IGS 2026 WORKSHOP
SANTIAGO DE CHILE
33°26' S 70°39' O

1-5 June 2026

Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

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Using GNSS-TEC to Monitor Ionospheric Responses to Solar Eclipses

ORGANIZING INSTITUTIONS

IGS INTERNATIONAL GNSS SERVICE

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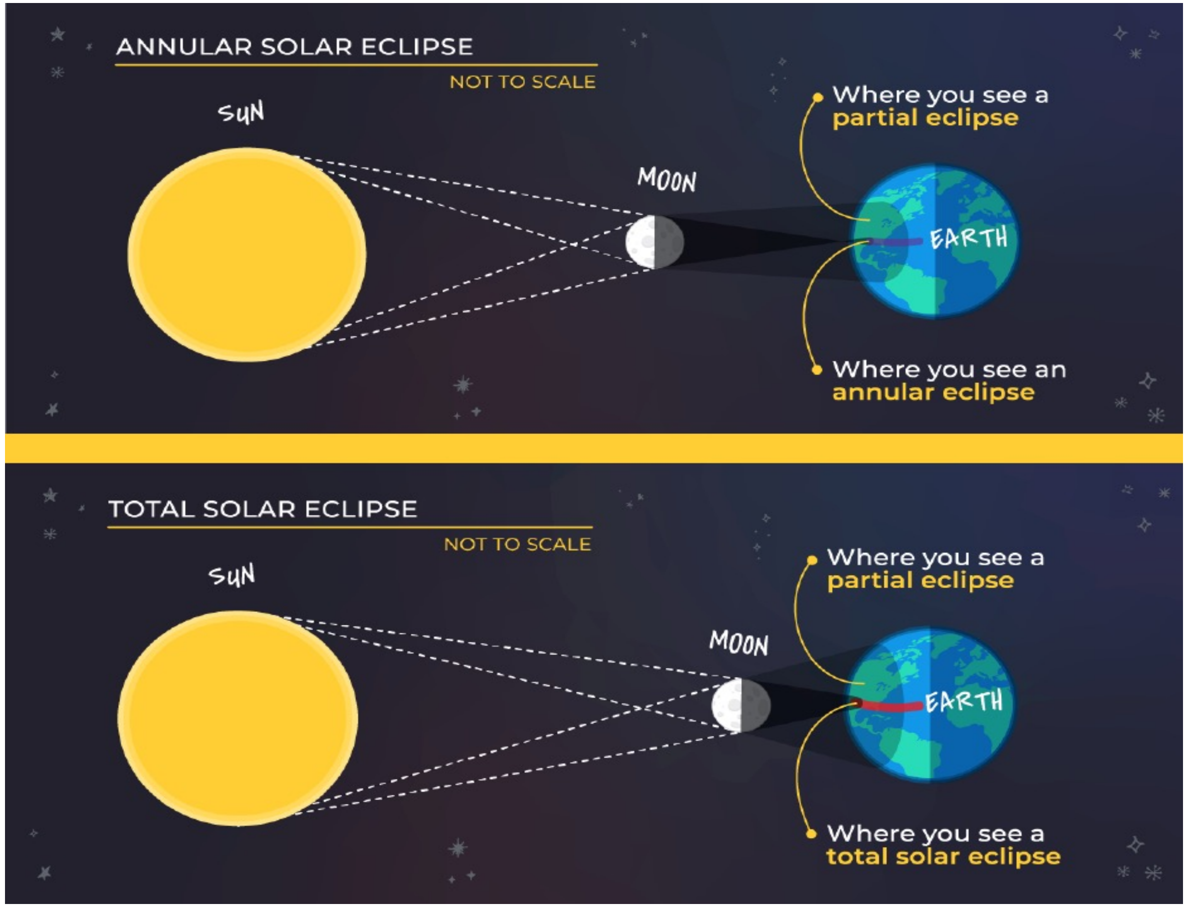
FACULTAD DE INGENIERÍA

DEPARTAMENTO DE INGENIERÍA GEOESPACIAL Y AMBIENTAL

PROCESSING CENTER AND GEODETIC ANALYSIS USC

Solar Eclipses

Solar eclipses are natural phenomena that have accompanied humanity for thousands of years.
They occur when the Moon passes between the Earth and the Sun, partially or completely blocking solar radiation and casting a shadow over the Earth



https://www.adlerplanetarium.org/blog/different-types-of-solar-eclipses-explained/

- **Partial** - Moon's penumbral shadow traverses Earth (umbral and antumbral shadows completely miss Earth)
- **Total** - Moon's umbral shadow traverses Earth (Moon is close enough to Earth to completely cover the Sun)
- **Annular** - Moon's antumbral shadow traverses Earth (Moon is too far from Earth to completely cover the Sun)

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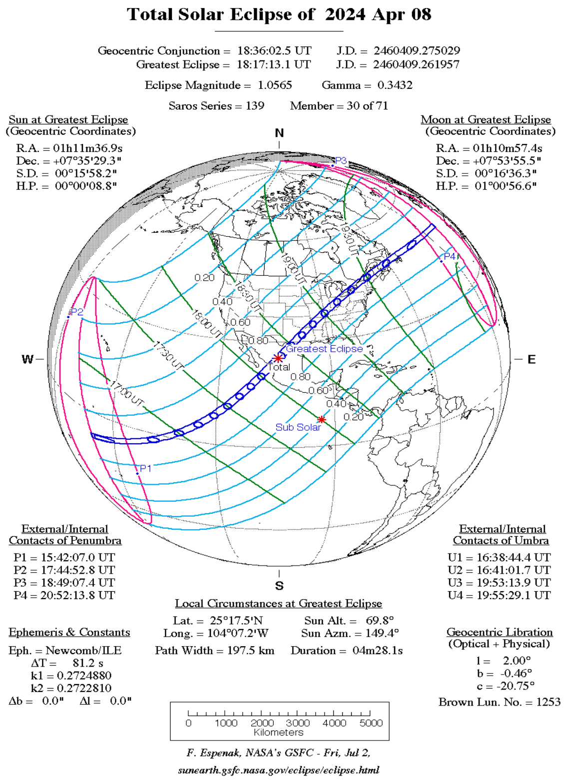
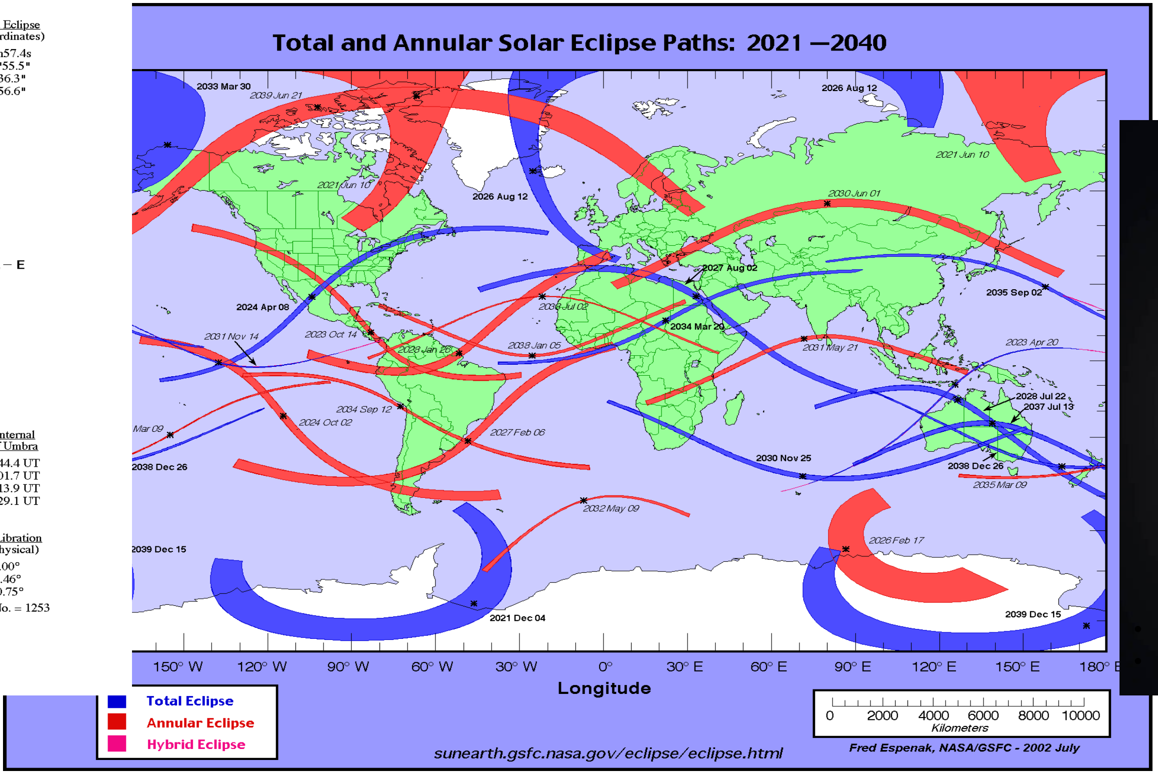
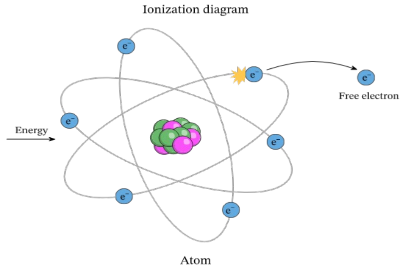
Solar Eclipses

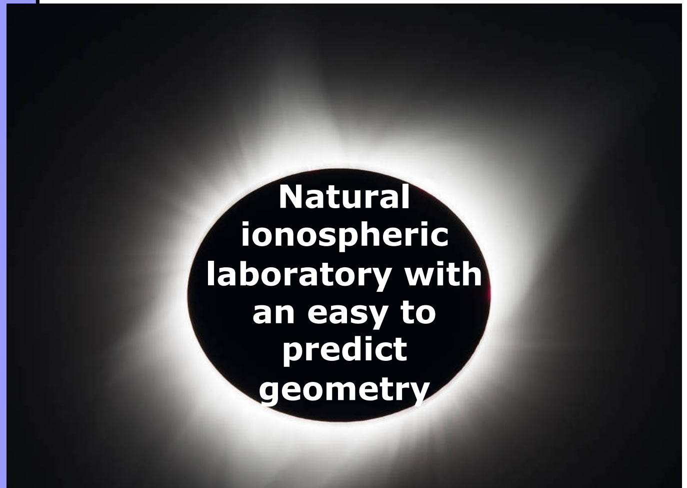
Solar eclipses are highly predictable phenomena because they depend on the orbital motion and geometry of the Sun, Moon, and Earth. Using precise astronomical models, eclipses can be predicted decades or even centuries in advance.

The gradual decrease in solar radiation to totality (in some cases) generates a geographic window with nocturnal conditions during sunlight hours.







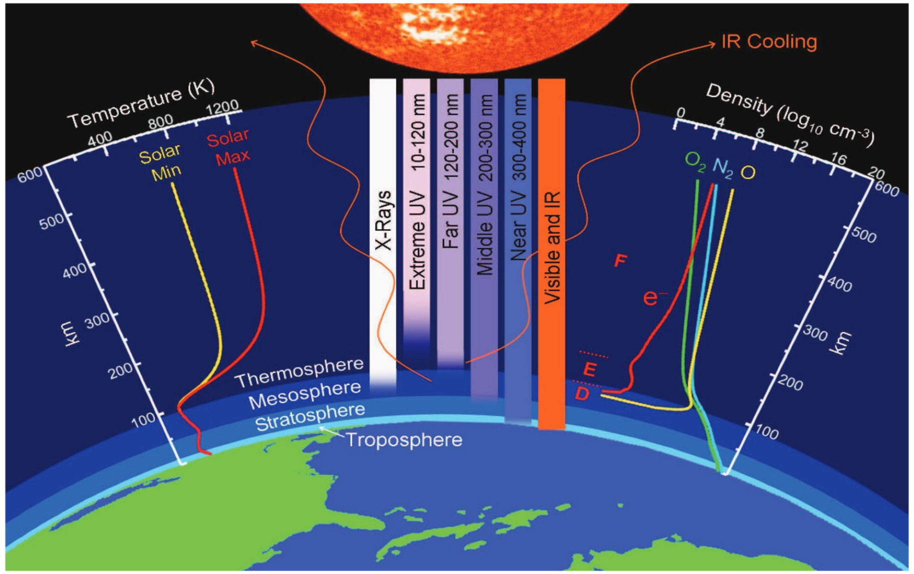


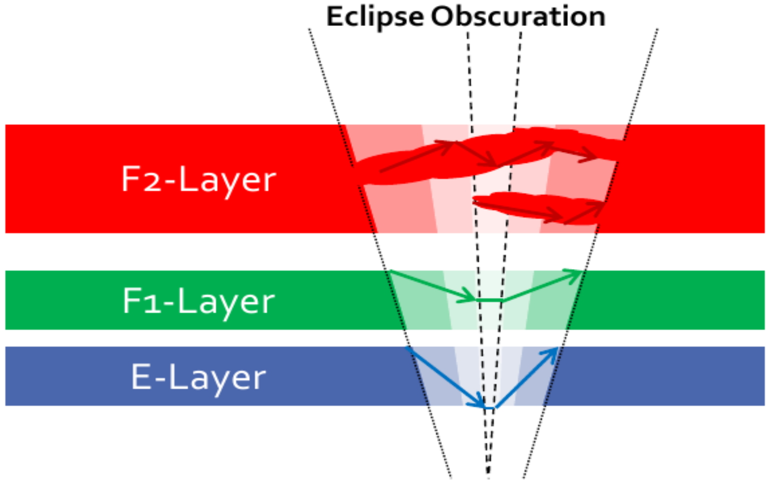
- To calculate recombination/ionization rates.
- To test ionospheric models

http://eclipse.gsfc.nasa.gov/

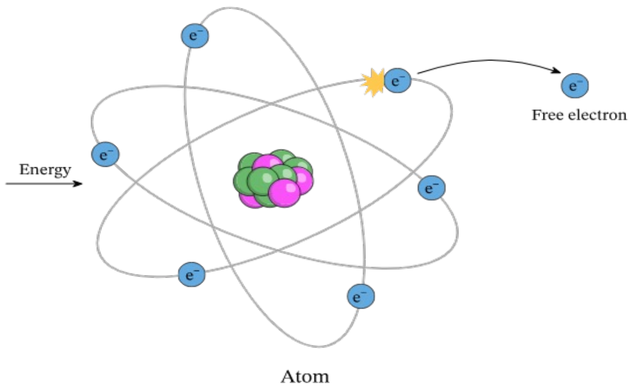
Ionospheric impact of Solar Eclipses

- The different layers of the ionosphere suffer different impacts effects during the eclipse obscuration
- E and F1 layers presents large density depletions due to the predominance of recombination among photoionization processes at these altitudes
- F2 layer response depends on diffusion and transport plasma processes
- Highly dependent on the eclipse geometry, the geomagnetic latitude, its previous status, the plasma electrodynamics, and external forcing (such as space weather activity or lower atmospheric interactions)





$$\frac{\partial N_i}{\partial t} + \nabla \cdot (N_i \mathbf{V_i}) = P_i - L_i$$



During totality, the Moon blocks the solar chromosphere, while coronal radiation still contributes weakly to ionospheric photoionization, mainly below 200 km (Reinisch et al., 2018).

Ionospheric impact of Solar Eclipses

Ionization Changes:
In the ionosphere, solar radiation is a primary source of ionization, which the process in which an atom or molecule becomes charged when it gains or loses electrons. During a solar eclipse, the reduction in solar radiation leads to a decrease in ionization

Temperature Changes:
The decrease in solar radiation during an eclipse can also lead to cooling of the upper atmosphere. This cooling can affect the temperature structure of the ionosphere, potentially causing changes in ionospheric densities and altitudes

[O]/[N_2] ratio changes

Thermospheric neutral winds changes

Disturbed dynamo

Electron Density Variations:
The reduction in ionization and cooling during an eclipse can lead to a decrease in the electron density in the ionosphere. This can affect the propagation of radio waves, particularly in the high frequency, or HF, range, which rely on ionospheric reflection for long-distance communication.

Ionospheric Anomalies:
The sudden changes in ionospheric conditions during an eclipse can lead to the formation of ionospheric anomalies, such as ionospheric holes or depletions.

- E x B drift changes
- EIA crests changes
- Gravity waves generation
- Sporadic layer occurrence

- Interhemispheric transport
- Magnetic field changes

Propagation Effects:
The altered ionospheric conditions during an eclipse can change how radio waves propagate through the ionosphere. This can cause signal fading, absorption, and refraction, affecting shortwave and satellite communication systems.

https://science.nasa.gov/solar-system/skywatching/eclipses/solar-eclipses/the-impact-of-solar-eclipses-on-the-structure-and-dynamics-of-earths-upper-atmosphere/

Solar eclipses trigger complex ionospheric and atmospheric processes beyond simple ionization reduction

GNSS-TEC Revolution in Ionospheric Studies

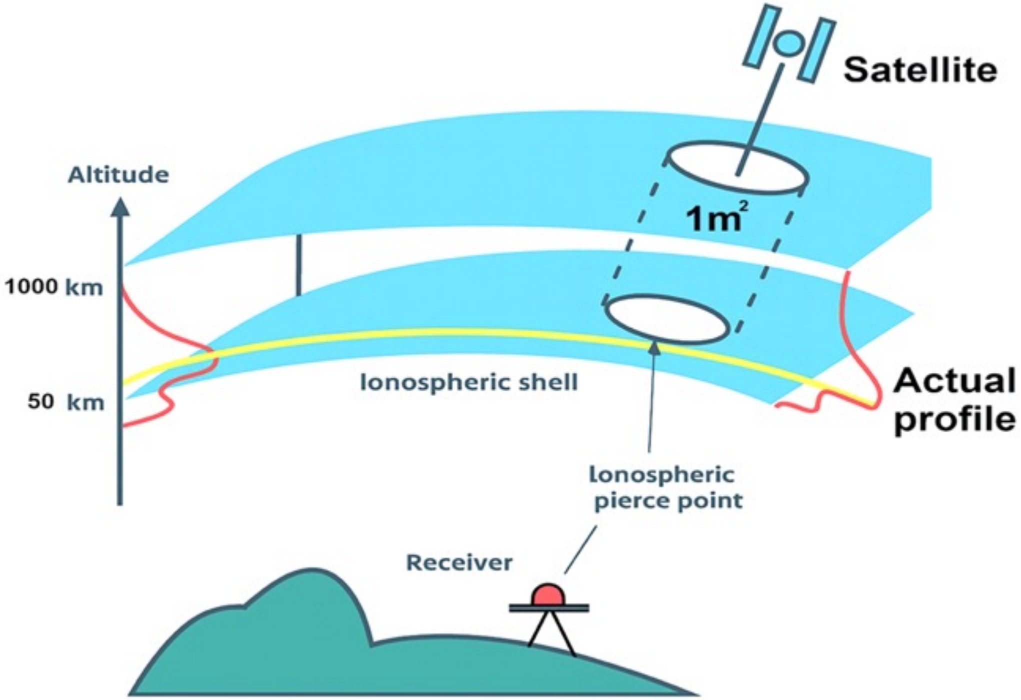
The development of dual-frequency GNSS systems enabled the use of Total Electron Content (TEC) as a powerful tool for ionospheric monitoring, providing much broader spatial and temporal coverage than traditional ionosondes.

Feature	**Ionosondes**	**GNSS-TEC**
Measurement type	Vertical sounding	Integrated electron content
Temporal resolution	15–60 min	~30 s
Spatial coverage	Single location	Regional to global
Ocean coverage	Very limited	Possible
Network density	Sparse	Very large

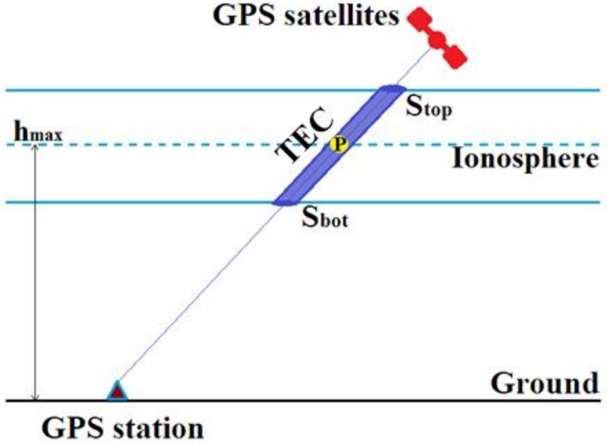
https://spotlight.unavco.org/how-gps-works/gps-basics/gps-and-geosciences.html

Total Electron Content (TEC)

GNSS dual-frequency observations allow the estimation of ionospheric TEC variations.



Kenpankho (2006)



The total electron content I is the electron density Ne integrated along a beam:

$$I = \int_{Sbot}^{Stop} N_e \, ds$$

TEC calculation using the phase measurements at two GNSS frequencies:

$$I = \frac{1}{40.308} \frac{f_1{}^2 f_2{}^2}{f_1{}^2 - f_2{}^2} \left[(L_1\lambda_1 - L_2\lambda_2) + const_{1,2} + \sigma L \right]$$

where $L_1\lambda_1$ и $L_2\lambda_2$ is the phase path increments of the radio signals; $L_1 = \frac{\Delta\varphi}{2\pi}$ and $L_2 = \frac{\Delta\varphi}{2\pi}$, phase measurements by GNSS-receiver made at frequencies of f_1 and f_2 ; $const_{1,2}$, ambiguity of phase measurements; σL, phase measurement error.

Baikal School, 2015 2

GNSS-TEC significantly expanded the capability to monitor ionospheric disturbances during solar eclipses.

Data and Methodology

Data and Methodology

This presentation summarizes GNSS-TEC observations reported in six independent studies of solar eclipses occurring under different geographic and ionospheric conditions.

Date	Region
26 Feb 2017	South America & Antarctica
15 Feb 2018	South America & Antarctica
02 Jul 2019	South America
14 Dec 2020	South America
30 Apr 2022	Antarctica
10 Jun 2021	Arctic Region

Using the same GNSS-TEC framework, these eclipses allow us to compare ionospheric responses across low-, mid-, and high-latitude regions

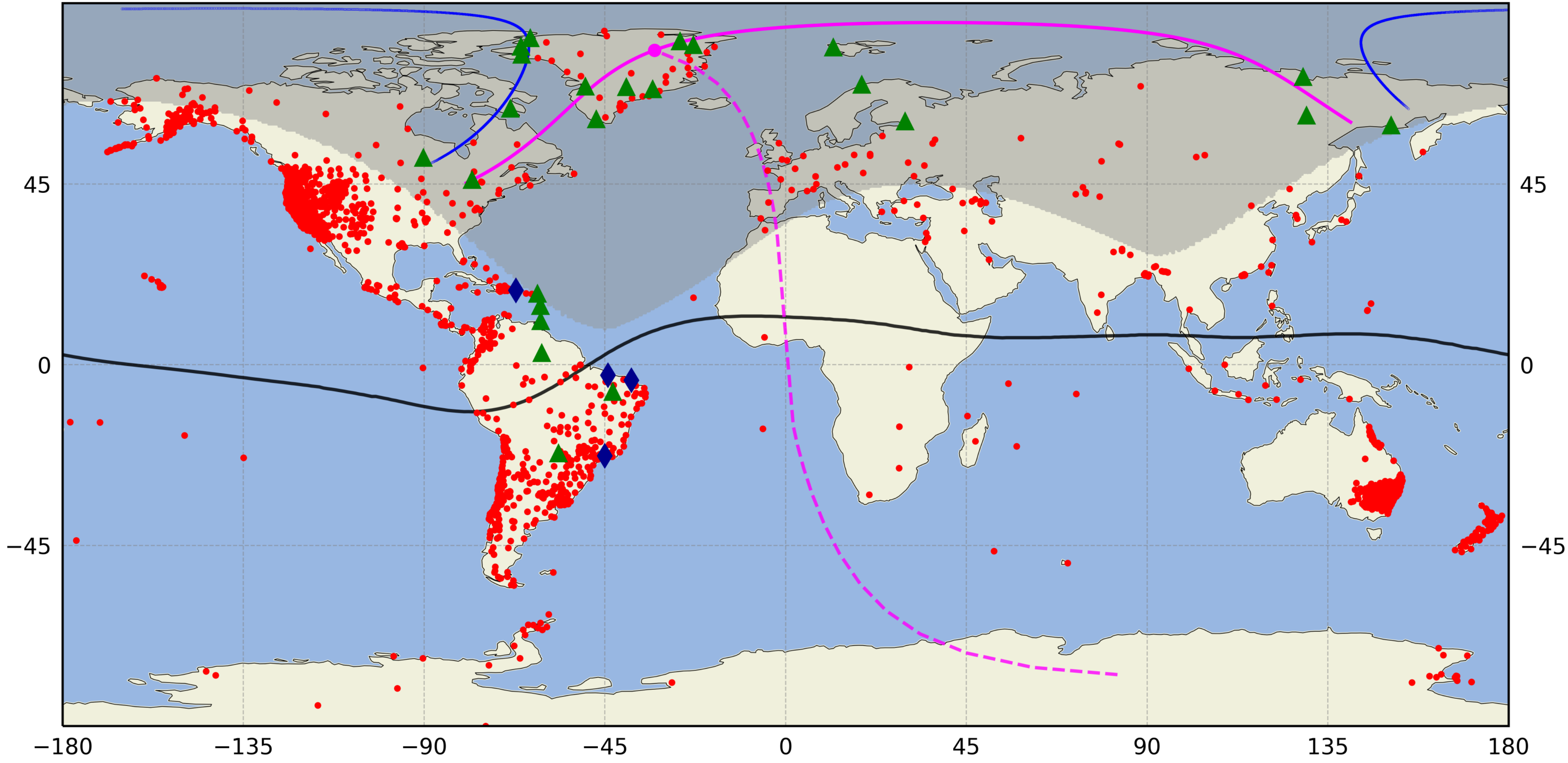
Dual-Frecuency GNSS observations

VTEC estimation
(Seemala & Valladares, 2011)

ΔTEC calculation relative to reference conditions

Temporal and spatial analysis

Data

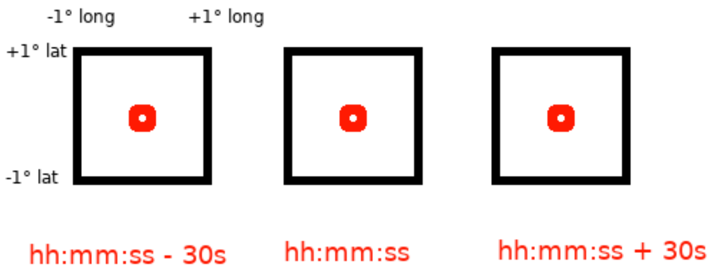


Results

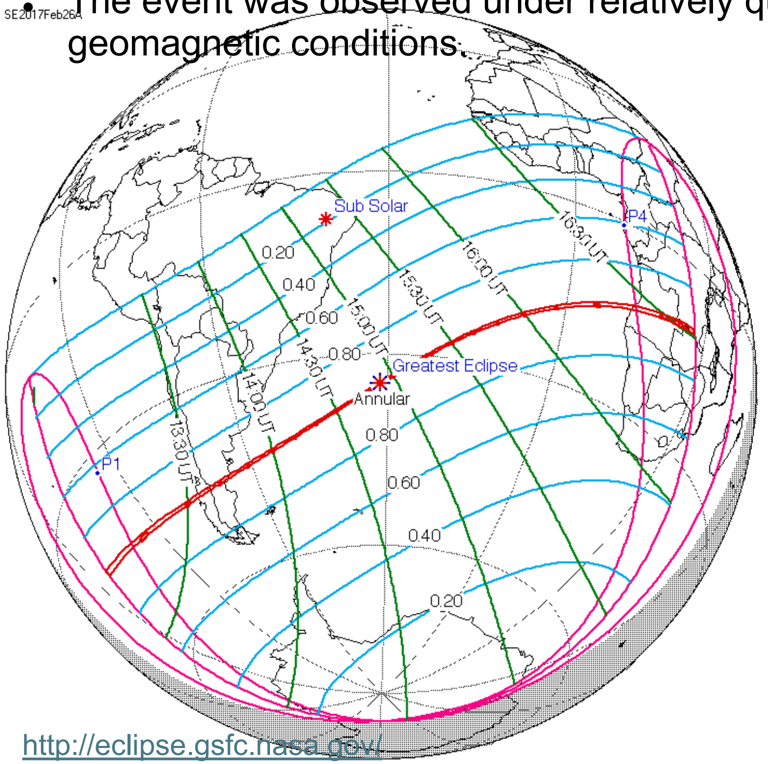
26 February 2017 Solar Eclipse

$$\Delta TEC(\%) = \frac{TEC_d - TEC_{d-1}}{TEC} \times 100$$

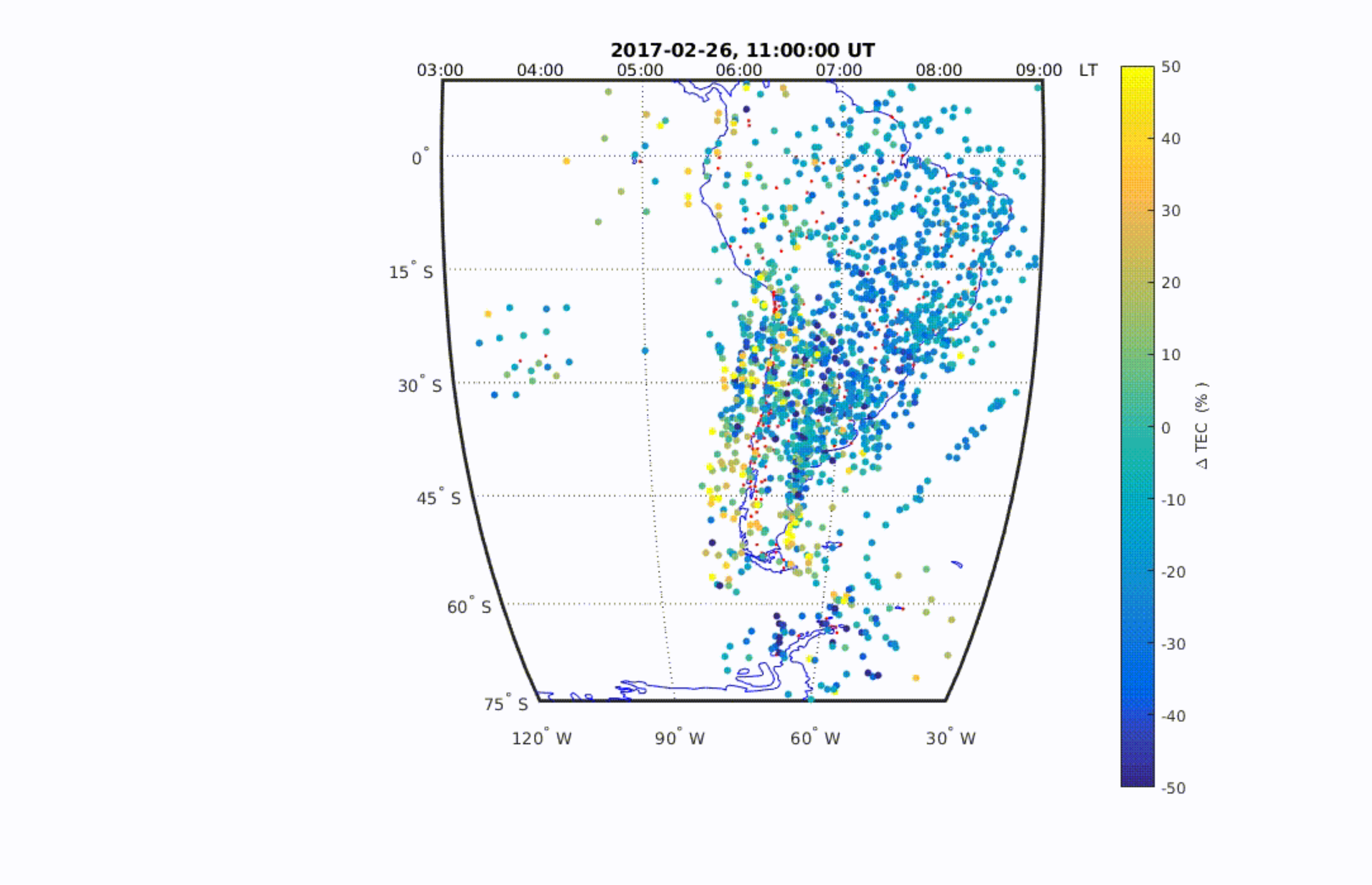
$TEC_{d-1} \rightarrow$



- Annular eclipse.
- Maximum obscuration occurred over southern Chile and Argentina.
- Extensive GNSS coverage was available across South America.
- The event was observed under relatively quiet geomagnetic conditions.



http://eclipse.gsfc.nasa.gov/



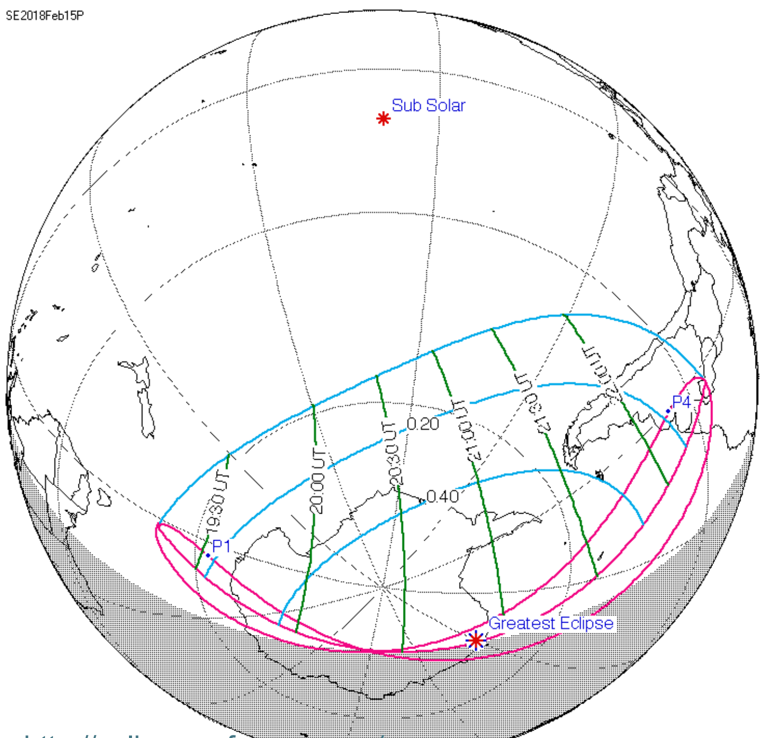
15 February 2018 Solar Eclipse

- Annular eclipse over Antarctica.
- Partial eclipse over southern South America.
- High-latitude ionospheric conditions.
- GNSS observations from Antarctic and South American stations.

$$DVTEC_t = VTEC_t - \overline{VTEC_t}$$

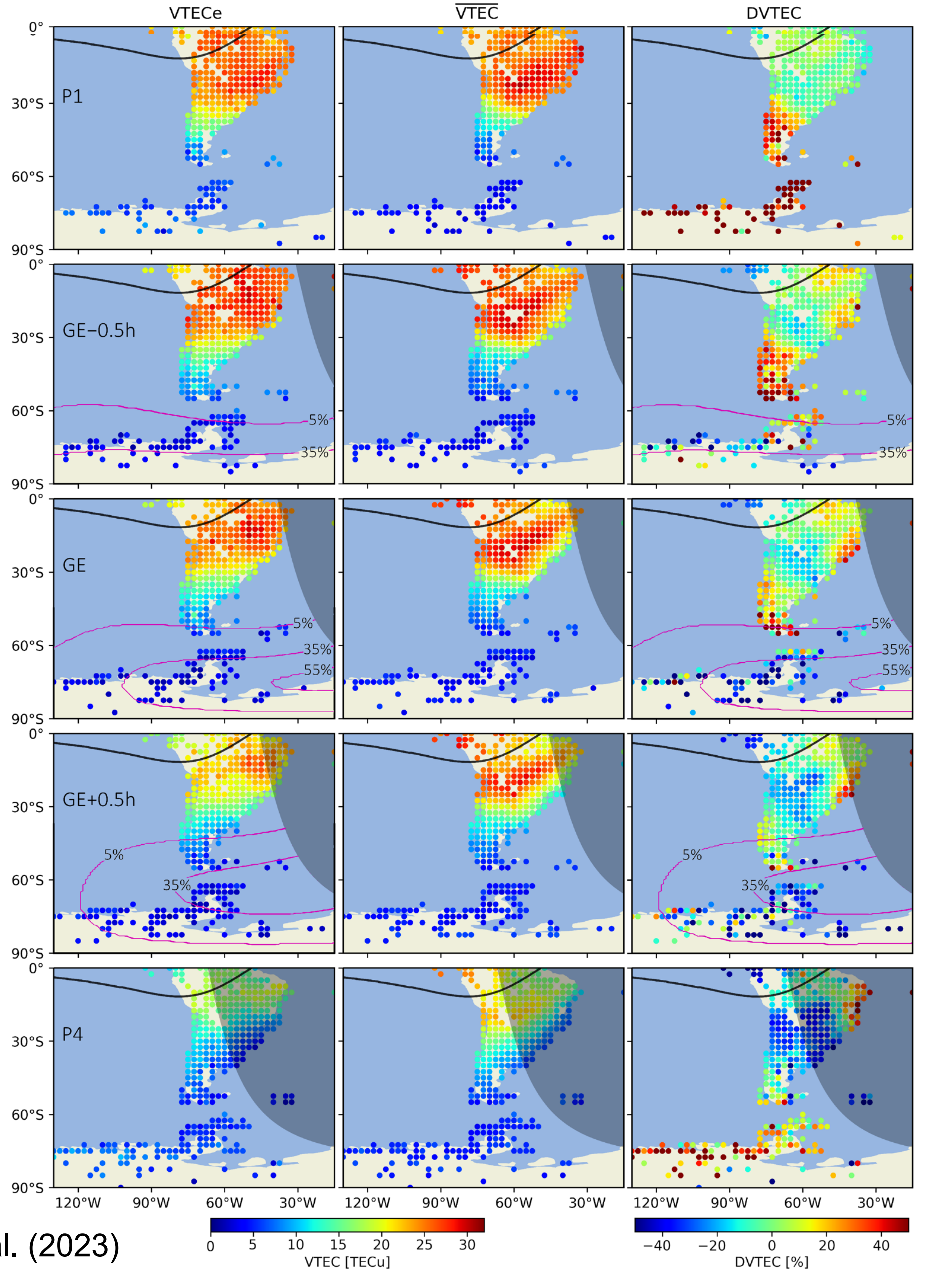
$$DVTEC[\%]_t = \frac{DVTEC_t}{\overline{VTEC_t}} \cdot 100$$

Reference days = ± 5 days (Kp ≤ 2+ , Dst > −30 nT)



http://eclipse.gsfc.nasa.gov/

- Despite enhanced geomagnetic activity, a clear eclipse-induced TEC depletion was observed beneath the penumbra, reaching DVTEC < −40%.
- The ionospheric disturbance persisted beyond the end of the eclipse.
- A pronounced depletion of the southern crest of the Equatorial Ionization Anomaly (EIA) was detected, with DVTEC approaching −50%.
- The eclipse signature remained clearly identifiable despite the presence of geomagnetic forcing.



Valdes-Abreu et al. (2023)

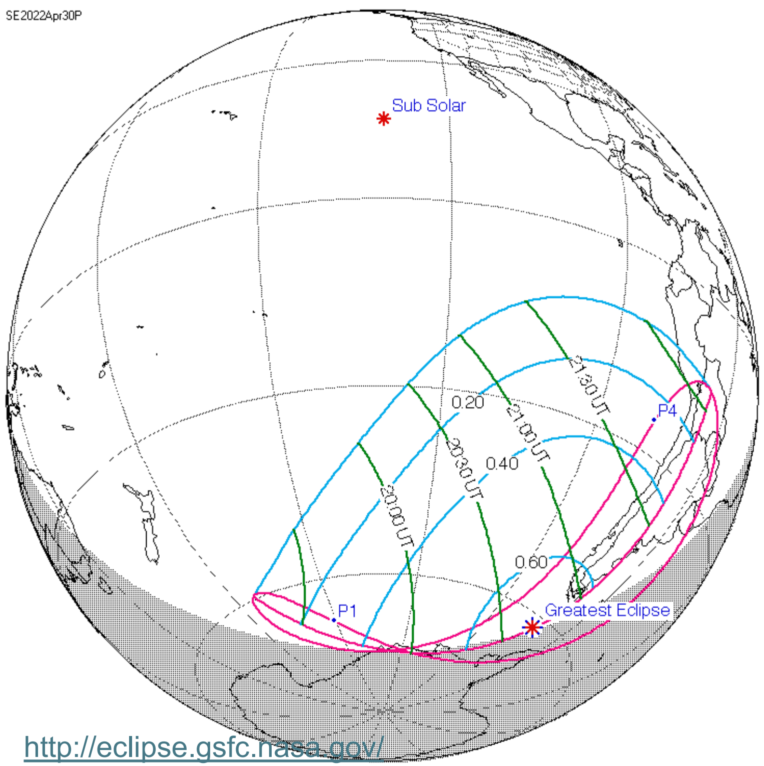
30 Abril 2022 Solar Eclipse

- A partial solar eclipse over south america provided a unique opportunity to investigate the ionospheric response at high southern latitudes using GNSS-TEC observations.

$$DVTEC_t = VTEC_t - \overline{VTEC_t}$$

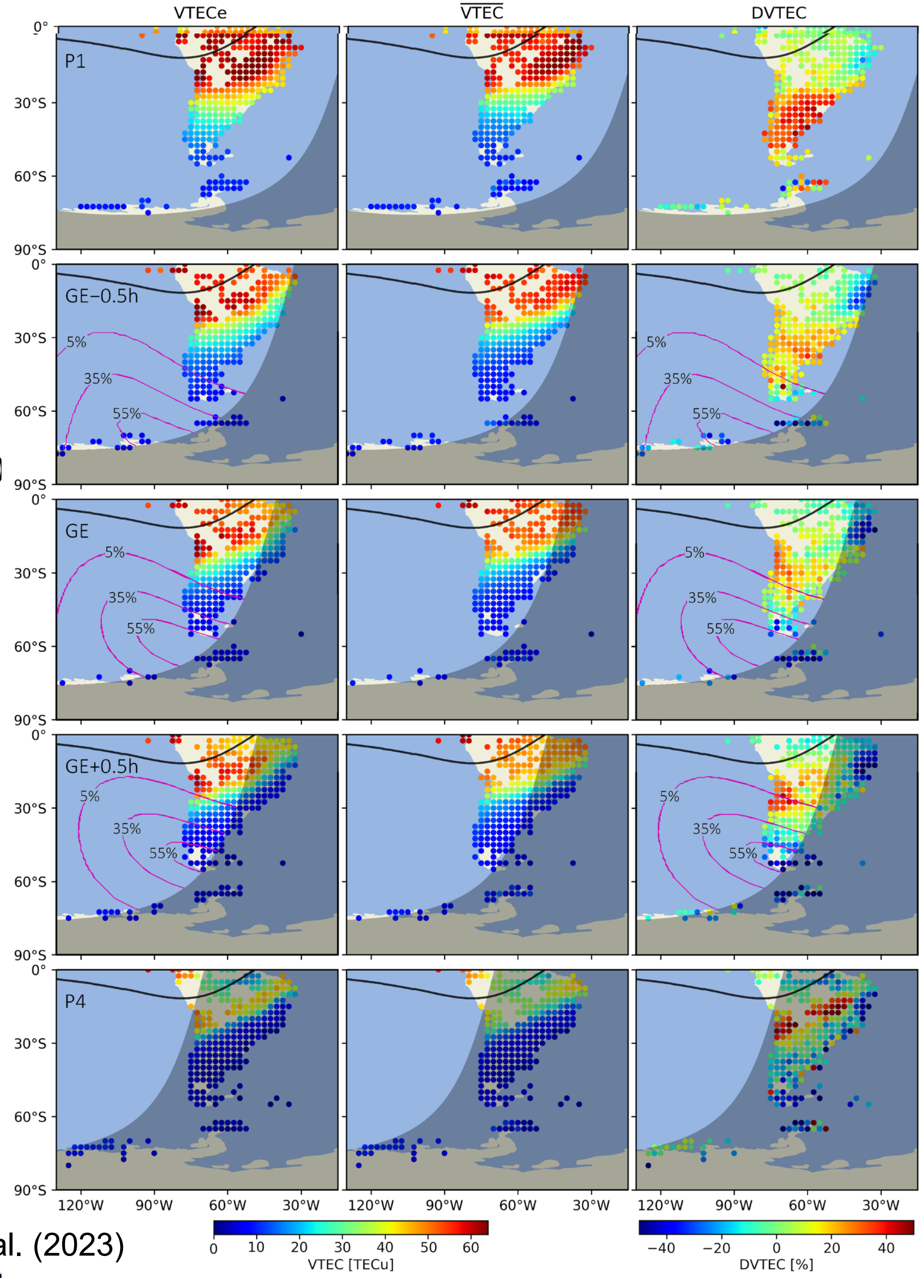
$$DVTEC[\%]_t = \frac{DVTEC_t}{\overline{VTEC_t}} \cdot 100$$

Reference days = ± 5 days (Kp ≤ 2+ , Dst > −30 nT)



http://eclipse.gsfc.nasa.gov/

- A pronounced enhancement of the southern EIA crest was observed, with DVTEC approaching +50%. The enhancement persisted beyond sunset and remained detectable after the passage of the solar terminator.



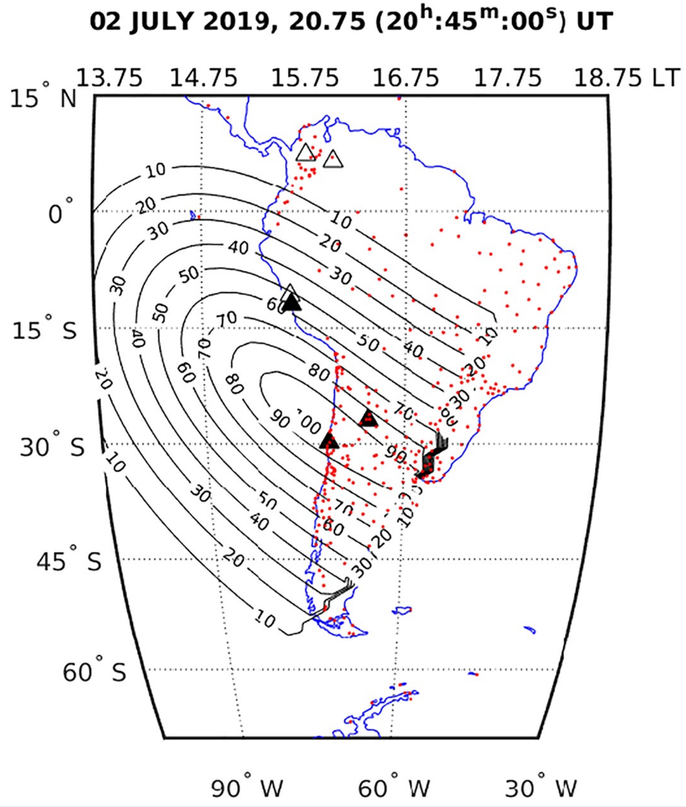
Valdes-Abreu et al. (2023)

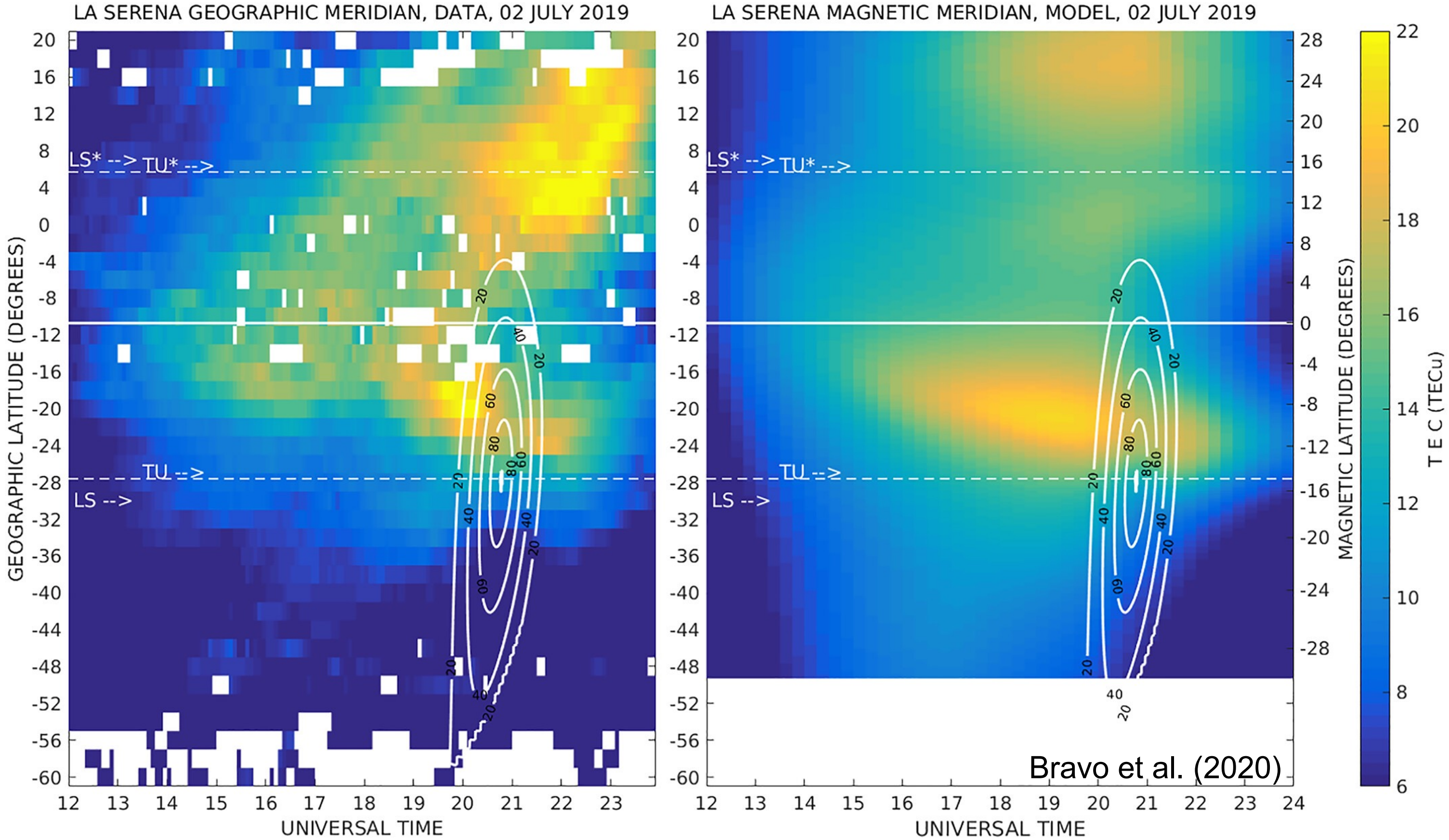
2 July 2019 Total Solar Eclipse

SUPIM-INPE: Sheffield University Plasmasphere-Ionosphere Model (Bailey & Sellek, 1990; Bailey et al., 1993) modified at INPE

$$I_R = I_{NT} + I_{R0}^{\lambda<30.4}(1 - 0.7 \times ObscMask) + I_{R0}^{\lambda \geq 30.4}(1 - ObscMask)$$

- Total eclipse over northern Chile and Argentina.
- Extensive GNSS coverage across South America.
- Opportunity to investigate the ionospheric response from low to mid latitudes.

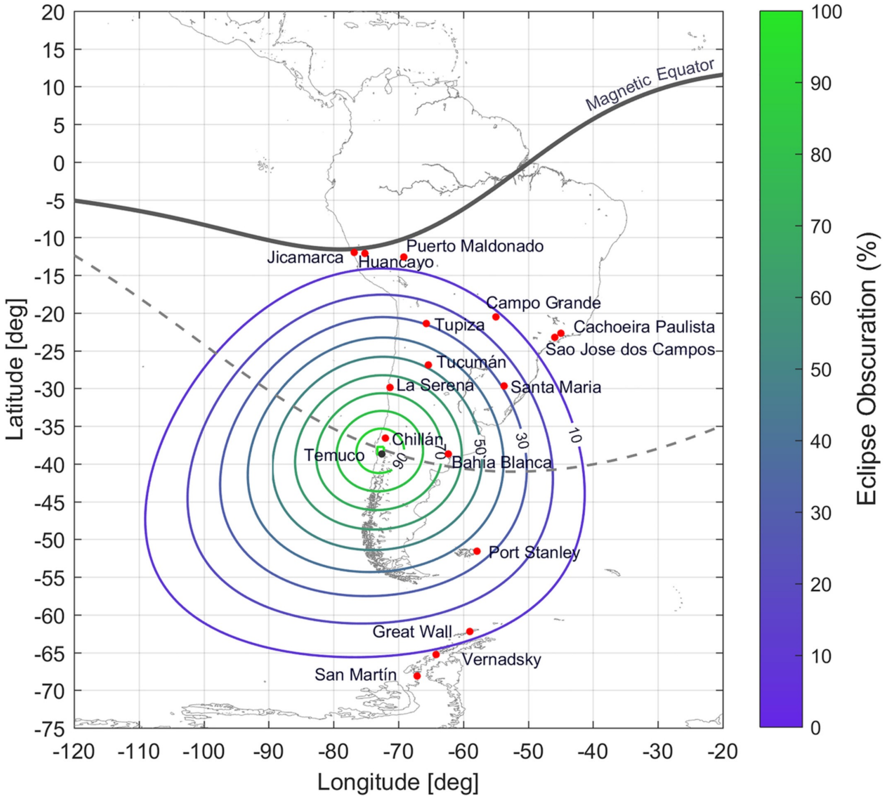


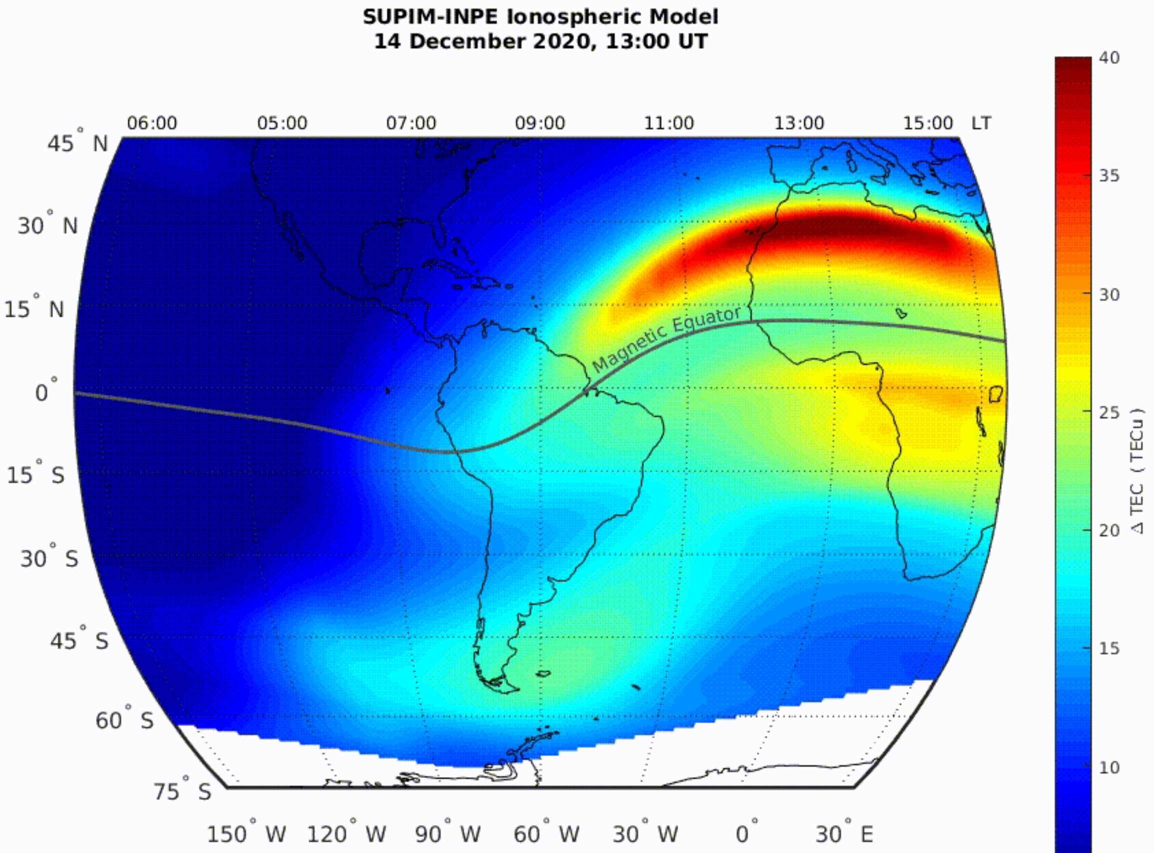


- TEC observations were compared with simulations from the SUPIM-INPE model.
- GNSS-TEC observations and SUPIM-INPE simulations showed a consistent ionospheric response to the eclipse, supporting the use of physics-based models for TEC prediction during solar eclipses.

14 December 2020 Total Solar Eclipse

- For this event, we attempted a pre-eclipse prediction of TEC variations at ionosonde stations, several months before the eclipse occurred.





(Martinez-Ledesma, M., Bravo, M., Urra, B., Souza, J., & Foppiano, A. (2020). Prediction of the Ionospheric Response to the 14 December 2020 Total Solar Eclipse Using SUPIM-INPE. J. Geophys. Res.: Space Physics, 125, e2020JA028625. doi:10.1029/2020JA028625)

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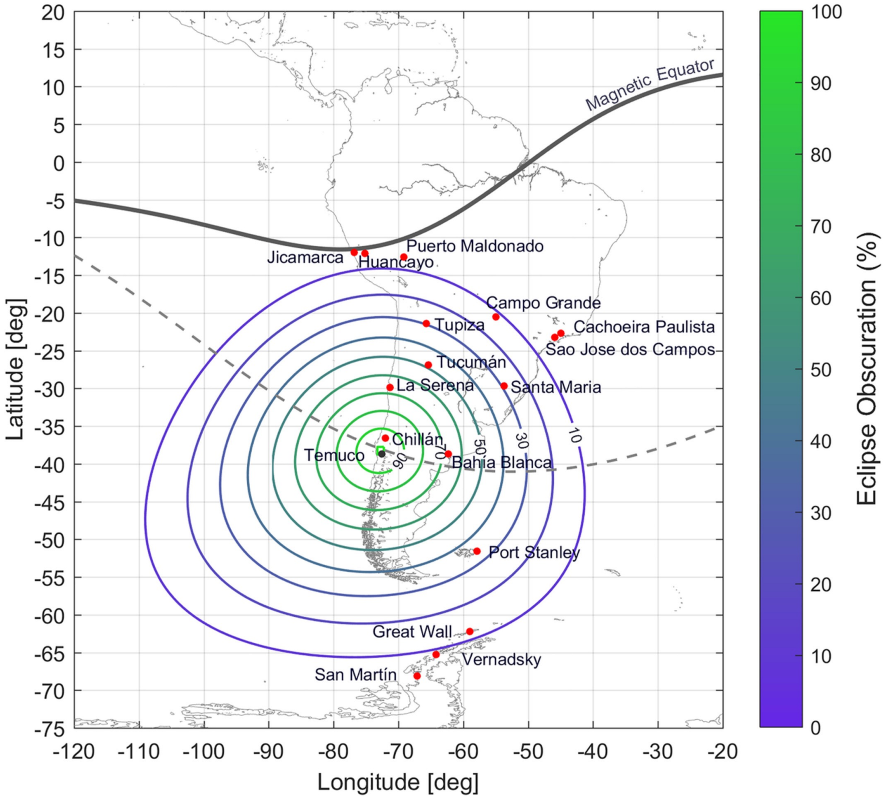
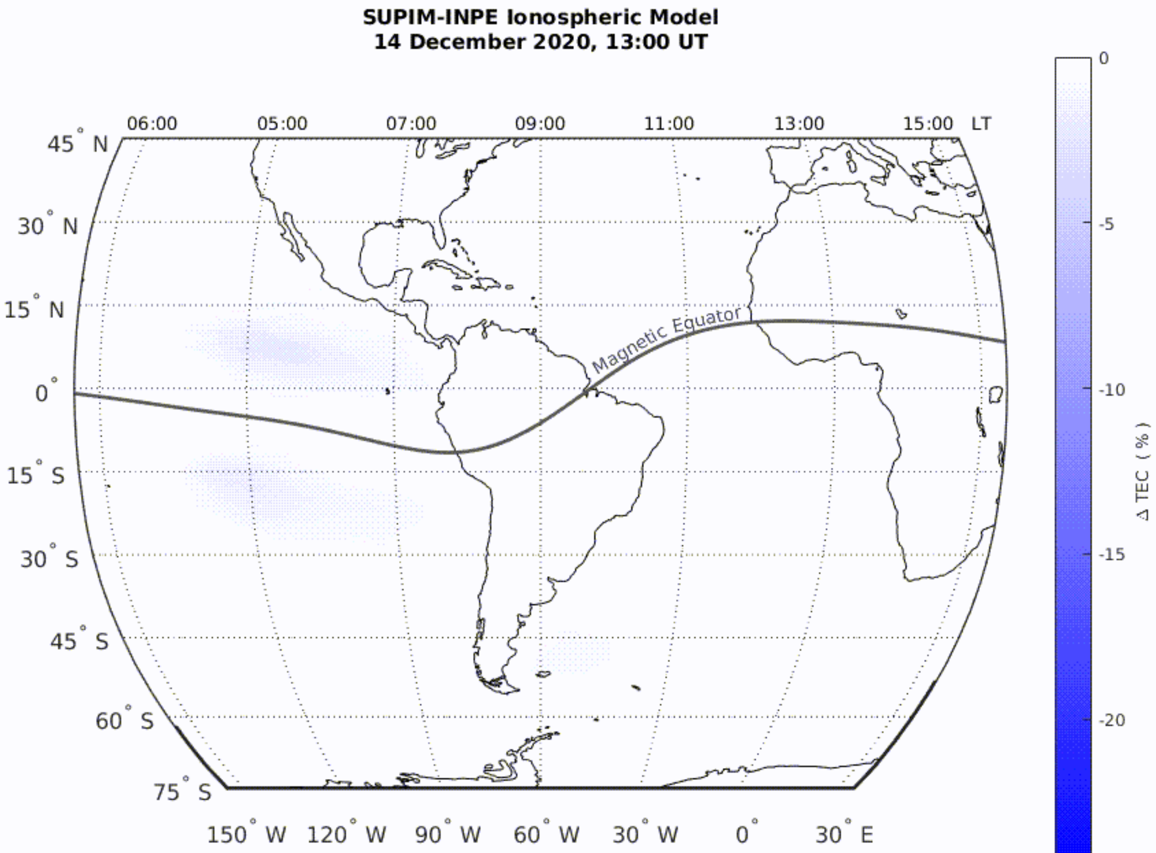
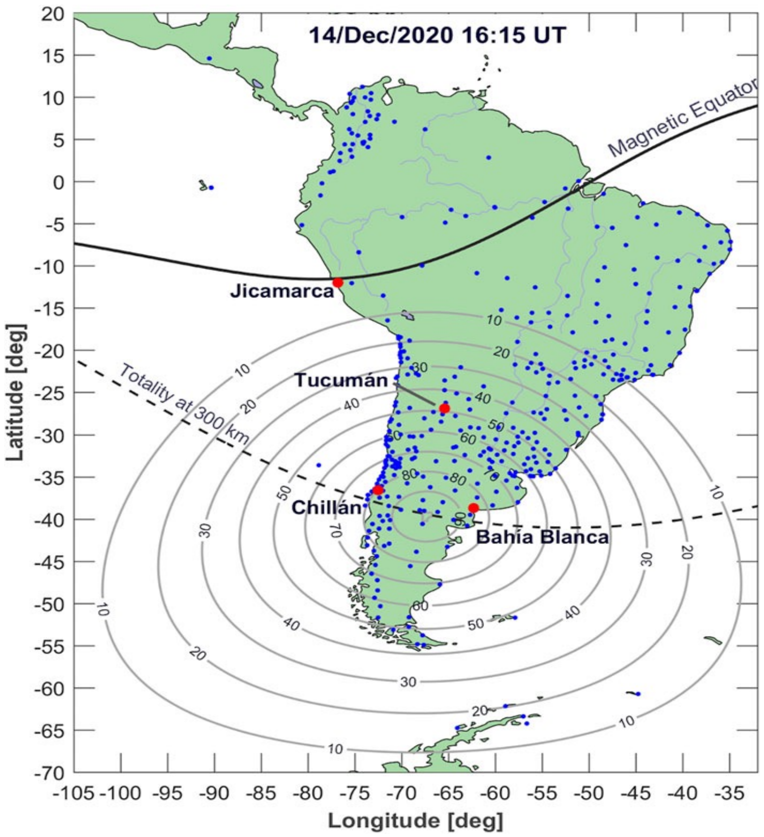


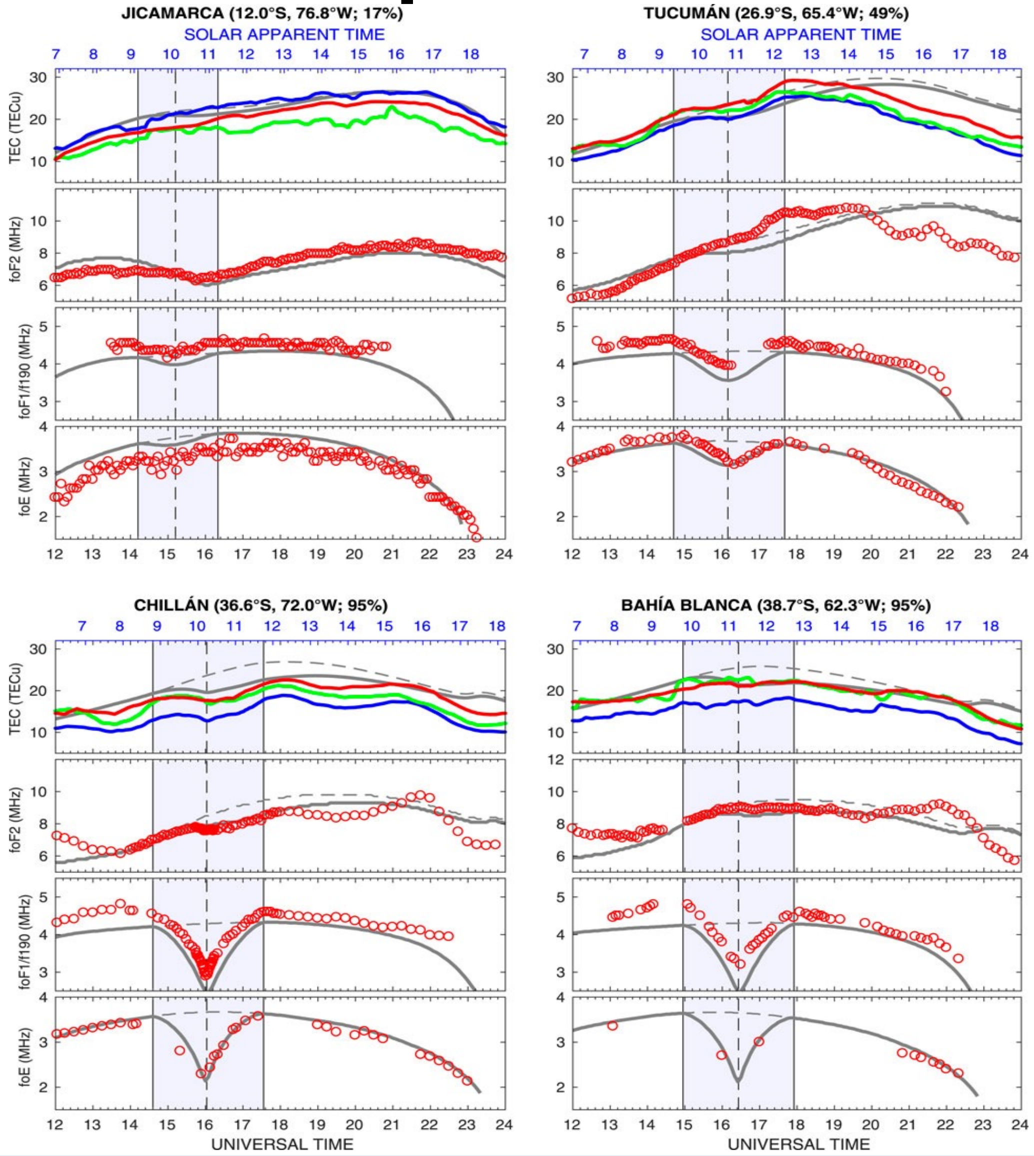


(Martinez-Ledesma, M., Bravo, M., Urra, B., Souza, J., & Foppiano, A. (2020). Prediction of the Ionospheric Response to the 14 December 2020 Total Solar Eclipse Using SUPIM-INPE. J. Geophys. Res.: Space Physics, 125, e2020JA028625. doi:10.1029/2020JA028625)

14 December 2020 Eclipse: Prediction Validation

- Following the eclipse, we evaluated the model performance by comparing the predicted TEC response with GNSS observations.





3 different methods of obtaining TEC are used to compare.

- Seemala method - blue (Seemala & Valladares, 2011)
- Ciraolo method – red (Ciraolo et al., 2027)
- IONOTEC method – green (Universidad de Chile)

Although these methods provide TEC with different amplitudes, all of them obtain similar reductions to the prediction.

NRMSE ~10% in foE, foF1, foF2

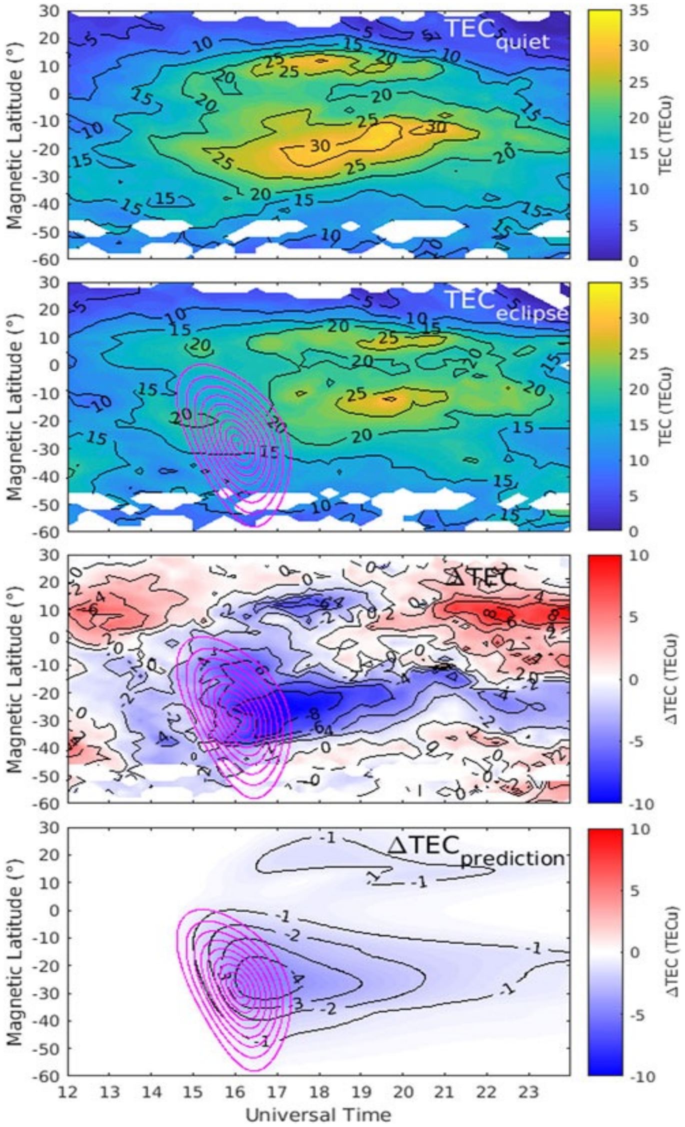
NRMSE up to 30% in some TEC cases

Bravo et al. (2022)

14 December 2020 Eclipse: Prediction Validation

TEC response time evolution obtained with the IONOTEC technique along the magnetic meridian of Chillán (36.6°S, 72.0°W)

Reference days = five quietest days of December



Bravo et al. (2022)

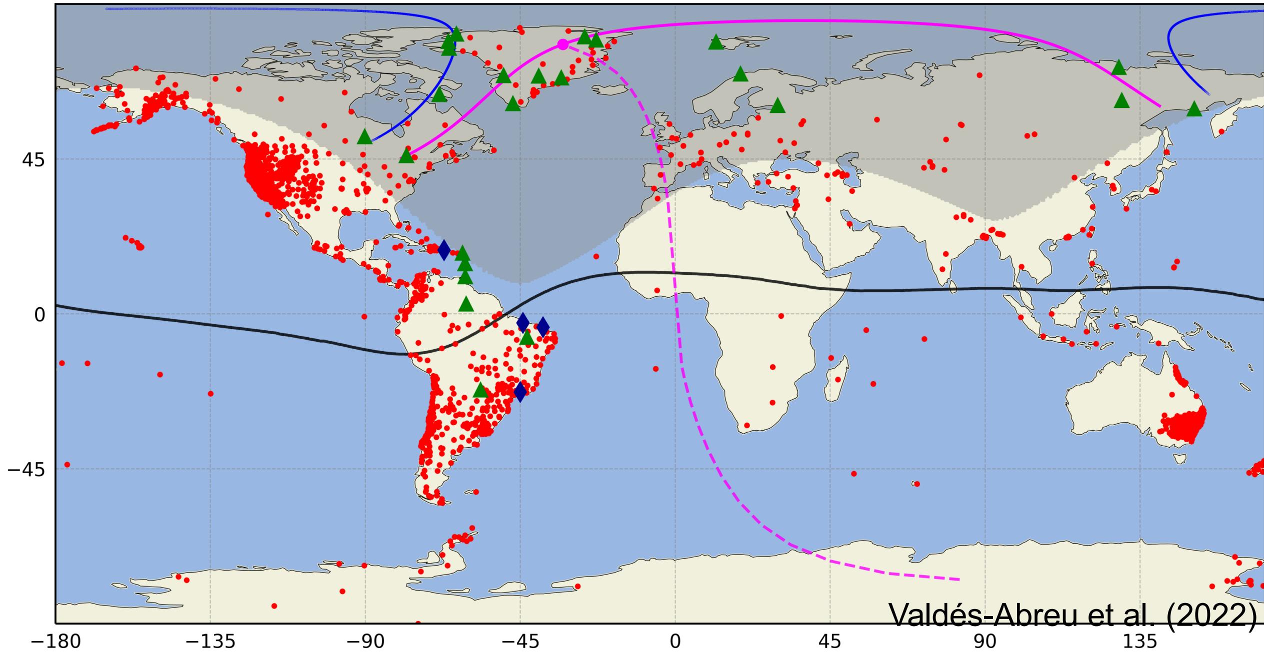
10 June 2021 Solar Ec

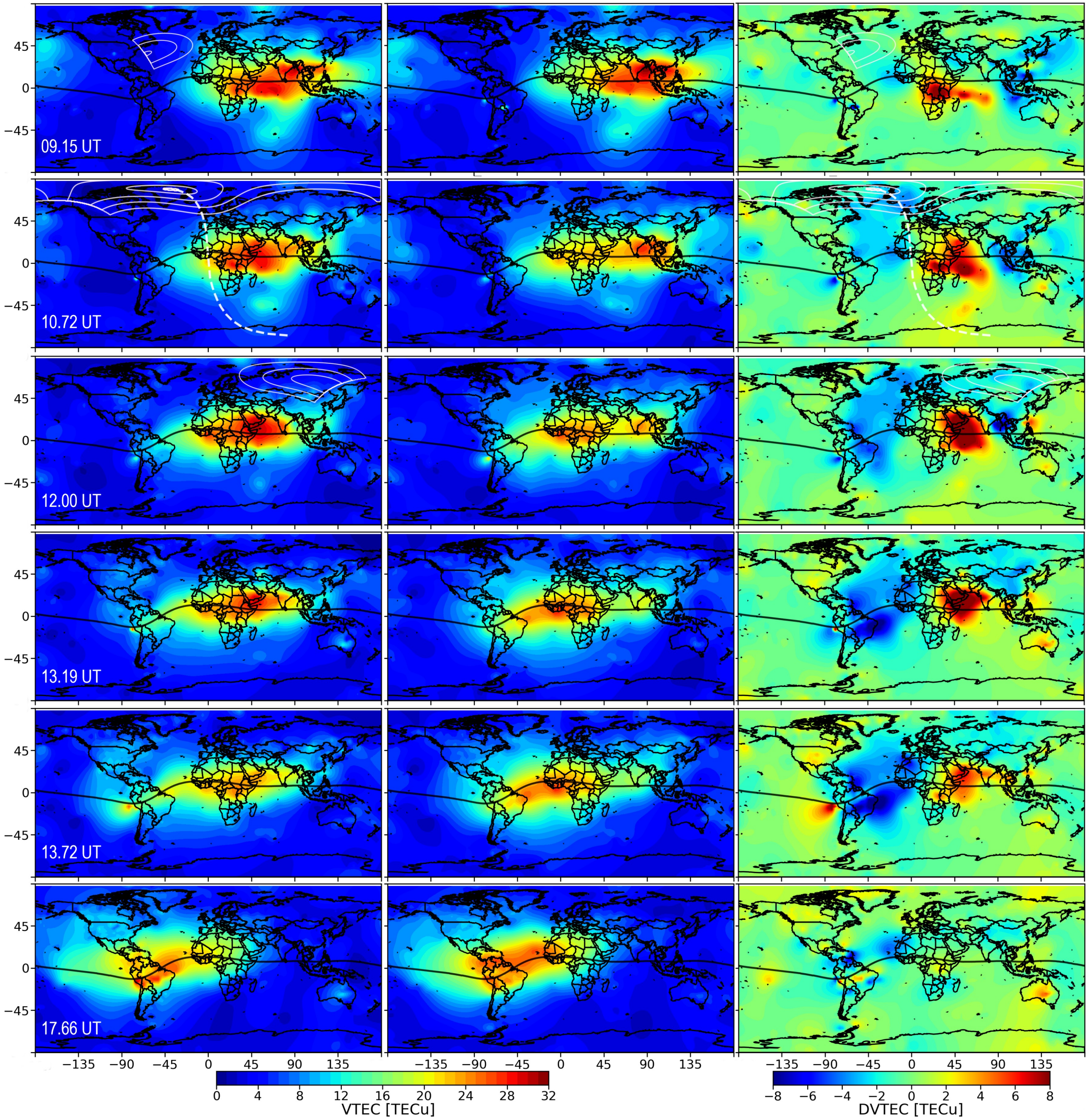
- Unlike the previous studies over South America and Antarctica, this event provided an opportunity to investigate eclipse-induced ionospheric disturbances in the Arctic region using GNSS-TEC observations.

$$DVTEC_t = VTEC_t - \overline{VTEC_t}$$

$$DVTEC[\%]_t = \frac{DVTEC_t}{\overline{VTEC_t}} \cdot 100$$

Reference days = ± 2 days





10 June 2021 Solar Eclipse

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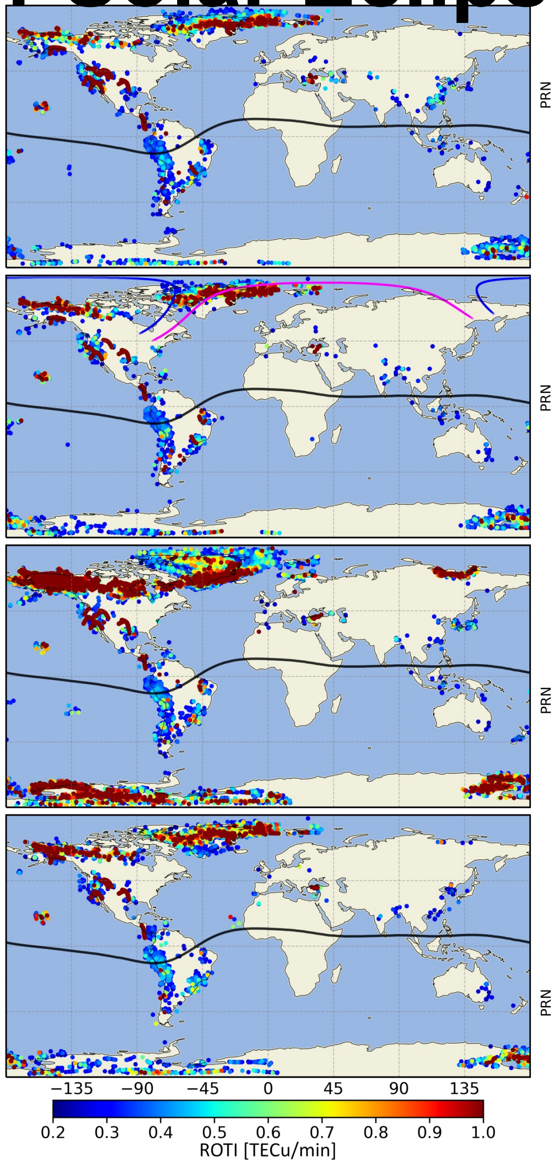
- Rate Of TEC Index. (ROTI) was used to characterize changes in ionospheric irregularities during the event.
- The Corrected Apparent Position (CAP) was estimated to quantify eclipse-induced positioning errors.
- Although the eclipse path was restricted to high latitudes, positioning errors were also detected at low and equatorial latitudes.
- While the positioning errors derived from dual-frequency GNSS observations were relatively small, equivalent errors for **single-frequency receivers could be one to two orders of magnitude larger**.

$$ROT = \frac{STEC_t^i - STEC_{t-1}^i}{k_t - k_{t-1}}$$

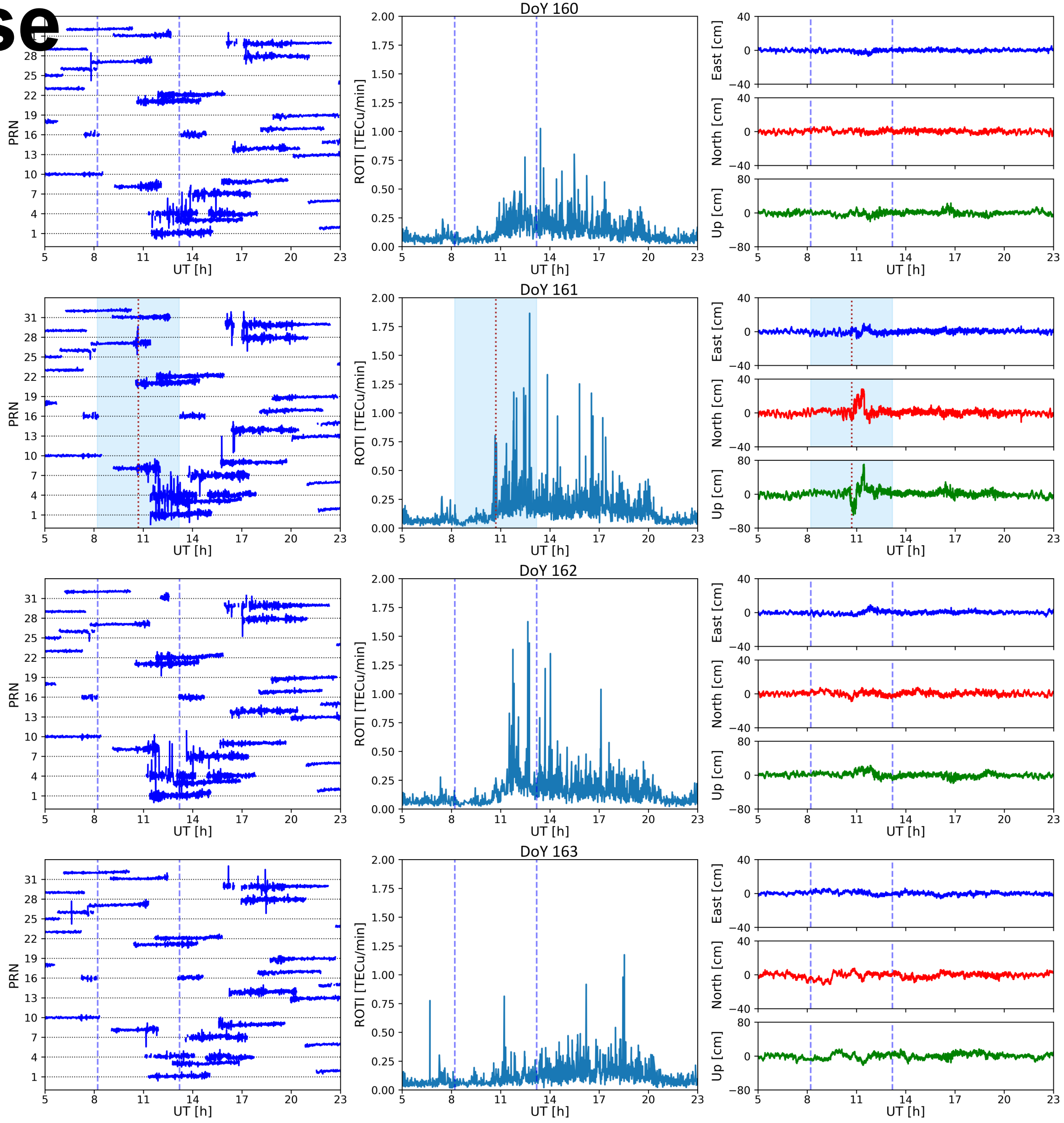
$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}$$

$$CAPdoy_t = APdoy_t - RP_t$$

https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php



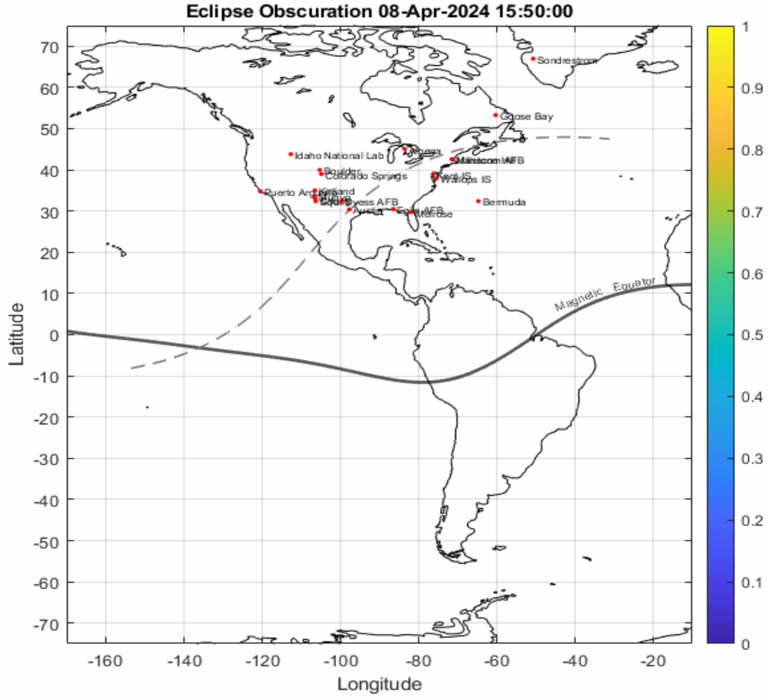
Valdés-Abreu et al. (2022)

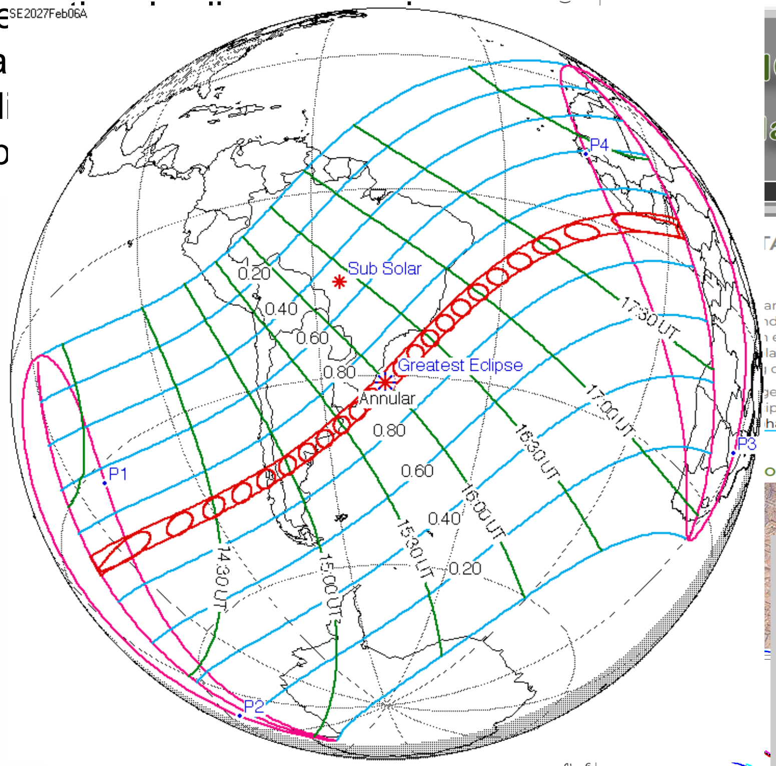


Bravo et al. (2026)

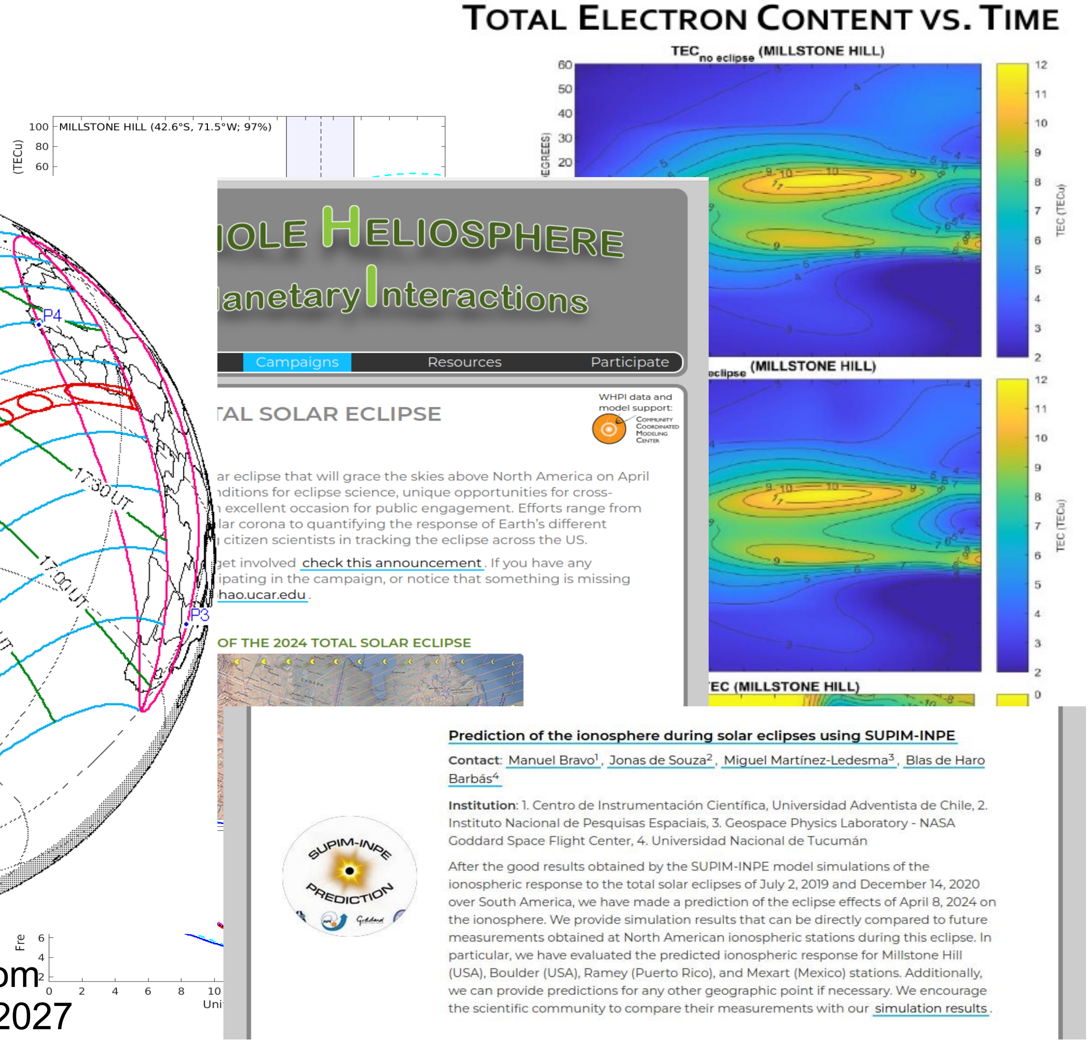
Ongoing Work: Eclipse TEC Forecasting

- TEC forecasts were produced in advance for the 14 October 2023 annular solar eclipse and for the 8 April 2024 total solar eclipse.
- These forecasts were incorporated into the inte
coordinated by the Whole Heliosphere and Pla
- The objective is to provide physics-based predi
responses before eclipse occurrence and supp
observational campaigns.





The next solar eclipse visible from Chile will occur on February 6, 2027



https://whpi.hao.ucar.edu/whpi_campaign-2024-total-eclipse.php

Conclusions

- GNSS-TEC provides an effective tool for monitoring ionospheric responses to solar eclipses with high spatial and temporal resolution.
- Eclipse-induced TEC disturnaces were observed under a wide range of geophysical conditions, from equatorial, low and mid-latitude regions to Antarctica and the Arctic.
- The ionospheric response extended beyond the obscured region and, in some cases, persisted beyond local sunset
- Comparisons with physics-based models showed good agreement and supported the development of eclipse TEC forecasting capabilities.
- Recent studies demonstrated that eclipse effects can also influence GNSS positioning performance, with potentially much larger impacts on single-frequency users.
- Solar eclipses provide unique natural laboratories for studying ionospheric dynamics, while GNSS-TEC has become an essential tool for both monitoring and forecasting their impacts on the near-Earth space environment and GNSS applications.

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Thank you!!!