Different several-day TEC variations over different regions at the same geomagnetic latitude

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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 previous research on specific VTEC anomalies concentrated over tectonic plate boundaries suggested possible coupling between the lithosphere and ionosphere.

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

- 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

Differential VTEC (dVTEC) - spatial context

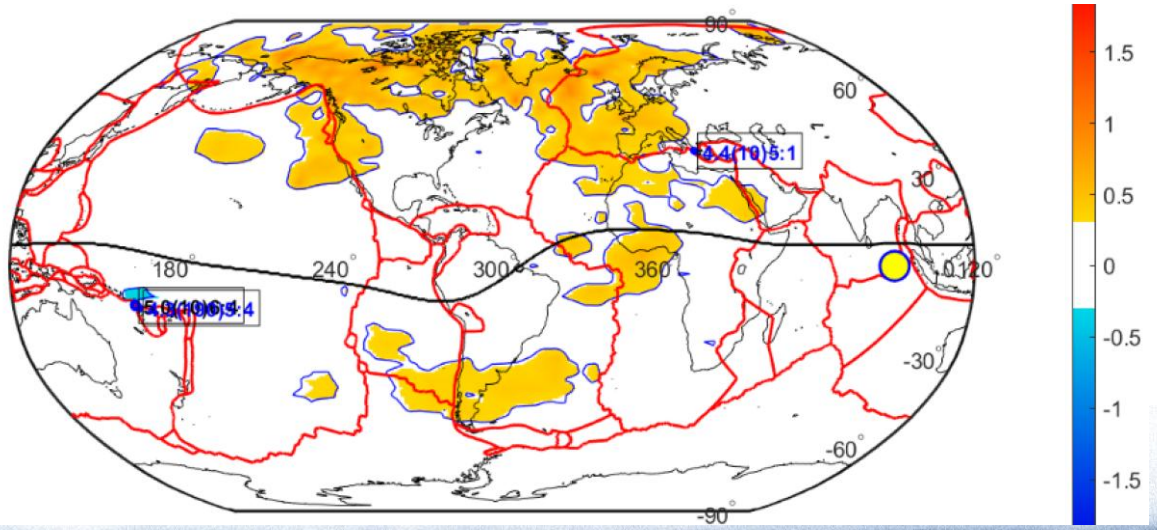
The applied GIMs are the Kriging-based UPC-IonSAT quarter-of-an-hour time resolution rapid global ionospheric maps (**UQRG**). The dVTEC maps are generated from UQRG VTEC maps by the differencing of the actual VTEC value and 9-day mean calculated at the same UTC epoch. This short 9-day window used in averaging assures elimination of potential periodicities

$$dVTEC(d0,h0,\varphi 0,\lambda 0) = \frac{VTEC(d0,h0,\varphi 0,\lambda 0) - VTEC_m(d0,h0,\varphi 0,\lambda 0)}{|VTEC_m(d0,h0,\varphi 0,\lambda 0)|}$$

where

$$VTEC_m(d0,h0,\varphi 0,\lambda 0) = \sum_{d=d0-4}^{d0+4} VTEC(d,h0,\varphi 0,\lambda 0)/9$$

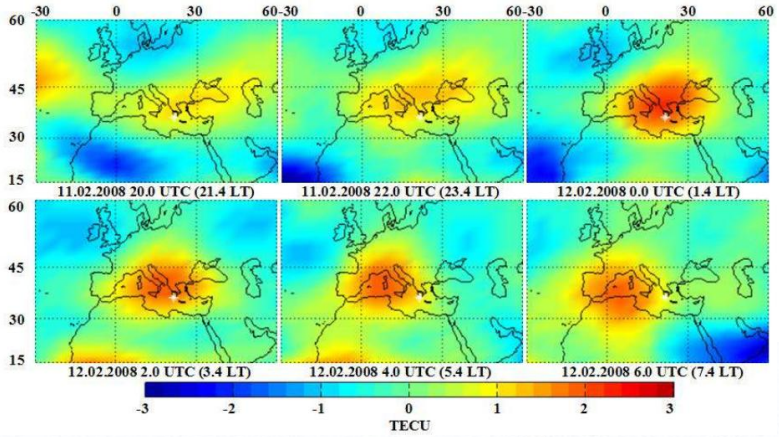
The terms d0 in days, together with h0 in hours, determine the day and UTC epoch of dVTEC map, whereas ϕ0 and λ0 refer to the node of dVTEC 2D grid.



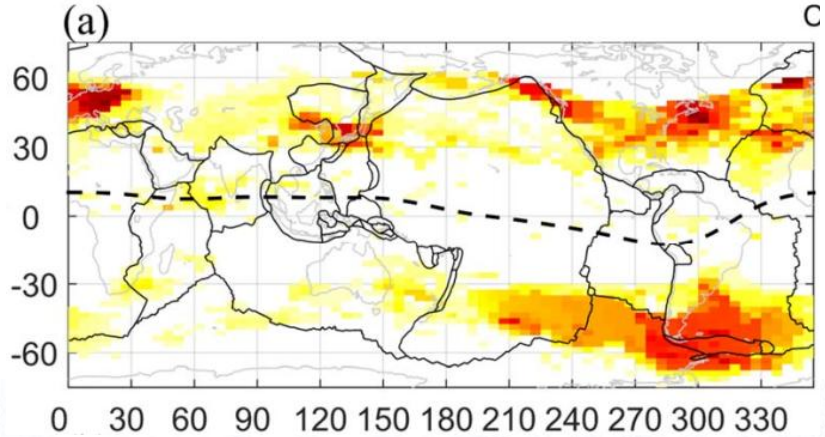
TEC anomalies in the previous studies

- 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

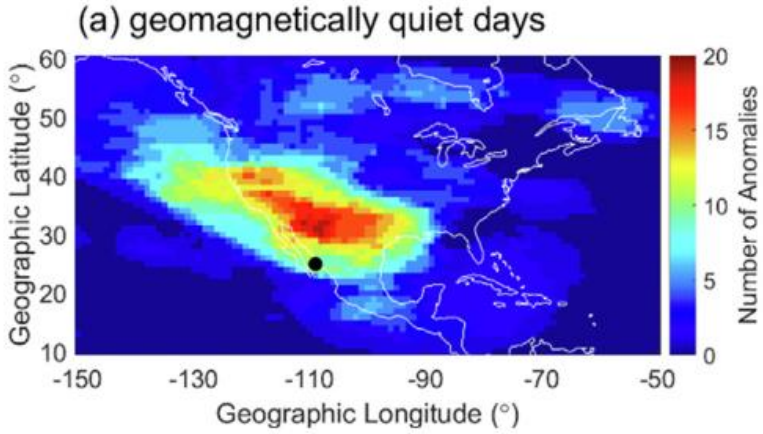
Pulinets, S.A., Davidenko, D.V. The Nocturnal Positive Ionospheric Anomaly of Electron Density as a Short-Term Earthquake Precursor and the Possible Physical Mechanism of Its Formation. Geomagn. Aeron. 58, 559–570 (2018). https://doi.org/10.1134/S0016793218040126



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.



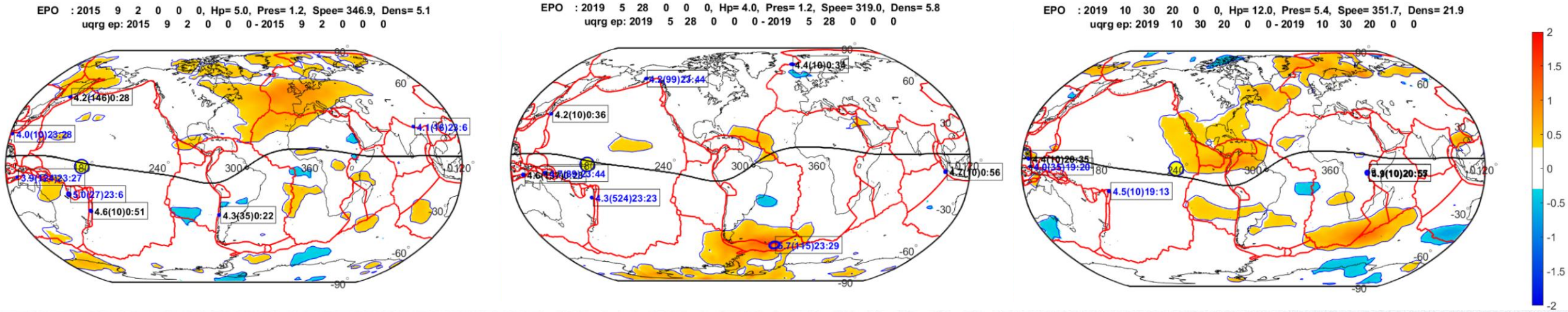
Park S.M., Ryu K. and Min K. (2021) Ionospheric anomalies related to strong earthquakes in North America as observed by TEC. Advances in Space Research 68, 4137–4154. https://doi.org/10.1016/j.asr.2021.07.026



TEC anomalies from the abovementioned previous studies found again

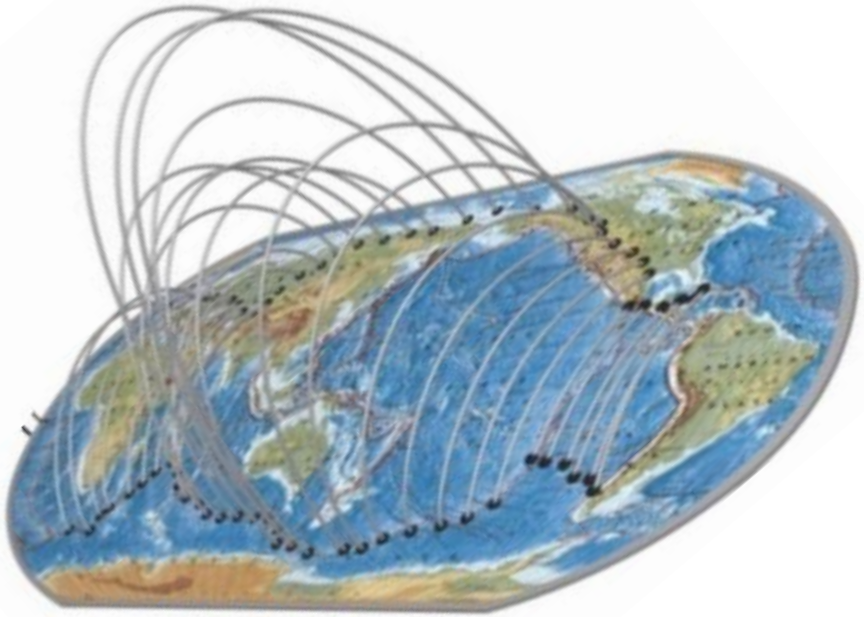
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- The colured part of contours shows VTEC anomalies (dVTEC) > 0.3
- The plot also shows the erthquakes within time window ±2.4 h from VTEC anomaly epoch
- You can find the same VTEC anomalies in reference papers by Pulinets et al. 2018, Sun et al.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



The role of geomagnetic field

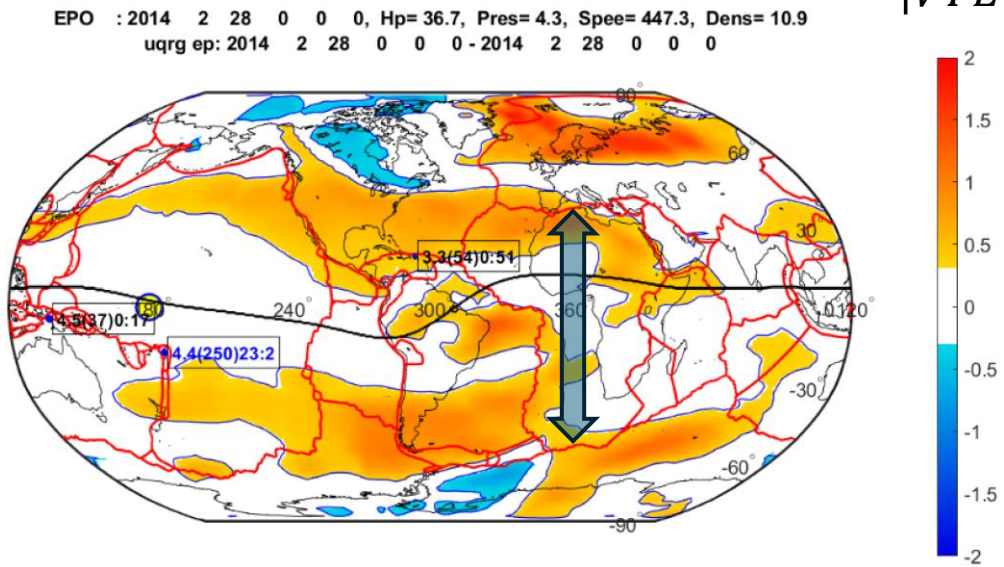
- Recent works present geomagnetic field lines (including newly created) as connecting magnetically conjugated sites nearby tectonic plate boundaries



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)

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

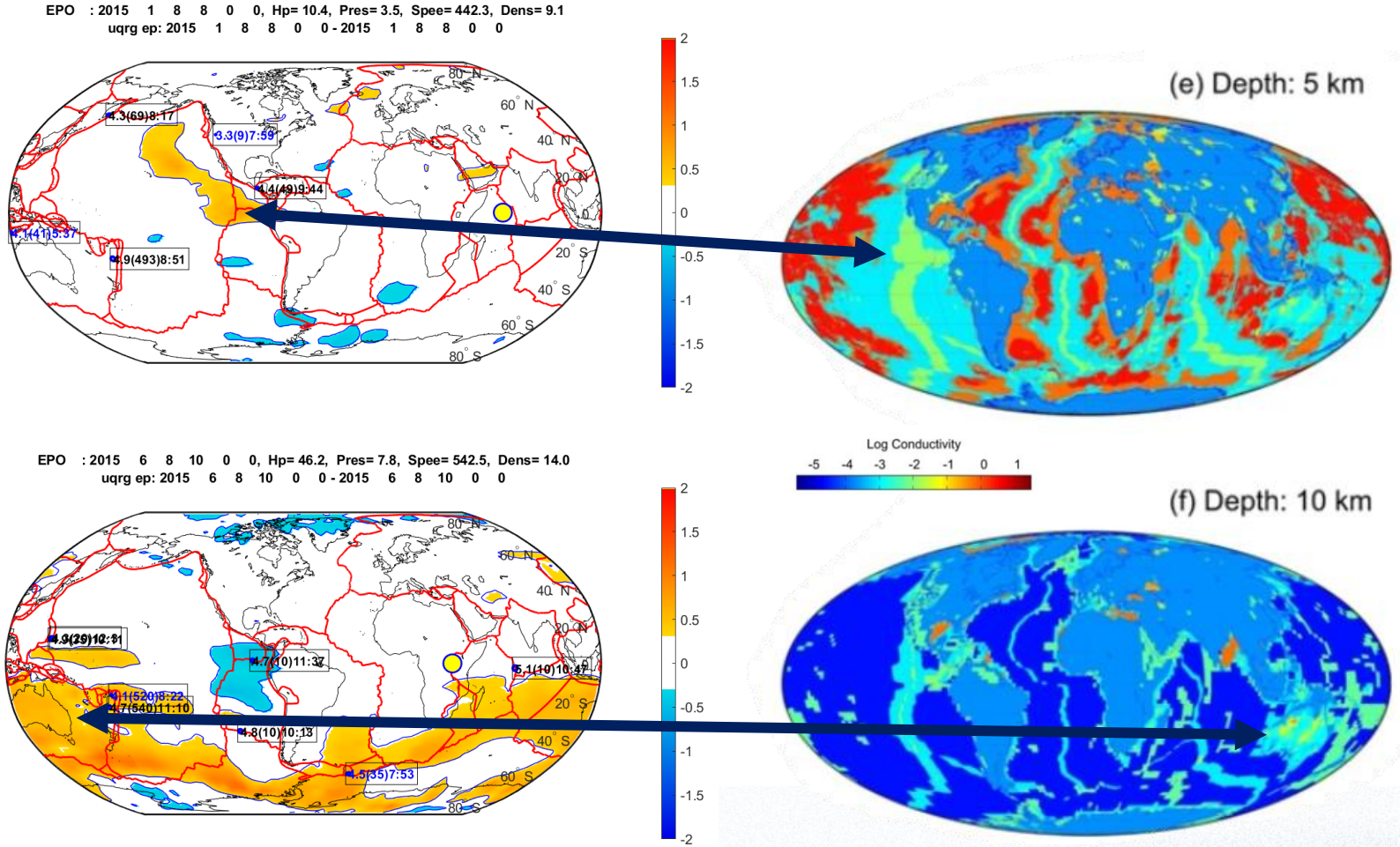


Wielgosz, P.; Jarmołowski, W.; Mazur, S.; Milanowska, B.; Krypiak Gregorczyk, A. Vertical Total Electron Content Enhancements and Their Global Distribution in Relation to Tectonic Plate Boundaries. Remote Sens. 2025, 17, 614. https://doi.org/10.3390/rs17040614

Conductivity of the Earth (different depths)

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- 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

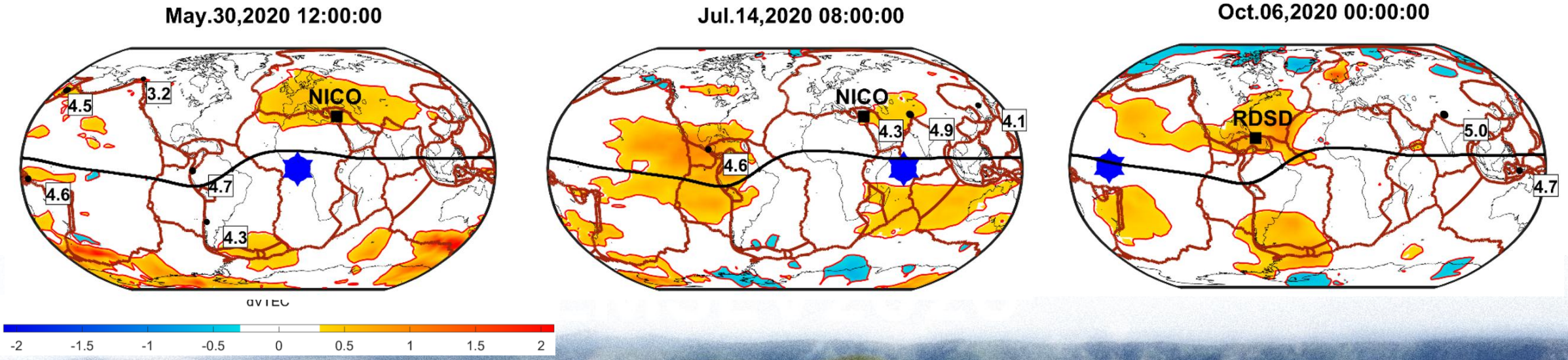


Alekseev, D., Kuvshinov, A. & Palshin, N. (2015). Compilation of 3D global conductivity model of the Earth for space weather applications. Earth Planet Space, 67, 108. https://doi.org/10.1186/s40623-015-0272-5

dVTEC over two different tectonic plate boundaries (EU-AF and NA-CA)

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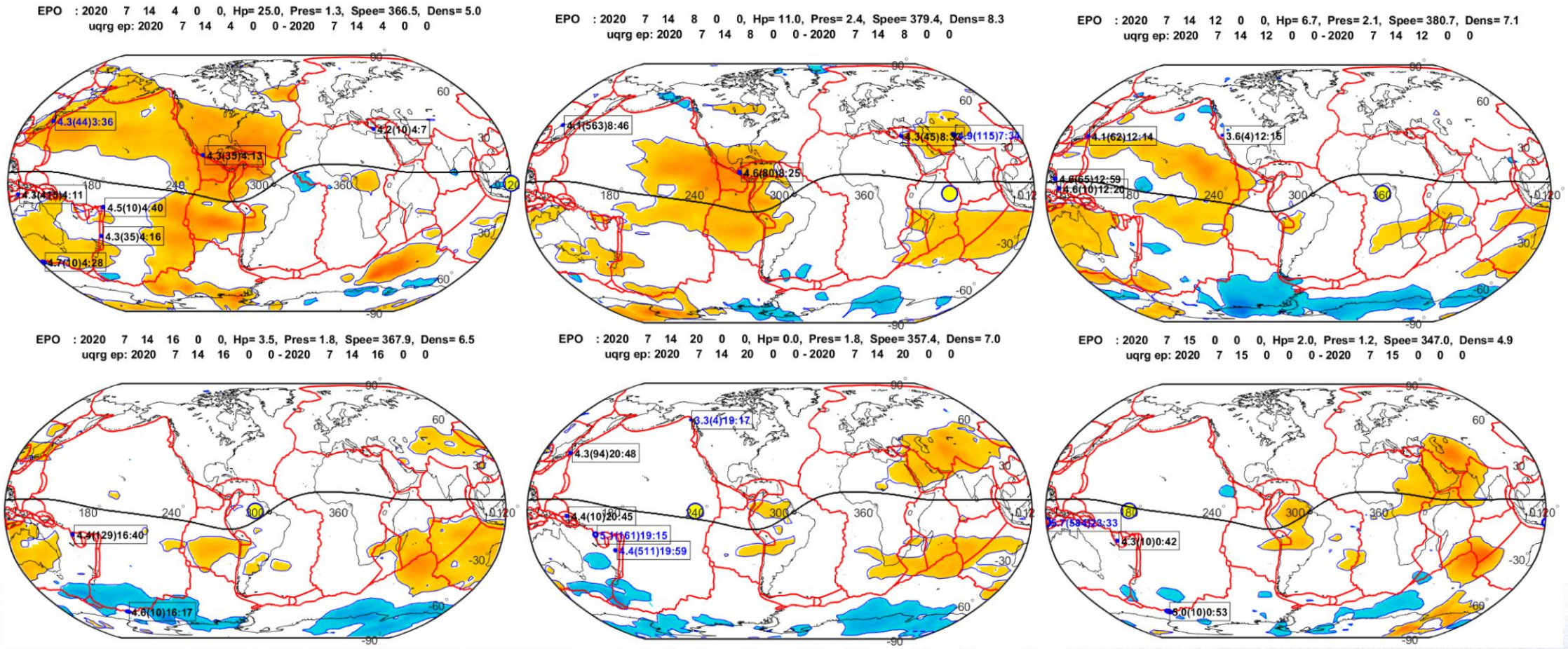
- This work analyses VTEC anomalies in 2020 over two tectonic plate boundaries located at very similar geomagnetic latitudes: the Eurasian-African tectonic plate boundary (EU-AF) and North-American-Caribbean (NA-CA) tectonic plate boundary.
- Three epochs of dVTEC are only shown to assure conciseness.
  The middle one shows presence of VTEC response over both tectonic plate boundaries/stations.
- The left one shows significant (>0.3) dVTEC only over EU-AF/NICO, and the right one only over NA-CA/RDSD



Evolution of dVTEC (anomaly) on 14 July 2020

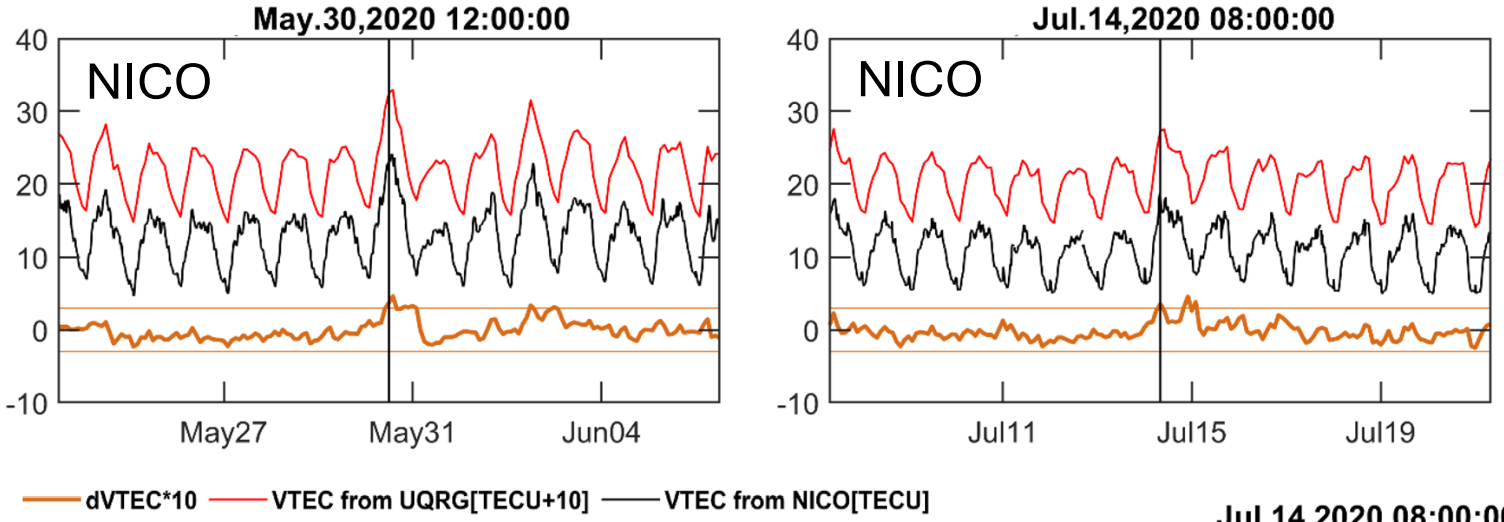
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ΕΘΝΙΚΟΝ ΑΣΤΕΡΟΣΚΟΠΕΙΟΝ ΑΘΗΝΩΝ NATIONAL OBSERVATORY ATHENS



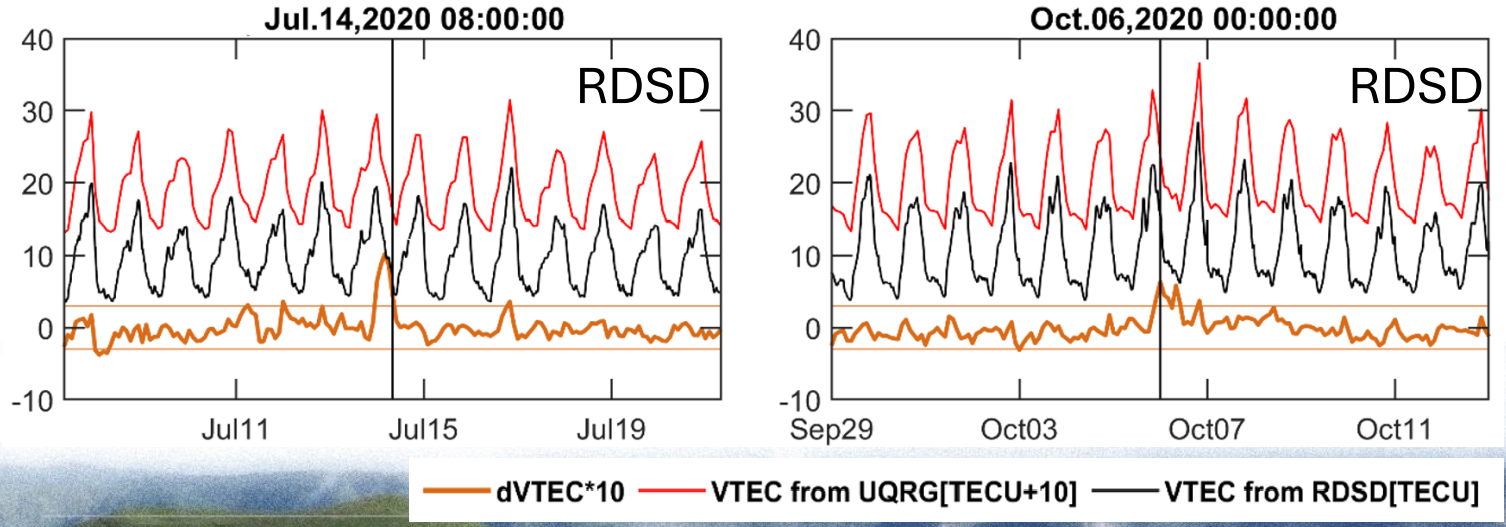
UQRG VTEC, station-based VTEC, and dVTEC (rescaled)

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- **dVTEC** time series interpolated at the positions of NICO and RDSD drawn as orange lines together with the 0.3 threshold shown as orange horizontal lines (both multiplied by 10 for comparison with VTEC)

- The vertical black lines determine the epochs of dVTEC snapshots
- **black lines** are **station-based** VTEC
- red lines represent **UQRG** interpolated at NICO and RDSD, respectively

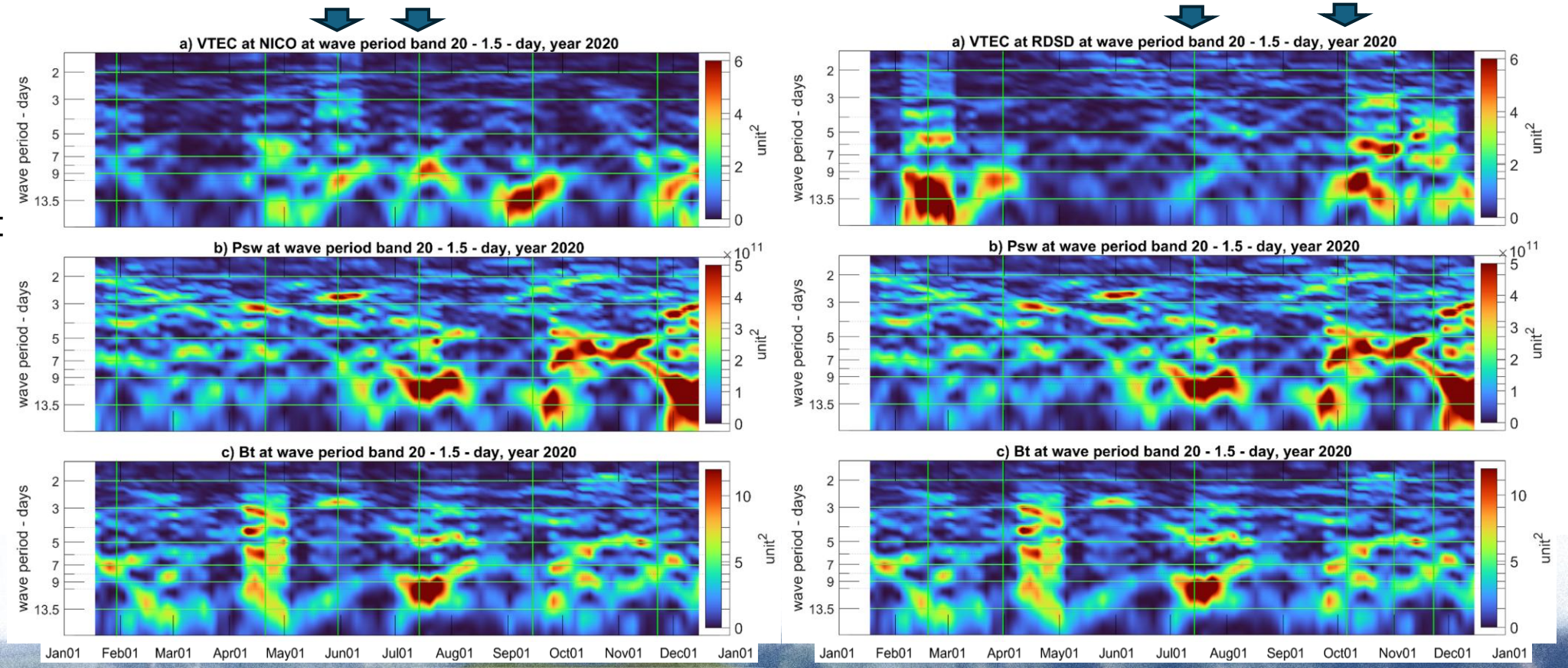


Auto spectral time-frequency analysis

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- The first objective is to determine **inter-diurnal time-frequency scales** of VTEC variations
  The second objective is investigation of resonant frequencies between **VTEC and solar wind parameters** (**Psw, Bt**)
- More strong dVTEC moments are marked (6 yearly), but we analyse only three here (arrows)

- Several-hour VTEC peaks are easy to identify by naked eye, but several-day increases have weaker amplitude and are **masked by diurnal and other variations**



M8.2 earthquake in Mexico in 2017

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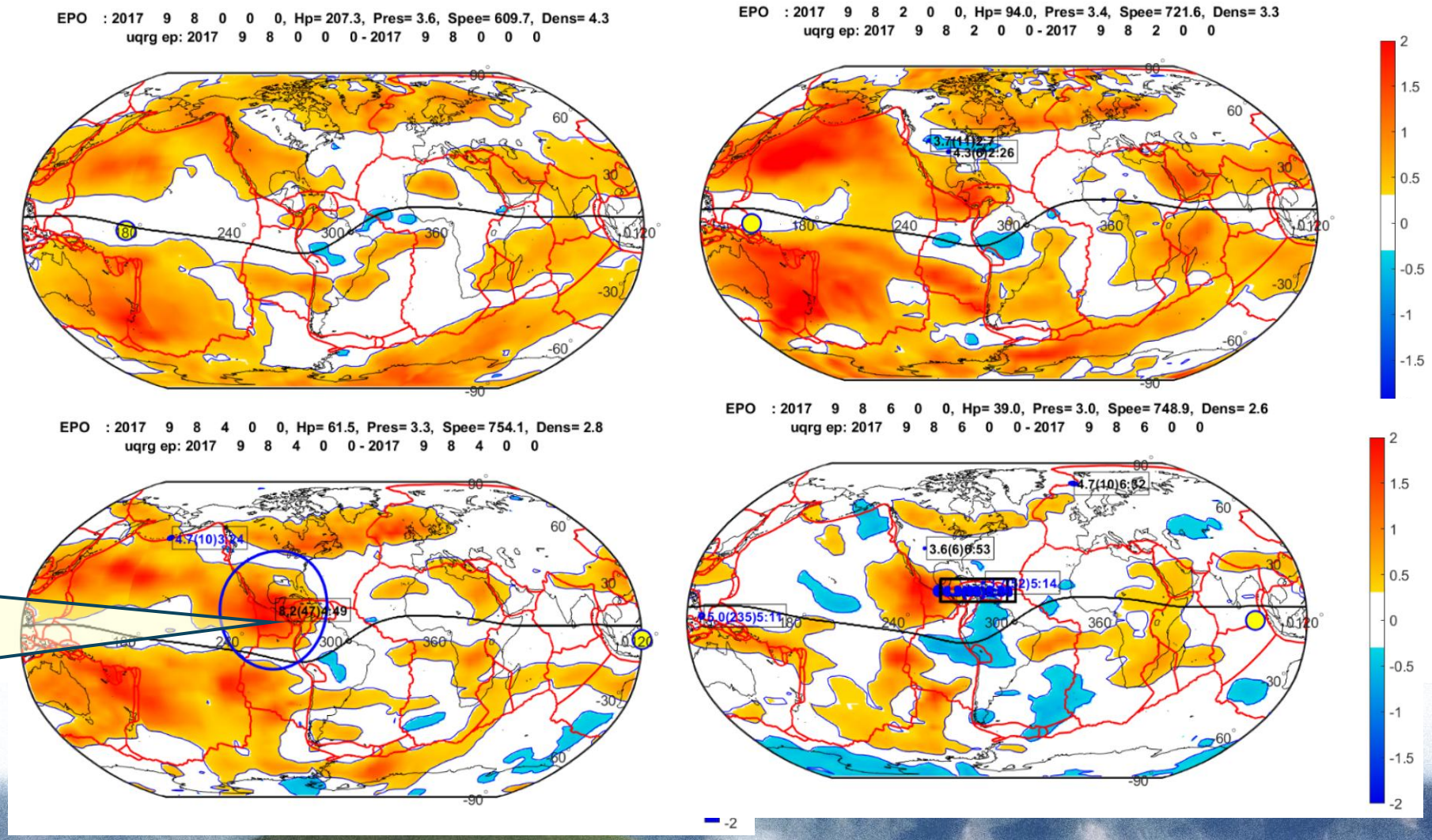
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At the time of strong geomagnetic storm we can find extensive anomalies following the Sun on the dayside.

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

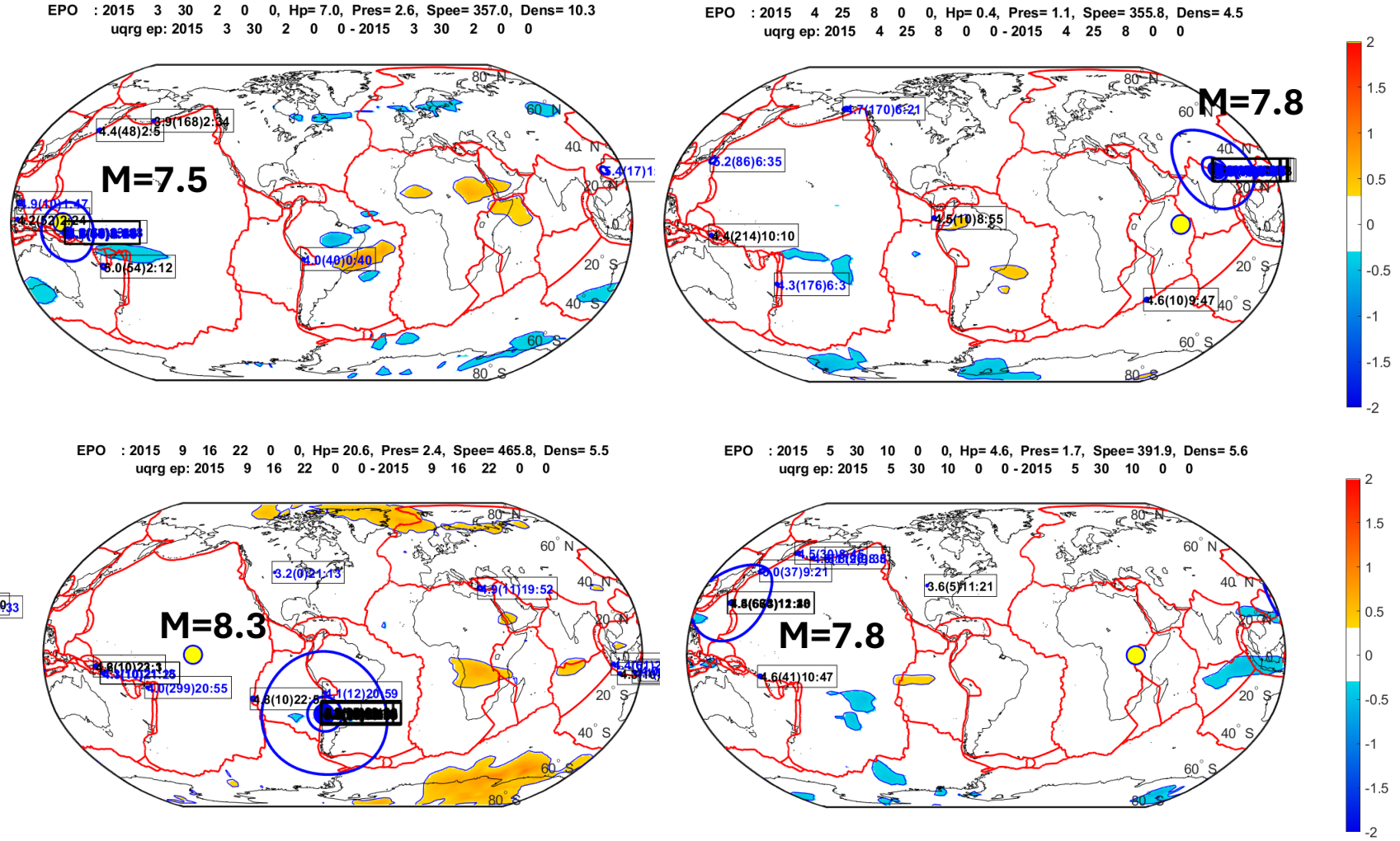
Plate boundary NA-CA (North American-Caribbean)

M=8.2 earthquake in Mexico



Other strong 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

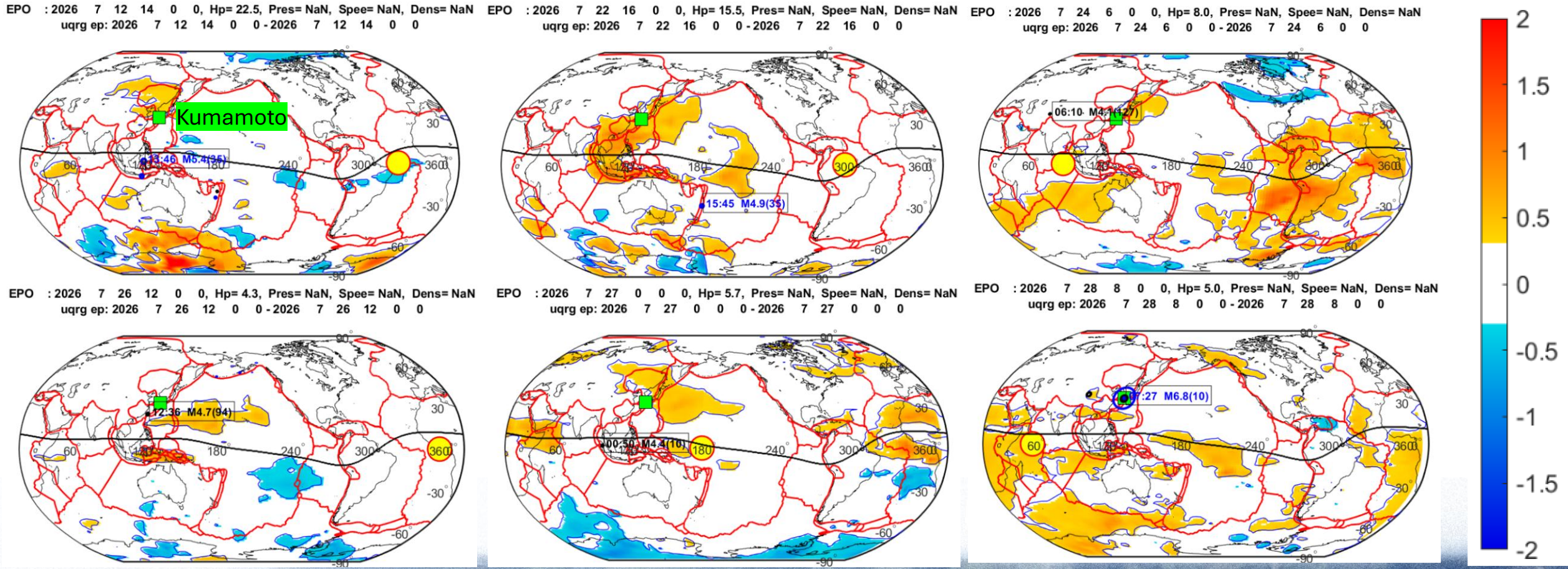


Before M6.8 earthquake in Kumamoto in 2026

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- Different days before M=6.8 earthquake show pronounced dVTEC anomalies
- Presented anomalies are instantaneous, but often represent longer (weaker) VTEC increase



August 24-28, 2026, Kumamoto, Japan

Averaged dVTEC compared to solar wind and cumulative seismic energy (2017, 2018)

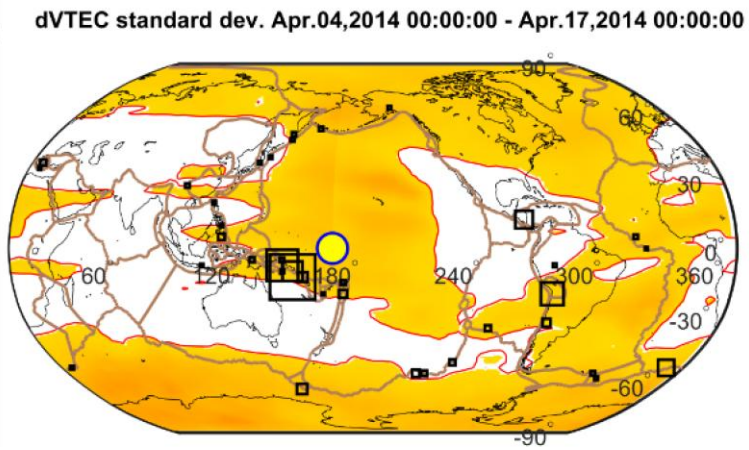
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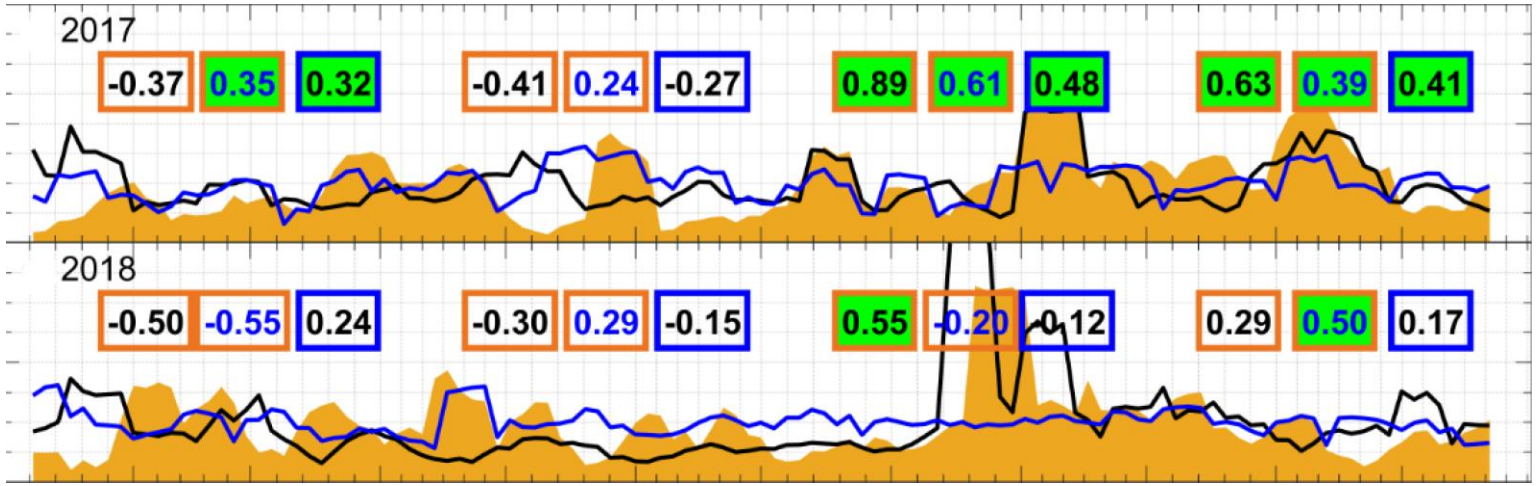
- Calculated are st. Dev. of dVTEC (14-day time window), Solar wind parameter (SWP) in time epochs (product of solar wind speed and proton density) and CSE in UQRG pixels (cumulative seismic Energy)

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

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

- 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)





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.**

GdVTEC — GCSE — GSWP

Acknowledgements

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Data Availability Statement

- 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

Conclusions/open issues

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- 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?
- Is descending part of the solar cycle important for the coupling and earthquakes?

