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Analysis of methods for identifying anomalous pre-seismic total electron content (TEC) changes from global ionosphere map (GIM) data

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ABSTRACT: There are many published reports of anomalous changes in the ionospheric total electron content (TEC) prior to large earthquakes. However, whether or not these TEC changes are reliable precursors that could be useful for earthquake prediction is controversial within the scientific community. The statistical analysis by Le et al. (2011), which claims to have found an increase in TEC anomalies within a few days before M≥6.0 worldwide earthquakes during 2002-2010, uses a nonstandard methodology for classification of anomalies, declustering earthquakes, and determining quake-anomaly rates. By first attempting to replicate the methods proposed by Le et al. (2011), then performing a more classical method for precursor detection, we look for this controversial precursor signal. To test a possible statistical relationship between the ionosphere and earthquakes, we compare TEC changes with occurrences of M≥6.0 worldwide earthquakes during a 15 year period, from 2000 to 2014. We use TEC data from a global ionosphere map (GIM) and an earthquake list declustered for aftershocks. For each earthquake, we look for anomalous changes in TEC within ±30 days of the earthquake time and within 2.5° latitude and 5.0° longitude of the earthquake location (the spatial resolution of GIM). Our preliminary analysis has not found any statistically significant changes in TEC prior to earthquakes at GIM resolution, and we thus have found no evidence that would suggest that TEC changes are useful for earthquake prediction. Each method is carefully compared, and potential pitfalls are analyzed. By determining the validity of these techniques, a common approach to identifying precursors may be established.

Introduction

Motivation: The ability to identify earthquake precursors using radiometry of the surrounding atmosphere would greatly aid in earthquake detection and consequent damage prevention and relief programs. Due to the importance of finding such a methodology, the required rigor of science may be easier to overlook. However, true progression can only be developed through scientific skeptiscism and looking the other way could ultimately lead to doing more harm than good.

Question: Potential total electron content (TEC) earthquake precursor signals found in the atmosphere are controversial within the scientific community. One such published report using statistical analysis of global ionosphere maps (GIM) (Le et al., 2011) claims to have found such a signal; an increase in TEC anomalies in the days leading up to earthquakes. Is this technique valid? How can such methods for finding precursors be made more rigorous?

Datasets and Approach: The GIM is a 71 by 73 point grid (5183 points total) of 2-hour sampled, TEC values taken from more than 200 GPS receivers. This investigation explores two techniques to analyzing the GIM data and finding potential earthquake precursors. The first is that proposed by Le et al. (2011), which counts anomalous days before an earthquake. The classification of anomalous days in this approach counts days with one-sigma standard deviation (+/- one standard deviation) from median, and looks to see if there are 6 consecutive hours in a given day. Then, the day must also contain at least one deviation greater than parameter R. The second method uses a similar approach that attempts to address several potential issues present in Le et al.'s technique. A declustered set of earthquakes is compared with filtered TEC signals, which also compensate for seasonal changes, and then use total percent deviation per day rather than 'anomalous' marked days.

References

Le, Huijun, Jann-Yeng Liu, and Libo Liu. "A statistical analysis of ionospheric anomalies before 736 M6. 0+ earthquakes during 2002–2010." Journal of Geophysical Research: Space Physics (1978–2012) 116.A2 (2011).

Michael, Andrew J. "Random variability explains apparent global clustering of large earthquakes." Geophysical Research Letters 38.21 (2011).

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Method 1: Le et al.

3 Steps: preprocessing, anomaly detection, and statistical analysis
(1. Preprocessing) The earthquake set is clustered in space, and the first occurring earthquake in a given radius is preserved; any further earthquakes in this zone occurring within 15 days are removed. Next the 2-hour interval TEC values are linearly interpolated from 12 to 24 hours.
(2. Anomaly detection) The different cells of the TEC map are searched for anomalous days. An anomalous day is defined in this method as a day with 6 or more consecutive deviations from median (6 consecutive hours), and at least one deviation greater than parameter R.
(3. Statistical analysis) Each earthquake is confined to a single grid point, and this grid point is then inspected. A range of days prior to the earth quake day, from 1 to 21 are checked for anomalous days, and totaled as Nrt. This is then normalized by the day count, making sure to compensate for geomagnetic disturbances by removing days with a disturbance storm time index (DST) that suggests interference. The results of Le et al.'s investigation are shown below, appearing to show a precursor with higher magnitude earthquakes.

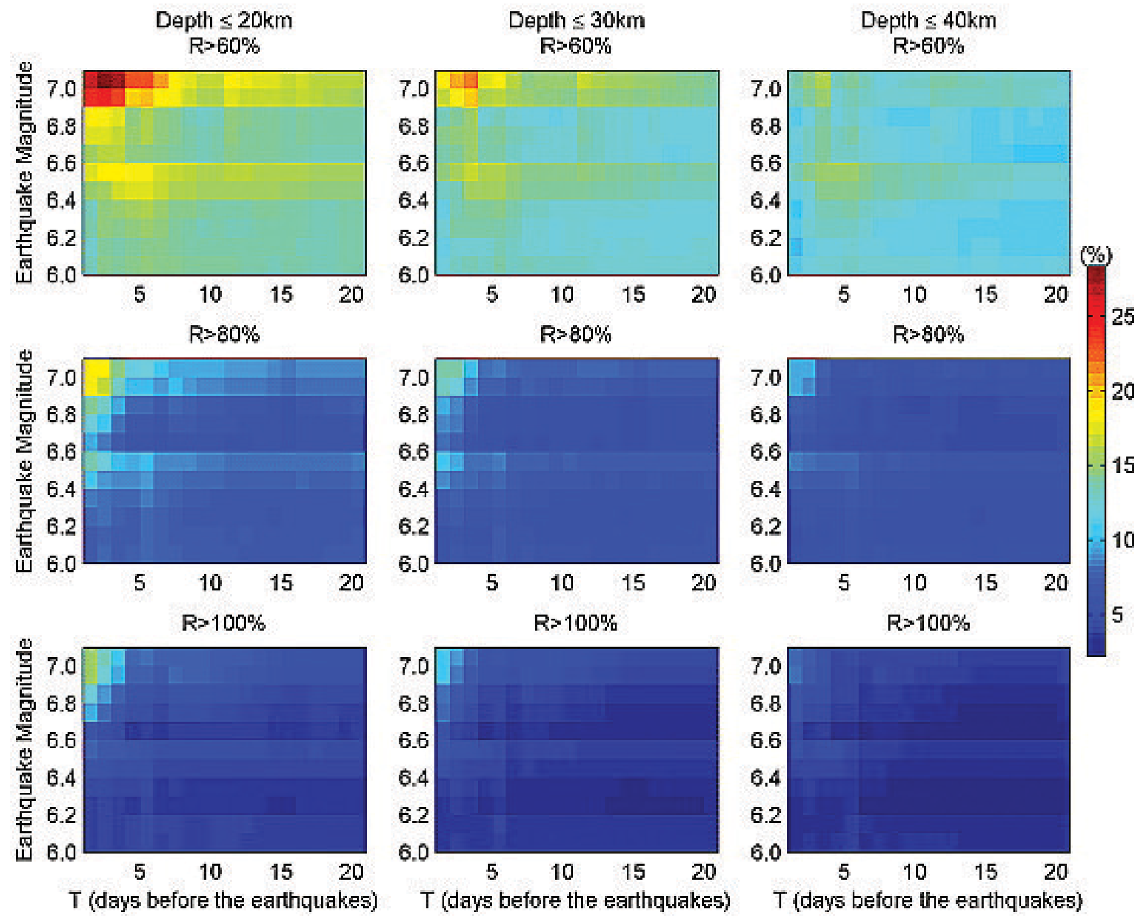

Figure 1: Occurrence rate within T days, plots generated by Le et al. (their Figure 2). At very low sample count (between 29 to 66 earthquakes) a potential precursor is seen. As sample count increases, the signal diminishes.

(Stretching) When calculating the occurrence rate for an earthquake the anomaly count Nrt is divided by the amount of days T minus the discounted days S, Pe = Nrt / (T - S). Small T days (as for small T, S approximately equals T) may be baised to having larger occurrence rates, and certain anomalous days may be 'stretched' to be included in higher T values.
(*Sample size)* This may be further effected as the number of earthquakes given magnitude and depth restrictions get as low as 29. The graphs with the seemingly most significant signal have the lowest included samples. Including more earthquakes by increasing the allowed maximum depth to <40km, this signal seems to nearly disappear. Using a different color scheme helps to highlight the 'stretching' effect potentially inherent in algorithm, seen below.

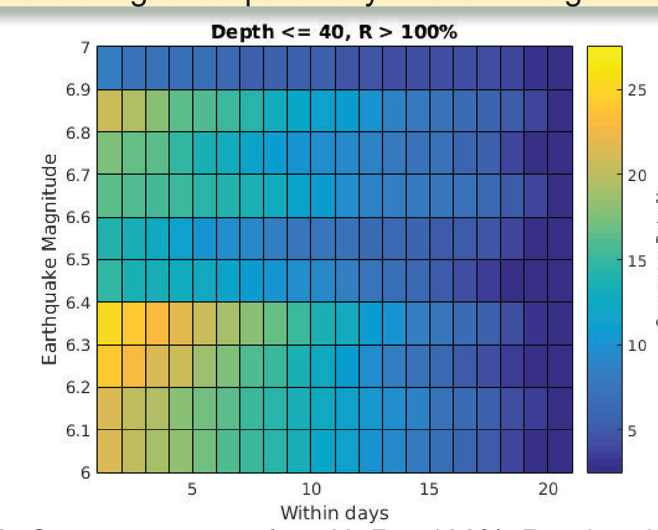

Figure 2: Occurrence rate plot with R > 100%, Depth < 40km. Generated using methods described in Le et al. with different color scheme to highlight 'stretching' effect. Pre-seismic signal here appears to be artifact of methodologies.

Method 2: Trend/Detrend Analysis

4 Steps: Decluster, filter, trend/detrend, statistical analysis
(1. Declustering) For the trend analysis method a declustered earthquake set provided by Andrew J Michael of the USGS.
(2. Filtering) The raw TEC data itself is highly sinusoidal, with a distinct 24 hour cycle. To keep this from influencing anomaly detection, a simple 24 hour running average filter is applied to the data with a window of two months (+30 days, -30 days from the earthquake day). The filtered example is on the right.

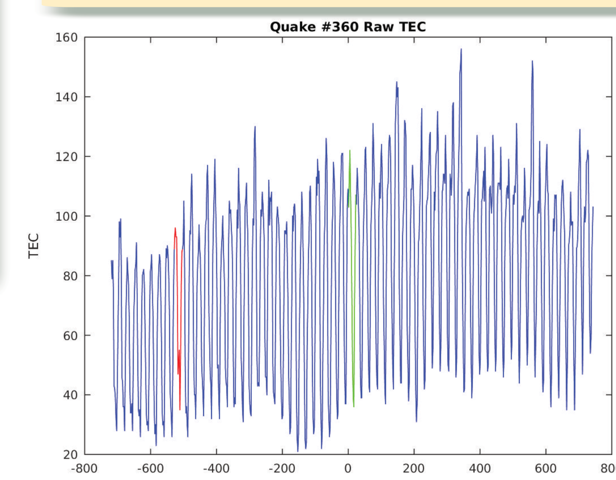

Figure 3: Raw two month TEC plot from GIM cell around quake #360.

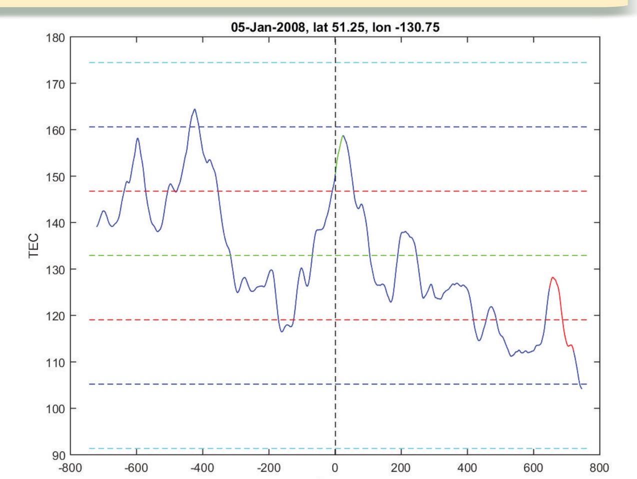

Figure 4: 24-hour averaged plot for earthquake #360.

(3a. Trend analysis) For each earthquake, the closest grid cell associated in the GIM is examined. For -15 days up to +15 days from the earthquake day (31 days total) the number of >1 sigma hourly events are counted in a given day. The counts are then normalized by 24 hours, and then plotted. This is done at each magnitude between 6 and 7.1, at different depths. Figure 5 illustrates this.

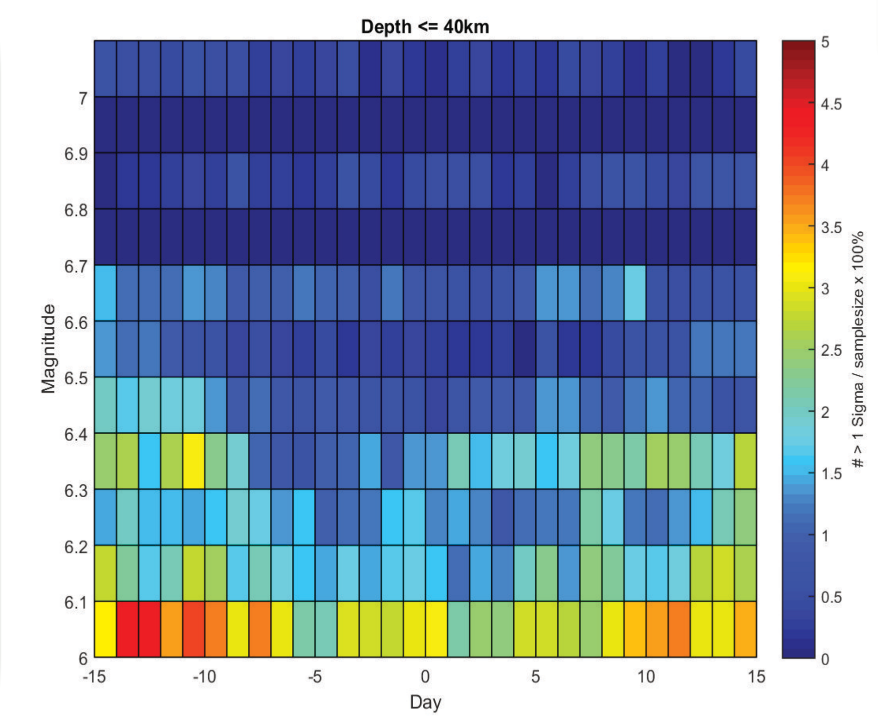

Figure 5: Daily 1-sigma TEC deviation rate for +/-15 days of earthquake event. Seasonal trends preserved. No pre-seismic signal is apparent.

(3b. Detrend) A potential issue that could affect the TEC data is the more long term changes that come from monthly seasonal changes. These changes are then rectified by using a cubic polynomial fit to the data over a two month period, and then subtracting this trend line from the original plot to generate a 'detrended' signal. This detrended signal then represents deviations from the seasonal average.

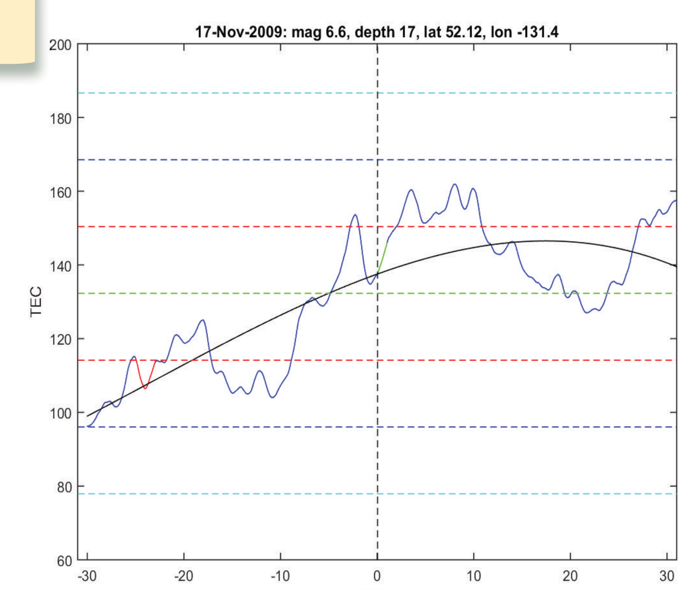

Figure 6: Earthquake M=6.6 depth=17km (blue), black line is cubic polynomial fit (seasonal trend estimate).

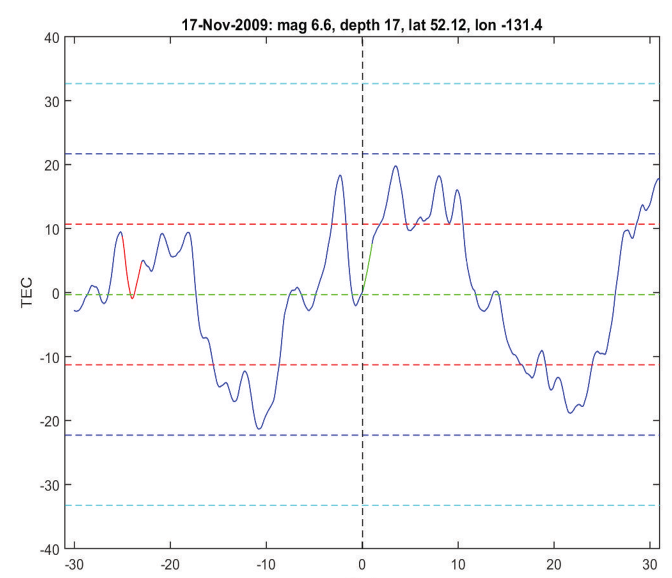

Figure 7: Detrended Figure 6. Green dashed line is median, red 1-sigma deviation, blue 2, cyan 3 sigma.

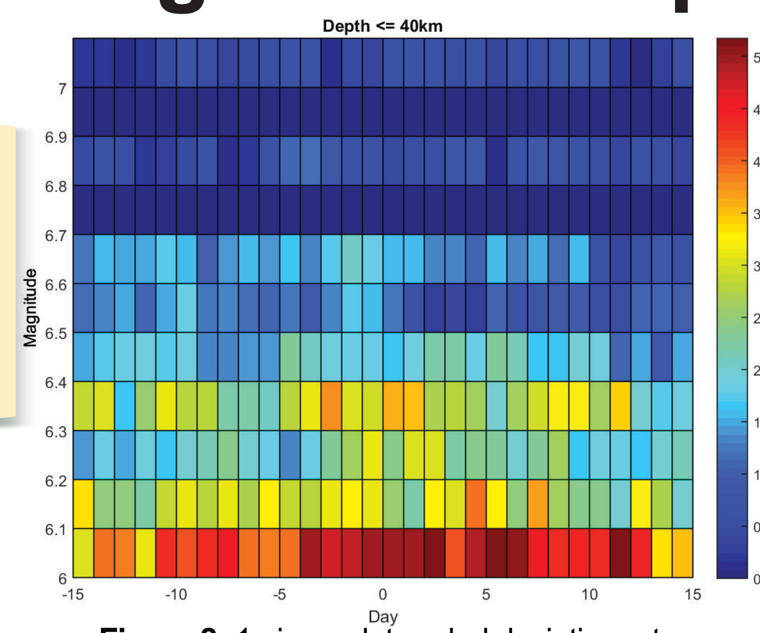

Figure 8: 1-sigma detrended deviation rates.

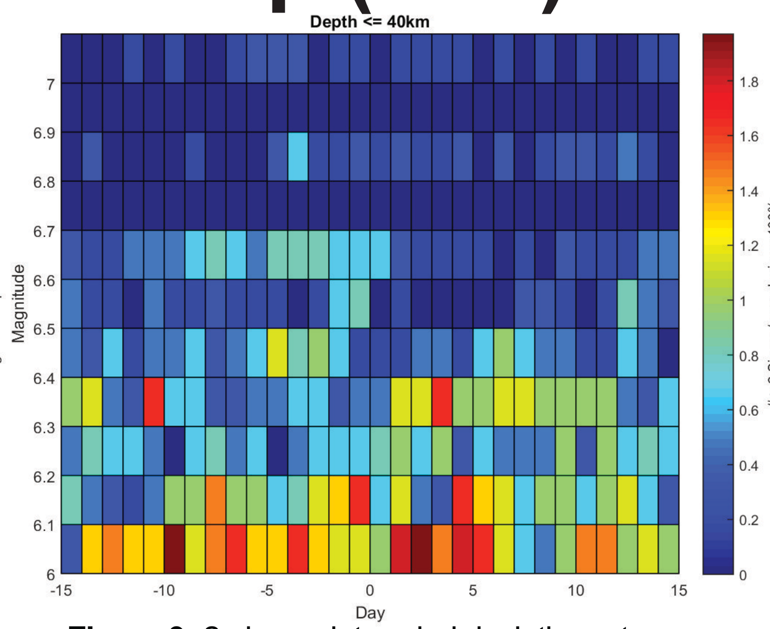

Figure 9: 2-sigma detrended deviation rates.

(4. Statistical analysis) Here we see the rate of 1 sigma deviations (Figure 8) and 2 sigma deviations (Figure 9). No signal is evident, and instead seems to be random noise. Note the change in scale from 25% occurrence rate, the rate of deviation is now down a maximum of 5% and 2% deviation.
(Note) A major issue with this process is the resolution of the GIM. Example below. TEC cloud appears visually unaffected by M=7.9 event. While visual inspection is not rigorous enough to eliminate the potential for analysis, it is clear that the resolution of the TEC map is too poor for anything but the most powerful disturbances to make visually recognizable changes. If this large event had significant effect over the TEC in its vicinity (as suggested by Le et al.'s observations, see top left checkerboard plot), then visual inspection should show some sort of recognizable change.

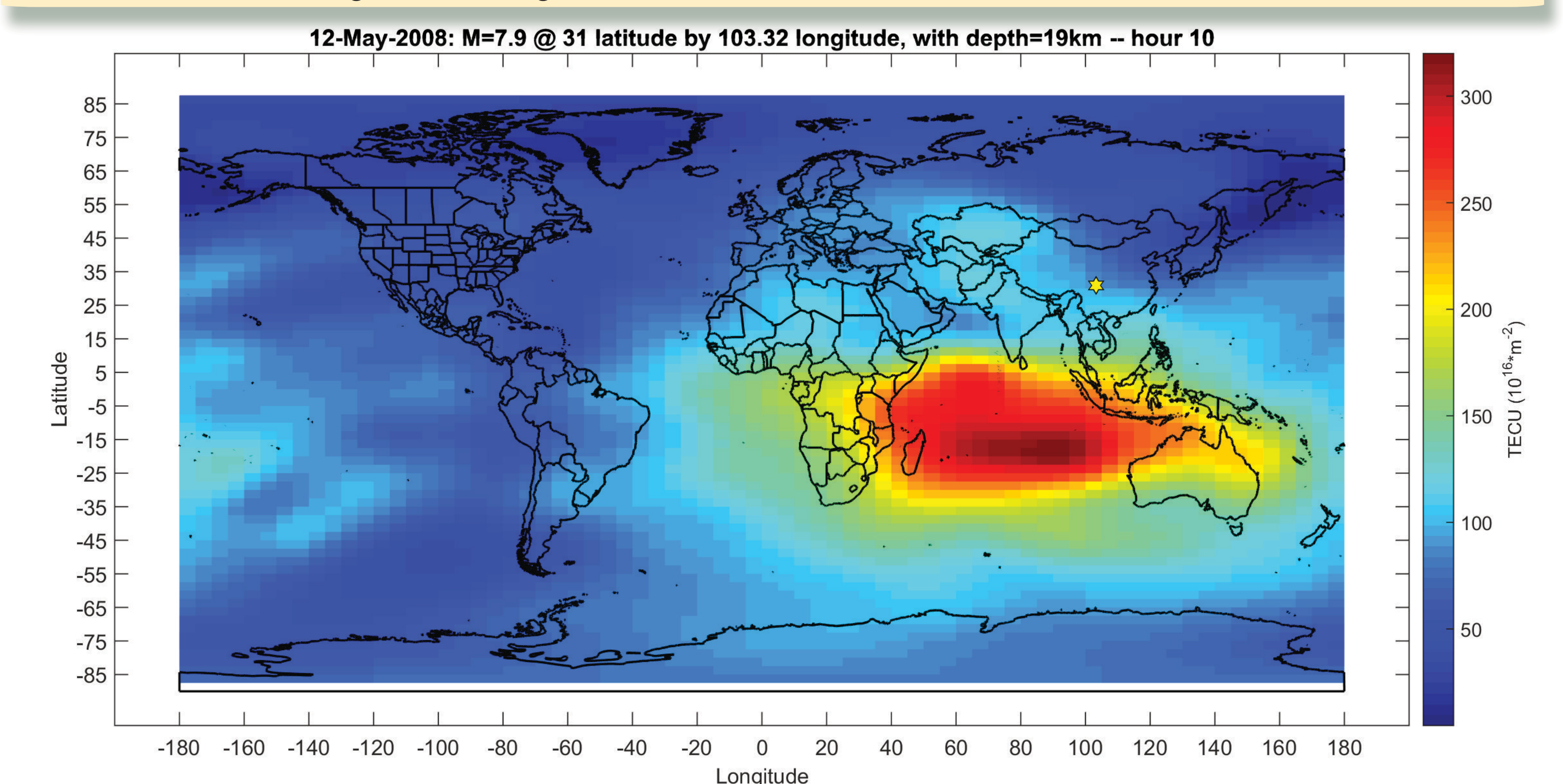

Figure 10: Plotted is the GIM for the 2008 Sichuan earthquake, a notably destructive seismic event. The gold star represents the earthquake's location, 80km from the provincial capital, and was felt as far as 1700km (Shanghai) from the epicenter.

Conclusions

Using a straight forward statistical method no precursors are found in the GIM. There are several important factors that need to be considered before reporting a precursor. Perhaps most obvious is the GIM resolution; while great for visualization, the sample rate is low and resolution poor, making signal detection difficult. The nature of the TEC values themselves must also be considered. As the 24-hour sinusoidal progression of the TEC is dominant, methods analyzing this data must compensate for this as to ensure no alias' have influenced their results. Another easily overlooked factor is how earthquakes are declustered; using an improperly generated earthquake list greatly effects how anomalous features are counted, which could lead to misleading results. When these are taken into consideration, as in the second method, the supposed precursor relation is greatly diminished. Not only is the overall scale of occurrence rate decreased (from a maximum of 25% to a maximum of 5%, even as low as 2%) but the apparent relation to earthquake magnitude and earthquake occurrence are decreased to the point of being unrecognizable.

Further Research

Further studies of relating ionospheric activity to seismic events, particularly as precursors, would benefit greatly from a more distinct classification of earthquake precursor signal. Using a scientific explanation for how a precursor may be generated, and then looking for this expected signal before earthquakes would be a much more reliable method for precursor identification. A similar method could also lead to more meaningful results: if ionospheric TEC data were clustered in space and time leading up to an earthquake, then this signal classification could be used to look for other similar features before earthquakes. This method would more clearly show if a pattern were present or not. However, any techniques would greatly rely on the source of data available, and **the resolution of the GIM may not be precise enough for any exploration of this kind.**