Total electron content anomalies over tectonic plate boundaries indicating lithosphere-ionosphere coupling

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GF: Electromagnetic Seismic precursors and radio remote sensing of Earth

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The research was also supported by the National Science Centre (NCN) of Poland in the frame of Research Grant no. 2021/41/B/ST10/03954.

Abstract

- Larger-scale local anomalies of VTEC called TEC enhancements are often analyzed in the studies of lithosphere–atmosphere–ionosphere coupling (LAIC)
- TEC enhancements are often temporally correlated with geomagnetic storms, but their simultaneous occurrence with strong earthquakes has also been proven
- The present study brings additional observations and shows that TEC enhancements only sometimes coincide with strong earthquakes
- The application of UQRG VTEC maps from the Polytechnic University of Catalonia (UPC) IonSAT group makes reliable the detection of high-resolution VTEC anomalies
- Our study describes VTEC anomalies having spatial and temporal behavior strongly indicating their connection with both geomagnetic storms and tectonic plate system

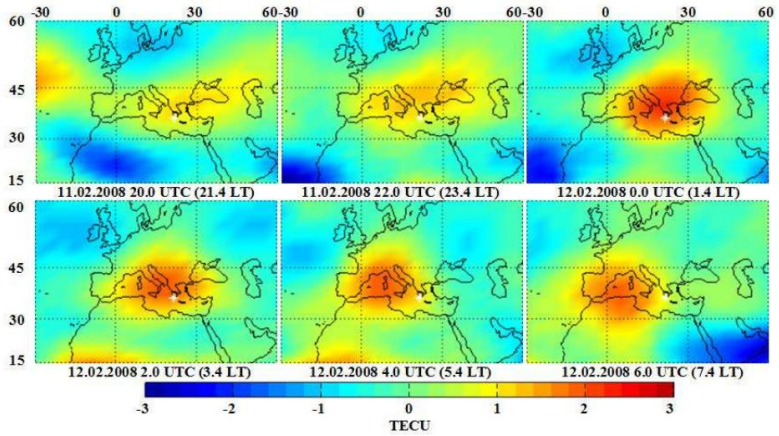
TEC anomalies in the previous studies

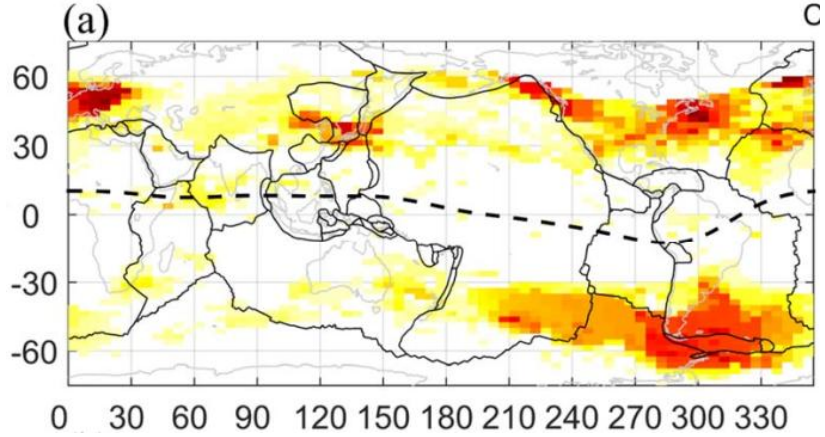
- TEC anomalies are probably studied for 2-3 decades
- The researchers link them with both geomagnetic storms and earthquakes
- The researchers also notice that VTEC anomalies are conjugated in both hemispheres

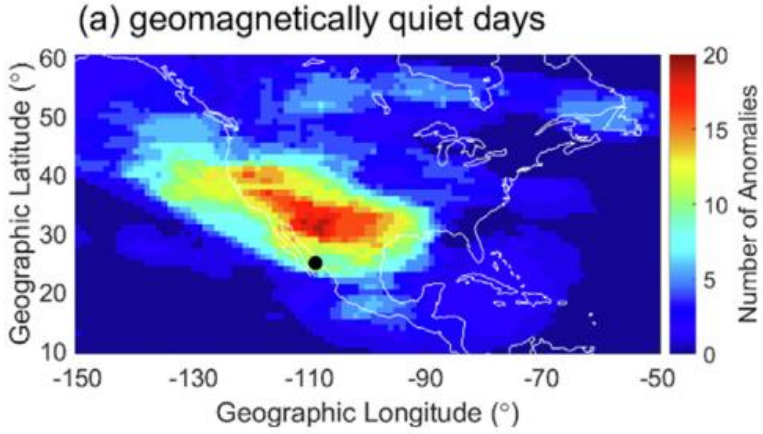
Pulinets, S.A., Davidenko, D.V. The Nocturnal Positive Ionospheric Anomaly of Electron Density as a Short-Term Earthquake Precursor and the Possible Physical Mechanism of Its Formation. Geomagn. Aeron. 58, 559–570 (2018). https://doi.org/10.1134/S0016793218040126

Sun Y-Y, Liu J-Y, Wu T-Y, Chen C-H. (2019) Global Distribution of Persistence of Total Electron Content Anomaly. Atmosphere 10(6), 297. https://doi.org/10.3390/atmos10060297.

Park S.M., Ryu K. and Min K. (2021) Ionospheric anomalies related to strong earthquakes in North America as observed by TEC. Advances in Space Research 68, 4137–4154. https://doi.org/10.1016/j.asr.2021.07.026

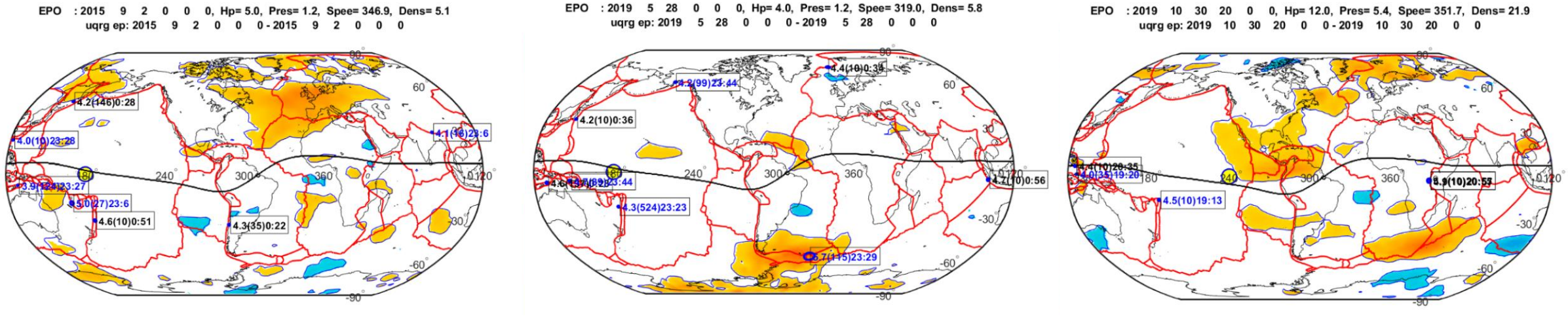






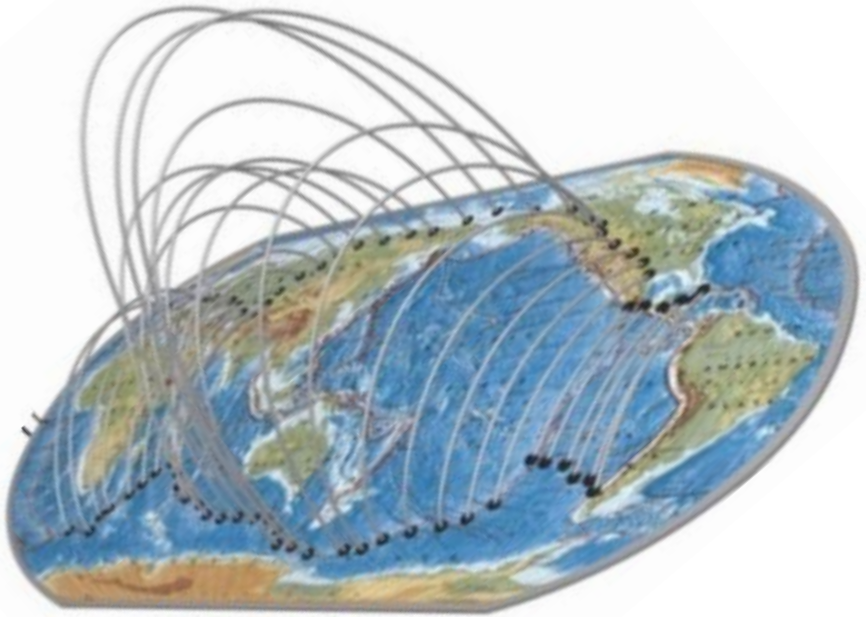
TEC anomalies from the abovementioned previous studies found again

- The colured part of contours shows VTEC anomalies (dVTEC) > 0.3
- The plot also shows the erthquakes within time window ±2.4 h from VTEC anomaly epoch
- You can find the same VTEC anomalies in reference papers by Pulinets et al. 2018, Sun et al. 2019, and Park et al. 2021.



The role of geomagnetic field

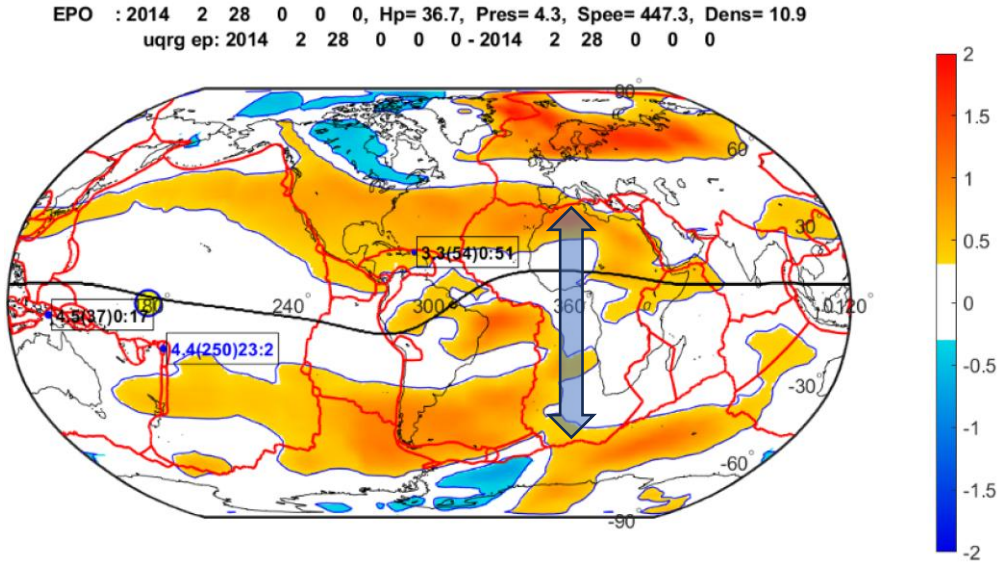
- Recent works present geomagnetic field lines (including newly created) as connecting magnetically conjugated sites nearby tectonic plate boundaries



Ouzounov, D.; Khachikyan, G. Studying the Impact of the Geospace Environment on Solar Lithosphere Coupling and Earthquake Activity. Remote Sens. 2024, 16, 24. https://doi.org/10.3390/rs16010024

- Such shape of geomagnetic field lines is suspected to have a key importance in the distribution of normalized VTEC anomalies (enhancements)

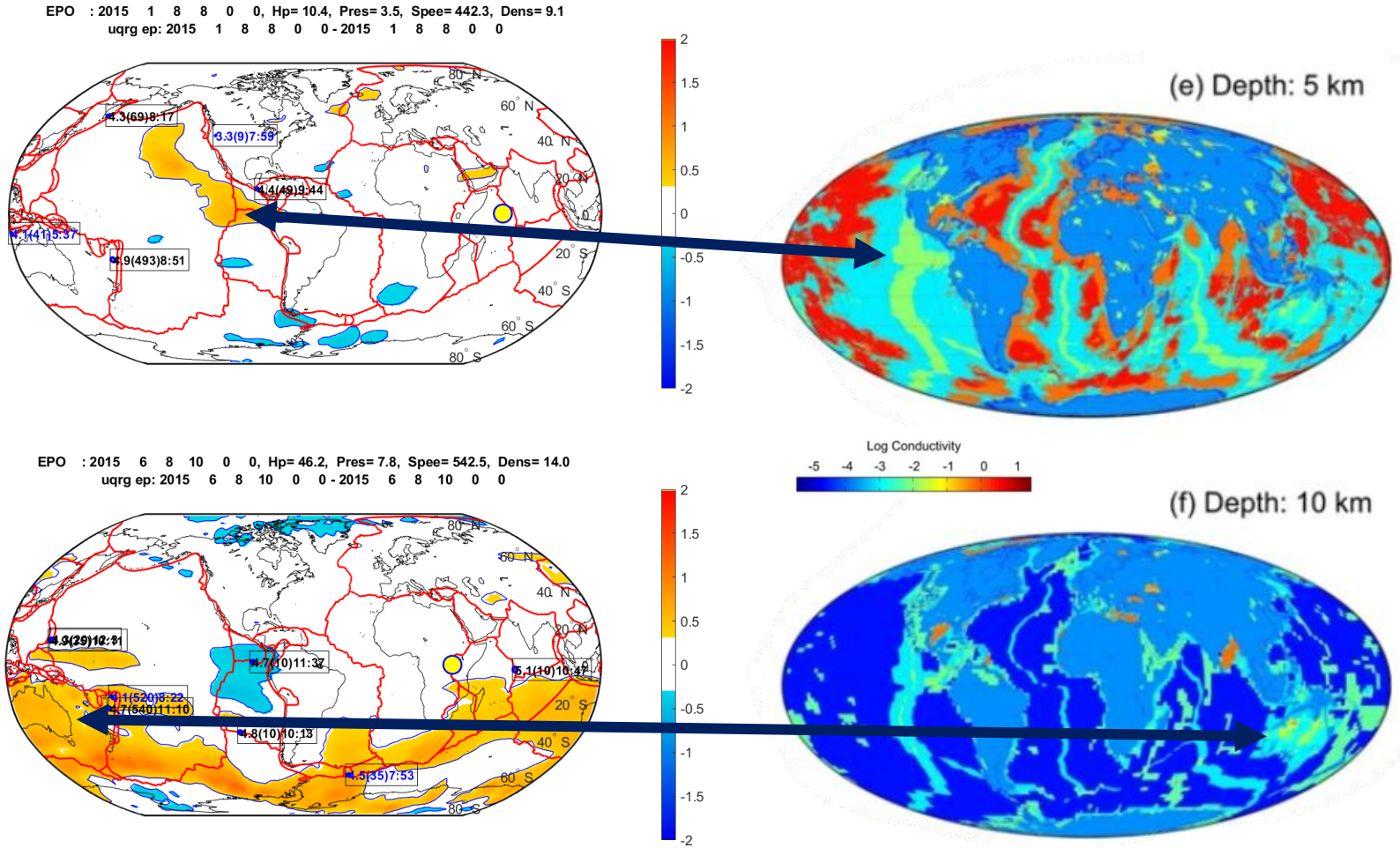
$$dVTEC_e = \frac{VTEC_e - VTEC_m}{|VTEC_m|}$$



Wielgosz, P.; Jarmołowski, W.; Mazur, S.; Milanowska, B.; Krypiak Gregorczyk, A. Vertical Total Electron Content Enhancements and Their Global Distribution in Relation to Tectonic Plate Boundaries. Remote Sens. 2025, 17, 614. https://doi.org/10.3390/rs17040614

Conductivity of the Earth (different depths)

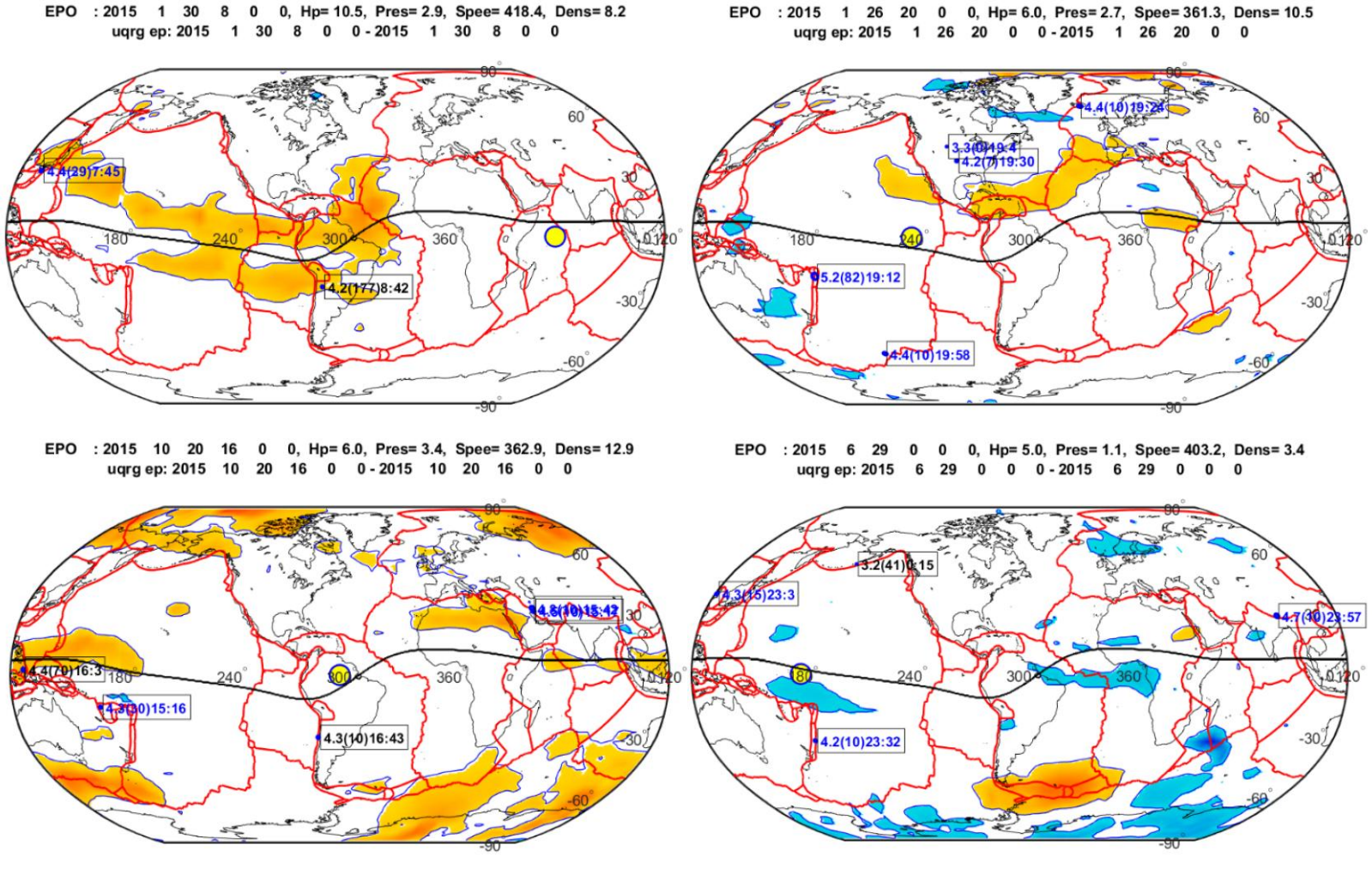
- The studies on conductivity provide global maps of Earth conductivity at different vertical layers
- We suspect that conductivity patterns can have additional importance in VTEC anomaly creation



Alekseev, D., Kuvshinov, A. & Palshin, N. (2015). Compilation of 3D global conductivity model of the Earth for space weather applications. Earth Planet Space, 67, 108. https://doi.org/10.1186/s40623-015-0272-5

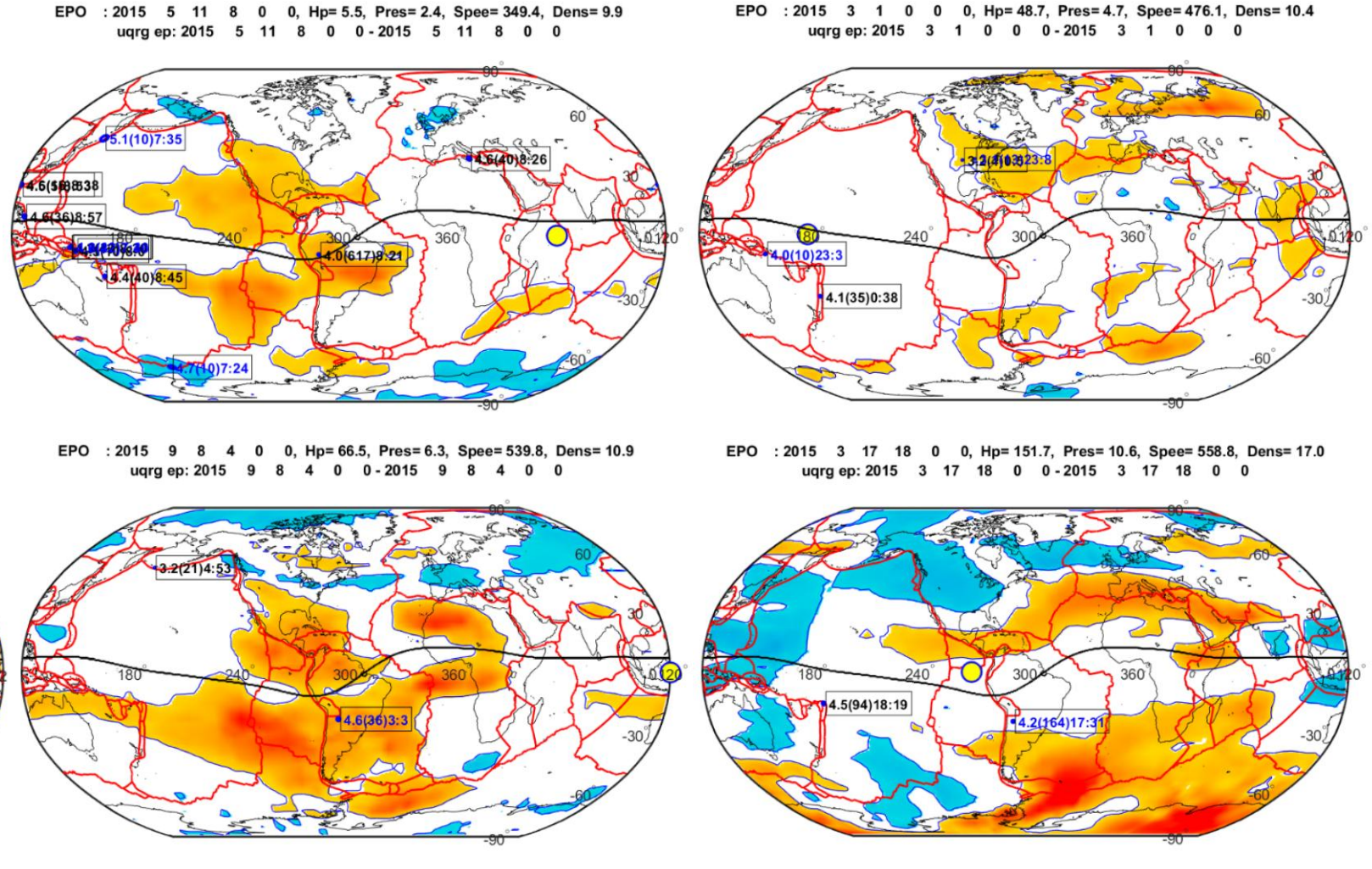
The most pronounced (conductive) places quiet conditions

- The quiet geomagnetic conditions reveal VTEC anomalies repeating and persisting for hours in characteristic places
- Even if they are geographically extended, their extrema go towards tectonic plate boundaries



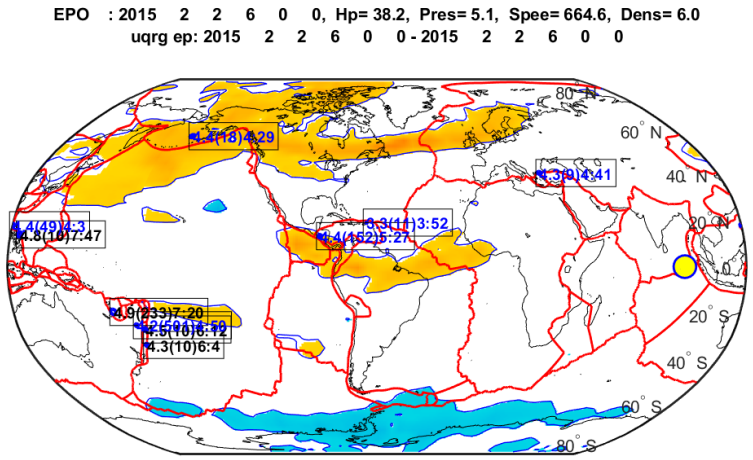
The most pronounced (conductive) places geomagnetic storms

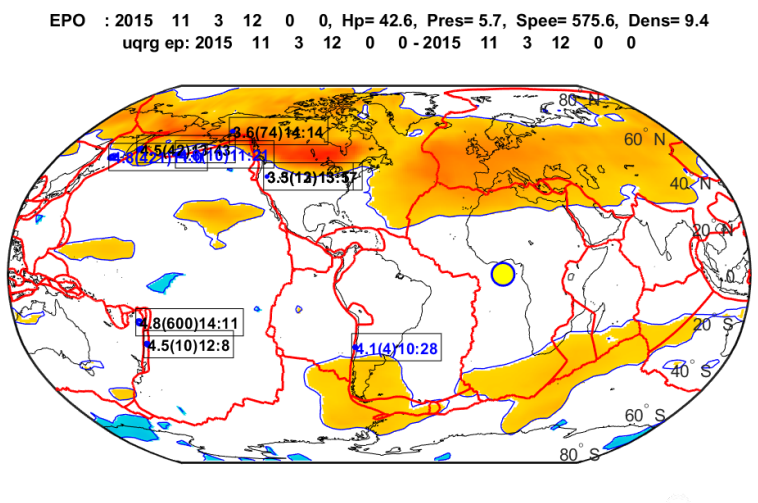
- Geomagnetic storms produce extensive TEC anomalies reaching different places, but their extrema again follow the specific places

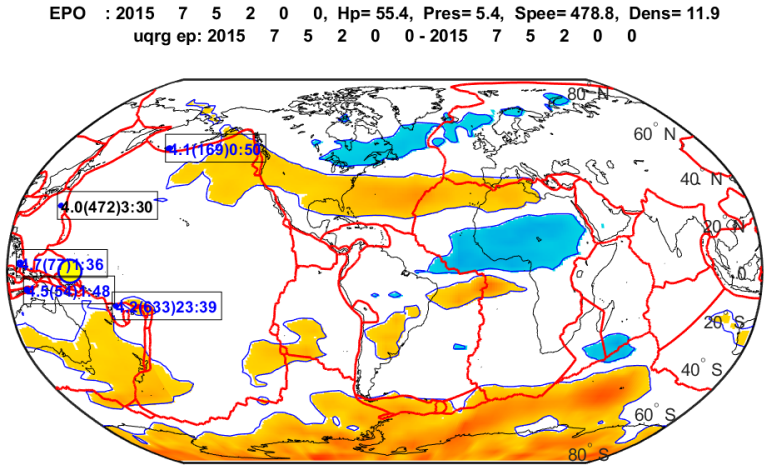


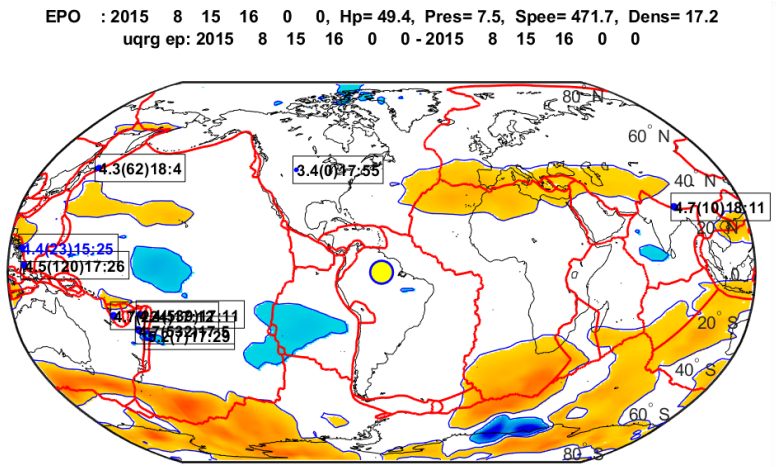
Simultaneous formation with high-latitude anomalies

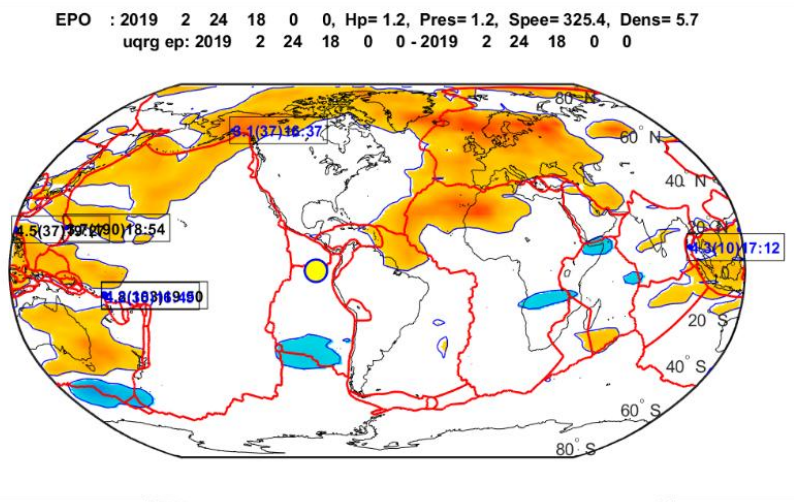
- The auroral regions reveal known TEC anomalies originating from high-latitude particle precipitation
- They occur simultaneously with those over tectonic plate boundaries
- In the horizontal view the former VTEC anomalies are looking as sliding to lower latitudes to „attracting” places at lower latitudes











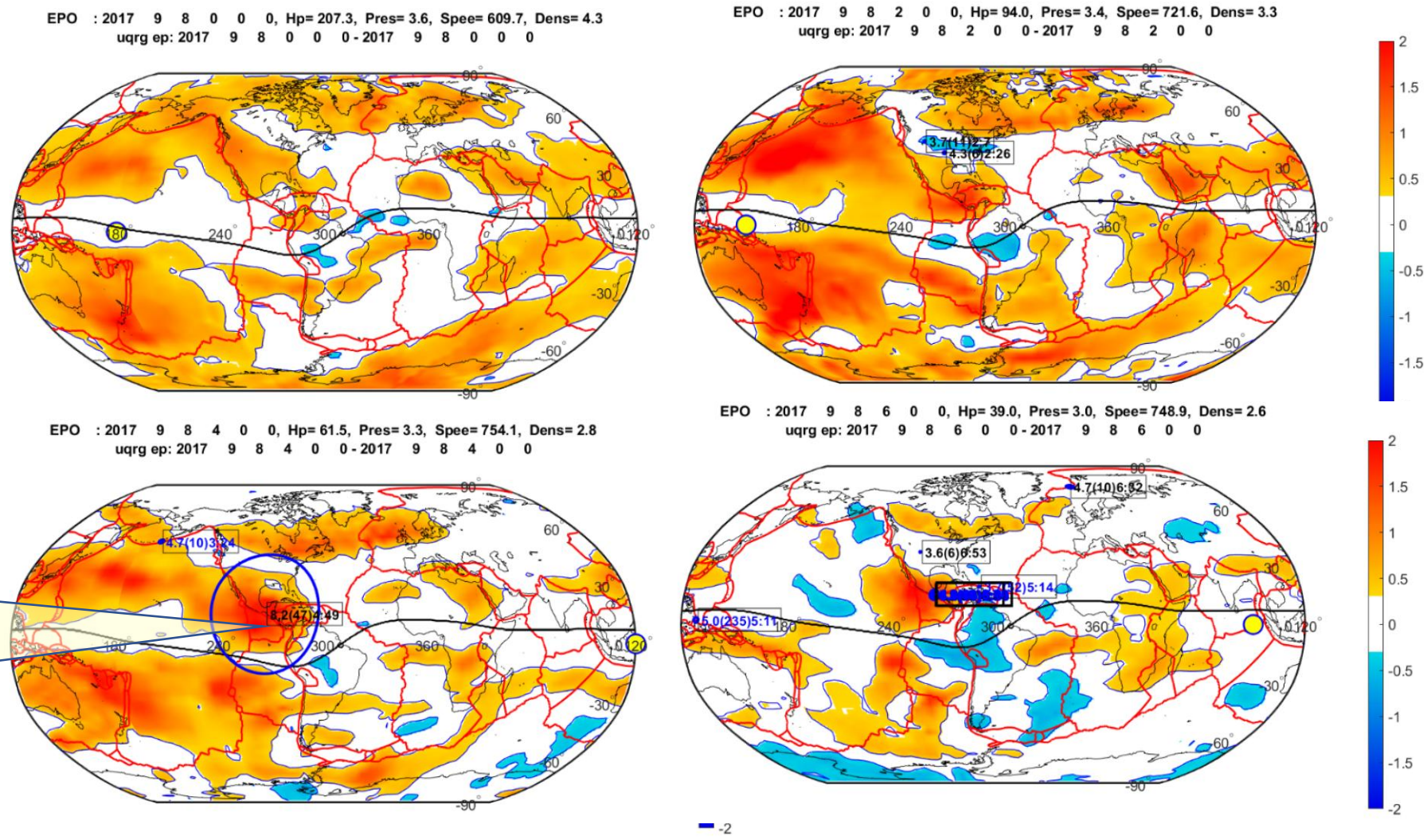
The strongest earthquakes

At the time of strong geomagnetic storm we can find extensive anomalies following the Sun on the dayside.

However, the anomaly over M8.2 earthquake in Mexico persists also during the nightime.

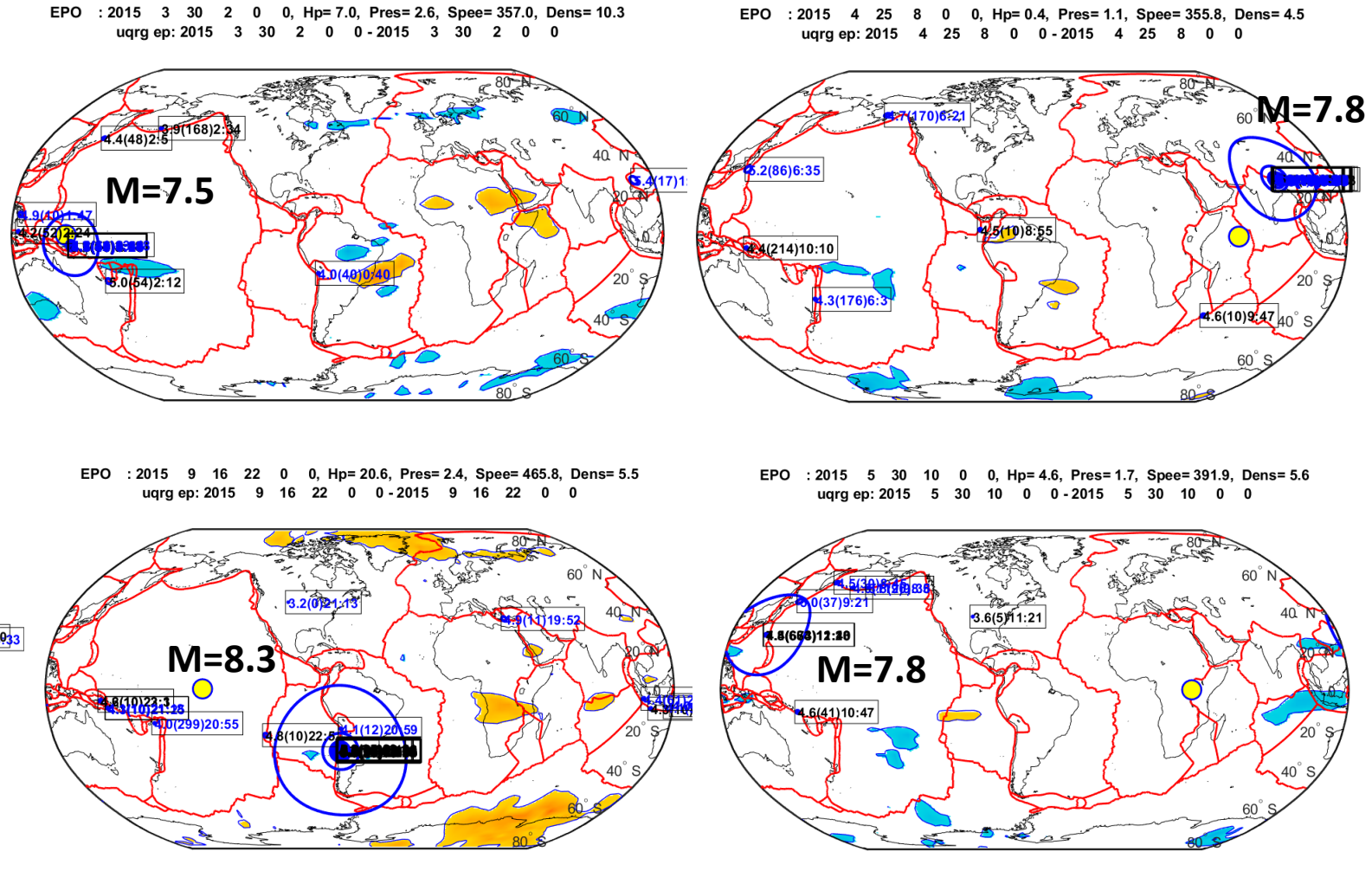
Plate boundary NA-CA (North American-Caribbean)

M=8.2 earthquake in Mexico



Other strongest earthquakes

- The time of the strongest earthquakes is often free from VTEC anomalies
- e.g. we had problems with finding case with strong dVTEC in 2015



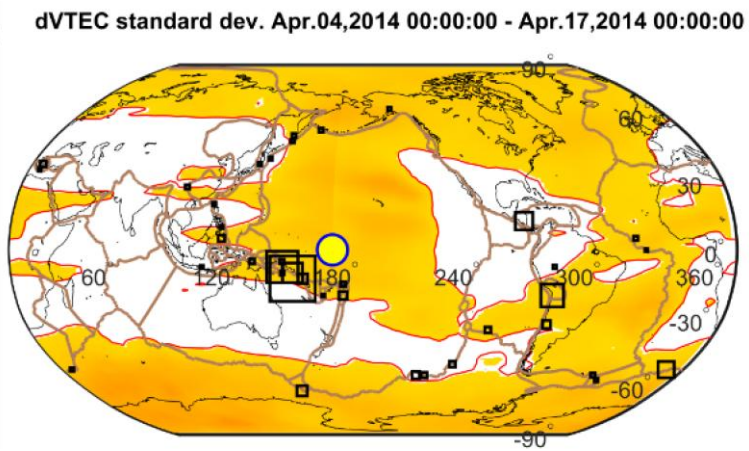
Averaged dVTEC compared to solar wind and cumulative seismic energy

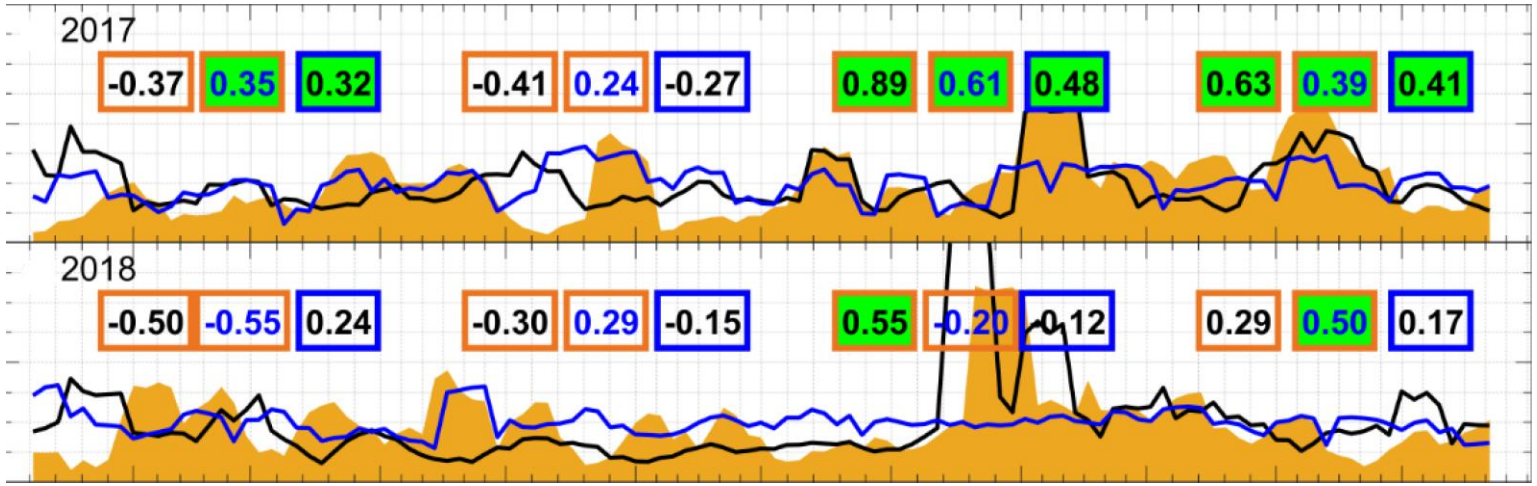
- Calculated are st. Dev. of dVTEC (14-day time window), SWP in time epochs (product of solar wind speed and proton density) and CSE in UQRG pixels (cumulative seismic Energy)

$$SdVTEC(d0,\varphi 0,\lambda 0)=\sqrt{\frac{2}{w\cdot 12}\sum_{d=d0-w/2,h=0UTC,2h}^{d0+w/2,h=24UTC}(dVTEC(d,h,\varphi 0,\lambda 0)-\mu)^2}$$

$$CSE(d0,\varphi 0,\lambda 0)=\sum_{\varphi=\varphi 0-1.25^\circ}^{\varphi 0+1.25^\circ}\sum_{\lambda=\lambda 0-2.5^\circ}^{\lambda 0+2.5^\circ}\sum_{d=d0-w/2}^{d0+w/2}\sqrt{10^{1.5M}+4.8}$$

- SdVTEC is a 14-day average, GdVTEC is its global average, two remaining values are also averaged in 14-day windows (and globally if not global directly)





GdVTEC — GCSE — GSWP

Jarmołowski W, Wielgosz P, Krypiak-Gregorczyk A, Milanowska B. 2026, An eight-year global look at correlations between total electron content, earthquakes and solar wind, Advances in Space Research 77(2), 2508-2521, **https://doi.org/10.1016/j.asr.2025.10.064.**

Data Availability

- The authors wish to thank the UPC IonSAT for UQRG GIMs available at https://cddis.nasa.gov/archive/gnss/products/ionosphere/
- The station GNSS data are downloaded from ftp://cddis.gsfc.nasa.gov/
- The earthquake series are downloaded from the service of United States Geological Survey available at: https://earthquake.usgs.gov/earthquakes/search/
- The OMNI datasets of solar wind parameters are downloaded from https://spdf.gsfc.nasa.gov/pub/data/omni/ (contact: Papitashvili N.)
- Tectonic plate boundaries are downloaded from data webpage: https://github.com/lcx366/PlateTectonic
- Dst indices are downloaded from the Data Analysis Center for Geomagnetism and Space Magnetism, Graduate School of Science, Kyoto available at: http://wdc.kugi.kyoto-u.ac.jp/dstdir/.

Conclusions/open issues

- The indicated diverging/transforming tectonic plate boundaries are suspected to participate in the lithosphere–ionosphere energy transfer.
- The formation of VTEC anomalies can be related to increased conductivity of the Earth in the indicated places, as their extrema repeat in the places of higher conductivity
- Their origin is suspected to be solar/geomagnetic, because they are large over thousands of kilometers and occur simultaneously with particle precipitation at high latitudes
- The conductivity increases from radon emmissions must be analyzed in parallel to the large-scale VTEC enhancements (smaller VTEC anomalies or parts of larger ones?)
- ~~Do the large-scale VTEC anomalies trigger the earthquakes?~~
  What is the regime/system of earthquake triggering linked with large-scale VTEC anomalies?
- Has descending part of solar cycle some meaning for the coupling and earthquakes?