Global VTEC Maps of the Geomagnetic Storm in May 2024 and Their Application to Study the Evolution of the Ionospheric and Plasmaspheric VTEC Distribution

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Motivation

We aim to produce global maps of the vertical total electron content (VTEC) measured by GNSS satellites and ground stations of the IGS and EUREF networks

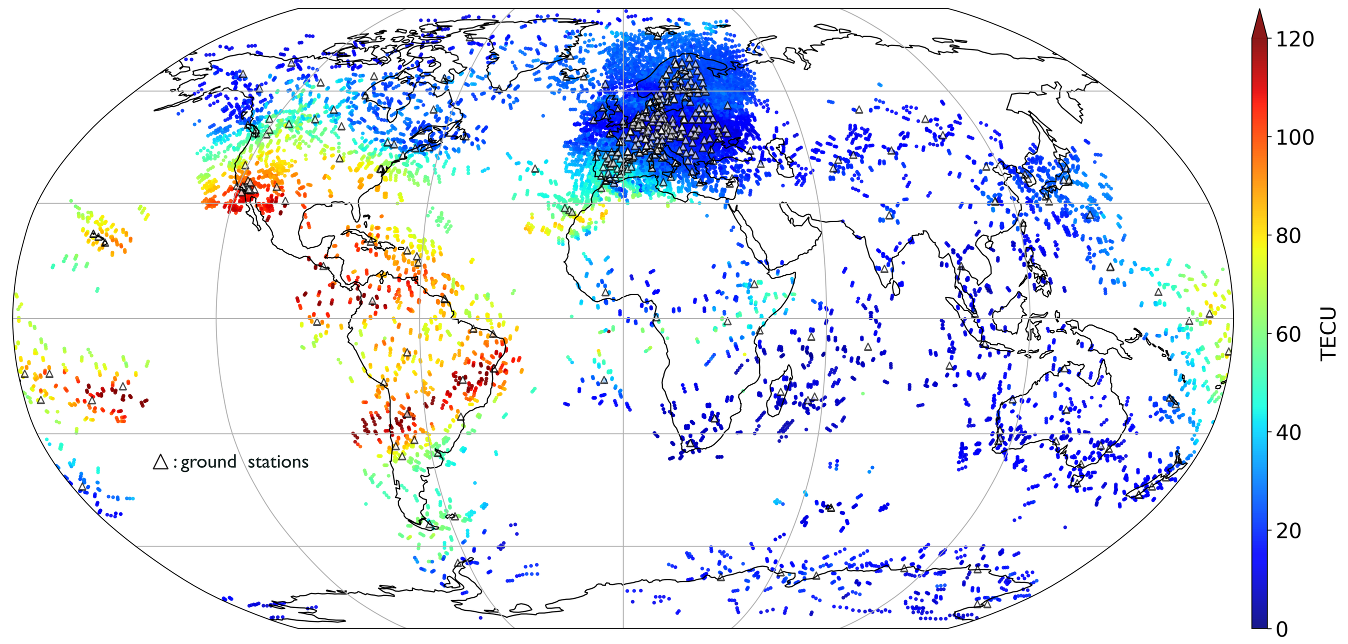
Kriging interpolation allows for assessment of the accuracy of the result surface (standard deviation) and is an entirely data-driven approach, requiring no model input

1. Input Data

VTEC at ionospheric piercing points (IPPs) from GNSS data and the ROB-IONO software [1], using the IGS and EUREF station networks:

For example 15-minute interval:
~ 28 500 data points global,
~ 18 800 (66%) from EUREF

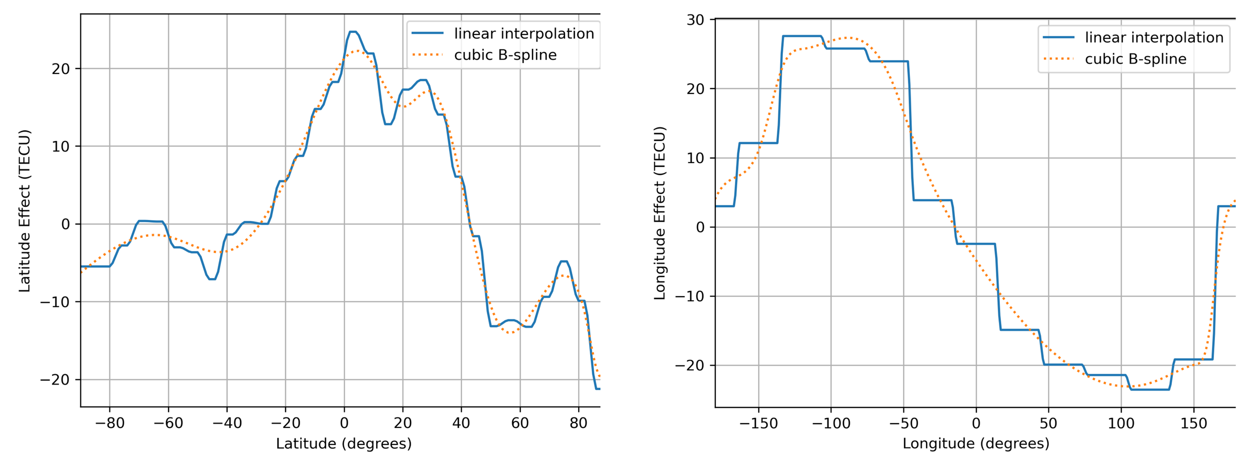
Example: 11 May 2024, DOY 131, 20:00-20:15 UTC



2. Median Polish

Bin data into 3x3 degree cells, taking weighted (by elevation) median VTEC in each cell

Iterative median polish [e.g., 2, 3] with 30° longitude bins and 9° latitude bins to retrieve longitude and latitude effects, fit cubic B-splines:

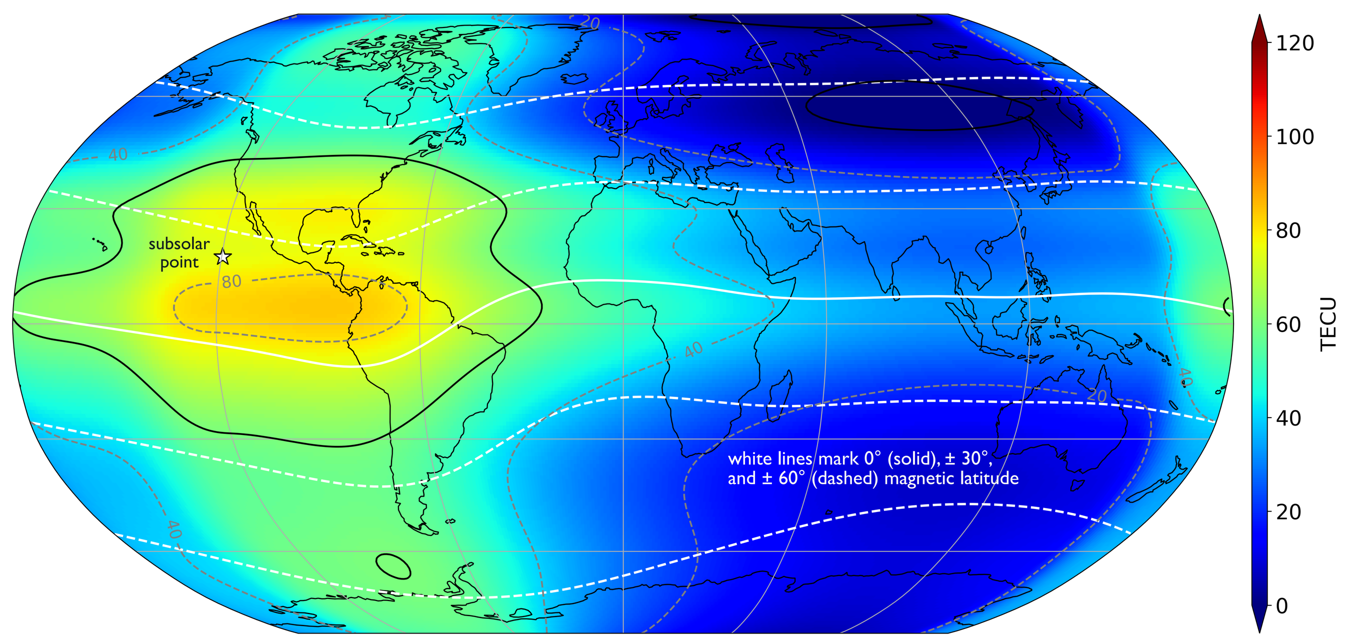


3. Trend Surface

Compute smoothed trend surface on 1°×1° grid with fitted B-splines:

This describes the large-scale trends in the data, for example higher plasma densities on the day- versus night side

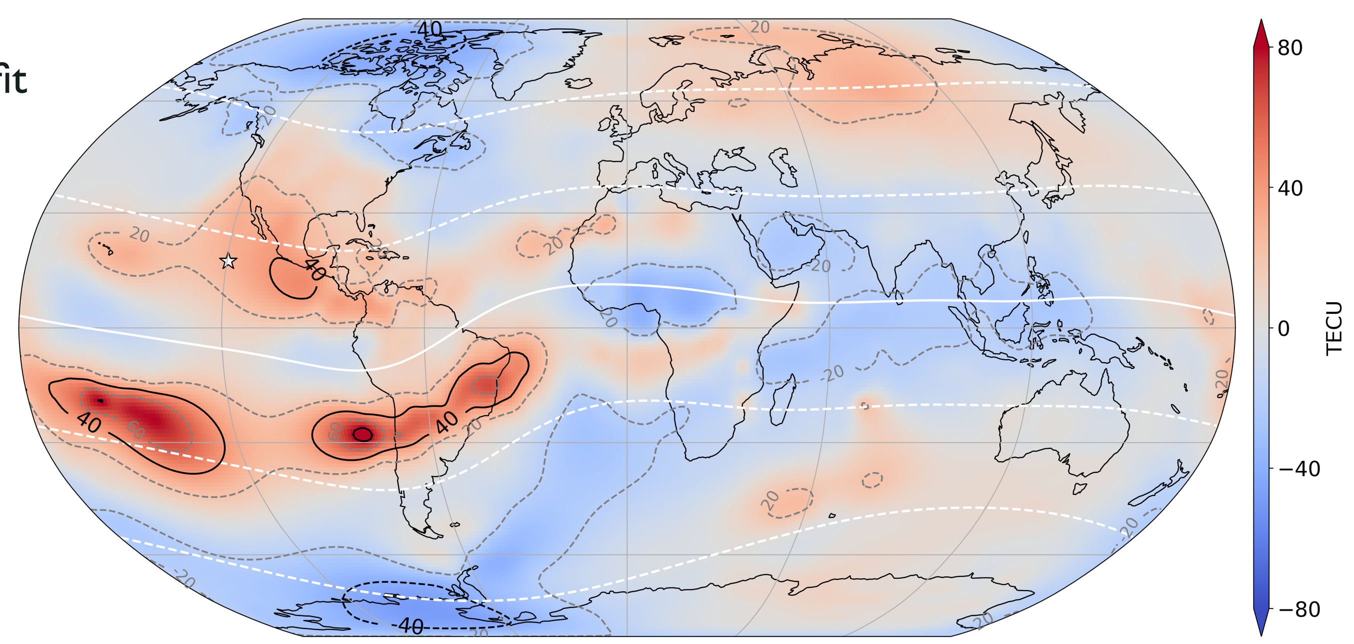
We then subtract the trend surface from the original data to calculate the residuals for kriging (which describe local variations)



4. Ordinary Kriging of Residuals

Compute empirical variogram of residuals, then fit a stable function for kriging

After removing the trend via mean polish, we can use ordinary kriging [2, 3] to interpolate the residuals to a 1°×1° grid:

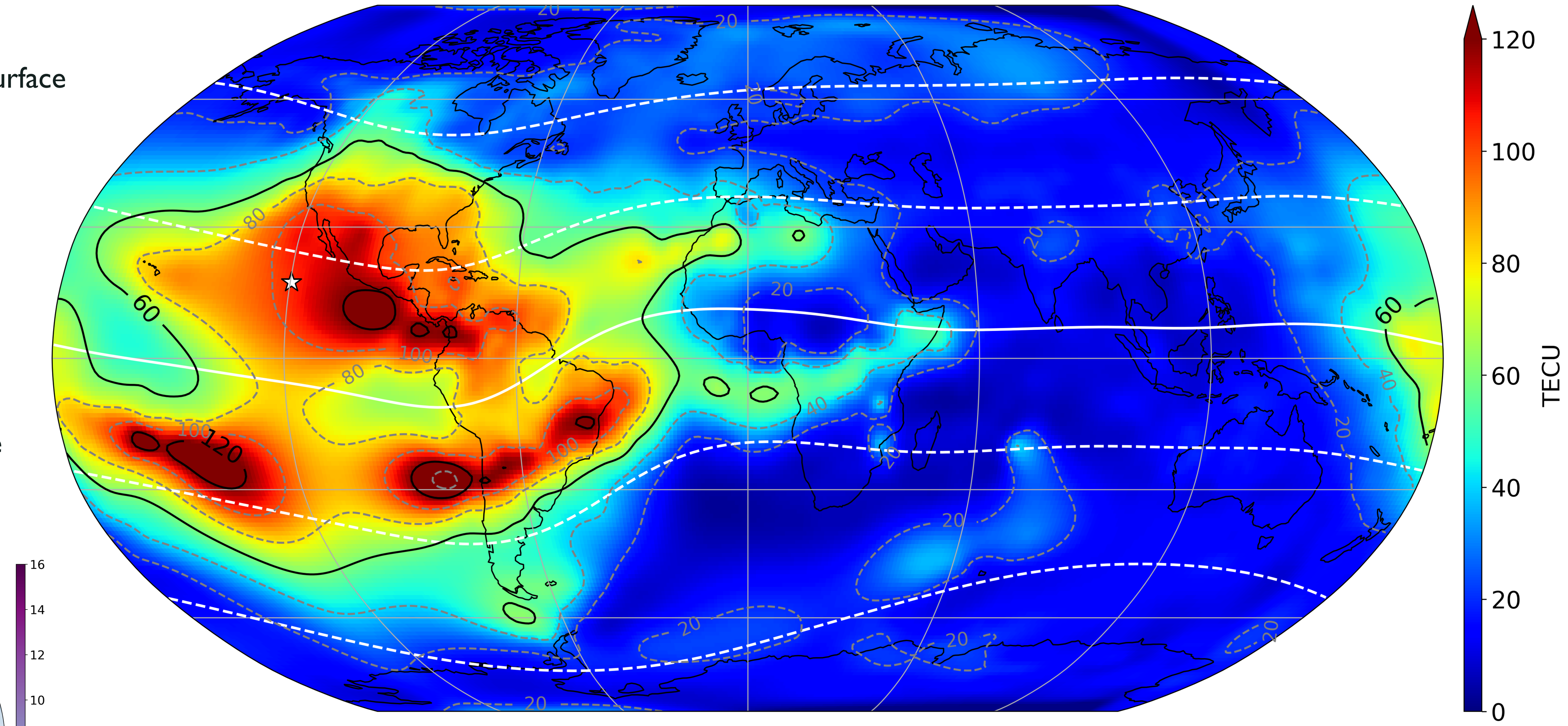


References

1. Bergeot et al. (2014), DOI: 10.1051/swsc/2014028
2. Cressie (1986), DOI: 10.2307/2288990
3. Cressie (1993), DOI: 10.1002/9781119115151

5. Global Map Results

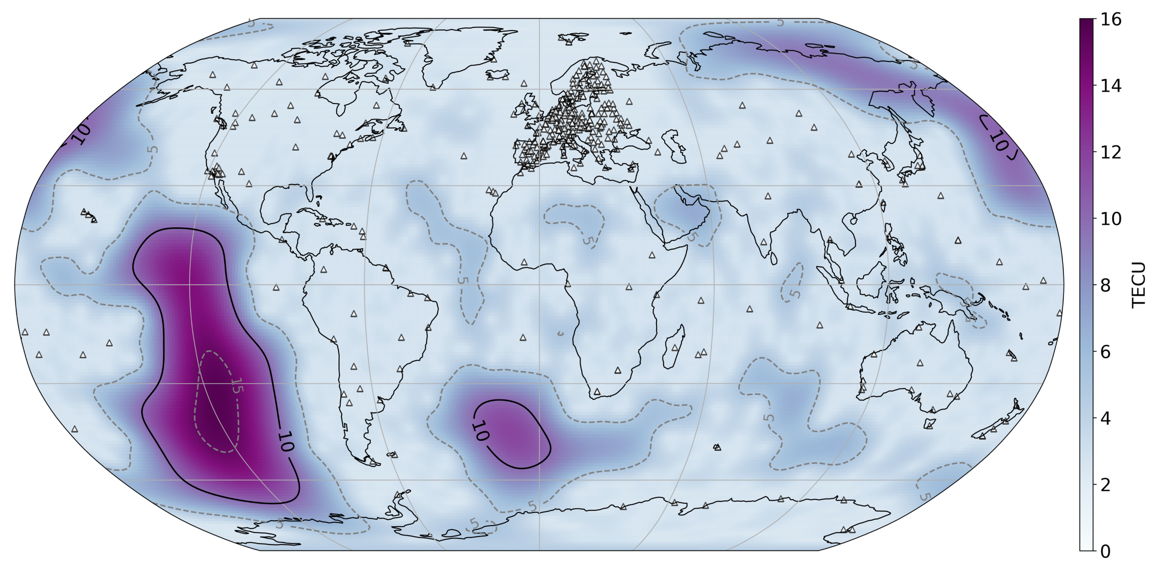
Adding the smoothed trend surface and kriged residuals surface results in the final map product:



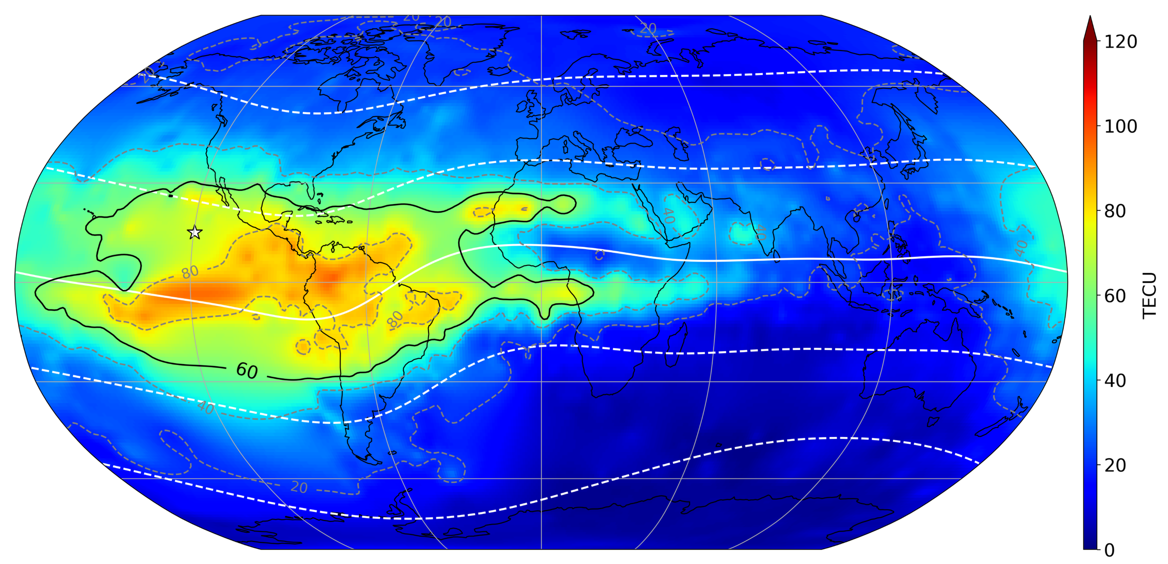
Well-defined equatorial trough, with peak VTEC at crests around ±15–20° magnetic latitude

High-resolution global VTEC maps, with mean differences to the original data of ~0.2 TECU and standard deviations of differences of ~2/4 TECU (quiet/storm-time)

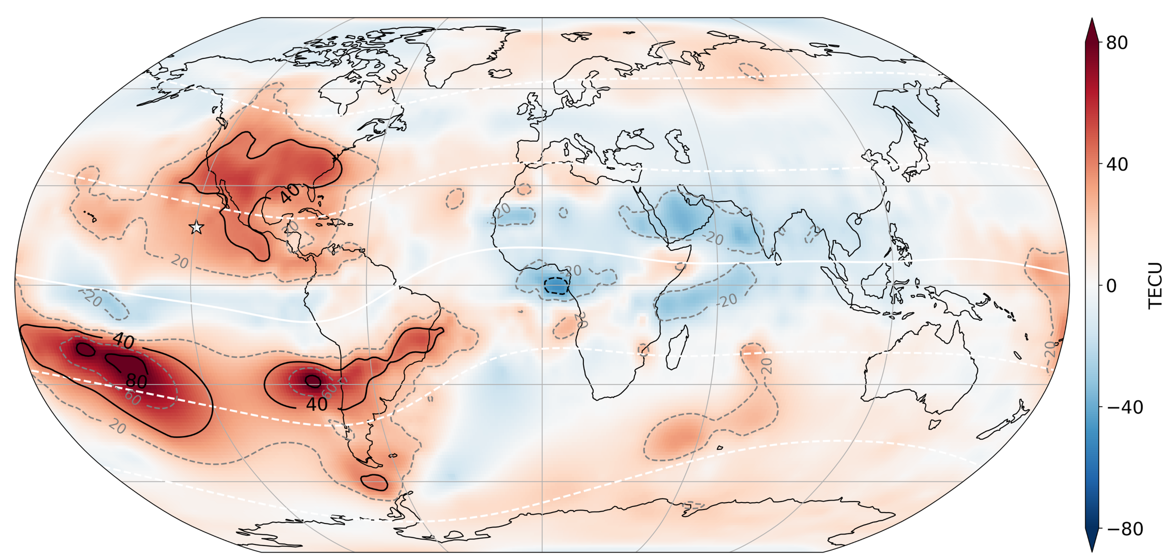
Kriging provides a standard deviation for the VTEC surface (an advantage over other methods, such as spline-based interpolation), see below:



We can compare with the averaged global VTEC maps from the previous 2 weeks of the same time interval…



… to derive the storm-time changes:



Geomagnetic Storm of 11–12 May 2024

- Storm onset ~18:30 UTC, peak ~21:30 UTC (11 May)
- Peak VTEC: 219 TECU, max. enhancement of 128 TECU compared to averaged calm state
- Post-storm maps show low and atypical VTEC for more than 24h after peak

see QR codes below for videos

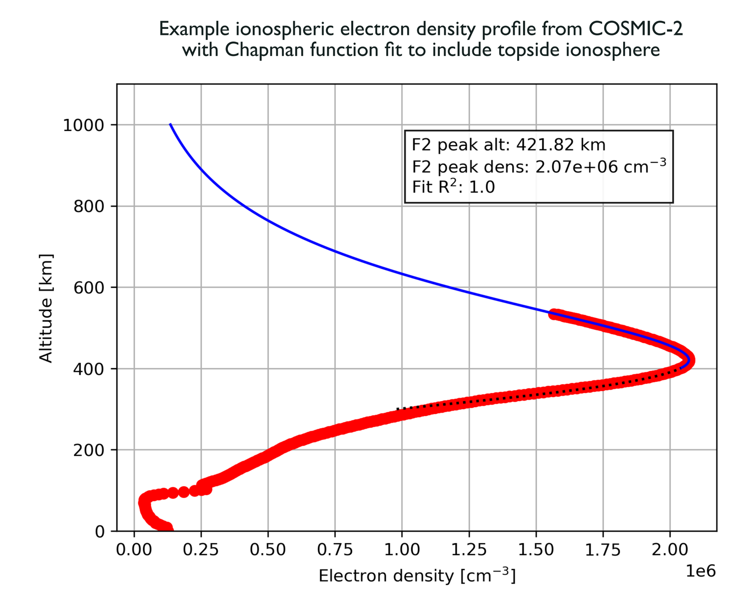
Scientific Application: Evolution of the Iono- and Plasmaspheric VTEC Distribution

We can utilise these global maps to study the distribution of plasma between ionosphere and plasmasphere and its evolution during the storm.

Scan Me
for a video!

But we need a comparison data set that allows us to isolate the ionospheric contribution to the VTEC at any given location.

Suitable data sets are COSMIC-2, EISCAT, and ionosonde profiles – all of which can be integrated to provide the ionospheric VTEC at varying longitudes/latitudes and temporal coverage.



Work in Progress and Plans

- Comparison to COSMIC, EISCAT, and ionosonde data to study the evolution of ionospheric/plasmaspheric VTEC during geomagnetic storms at varying latitudes (see above)
- Investigate post-storm distribution and recovery timescales
- Comparison with other global VTEC map products
  - Modify algorithm to run in near-real time, providing global, high-precision VTEC maps
  - Creation of variability maps, investigate the possibility to identify transient ionospheric features
  - Study of long-term global trends, making use of GNSS' great spatial and temporal coverage, possible comparison with relevant models

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Acknowledgements
The authors acknowledge funding through the EU Horizon 2020 PITHIA-NRF project.