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Spectral analysis of local ground-based GNSS-derived TEC time series in view of its' Sensitivity to Earthquakes in Aegean region (TECSEA)

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PITHIA-NRF Second TNA User Meeting, Brussels, 5 June 2025

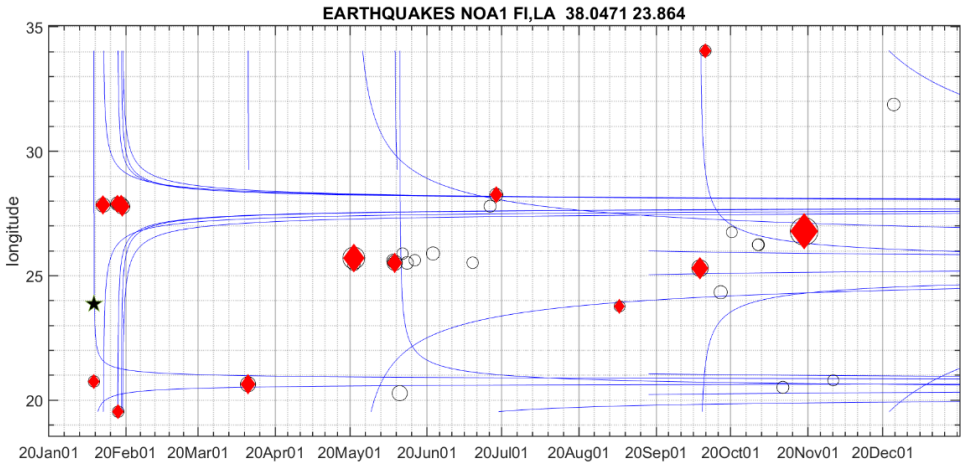
Sensitivity of VTEC – TECSEA

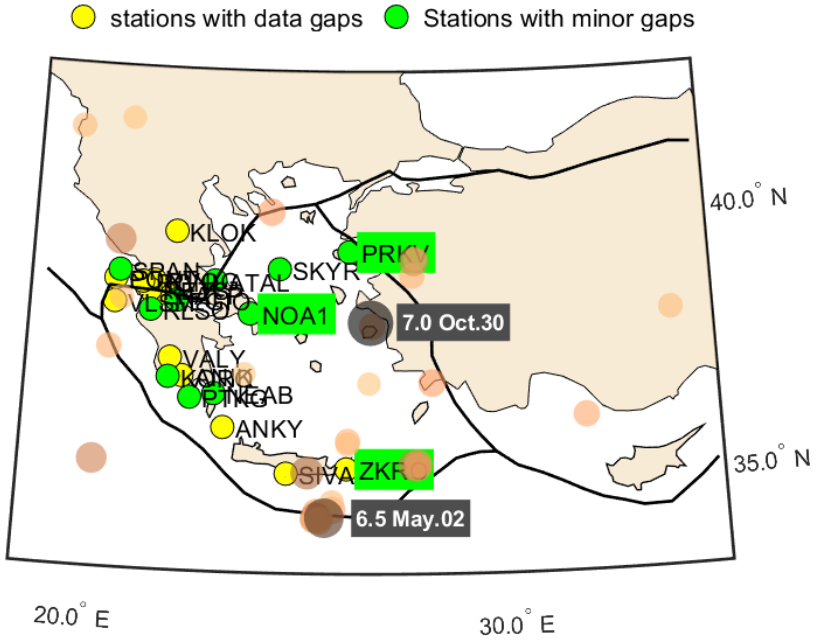
Objectives

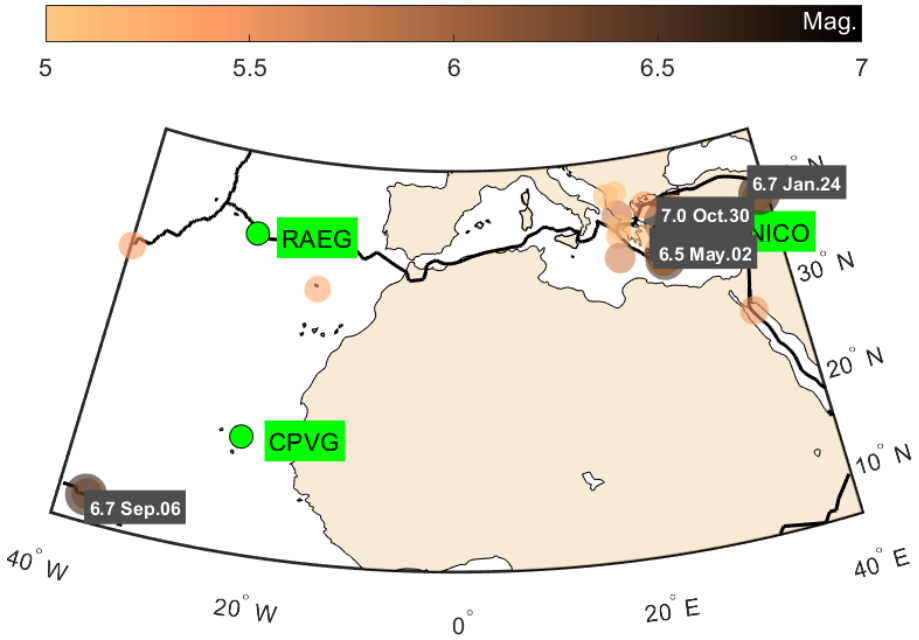
- The advantage of ground-based ionospheric data in comparison to satellite data is their good temporal resolution and fixed location assuring homogeneity of time series
- Several authors presented examples of **intra-diurnal** variations recorded in several-hour data series from GNSS stations nearby earthquakes (Sunil et al. 2015, Manta et al. 2020). Occhipinti et al. (2013) and Rolland et al. (2011) proceeded even further, and starting from the spectrogram of TEC time series they attempted to determine different spectral patterns for different types of disturbing waves.
- We do not analyse ionospheric activity close to the earthquakes nor the patterns of different perturbations. We analyse the ionosphere constantly over by the time-frequency analysis of **inter-diurnal (several-day)** and **intra-diurnal (several-hour)** wave periods in VTEC from the local stations of National Observatory of Athens (NOA)
- The study includes preliminary assessment of VTEC signal sensitivity to solar radiation and seismicity at different frequency bands, which is very complex.

The earthquakes in the region and outside

- Several selected separated IGS stations are used in the analysis of VTEC variations at different frequencies
- The objective is to check what is the extension of observed variations – therefore also 2 external stations
- Preliminary declustering was applied (but it is uncertain if it should be ..)

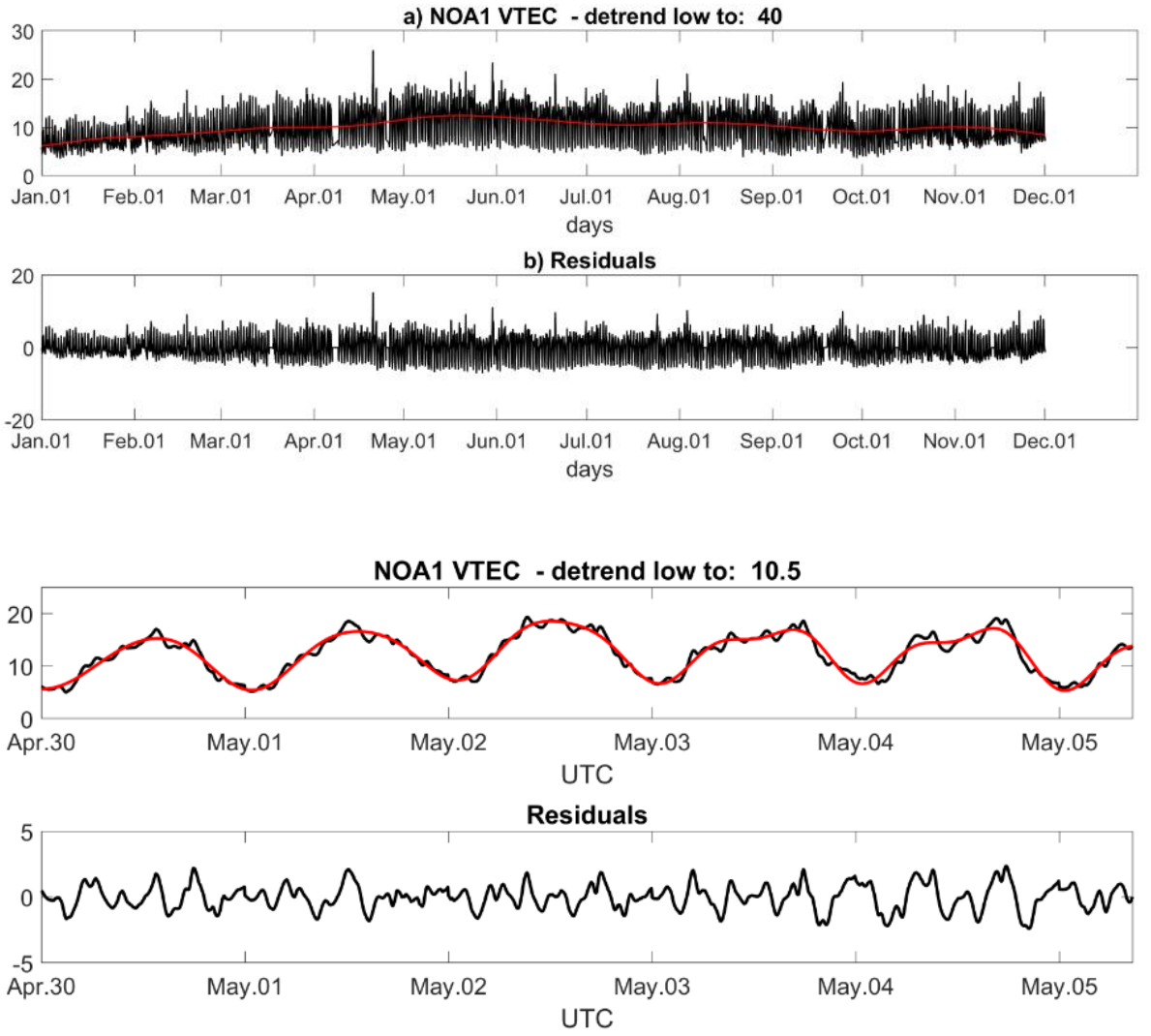






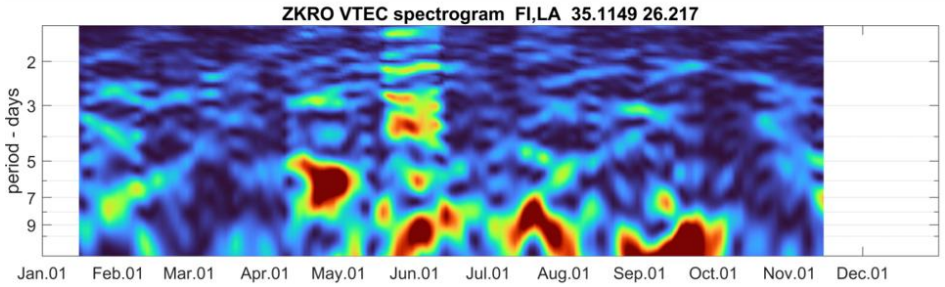
Filtering of VTEC data

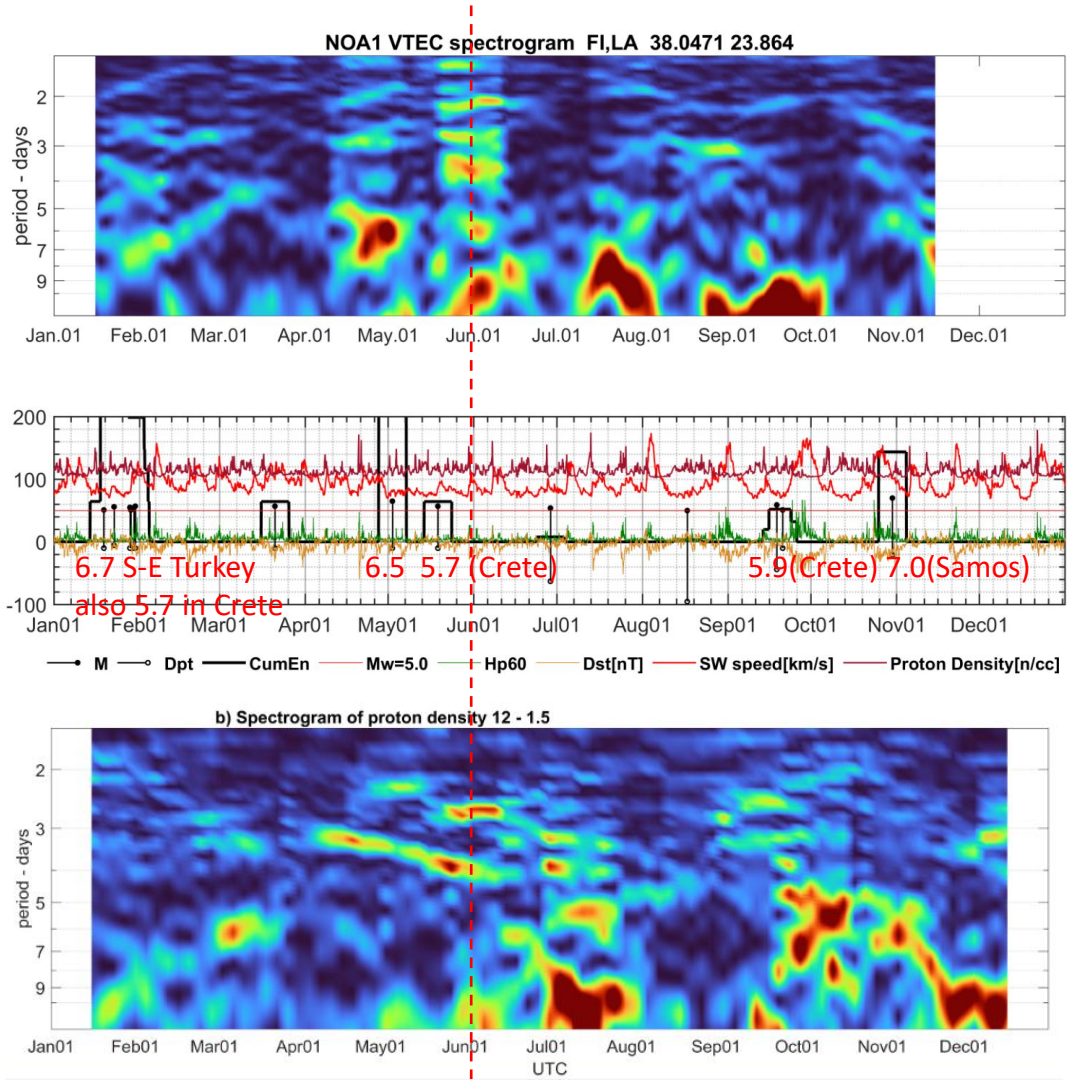
- Fourier-based high-pass filter for detrending the data to work with a narrower frequency band
- Inter-diurnal analysis (several-day wave periods) the data is high-pass filtered at 40-day wave period, but we present here spectrograms only to 12-day period to keep narrow band
  (helps if STFT window is constant)
- Intra-diurnal analysis (several-hour wave periods) the data is high-pass filtered at 10.5-hour wave period. This eliminates diurnal and semi-diurnal periods to significant extent. In the current analysis we work with averaged VTEC
  (its preparation must be reconsidered).



The several-day spectrum of VTEC and proton density

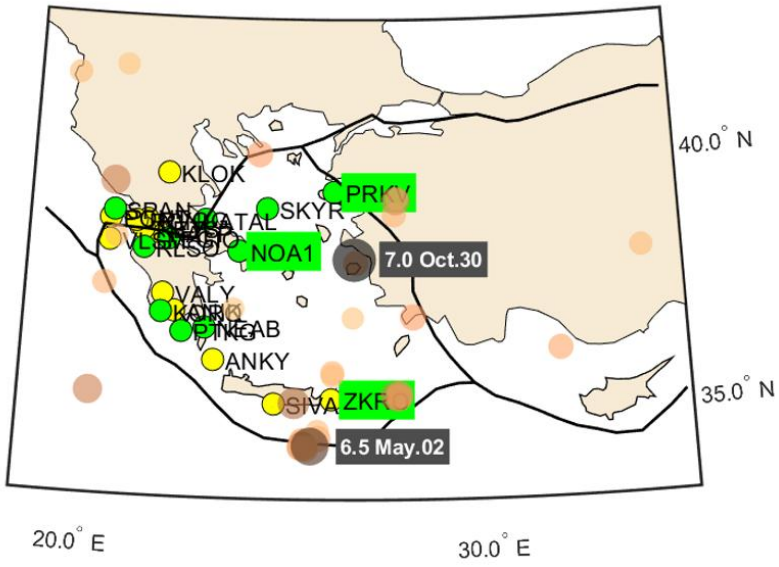
- There are several characteristic patterns over the year 2020 in VTEC spectra at NOA1 station (1.4-12-day)
- A common variations can be for instance found at the transition between May and June, in VTEC and proton density (https://spdf.gsfc.nasa.gov/pub/data/omni/high_res_omni/)
- Black stems denote M>5 earthquakes in the region, black line – cumulative seismic energy, green – Hp60 index, orange – Dst index, brown – proton density, red – solar wind speed (all rescaled and shifted for joint view)
- Below – the spectra from southernmost (Crete) station ZKRO, which are very similar to NOA1



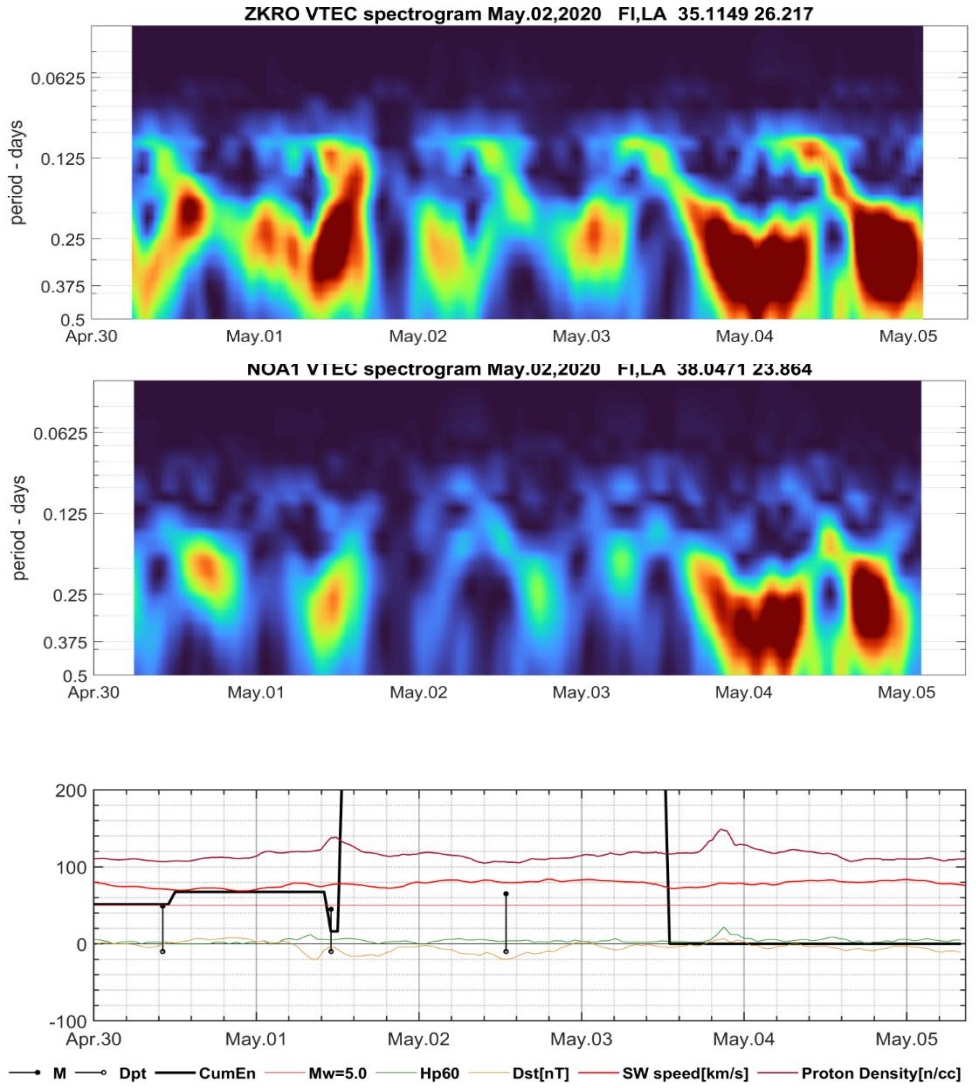


The several-hour spectrum of VTEC

- The southernmost station ZKRO (close to the earthquakes nearby Crete) has a stronger anomalous signal, especially before the earthquake on May 02 (M=6.5), in comparison to NOA1 station.
- There is however some uncertainty with respect to intra-day VTEC data, because it was derived by the weighted averaging of VTEC from almost all station-satellite pairs

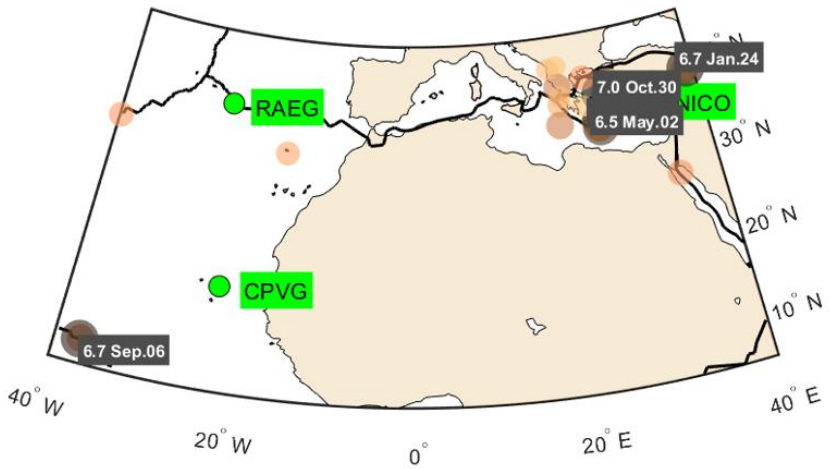


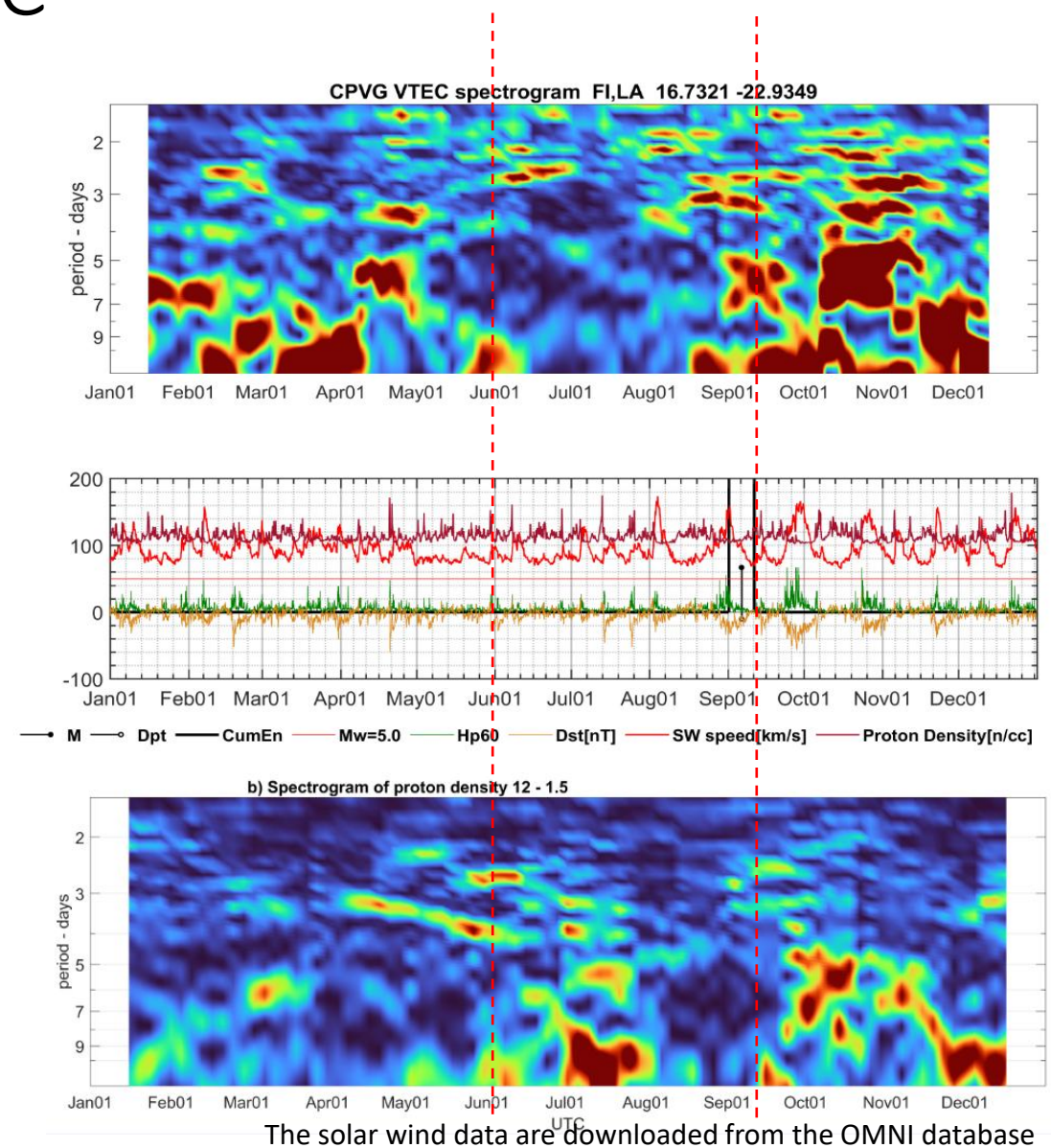
- This averaging was required, because otherwise we would be not able to calculate several-hour wave periods.
- However, this band will be reprocessed. The number of satellites must be increased together with check of potential diurnal leakage.



The several-day spectrum of VTEC outside the Aegean region

- The IGS station CPVG located outside the Aegean region (Cabo Verde) collects at the May/June transition weaker signals (in comparison to NOA1), which correspond less to anomalies in proton density.
- There is also interesting anomaly in September at 5-7-day wave period, which is totally absent in solar wind proton density
- On the other hand, there was an M=6.7 earthquake not so far from the region.

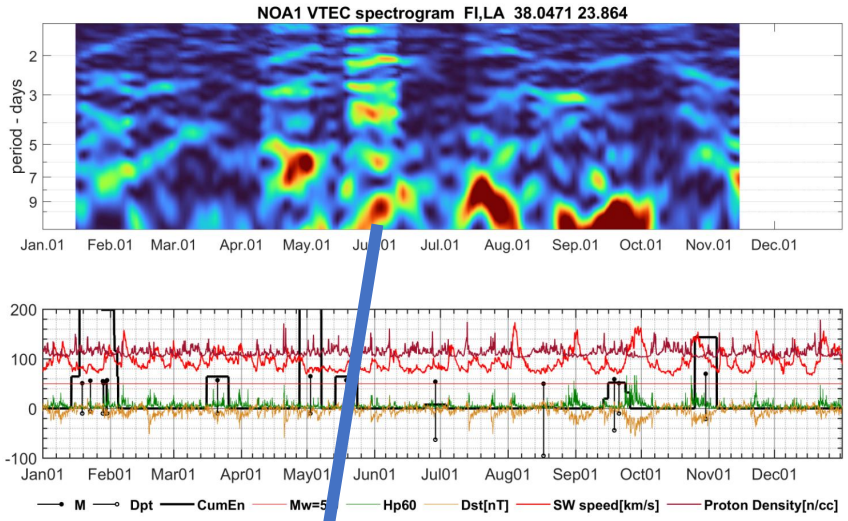


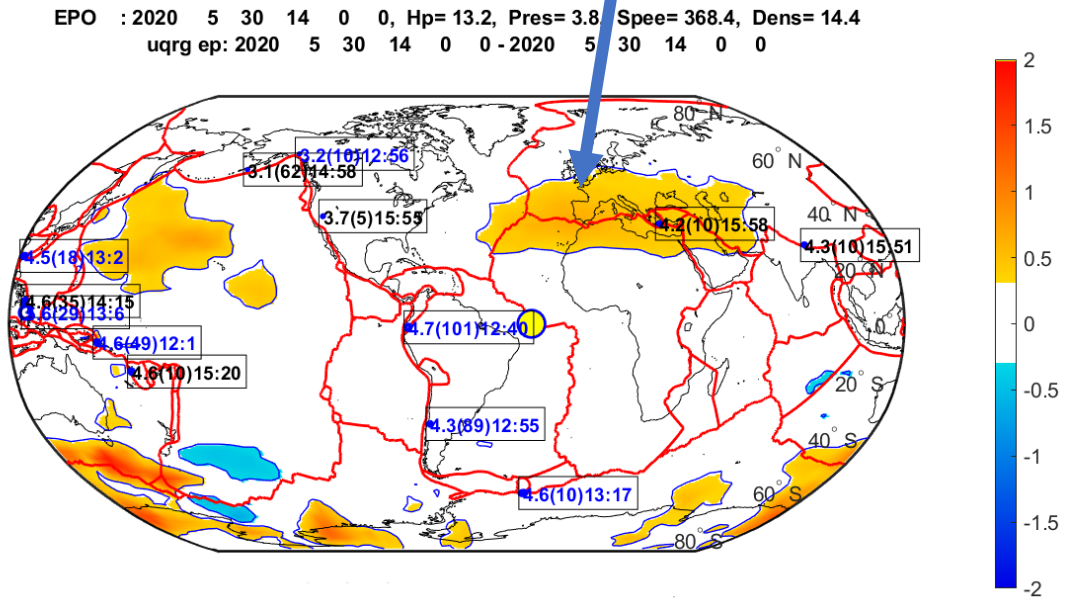


The solar wind data are downloaded from the OMNI database (https://spdf.gsfc.nasa.gov/pub/data/omni/high_res_omni/).

The spatial look on VTEC anomaly and several-day spectrum of VTEC

- After the spectrograms from CPVG and RAEG stations, it was suspected that observed variations are large, but limited to some region
- The specific inter-diurnal (several-day) VTEC anomalies are indeed spatially large, which can be validated with the use of GIM models. They occupy tectonic plate boundaries.
- They have common spectral pattern with solar wind proton density and common shape with tectonic plate boundaries
- Their relationship with earthquakes is complicated, because strong earthquakes not always occur together with these anomalies





Wielgosz, P., Jarmołowski, W., Mazur, S., Milanowska, B., & Krypiak-Gregorczyk, A. (2025). Vertical Total Electron Content Enhancements and Their Global Distribution in Relation to Tectonic Plate Boundaries. Remote Sensing, 17(4), 614. https://doi.org/10.3390/rs17040614

Conclusions

- Local stations have very similar signals (at frequencies 12-1.4 days), because (probably) the anomalies at this frequency band have spatial range of several hundred kilometres
- Distant stations CPVG and RAEG (western part of EU-AF plate) detect only some part of the NOA1 signals, but the signals are modified and have different amplitudes
- The spectra are generally interesting and complex, and probably time series of extended set of different phenomena impacting the ionosphere will explain complex spectra in joint cross-spectral analysis
- The spectral differences between Aegaan stations and e.g. CPVG station inform us that the latitude and geomagnetic lines are also suspected as playing role in the distribution of charged particles travelling from the Sun towards the ionosphere