements are tied to the Earth and are not due to a wave propagating in the atmosphere. The sloping points at latitudes below 38° and higher than 43° are due to propagating waves unassociated with the earthquake. Hence, the two effects can be distinguished.

The sloping dot groups for latitudes below 38° and above 43° in Figure 6 are due to common traveling ionospheric disturbances, e.g., TIDs and/or mesoscale-scale traveling ionospheric disturbances (MSTIDs). Figure 6 also shows that the earthquake effects are so strong for this large quake that they almost, but not quite, mask the TID effects between 38° and 43° latitudes. This difference in localized latitude dependences of the event timings demonstrates one way to flag earthquake effects separately from traveling disturbances.

Finally, Figure 6 illustrates how data from a number of GPS stations can be used to predict an earthquake 45–50 min before it happens. One would simply look for simultaneous events in data from multiple GPS stations spread over an appropriately sized geographic area.

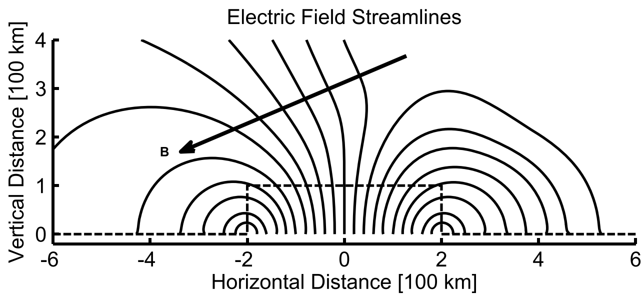

Figure 7. A model of electric field lines produced by a charged area on (or near) the Earth's surface and its modification by the conductivity along magnetic field lines in the ionosphere.

3. Discussion

The fact that there were substantial depressions in STEC, both north and south of the region fractured by the earthquake and prior to it, argues strongly against a release of ionizing alpha particles [*Mulargia and Gasperini*, 1992] that could only increase STEC. A similar disadvantage holds for release of a radioactive gas like radon [*Tributsch*, 1978], which could only decrease STEC, and it is unlikely that radon gas released from the ground could propagate up to *F* layer altitudes within the 1 h time scale of interest here. It is also doubtful that an ionization source could create a disturbance that could propagate over hundreds of kilometers without showing a propagating phase front during the times of interest to account for the depressions of STEC to the north and south of the Tohoku-Oki quake.

The simultaneous increase in STEC at latitudes of the quake with decreases north and south of the quake area suggests an electrodynamic effect where the perturbing electric field reverses direction over the latitudes of interest with a separation of hundreds of kilometers. Wavelengths this long correspond to frequencies in the ULF/ELF range, and hence, corresponding magnetic field perturbations would also be expected. The idea of STEC perturbations being driven by a large-scale electric field is supported by the ground-level ULF electromagnetic waves detected prior to the Loma Prieta quake [*Fraser-Smith et al.*, 1990]. The 0.01 Hz component amplitude of the magnetic field was at least 5 nT with rise and fall rates on the order of 2 nT/s over two cycles, occurring over a period somewhat longer than the 40 min precursors reported by Heki for the STEC response. This claim created some controversy [*Campbell*, 2009; *Thomas et al.*, 2009], but now there is more evidence in support of the claimed ULF magnetic precursor detection [*Culp et al.*, 2007; *Thomas et al.*, 2009]. The electric field associated with this magnetic field is given by $E = cB = 1.5$ V/m. We proceed to show that this field is sufficient to support our theory.

An underground disturbance leading to electromagnetic signals can be modeled as follows. The wavelengths of low-frequency signals can be modeled using quasi-statics since they are much longer than any other scale in the system [see *Swartz et al.*, 2012]. In a linear system, the source can be a system of charges (a Thevenin approach) or a system of currents (a Norton approach). We choose the former and note that a complicated system of underground charges can be expanded into its moments. The lowest moment will be the dominant one at a distance similar to that between the ground and the ionosphere. Since the system has no net charge, we use a dipole, either vertical or horizontal or a combination of the two. Underground origins of these electrical signals have been discussed [*Kuo et al.*, 2014; *Kamiyama et al.*, 2016]. The ionospheric effects were limited to near-equatorial latitudes in these studies.

To our knowledge, no measurements of the surface electric field near an earthquake have been made, although a vertical surface electric field resulting from an underground nuclear detonation test was reported [*Sweeney*, 1989]. We thus work the problem backward, asking first what ionospheric electric field is needed at the base of the ionosphere (100 km altitude) to create the apparent STEC changes observed, and then ask what the corresponding ground-level electric field would need to be.

Non-classical STEC disturbances due to mesoscale traveling ionospheric disturbances (MSTIDs) have been studied in some detail [*Beach et al.*, 1997]. They found that apparent STEC variations of ±10% could be generated by a 20 km upward or downward displacement of the main ionospheric layer. MSTIDs themselves are discussed in some length in *Kelley* [2009]. Such STEC changes are due to the line-of-site GPS signals from a satellite to the ground, alternatively going under the main layer (an apparent STEC decrease) or above the main layer, making an apparent increase. In a 40 min period such as those observed by Heki, the STEC changes require a vertical velocity of 8 m/s. For an electric field-induced drift and a 45° magnetic field dip angle, an $\mathbf{E} \times \mathbf{B}/B^2$ drift of 12 m/s requires a 0.5 mV/m electric field. Since the conductivity parallel to the Earth's magnetic field is high, the magnetic field lines are nearly equipotentials above about 100 km

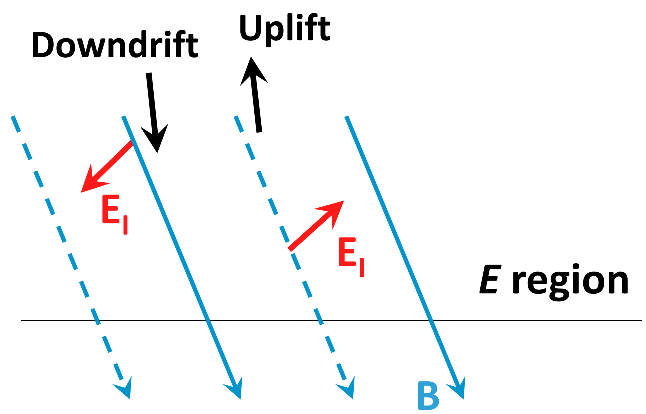

Figure 8. Schematic showing lift and lowering of the ionosphere with an electric field sign change.

[*Farley*, 1959; *Kelley*, 2009]. Hence, we expect the electric field at the bottom of the ionosphere to be within a factor of 2 or so of the field found above at around 250 km. A model approximating the configuration of the electric field is shown in Figure 7. This figure was created by solving for the potential above a charged plate surrounded by a ground plane and increasing the conductivity along **B** above 100 km. The gradient of the potential then produced the electric field streamlines shown in the figure. The asymmetry at higher altitudes is caused by ionospheric conductivity, and the turnover in the vertical component would explain why there are enhancements in STEC in some regions and depressions in others. Figure 8 shows how a variable electric field can cause localized uplift and downdraft of the ionosphere, leading to the observed apparent TEC changes.

To predict the electric field at the surface needed to generate the required 0.5 mV/m field at the base of the ionosphere, we compare the electric field just above a thunderstorm to the value at 90 km required to generate red sprites [*Sentman et al.*, 1995]. We take the latter to be what is needed for atmospheric breakdown, which, according to *Pasko* [2006], is 200 V/m. Just above the anvil cloud (the source of sprites), the field is 4×10^4 V/m and the attenuation ratio is thus estimated to be 200. We consider the top of the anvil to be very close to the Earth's surface for the distance scales of interest here. Thus, at the surface we need a field of 0.2 V/m to produce a field of 1 mV at the base of the ionosphere. This is 1/500 of the fair weather field and hence, might be difficult to measure. However, we note two reports that address the plausibility of such field strengths. The first is the 20 mV/m electric field reported after an underground nuclear test [*Sweeney*, 1989], and we believe that it is likely that the field due to the buildup to a large earthquake would be much larger than this. The second support comes from the magnetic field observations of *Fraser-Smith et al.* [1990] noted above that indicated an electric field more than 10 times larger than required to support our theory. Hence, a sufficient earthquake-induced electric field could well be measured at ground level.

We note in passing that (a) any time-varying electric field must be accompanied by a magnetic field and (b) that for any complex disturbance, the dipole moment will reach the largest distance compared to any other moments.

4. Conclusions

We have provided an explanation for STEC variations preceding large earthquakes. Since the variations begin simultaneously over a wide geographic area and are not propagating, they must be triggered by a large-scale electric field. In our model, some mechanism such as conductivity changes, tribo-electricity or piezo-electricity [*Breiner*, 1964], creates and maintains charge separation, the most important moment being a dipole. The necessary electric field at the base of the ionosphere need only be 1 mV/m. Using the known properties of upward field mapping and the theory of red sprites, this corresponds to a 200 mV/m field near the surface. A field of this magnitude is quite small, and it is easy to imagine such a field being generated by the stresses of an earthquake buildup, particularly since we know that corresponding magnetic fields, 10 times greater than required and produced prior to seismic shocks, have already been found. These magnetic fields were detected 40 min before the Loma Prieta event, as reported by *Fraser-Smith et al.* [1990].

More importantly, we show that there is a reaction to the earthquake buildup that was seen simultaneously over the length of Japan 45–50 min before this major earthquake. This means that the effect must be tied to the Earth, not to a propagating wave in the thermosphere. Propagating waves are seen very often, as described in *Kelley* [2009]. In fact, referring to Figure 1, one can see quite easily that there were disturbances moving north to south well prior to the event, whereas the disturbances just prior to the event were seen simultaneously at all latitudes in this format. In principle, the epicenter could be predicted from the effects of the sign change in the dipole field on either side of the source. In this case, there were no stations east of the epicenter to look for this effect.

The societal impact of earthquakes is enormous, and we believe that a significant research program is justified to prove or disprove whether a warning system for imminent earthquakes could be developed. A real-time correlation of STEC fluctuations should be explored as part of this effort.

Acknowledgments
Partial support was provided by the Podell Emeriti Awards for Research and Scholarship (PEARS) Program. A possible conflict of interest is a patent application by M.C. Kelley and W.E. Swartz for earthquake prediction using GPS, but no financial issues exist at present. The data are readily available from K. Heki and W.E. Swartz.

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