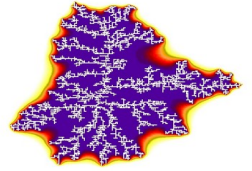


Spatial patterns of GNSS derived TEC for Space Weather applications



Juan Alejandro Valdivia⁽¹⁾, Sylvain Blunier⁽¹⁾, Nicolas Ramirez⁽¹⁾, Nicolas Dunkler⁽¹⁾, Jaime Campos⁽²⁾, Sebastian Riquelme^(2,3), Patricio Toledo⁽²⁾, Rodrigo Sanchez^(2,3), Gabriela Herrera Malig⁽²⁾

⁽¹⁾Departamento de Física, Facultad de Ciencias, Universidad de Chile.

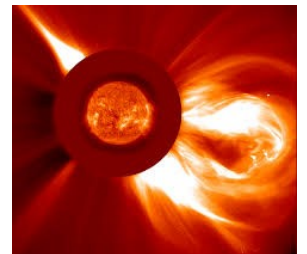
⁽²⁾Programa Riesgo Sísmico, Universidad de Chile.

⁽³⁾Servicio Sismológico Chile, Universidad de Chile.

**Laboratory
for Space and Astrophysical Plasmas**
<https://ccc.ciencias.uchile.cl/plasmas/>

**Laboratory and Service
for Space Weather**
<https://ccc.ciencias.uchile.cl/climaespacial/index.php>

The Chilean Complexity Cluster
<https://ccc.ciencias.uchile.cl/ccc/>



COMPLEXITY

"It is nice to know that the computer understands the problem. But I would like to understand it too."

-Eugene Wigner

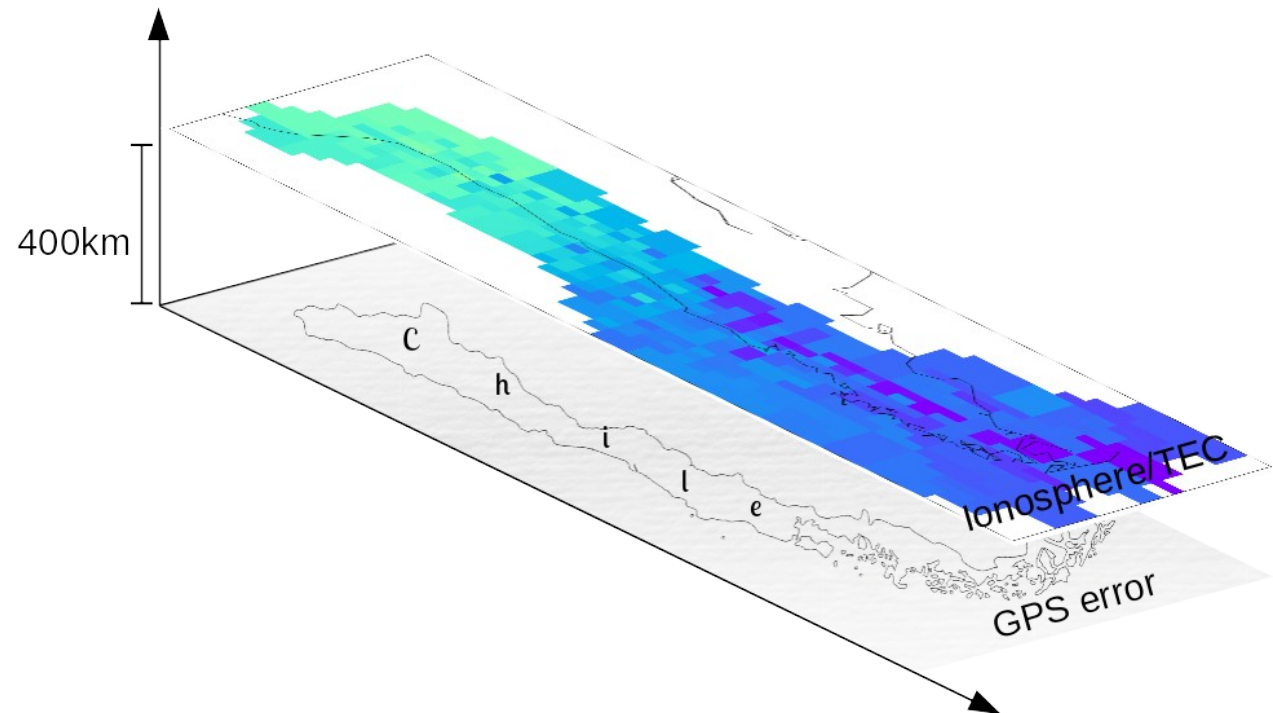


Nobel Prize foundation

Let us keep this in mind!!!

CONTENTS

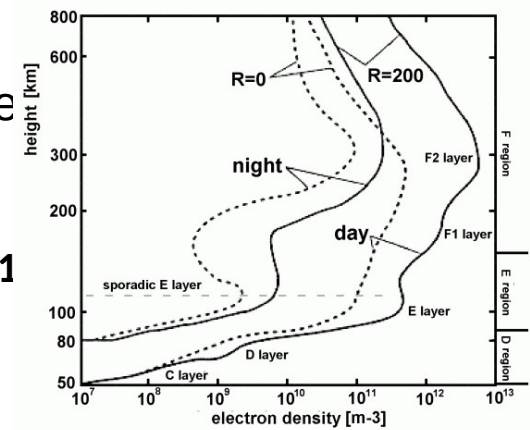
- Total Electron Content
- Monitoring complex Solar–Magnetospheric–Ionospheric Coupling & Its Impact on Technology
- Open Source Code Iontec.py → GPS y Glonass ... validated!
- High spatial resolution patterns **during large perturbations** ... eclipses, space weather applications
- Outlook



TEC + Geophysical applications

TEC : Total Electron Content

- Measures how many electrons are present in the ionosphere
- Measured from GNSS along the path of a radio signal.
- In TECU ($10^{16} \text{ e}^-/\text{m}^2$).
- Delay is proportional to TEC / f^2 ($\sim 1 \text{ TECU} \approx 0.16 \text{ m delay at GPS L1}$ causing range and position errors).



Navigation & GNSS positioning accuracy

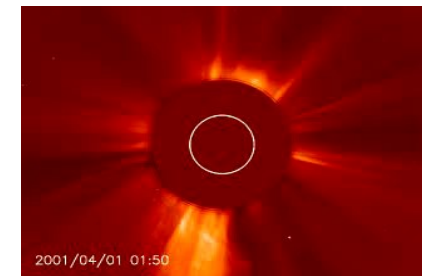
- essential for navigation, communications, etc.

Space weather monitoring, diagnostics

Sun → magnetosphere → ionosphere → technological systems

Solar driver vs Magnetospheric Driver

Understanding ionospheric electrodynamics



Ionotec Validation Eclipse 2019

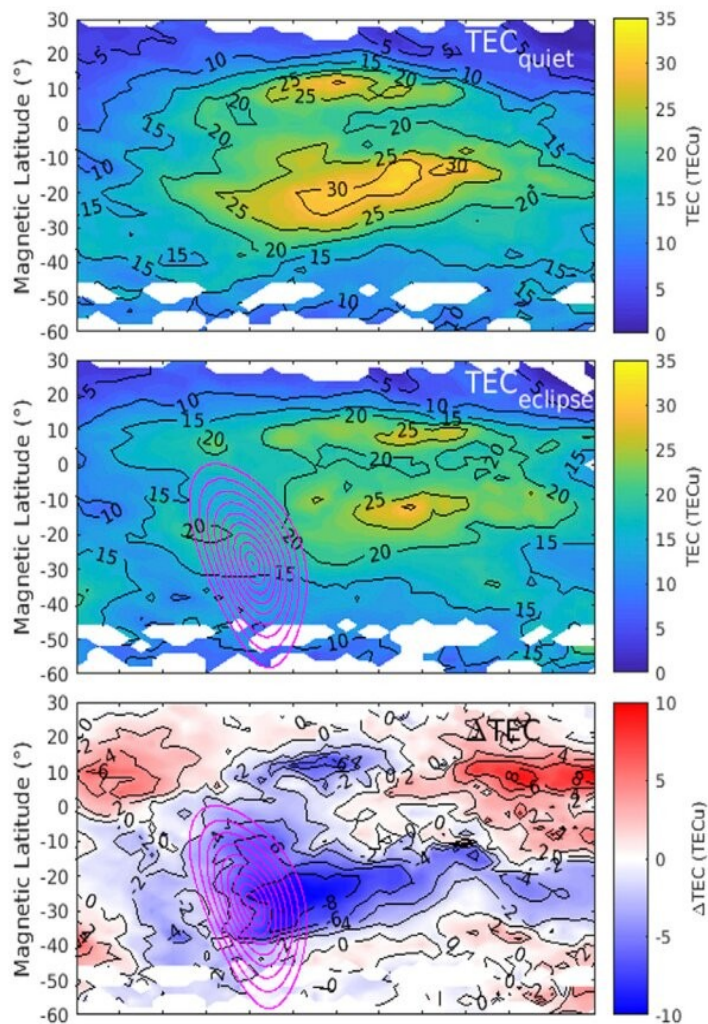
Ionotec Open Source



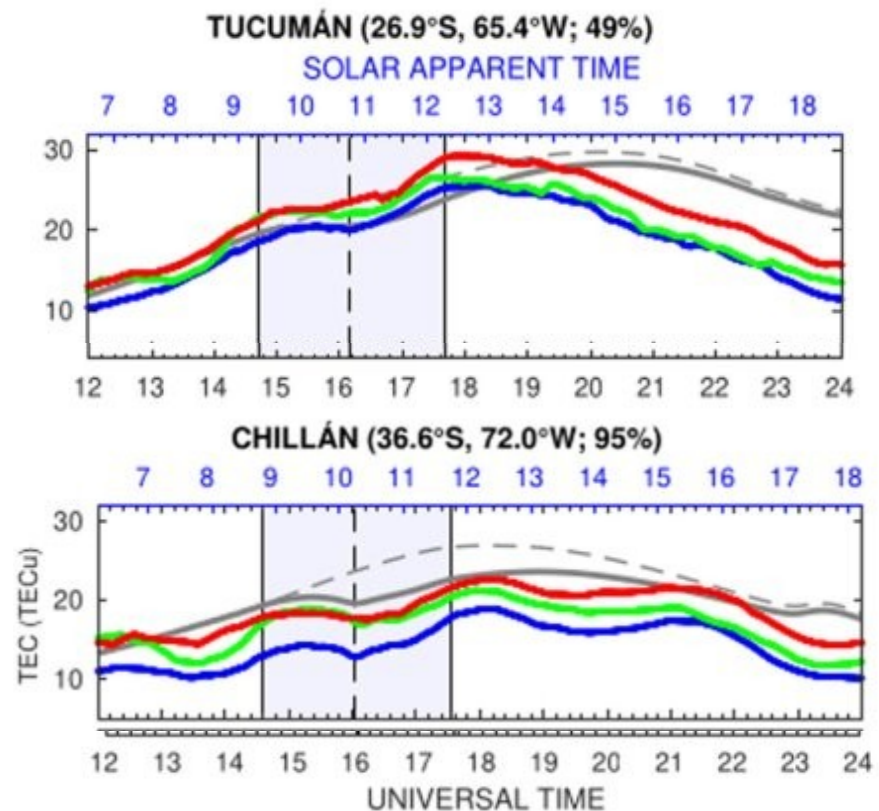
5-minute temporal resolution
~ variable spatial interpolation (meshless)
in latitude and longitude\

Validated with other TEC software
during Eclipse 2019
Variations on Chile and Argentina

Seemala (Blue)
Ionotec (Green)
Ciraolo (Red)

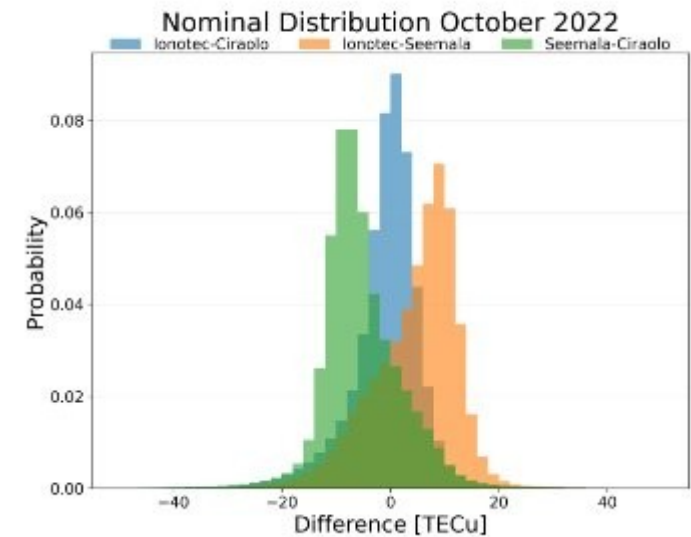
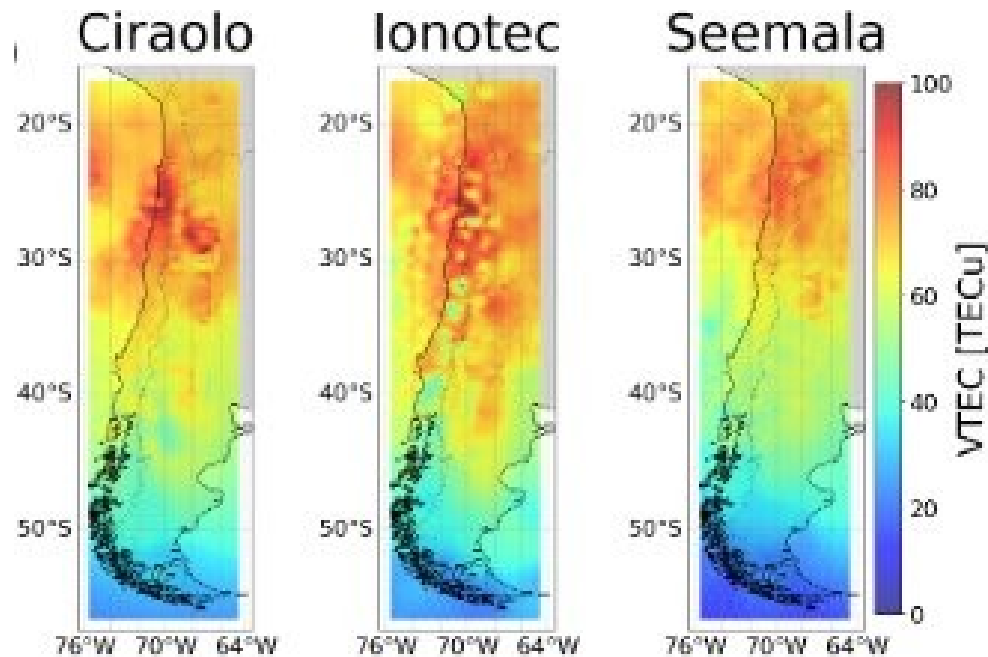
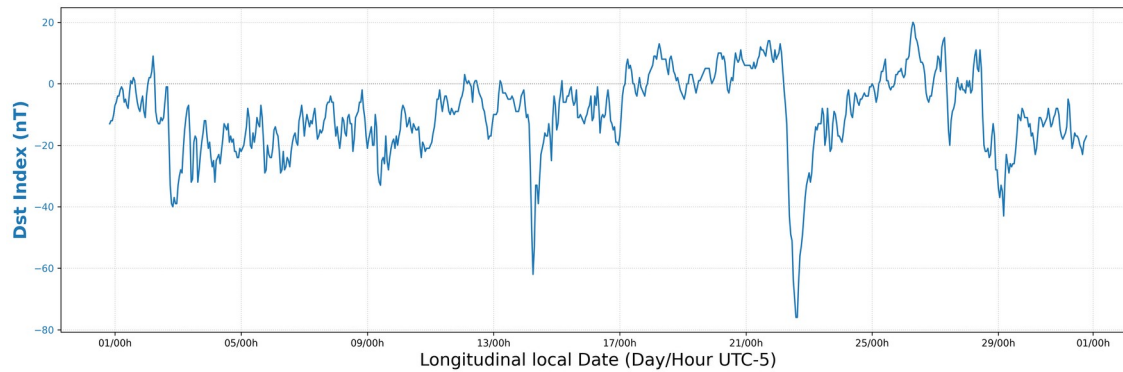


Time of eclipse



Mild Storm → over Chile during October, 2022

Dst Index: 01 Oct - 01 Nov 2022 Longitudinal local time UTC-5



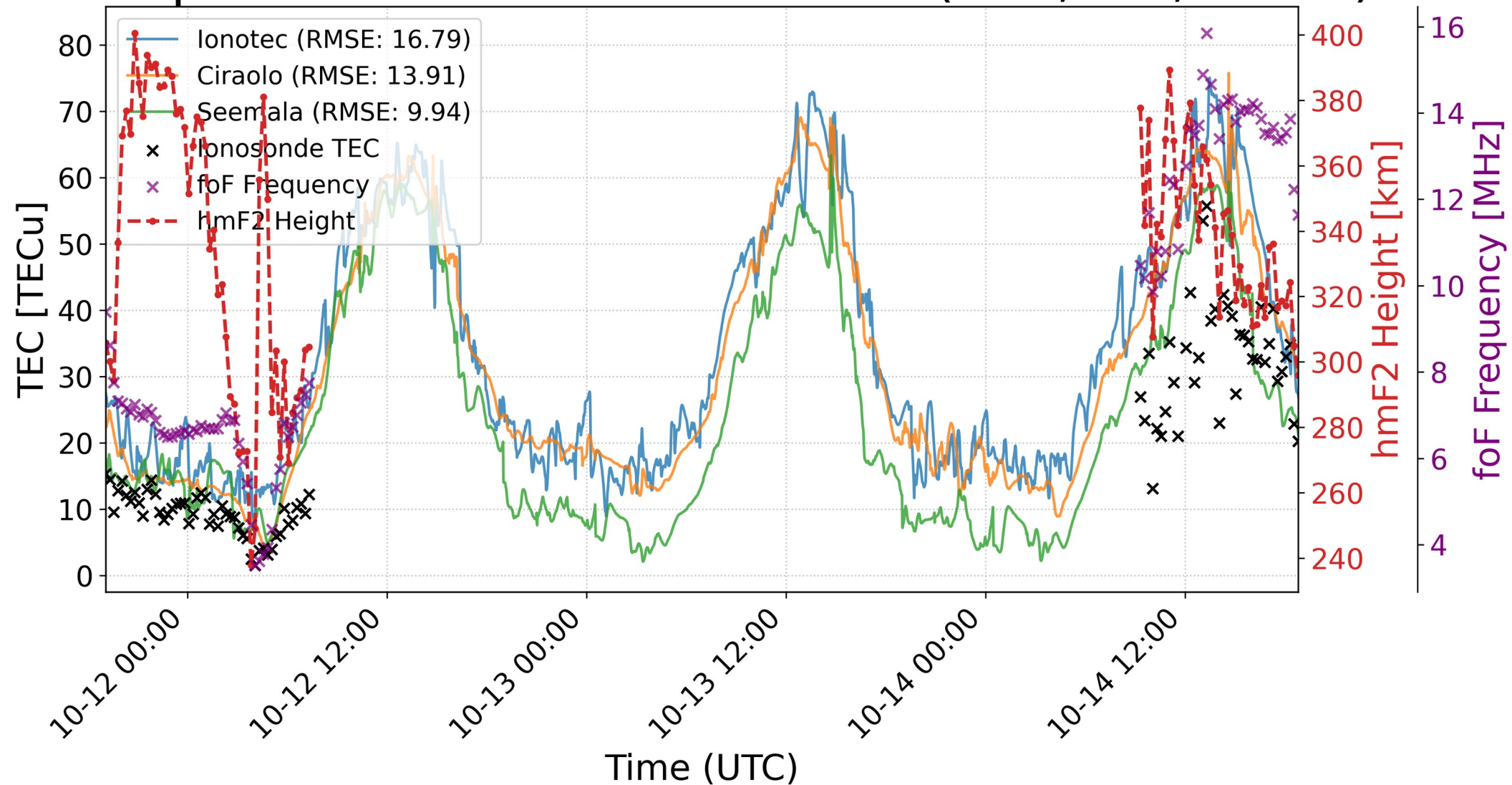
Submitted to ASR. 2026



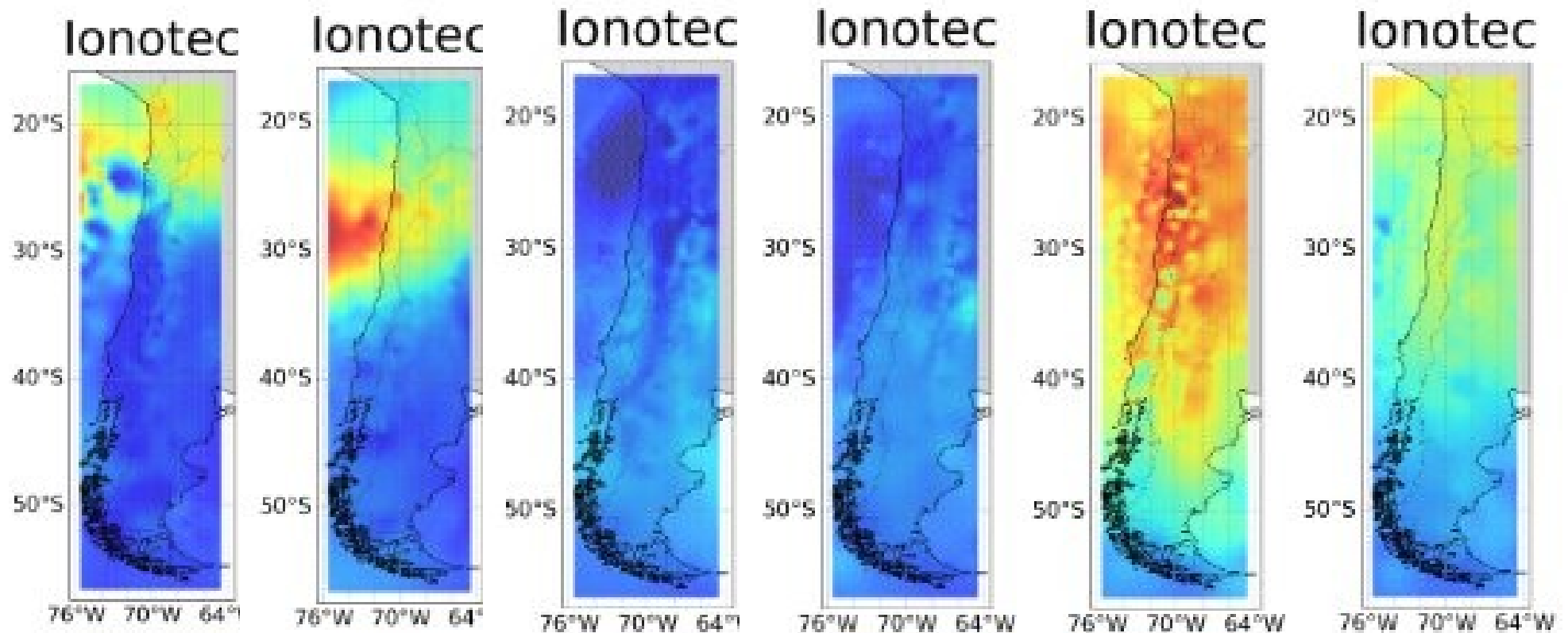
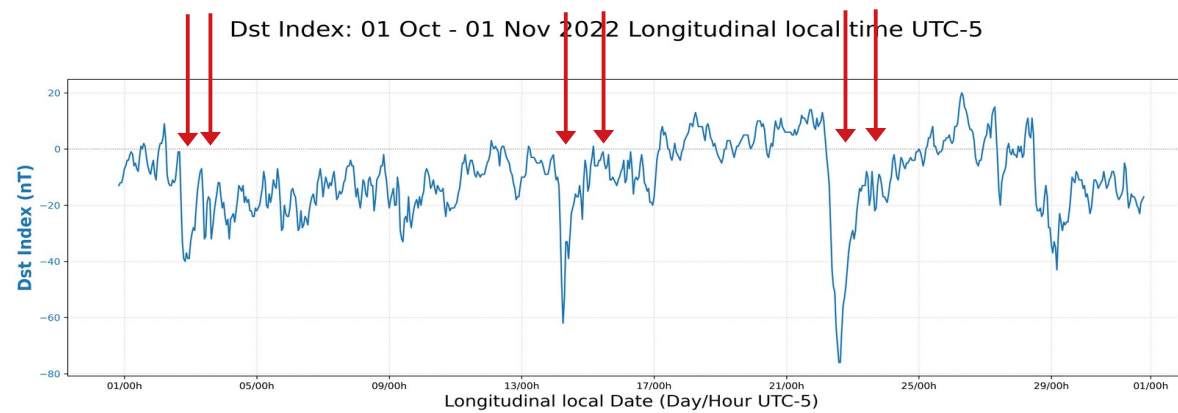
GPS y Glonass

Ionotec Validation with Ionosonde

Ionospheric Parameters Evolution (TEC, foF, hmF2)



Mild Storm over Chile during October, 2022

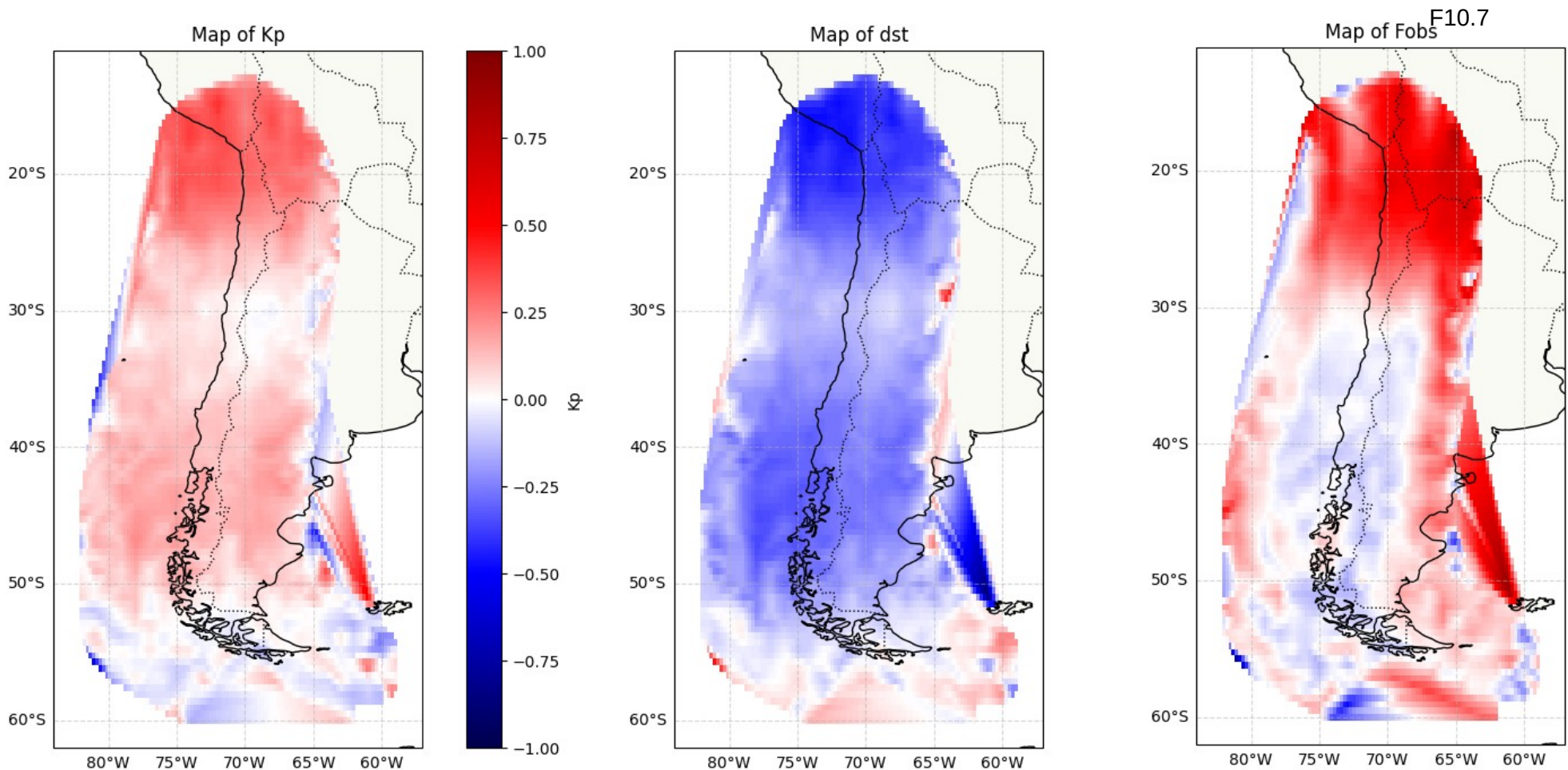


Cross Correlation → Drivers

TEC vs Magnetospheric + Ionospheric Indices

What are the drivers

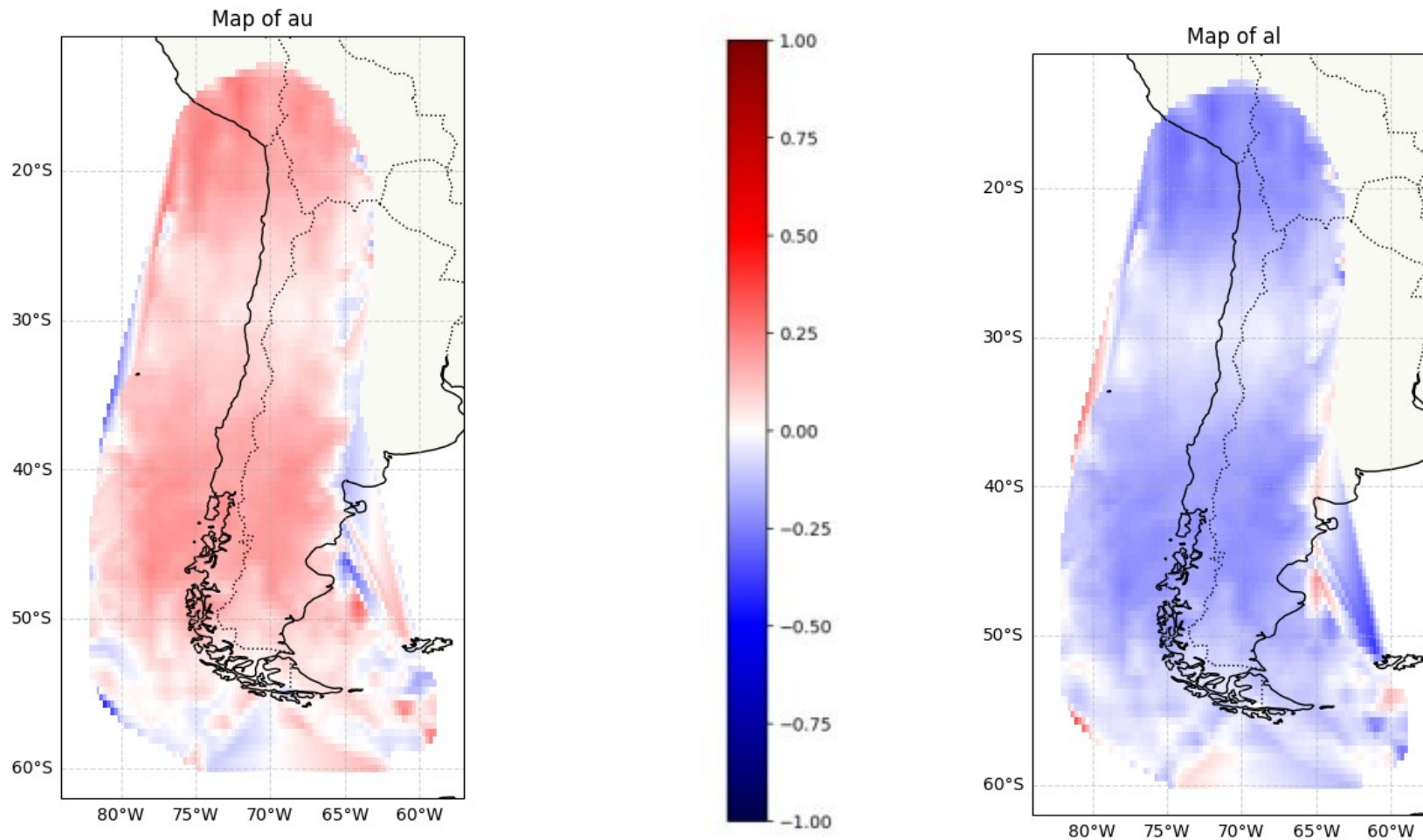
- to propose initial set of relevant variables for a ML model
- then apply strategy to select “robust” variables



Cross Correlation → Drivers

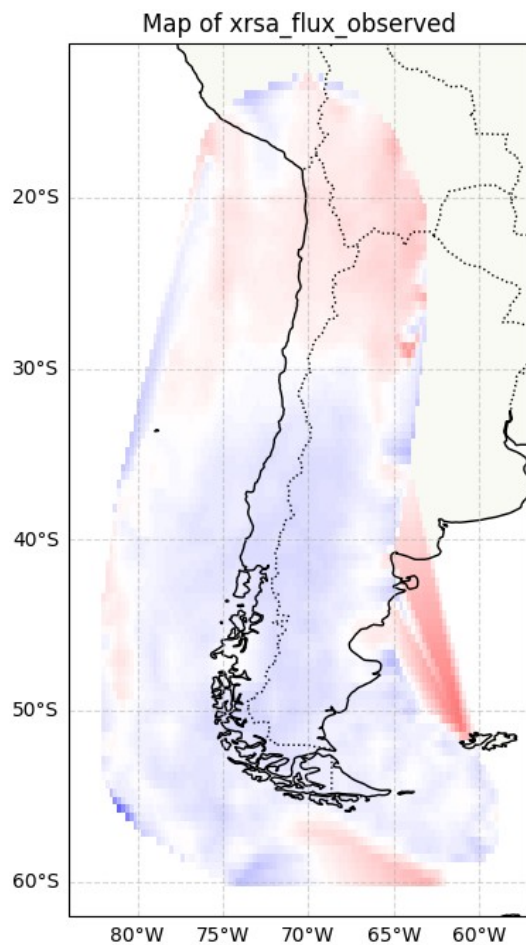
Magnetic Fluctuations → electrojets

Makes sense

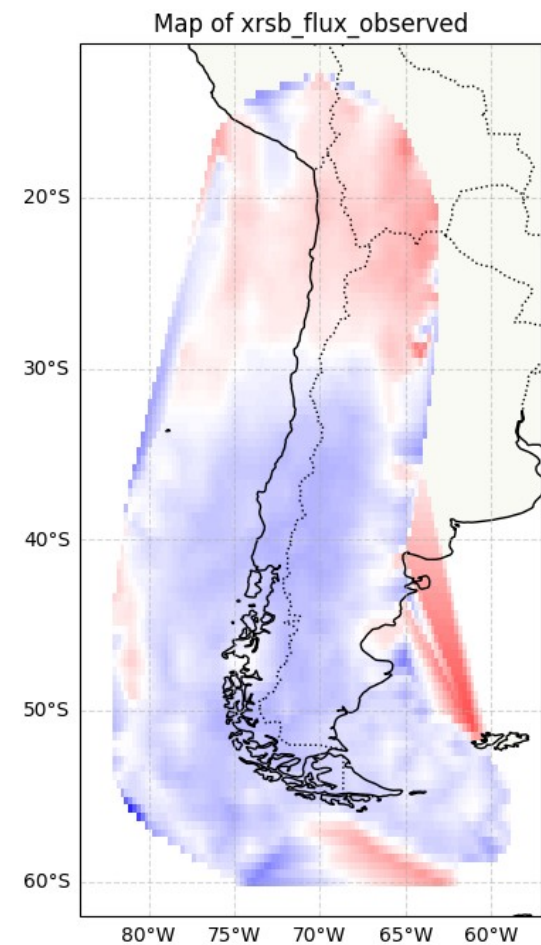
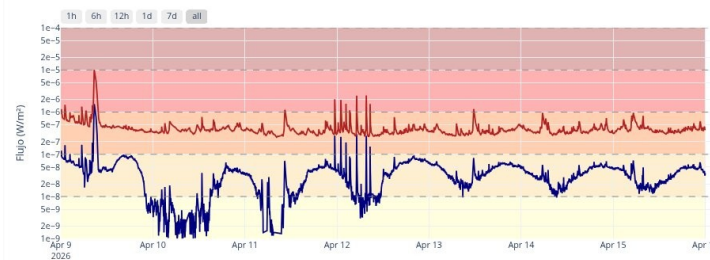


Cross Correlation → Drivers

Solar parameters → X rays (Goes)



Soft X-rays 0.05 to 0.4 nm

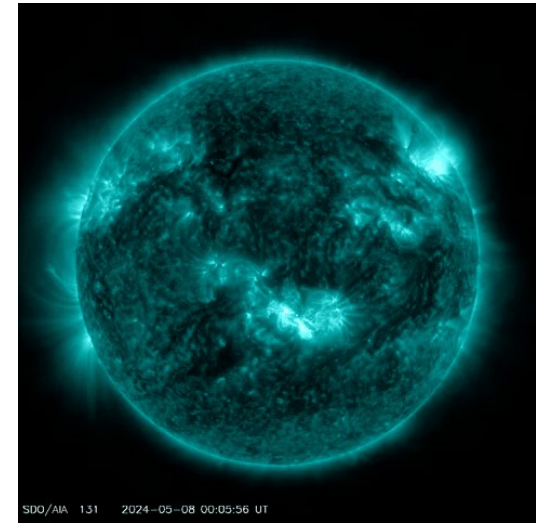


Soft X-rays 0.1 to 0.8 nm
classify the size of a solar flare (C, M, or X-class)

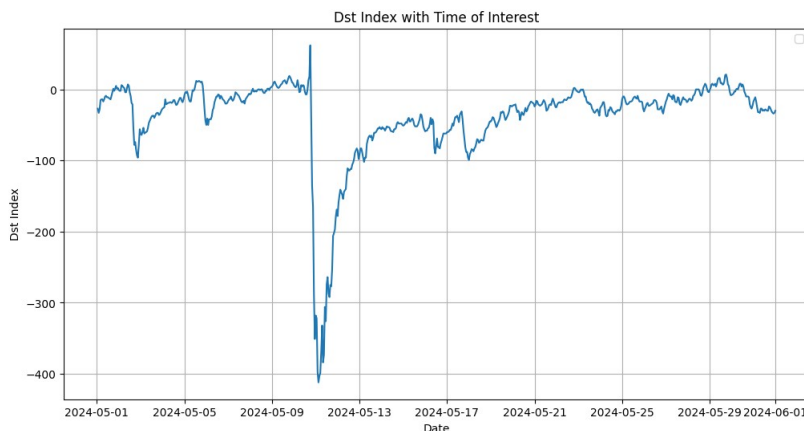
"Gannon Storm"

"Mother's Day geomagnetic storm"

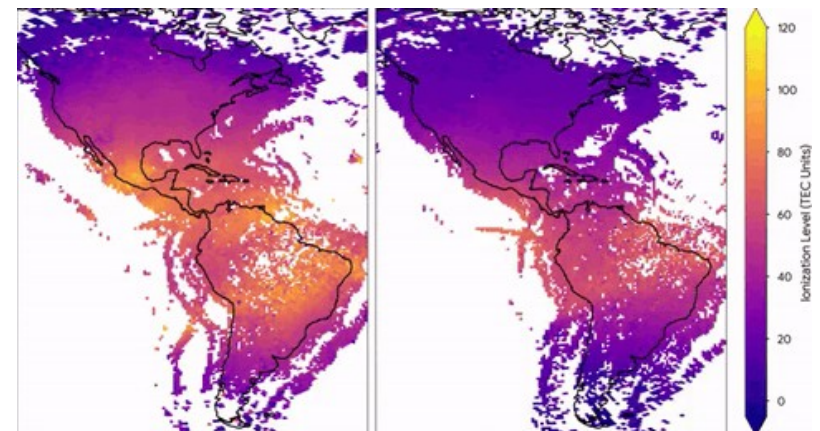
- Happened during 10-12 May 2024
- Greatest geomagnetic storm since oct. 1989
- dst minimal value: -406 nT
- Strong effects observed worldwide
- Especially on the American continents



Solar activity previous to Mother's day storm



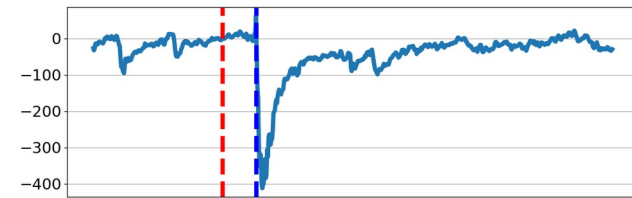
DST from World Data Center of Kyoto: <https://wdc.kugi.kyoto-u.ac.jp>



Smith, J., Kast, A., Geraschenko, A. et al. Mapping the ionosphere with millions of phones. *Nature* 635, 365–369 (2024).
<https://doi.org/10.1038/s41586-024-08072-x>

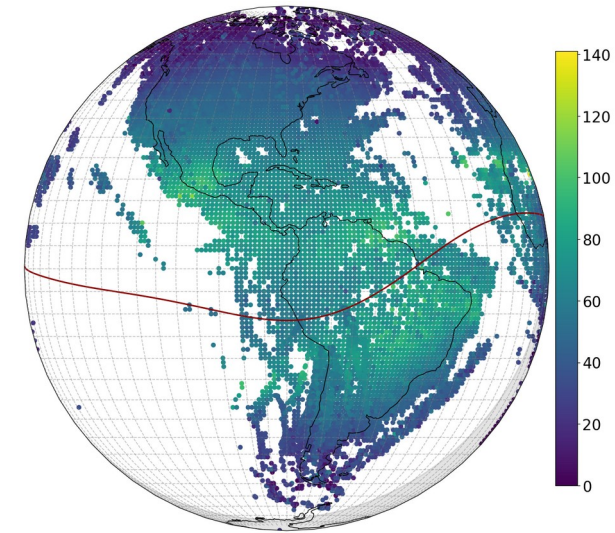
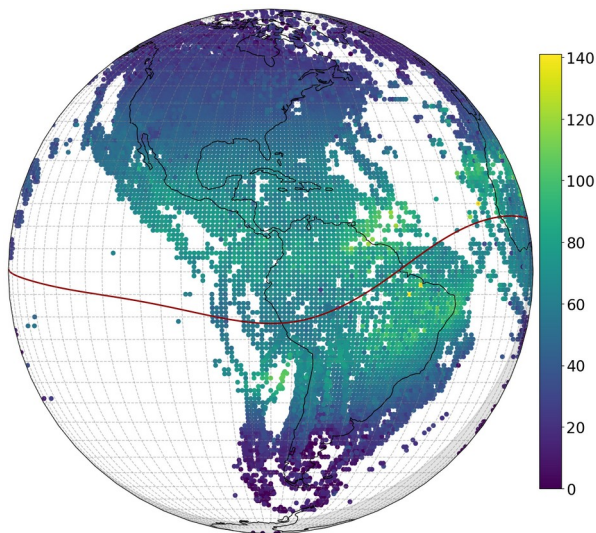
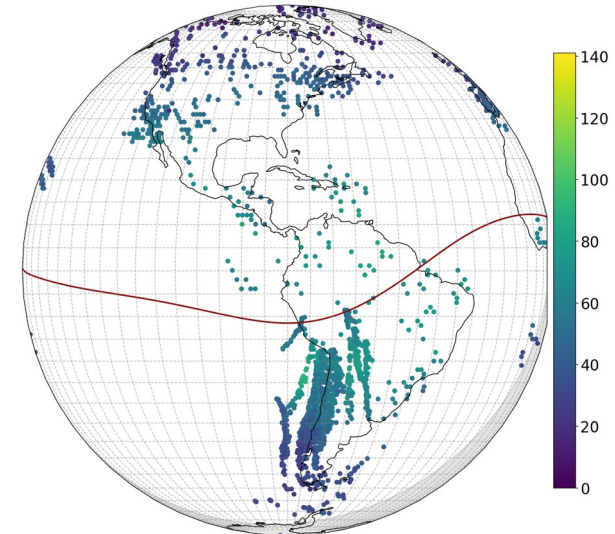
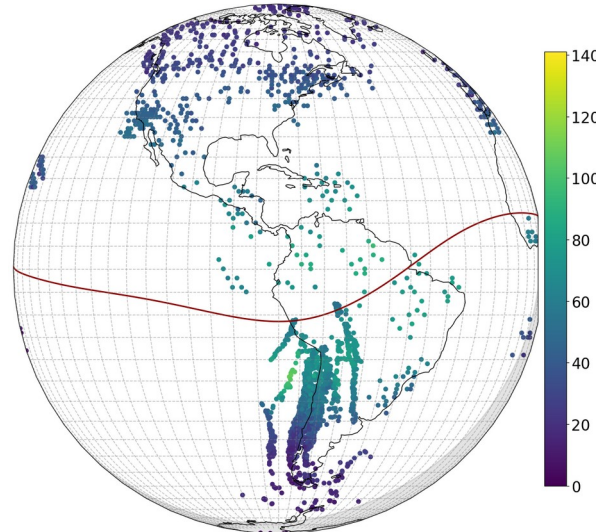
TEC → Before the storm

Complement with high resolution of CSN GNSS



The 8th at 18:00 UTC
DST=3 nT (quiet)

The 10th at 18:00 UTC
DST=66 nT (max reached)

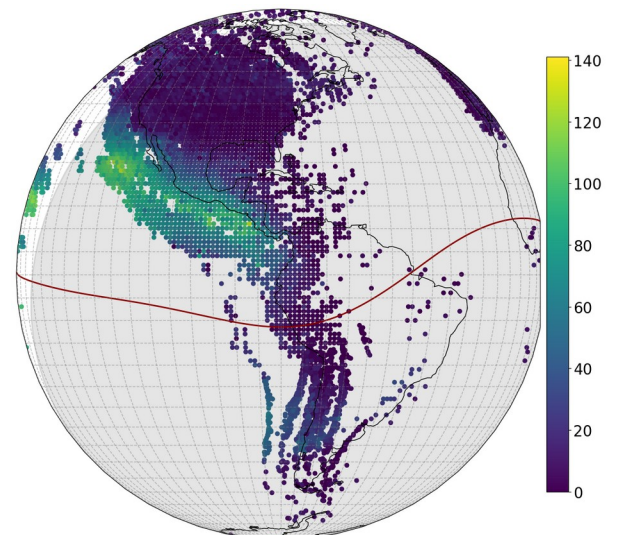
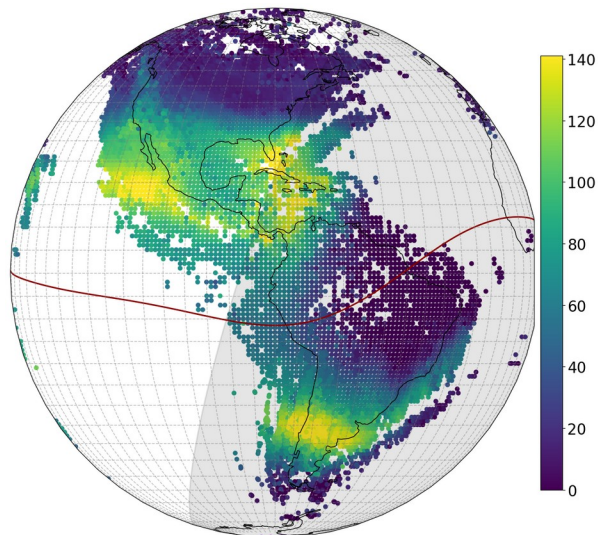
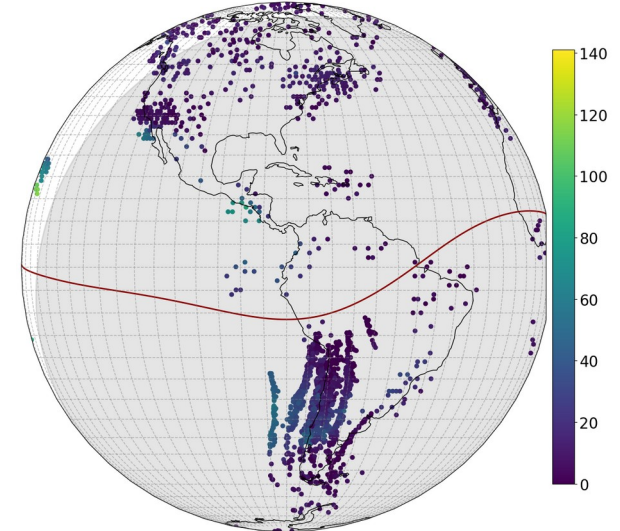
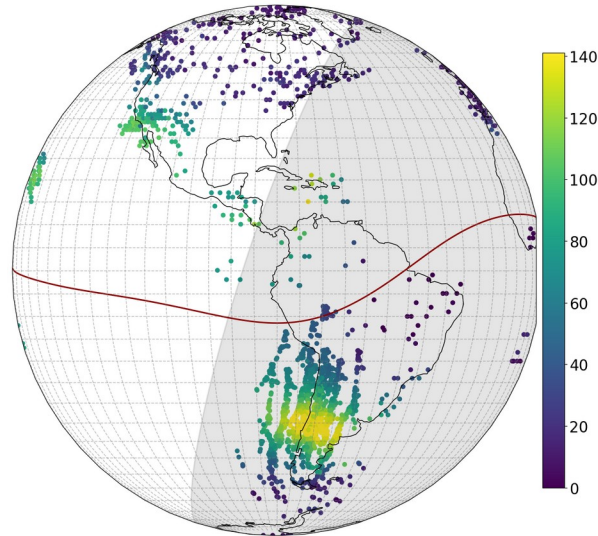
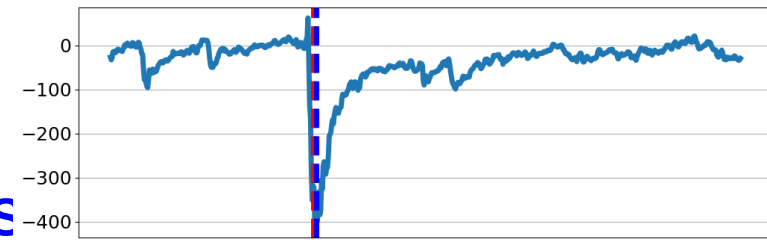


TEC → In the storm

Complement with high resolution of CSN GNSS

The 10th at 23:50 UTC
DST=-351 nT

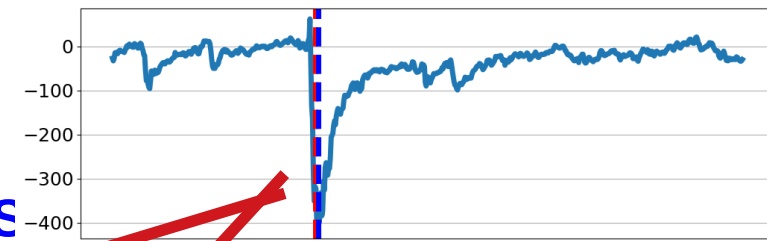
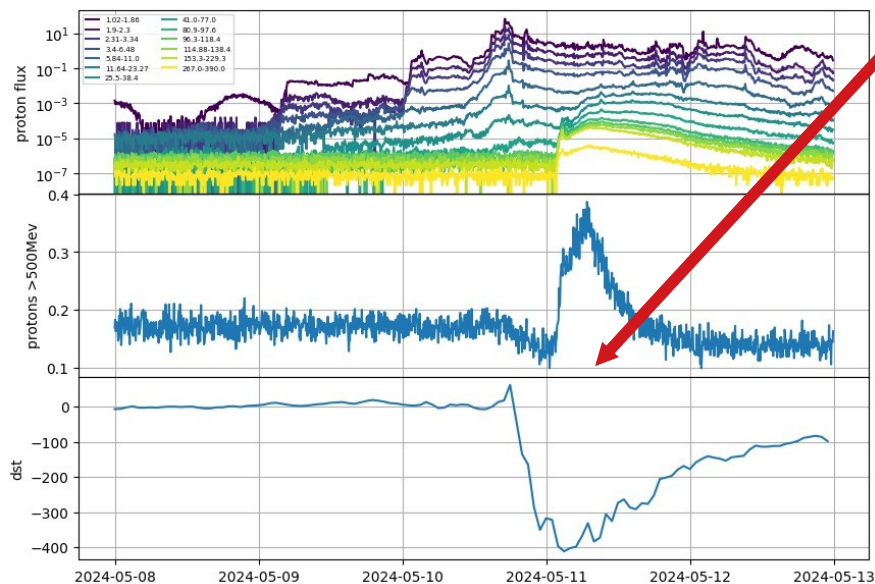
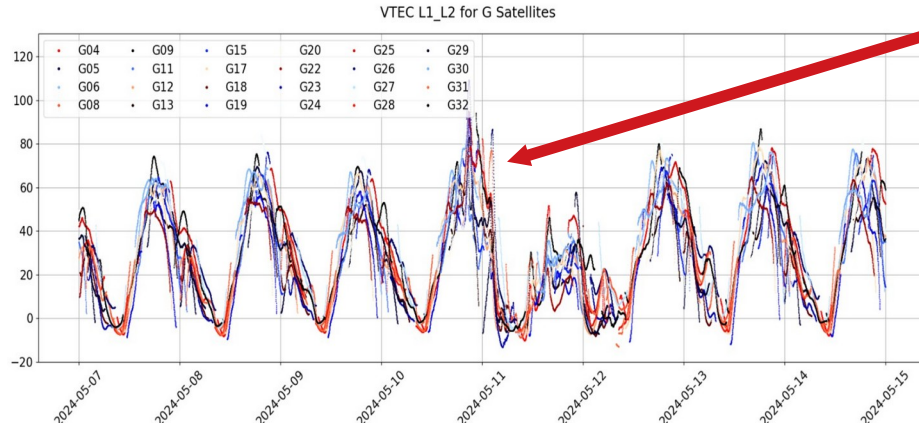
The 11th at 04:00 UTC
DST=-403 nT



TEC → In the storm

Complement with high resolution of CSN GNSS

Small TEC signal (Chile) at storm peak
Solar Large proton flux (a little later)



Mother's Day Geomagnetic Superstorm

MAY 10-14, 2024 · NOAA / NASA / IGS GNSS DATA · ALL PANELS SHARE SAME TIME AXIS

PEAK KP: 9.0 MIN DST (nT): -412 TEC DROP: -35 TECu AURORA BOUNDARY: ~20°N IMF BZ (nT): -50 SOLAR WIND: 990 km/s



KP



Dst

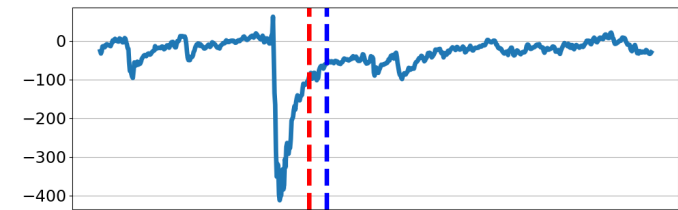


Auroral Boundary



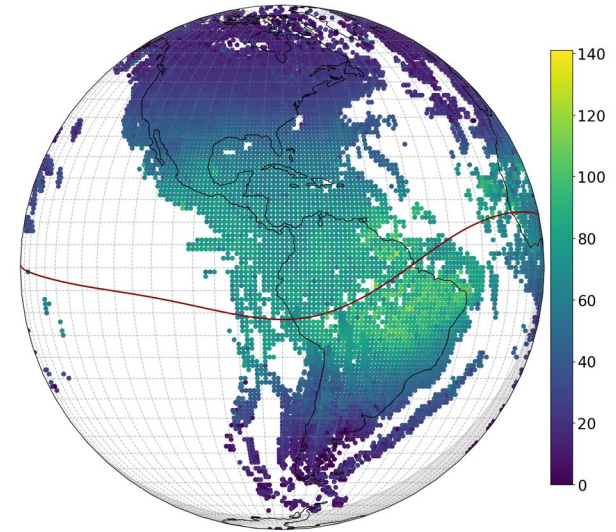
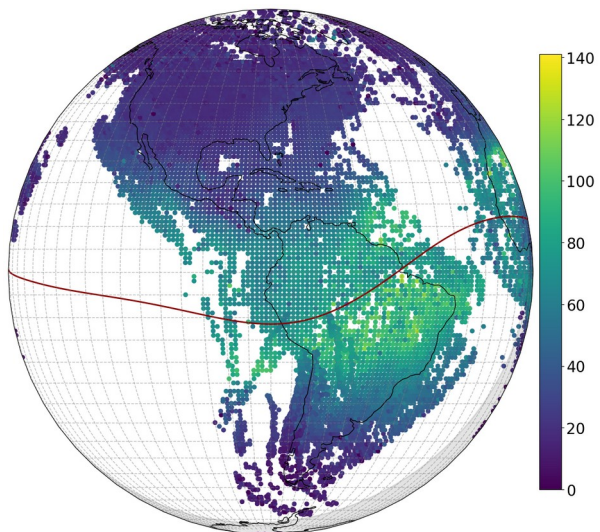
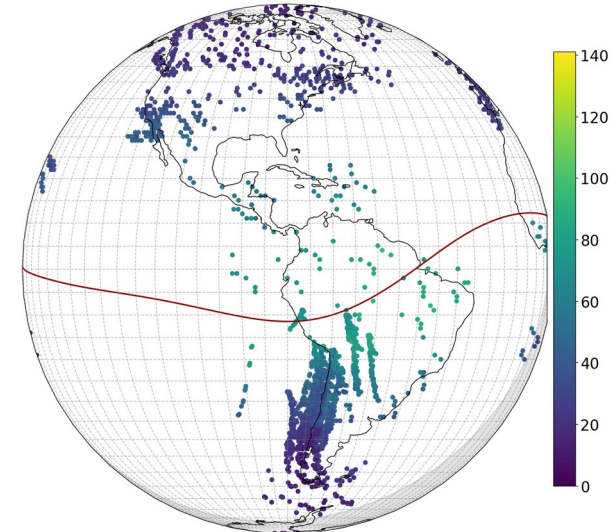
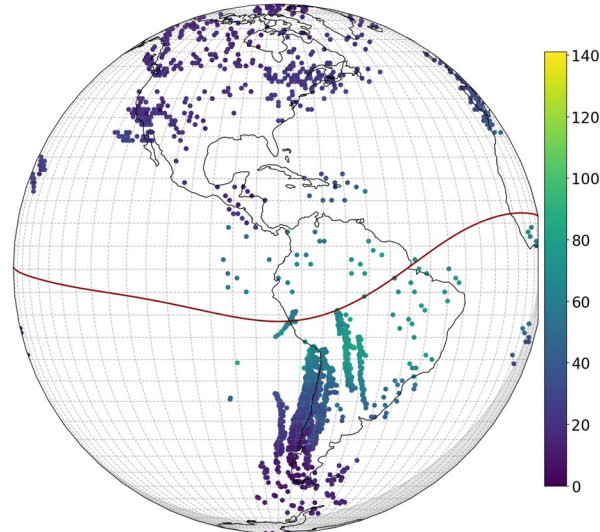
TEC Europe

TEC → Recovery



The 12th at 18:00 UTC
DST=-93 nT

The 13th at 18:00 UTC
DST=-55 nT



TEC Separate components (nonlinear) Relate to Magnetic Fluctuations

Made for the Northern Hemisphere

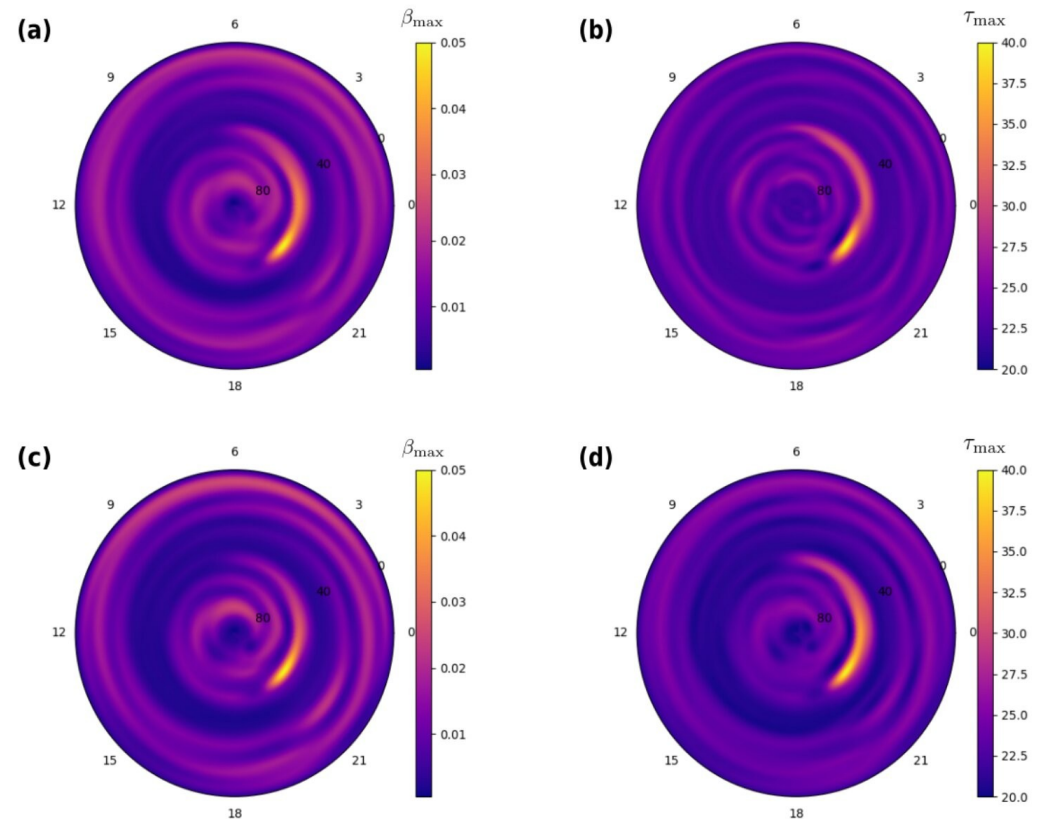
Example: To advance in the southern hemisphere what has already been achieved in the northern hemisphere

Spatially dependent models driven by the solar wind

$$\begin{aligned}
 H(\theta, \phi | t + 1) = & \sum_{\ell=0}^L \sum_{m=-\ell}^{\ell} \alpha_{\ell m} \bar{Y}_{\ell}^m(\theta, \phi) \\
 & + \sum_{\tau=0}^{T_I} \left[\sum_{\ell=0}^L \sum_{m=-\ell}^{\ell} \beta_{\ell m}^{(\tau)} \bar{Y}_{\ell}^m(\theta, \phi) \right] I(t - \tau) \\
 & + \sum_{\tau=0}^{T_O} \left[\sum_{\ell=0}^L \sum_{m=-\ell}^{\ell} \gamma_{\ell m}^{(\tau)} \bar{Y}_{\ell}^m(\theta, \phi) \right] H(t - \tau).
 \end{aligned}$$

Finding spatially dependent coupling coefficients for small and large activity levels

Quantifying the inherent fluctuation levels that affect forecast uncertainty



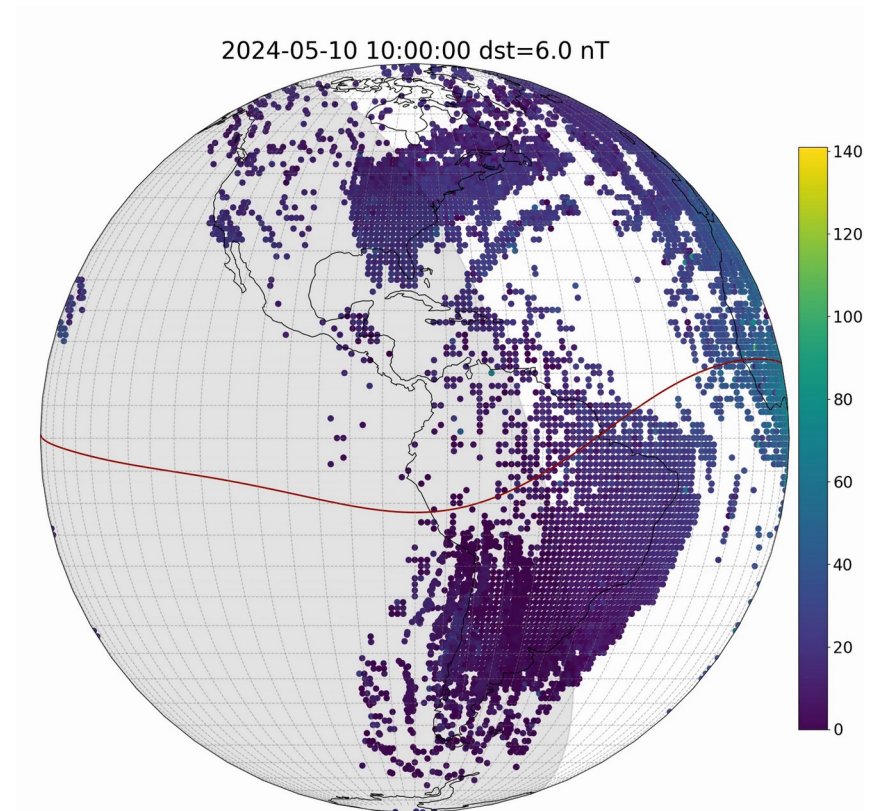
Submitted to ASR. 2026

CONCLUSIONS

- TEC patterns during large event (storms, substorms, eclipses, etc.)
 - Space weather monitoring, diagnostics, technological applications
- Complement with other measurements
 - geophysically induced magnetic fluctuations patterns
 - complement phone data at night
 - etc.

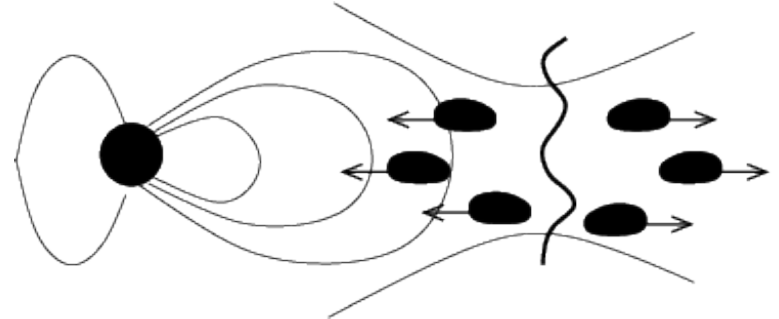
Ganon Storm

Iontec → GPS y Glonass



... and definitely not the end!

Thank you



Financial Support:

- 1) ANID (Chilean NSF) Fondecyt Grant: 1240697
- 2) ANID (Chilean NSF) IDEA i+d Grant: ID25I10556
- 3) US Air Force Office of Scientific Research (AFOSR) Grant (FA8655-25-1-8024), USA

Data:

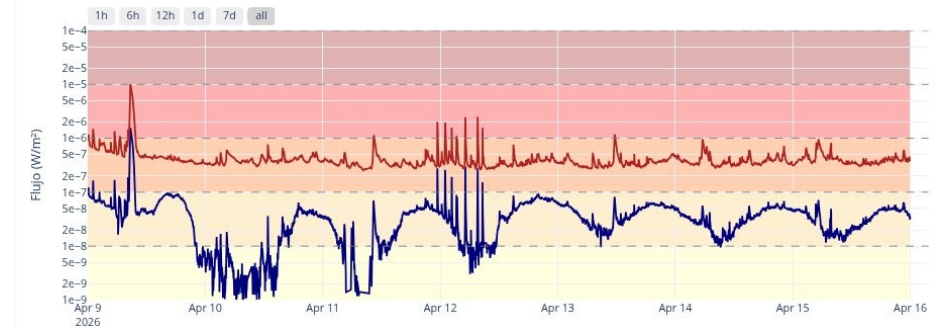
- 1) Centro Sismológico Nacional
- 2) International GNSS service
- 3) Android data for phones
- 4) OMNI/NASA data

The End

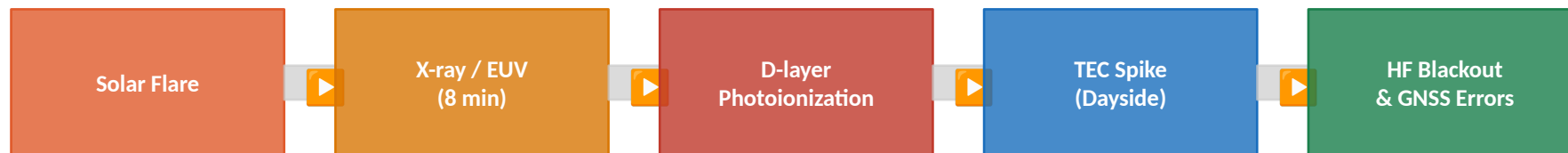
Solar driver vs Magnetospheric Driver

Solar Flares

→ Sudden Ionospheric Disturbances



Goes Satellite X ray data



Key Effects of Solar Flares

HF Radio Blackouts

The over-dense D-layer absorbs HF signals completely (shortwave fadeout). X-class flares can cause complete blackouts over the entire sunlit hemisphere.

GPS/GNSS Errors

Rapid TEC gradients cause positioning errors and loss of signal lock. Even moderate flares can disrupt precision navigation for minutes to hours.

Duration

The effect is immediate (8 min travel time) but short-lived — typically fading within minutes to ~1 hour as the flare dies down. Dayside only.

Solar driver vs Magnetospheric Driver

CMEs → Geomagnetic Storms → Ionospheric Storms



Storm Phases

Positive Phase (Early)

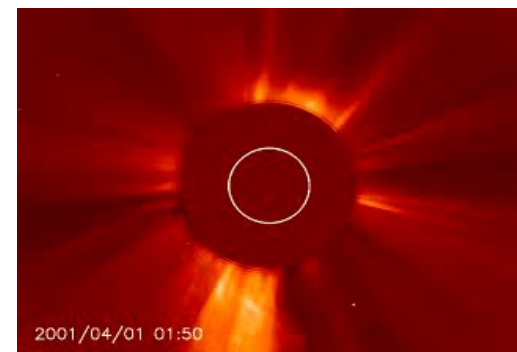
Prompt penetration electric fields push plasma upward and poleward → TEC increases → can worsen GPS errors.

Negative Phase (Main/Recovery)

Particle precipitation, long-lasting signal degradation, fluctuating propagation paths, and sometimes depression in higher HF frequencies

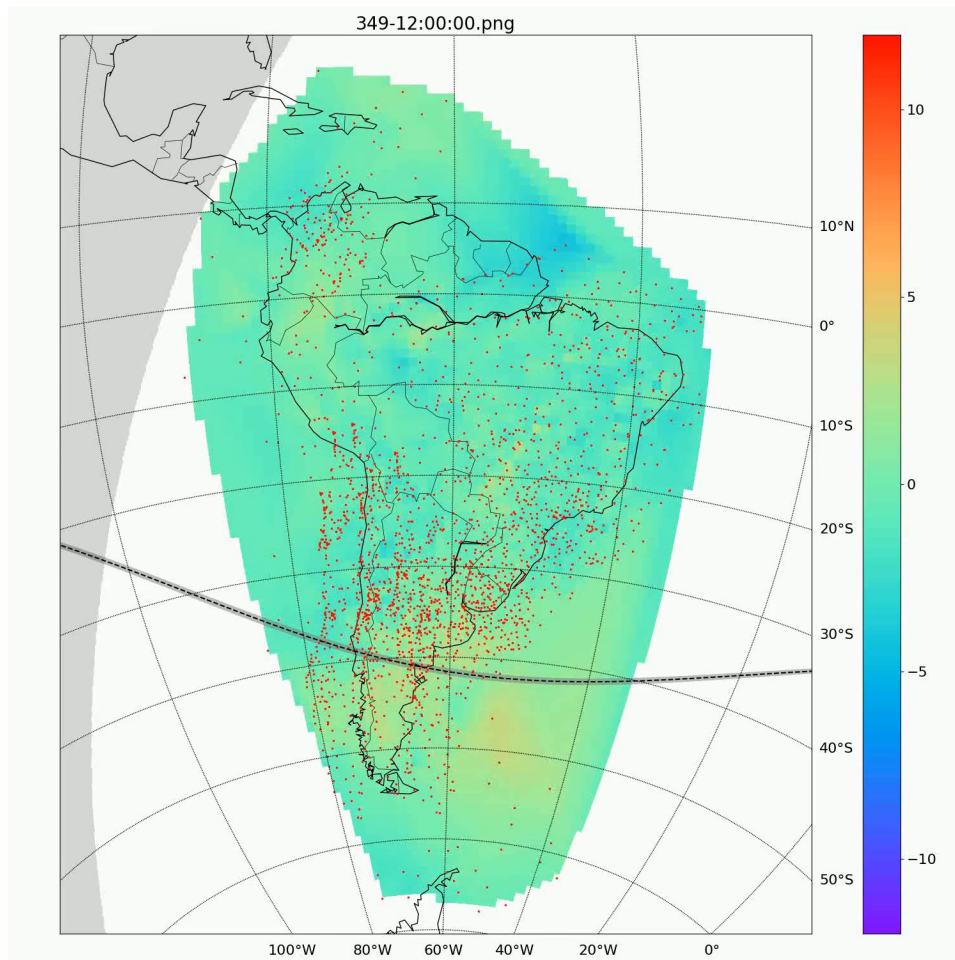
Notable Events: 1989 Quebec Blackout • 2003 Halloween Storms

- Aviation HF comms cut off at polar routes
- GNSS-dependent systems can fail silently
- Power grids damaged by induced currents (GICs)
- Satellite operations disrupted for hours to days

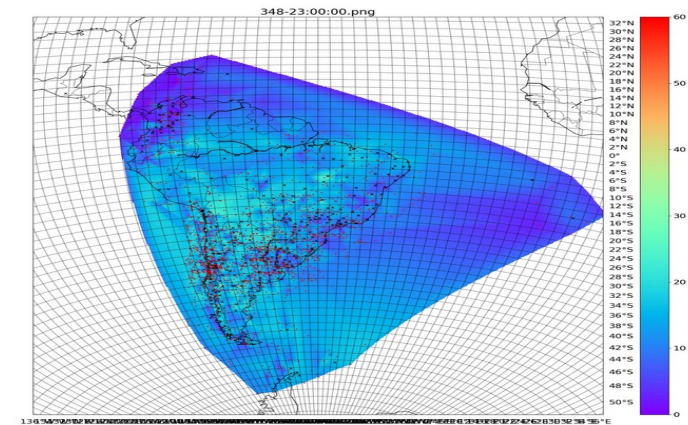


Iontec Validation Eclipse 2019

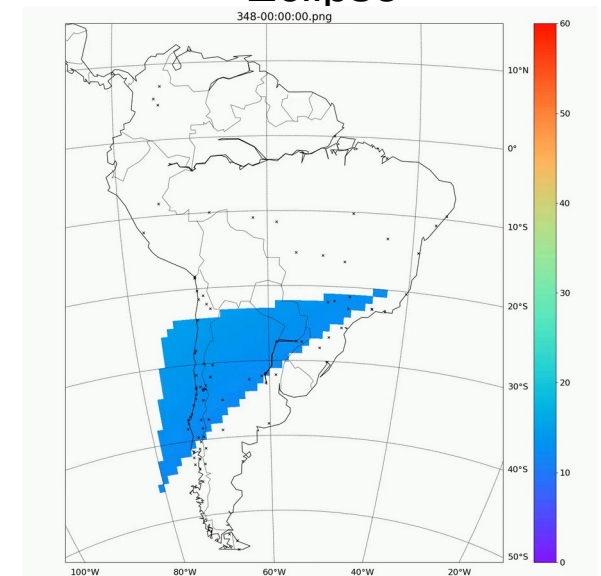
ECLIPSE 2019



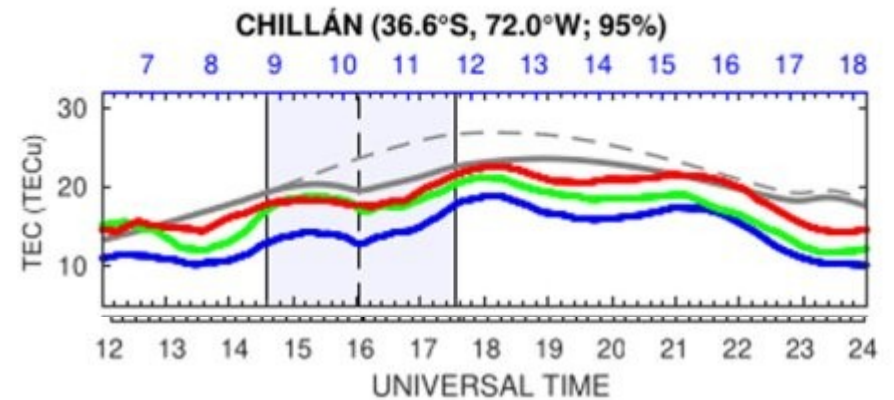
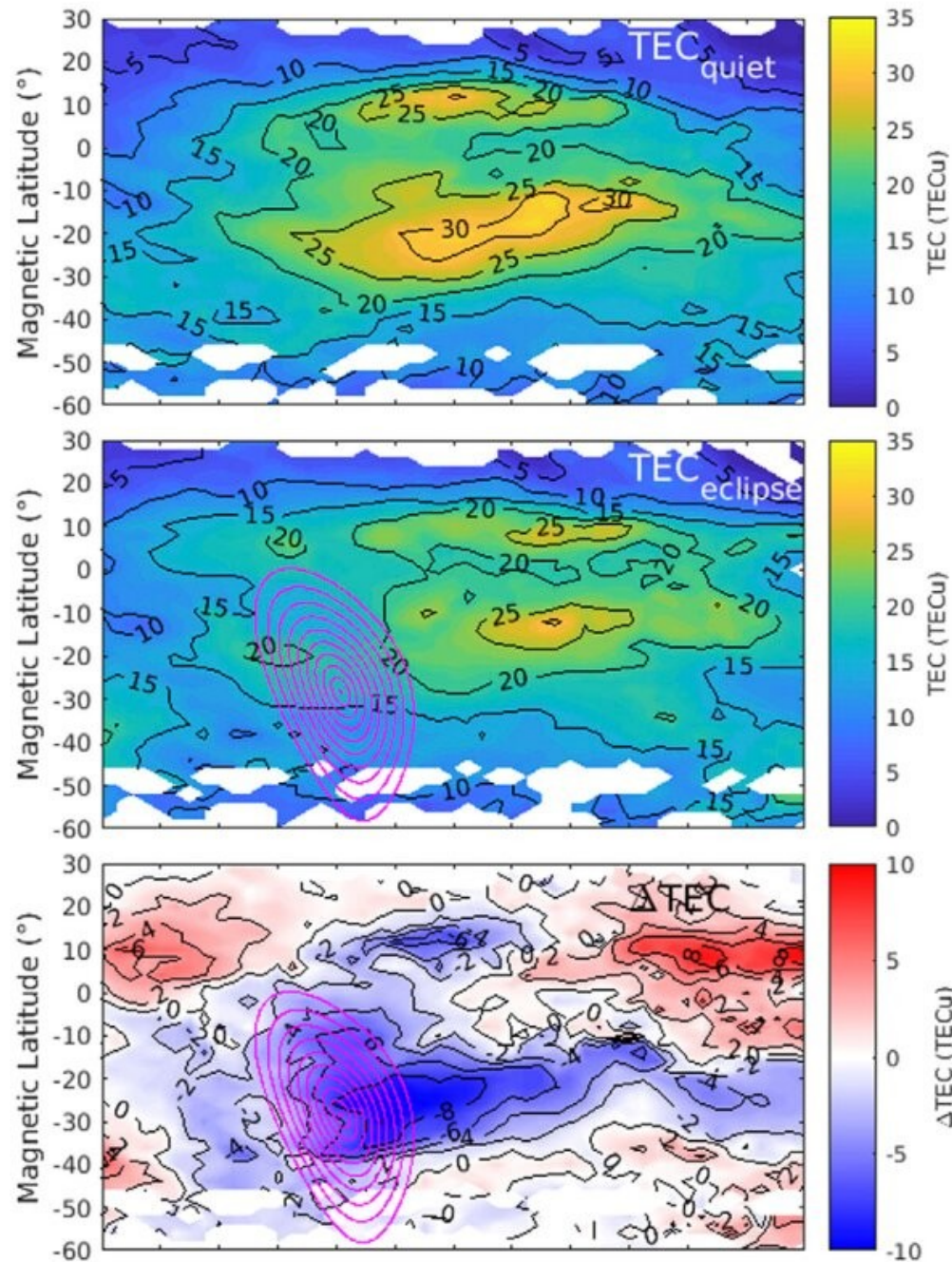
No Eclipse



Eclipse



Ionotec Validation Eclipse 2019



Temporal evolution of the TEC, using the validated Ionotec code, along the magnetic meridian of Chillán (36.6° S, 72.0° W), Chile, during the day of the eclipse (right), which occurred in Chile in December 2020.