Different frequency-time characteristics of total electron content anomalies over different tectonic plate boundaries

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Abstract

- **Large vertical total electron content (VTEC) anomalies** are typically linked to **geomagnetic storms**, but their common occurrence with strong earthquakes has been also reported in the literature.
- The **UQRG VTEC maps** from the Polytechnic University of Catalonia (UPC) IonSAT group are applied to analyze detailed **spatial characteristics** of VTEC anomalies

  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 **short-term Fourier** transform (STFT) is applied to analyze evolutionary power spectral density (PSD) of **VTEC time series** from GNSS stations and **solar wind parameters**.
- The **cross-spectral analysis** of VTEC time series and solar wind parameters is used to find **resonant inter-diurnal signals**.
- **Low-pass filtering** is suggested for space weather purposes, as assuring notable correlations within a **limited waveband** between VTEC and space weather parameters

Differential VTEC (**dVTEC**) - spatial context

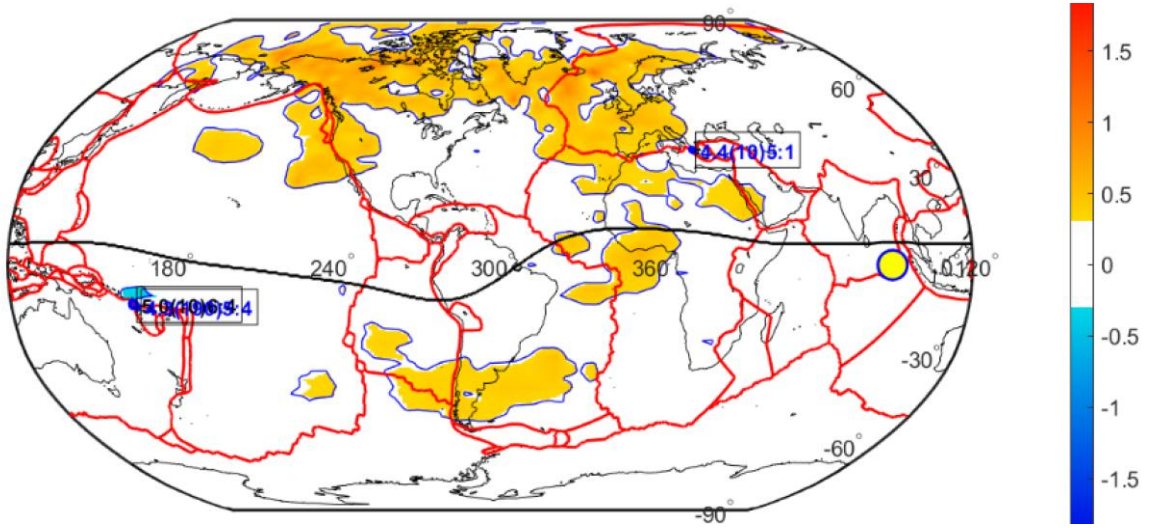
The applied GIMs are the Kriging-based UPC-IonSAT quarter-of-an-hour time resolution rapid global ionospheric maps (**UQRG**). The dVTEC maps are generated from UQRG VTEC maps by the differencing of the actual VTEC value and 9-day mean calculated at the same UTC epoch. This short 9-day window used in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

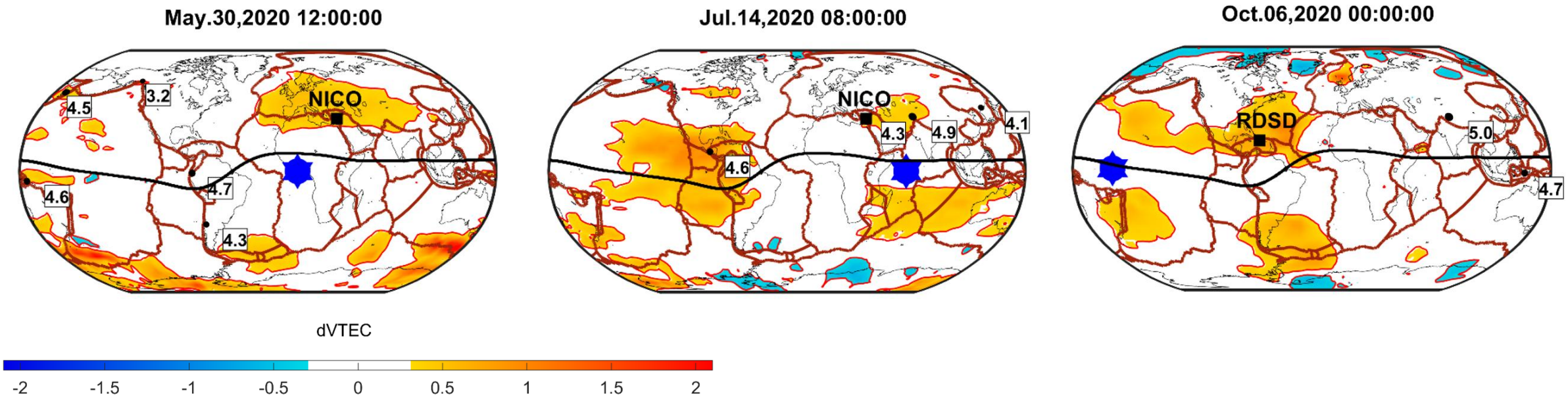
$$VTEC_m(d0,h0,\varphi 0,\lambda 0) = \sum_{d=d0-4}^{d0+4} VTEC(d,h0,\varphi 0,\lambda 0)/9$$

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.

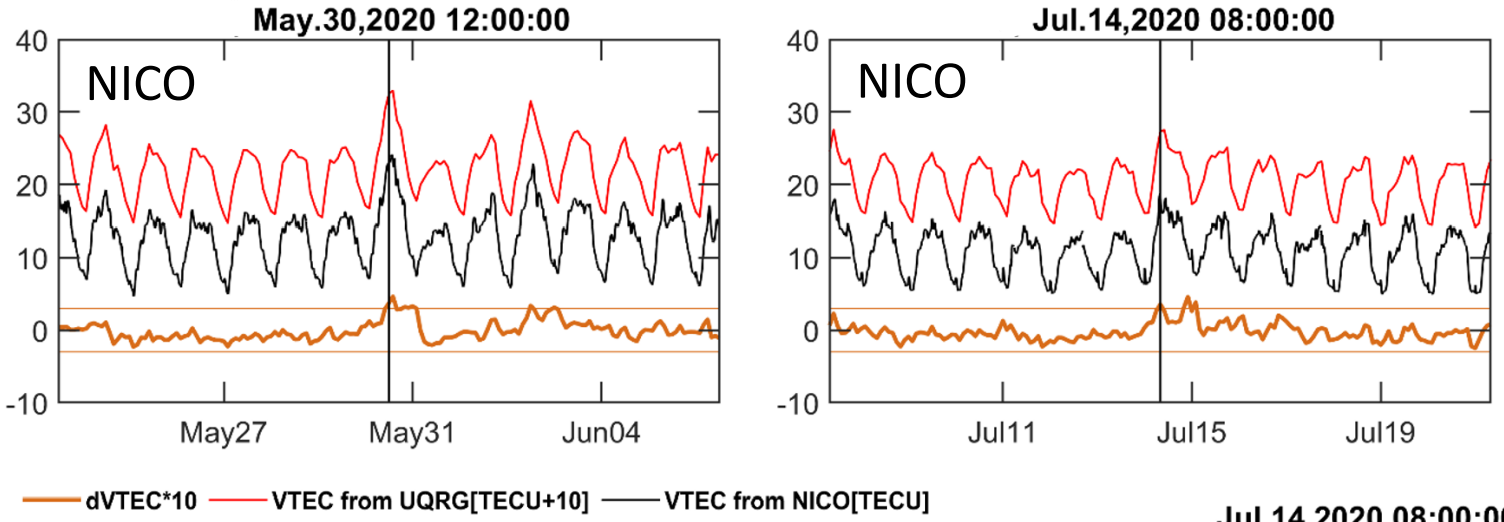


dVTEC over different tectonic plate boundaries (EU-AF and NA-CA)

- 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

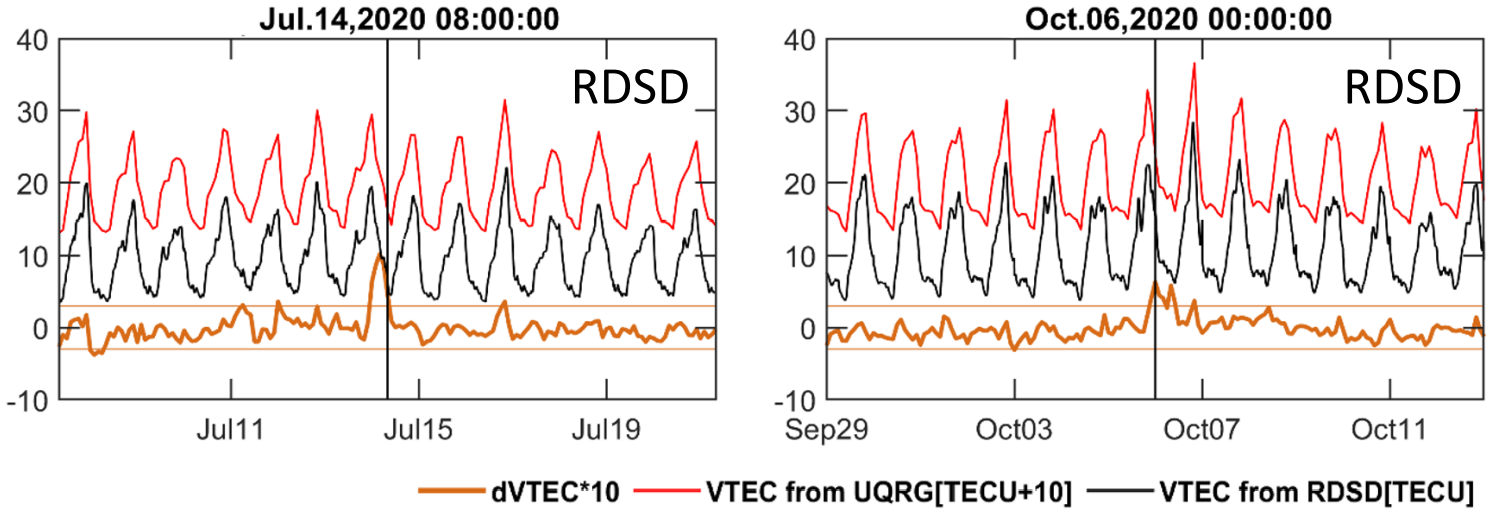


UQRG VTEC, station-based VTEC, and dVTEC (rescaled)



- **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)

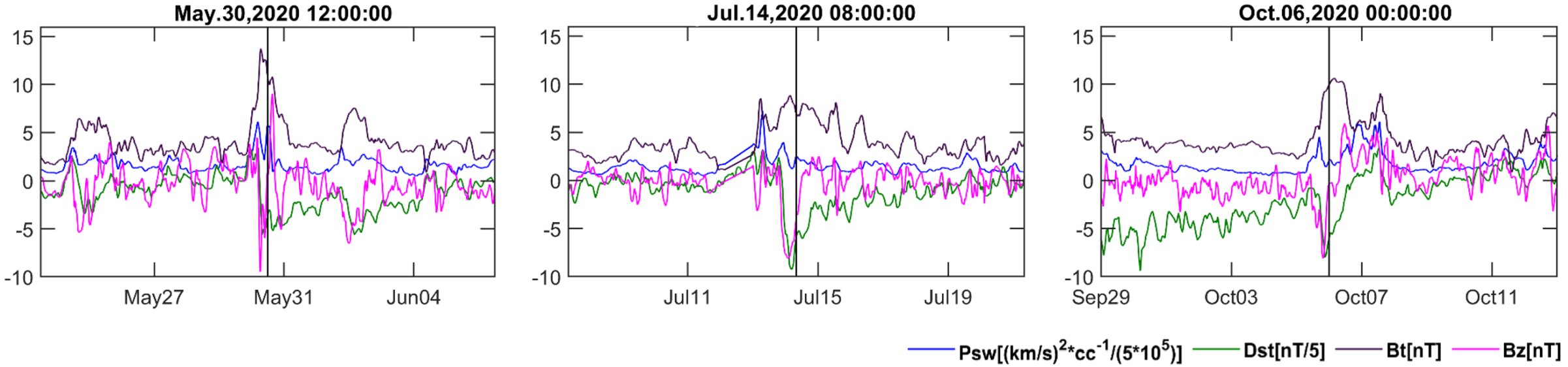
- The vertical black lines determine the epochs of dVTEC snapshots
- **black lines** are **station-based** VTEC
- red lines represent **UQRG** interpolated at NICO and RDSD, respectively



Space weather parameters during selected moments of pronounced dVTEC

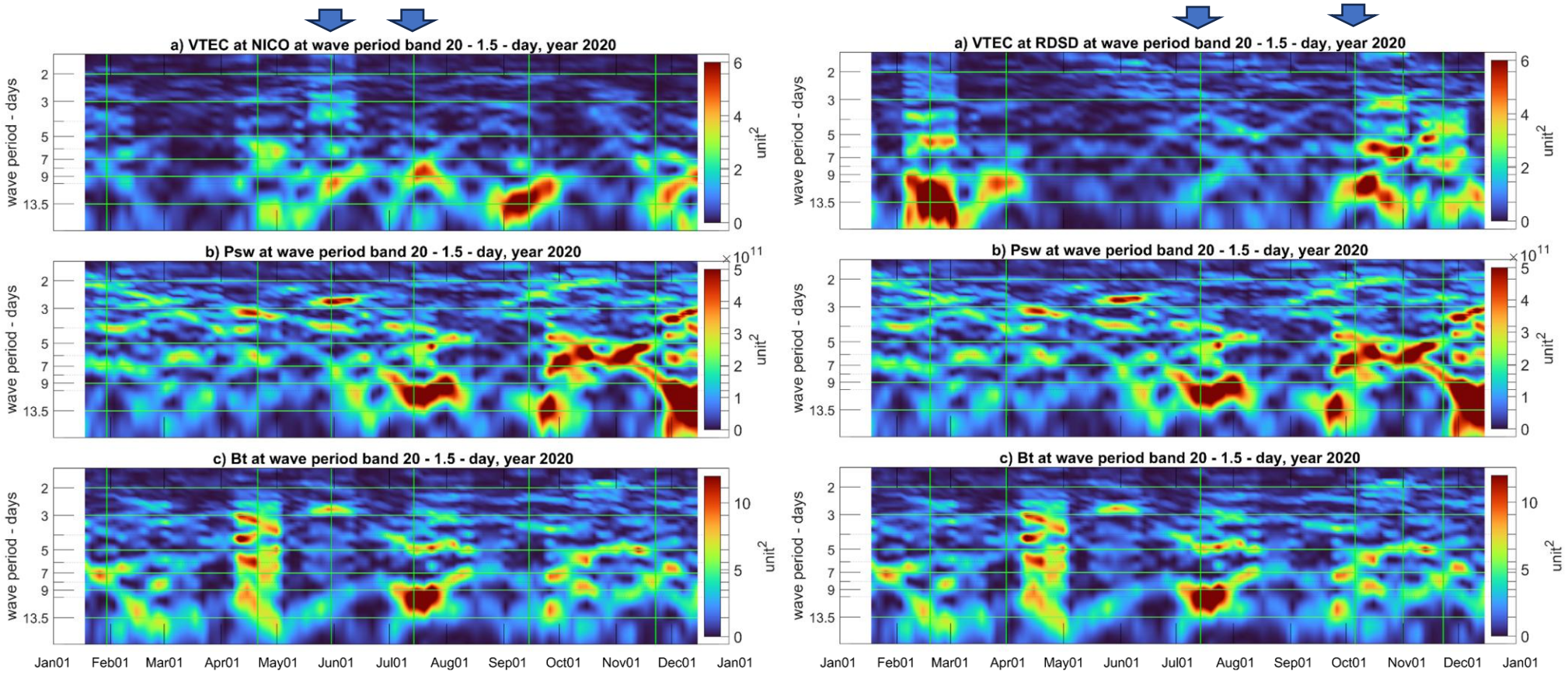
- The parameters representing solar magnetic field (detected by solar probes – OMNI product) include **Bt** and **Bz**
- The equatorial Earth's magnetic field component is represented by **Dst** index
- The electric field parameter of the solar wind applied here is **Psw** (solar wind dynamic pressure)

- **30 May** – M-class solar flare, a dense and slow-moving stream of solar wind hits Earth
- **14 July** – CME over the Sun's eastern limb, probably a farside event, solar flare alerts
- **6 October** – southward Bz allowed for solar wind flow



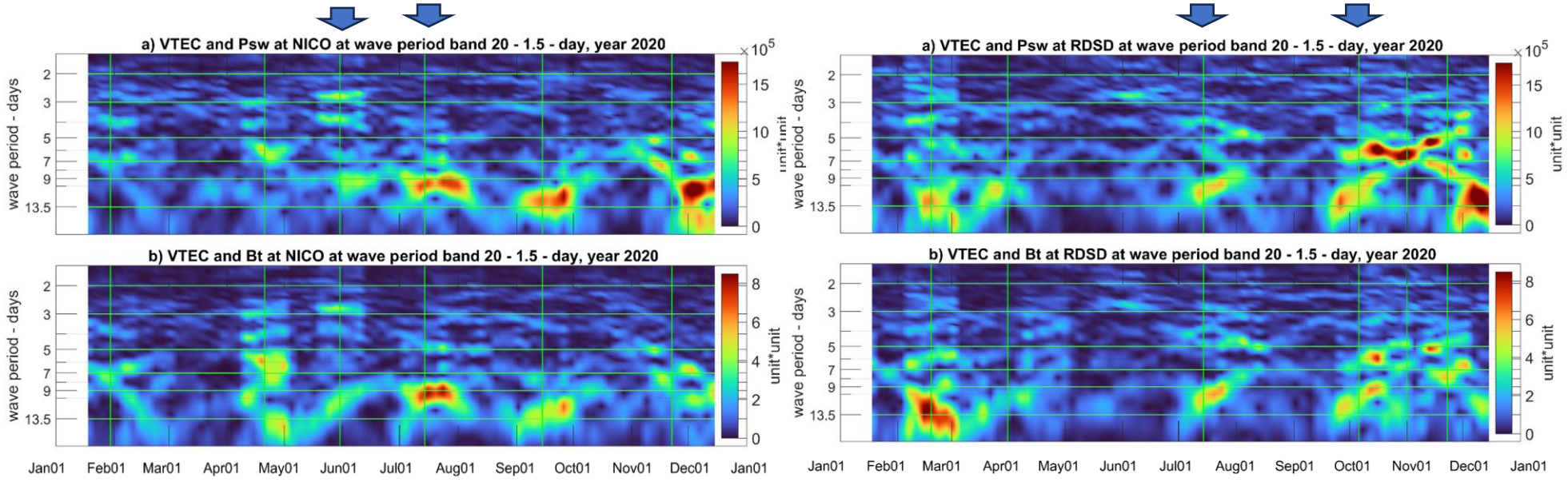
Auto spectral time-frequency analysis

- The first objective is to determine **inter-diurnal time-frequency scales** of VTEC variations from station-based VTEC over NICO and RDSD
- 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, but also sudden increases of solar wind parameters are easy to identify by naked eye, but several-day increases have weaker amplitude and are **masked by diurnal and other variations**



Cross-spectral time-frequency analysis

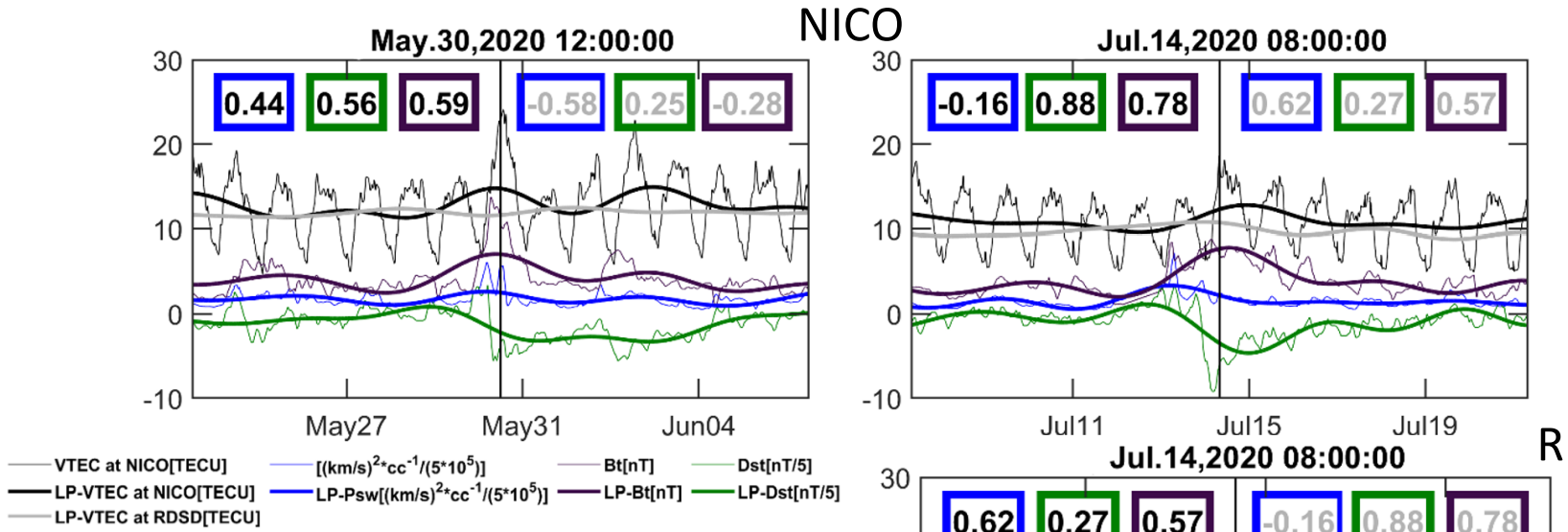
- The evolution of CIR-driven storms takes up to 6-7 days, the evolution of CME-driven ones is shorter. The solar minimum in **2020 is represented more by CIRs** and weak solar flares, than by CME.
- The spectrograms and cross-spectrograms prove **mostly 5-14 day wave periods** of evolution of strong and extensive anomalies over EU-AF and NA-CA tectonic plate boundaries
- several-day VTEC changes detectable **over NICO are mostly non-repeating over RDSD** and reversely, despite only 6-hour separation in longitude
- dVTEC on **30 May** is characterized by strong resonant inter-diurnal VTEC variation **only over NICO** and Psw variations at the same frequencies
- 14 July shows strong VTEC response to solar wind over NICO and weaker over RDSD
- **6 October** brings strong response over **RDSD only**



Low-pass filtering, correlation

- The **VTEC** includes a dominating diurnal signal in the spectrum, whereas the **Psw** and **Bt** include strong rapid several-hour variations, but they can coincide better at inter-diurnal wave periods
- Knowing their resonant wave periods we can set low-pass filtering bound for VTEC, Psw and Bt to 3 days

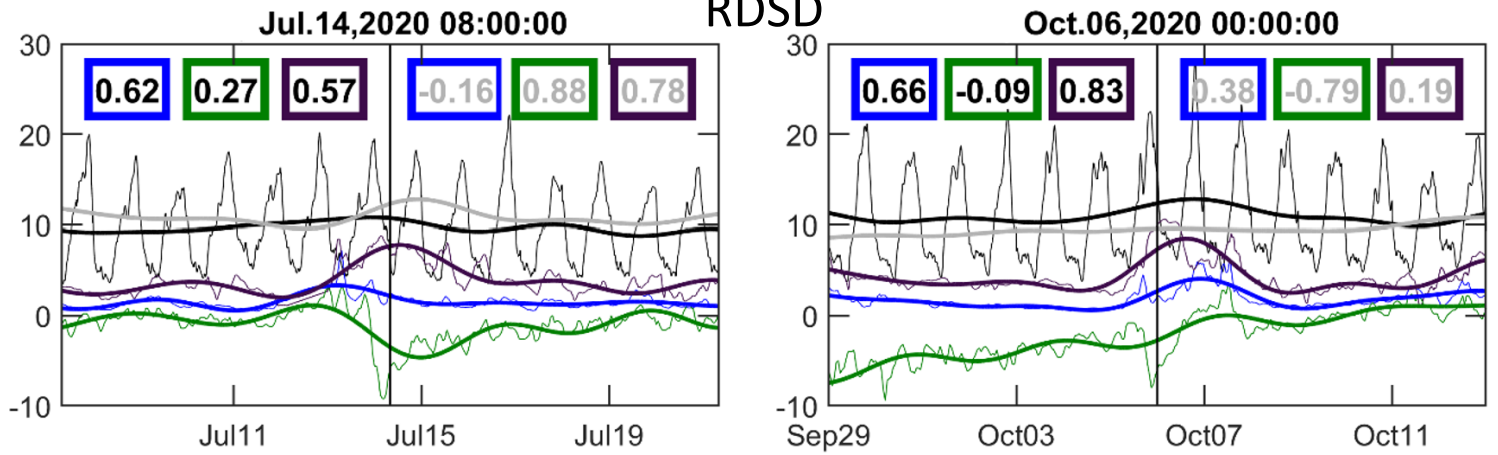
NICO



- Pearson Correlation Coefficients (PCC) are calculated for the pairs of **VTEC (black), Psw (blue), Bt (Purple)** and reverse Dst (green). Grey is VTEC from the second station

- original VTEC, Psw and Bt are shown as thin lines, whereas **low-pass filtered signals are presented as bold lines** of the same color

RDSD



Data Availability

- 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/
- 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/.

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Conclusions/open issues

- The sizes of TEC anomalies suggested their **solar origin** from the very beginning
- Extreme dVTEC occur at **different time** in the ionosphere over two different tectonic plate boundaries located **at the same geomagnetic latitude** and separated by 90° of longitude
- Derived **frequency-time characteristics are different** at different GNSS stations and linked with previously studied large-scale VTEC variations
- The spectrograms and cross-spectrograms prove this, as they reveal **resonant several-day** wave periods, which **several times a year** happen in VTEC and solar wind parameters
- The extreme peaks of dVTEC in the selected days **occur during a longer several-day VTEC increase** driven by the solar activity increase. Therefore, the influence of solar wind direction on dVTEC regionality is doubtful.
- Solar wind seems to be main energy source for high dVTEC, but **geographical location and extent of dVTEC** anomalies suggest lithospheric/magnetospheric participation in the particle precipitation process