



Ionospheric Response to the May 2024 Geomagnetic Storm within the SAA Region: Analysis with MSS-1, COSMIC-2, and ground-based GNSS Data

JinHuan Du¹, Zhe Yang¹

¹College of Surveying and Geo-Informatics, Tongji University, Shanghai, China

Email: zheyang@tongji.edu.cn



Abstract

Geomagnetic storms, typical space weather phenomena, are caused by the interaction between solar activity and the Earth's magnetosphere. On May 10, 2024, multiple Coronal Mass Ejections (CMEs) impacted the magnetosphere, triggering the strongest G5-level geomagnetic storm in the past two solar cycles. This study focuses on the ionospheric electron density response within the South Atlantic Anomaly (SAA) region during this storm. By analyzing ground-based GNSS Total Electron Content (TEC) and the Rate of TEC Index (ROTI), along with amplitude scintillation (S4) index from GNSS radio occultation onboard the Macau Science Satellite-1 (MSS-1) and both S4 and TEC data from the Constellation Observing System for Meteorology, Ionosphere, and Climate follow-on mission (COSMIC-2) observations, we conducted a comprehensive analysis from 2D ground-based to 3D space-based perspectives. The results show that a prompt positive ionospheric storm emerged in the SAA region immediately following the sudden storm commencement (SSC) at 17:00 UT on May 10. Significant TEC enhancements were observed by both ground-based and occultation data, persisting through the main and early recovery phases until midday on May 11. During the main phase, the Equatorial Ionization Anomaly (EIA) peaks extended beyond their typical latitudinal boundaries. Notably, MSS-1 observations in the northern hemisphere of the SAA region revealed a super plasma fountain effect triggered by a strong penetration electric field (PPEF), induced by a rapid southward turning of the interplanetary magnetic field (IMF) Bz component. Furthermore, 3D occultation profiles showed that PPEF uplifted the ionosphere, resulting in significantly increased TEC at higher altitudes. This uplift created favorable conditions for the development of ionospheric irregularities, with both the occurrence rate and intensity of scintillation increasing markedly with altitude. These findings demonstrate that combining MSS-1 with ground-based and COSMIC-2 observations provides a comprehensive understanding of ionospheric responses to geomagnetic storms.

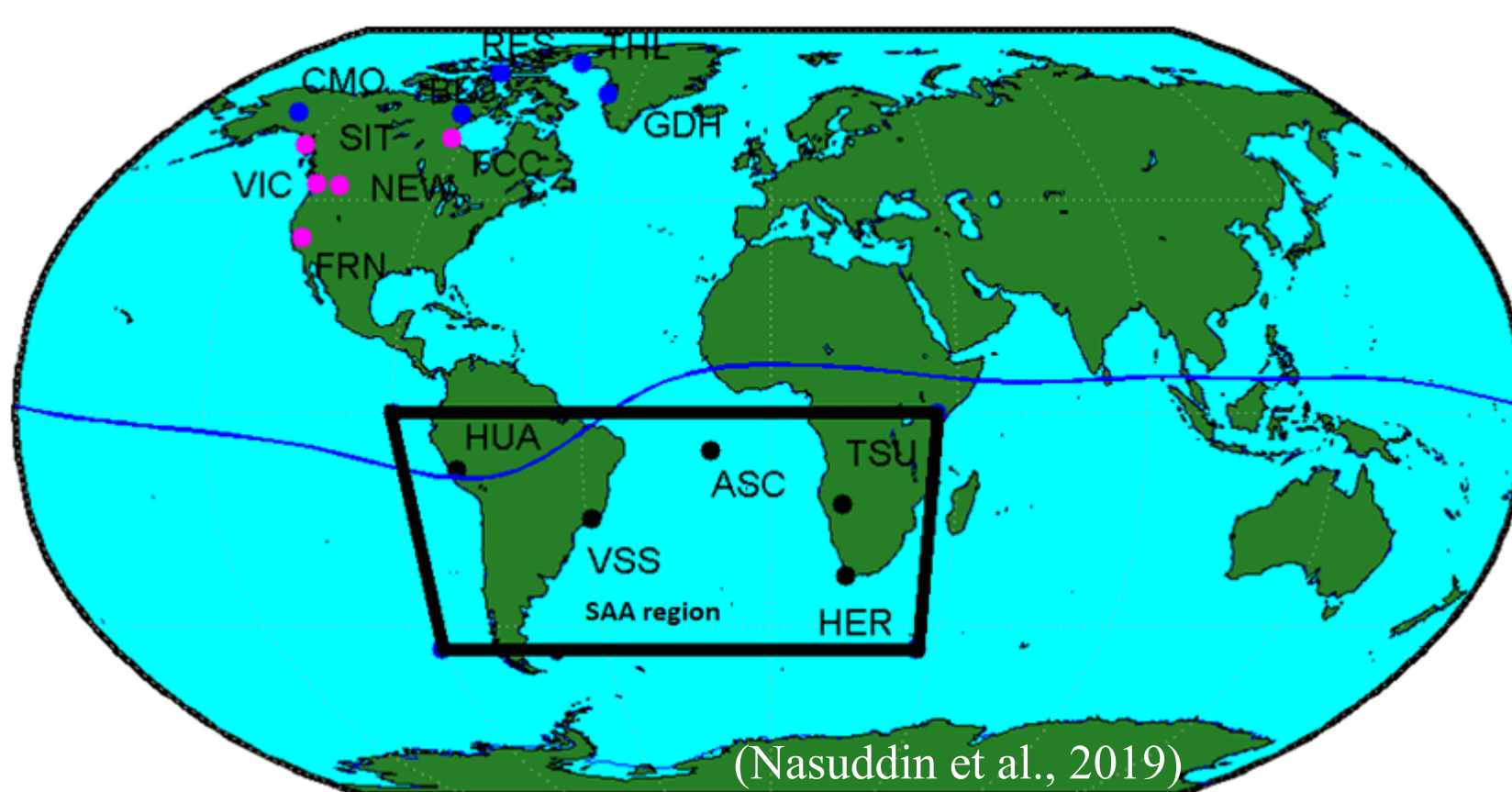
Background

Geomagnetic Storm

Geomagnetic storms are space weather phenomena triggered by solar activity, typically characterized by intense disturbances in the Earth's magnetic field. The mechanisms underlying these storms primarily result from interactions between solar activity and the Earth's magnetosphere (Gonzalez et al., 1994). Solar activities such as coronal mass ejections (CMEs) and high-speed solar winds release large amounts of charged particles into space. When these charged particles collide with the Earth's magnetic field, they cause significant changes which are characterized by increased particle flux and current density, which subsequently affect the structure of the Earth's magnetosphere, resulting in a geomagnetic storm (Lakhina et al., 2016).

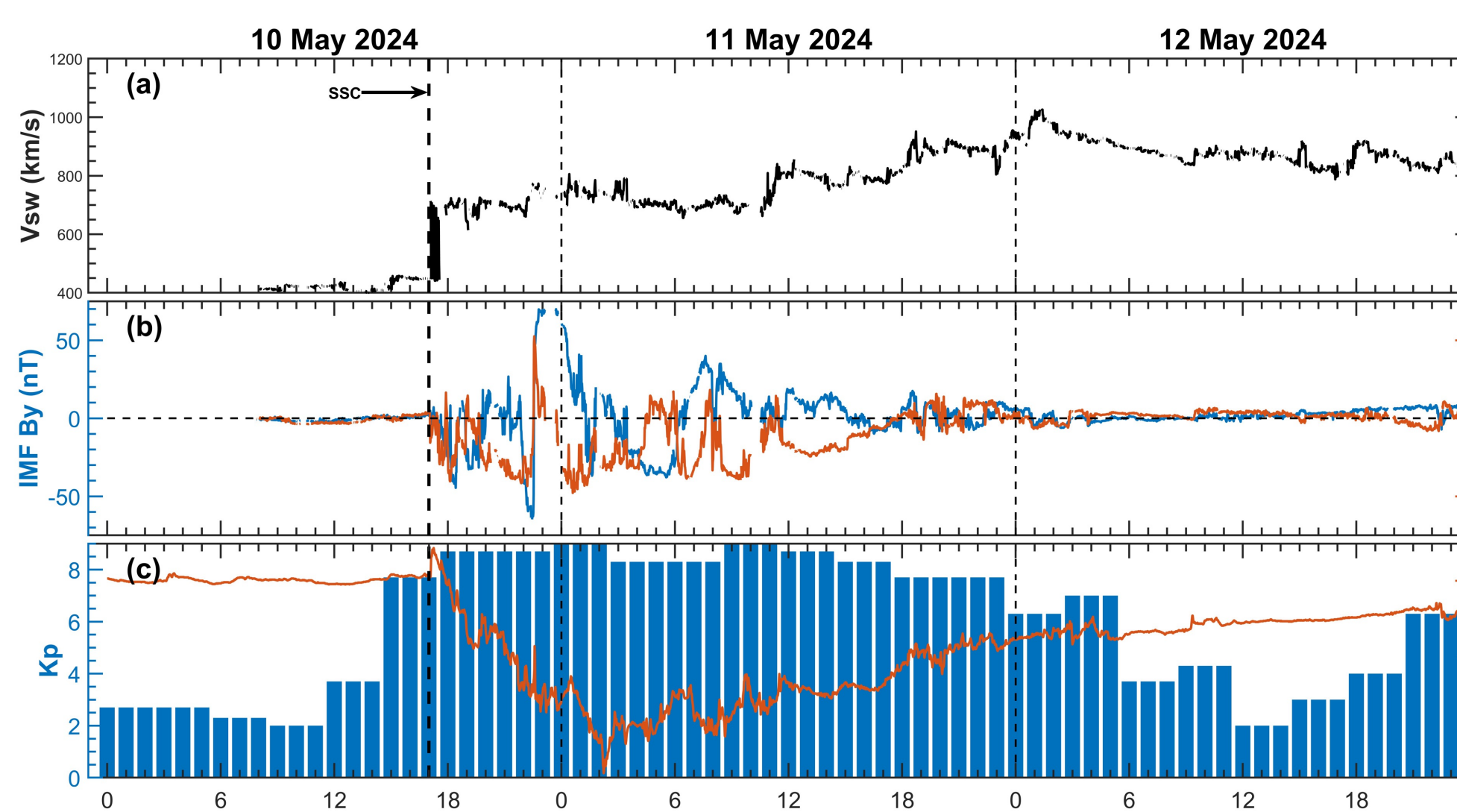
On May 10, 2024, multiple CMEs impacted the Earth's magnetosphere, triggering one of the strongest geomagnetic storms in the past two solar cycles, reaching the G5 level (NOAA Space Weather Scales).

South Atlantic Anomaly



The South Atlantic Anomaly (SAA), extending from 120° W to 60° E and above 150 km altitude across equatorial and low-latitude regions, is characterized by a significantly weakened magnetic field. Its unique geomagnetic environment, interacting with other ionospheric electrodynamic processes, plays an important role in modulating ionospheric irregularities, making the SAA a key region for studying storm-time ionospheric disturbances.

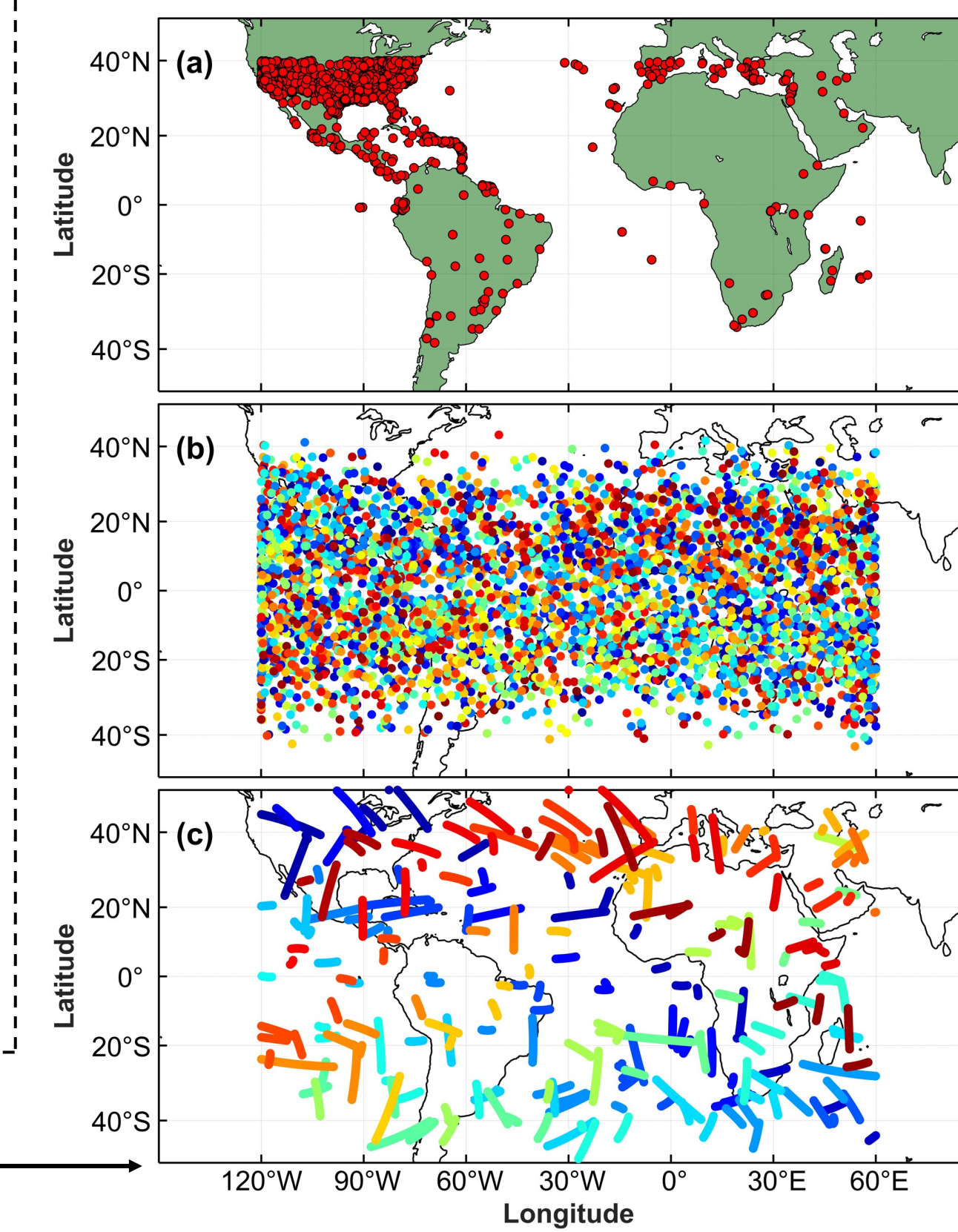
2024 May 10-11 Geomagnetic Storm



Geomagnetic and interplanetary parameters during 10–12 May 2024. The black thick dotted line represents the SSC at 17:00 UT on May 10, 2024.

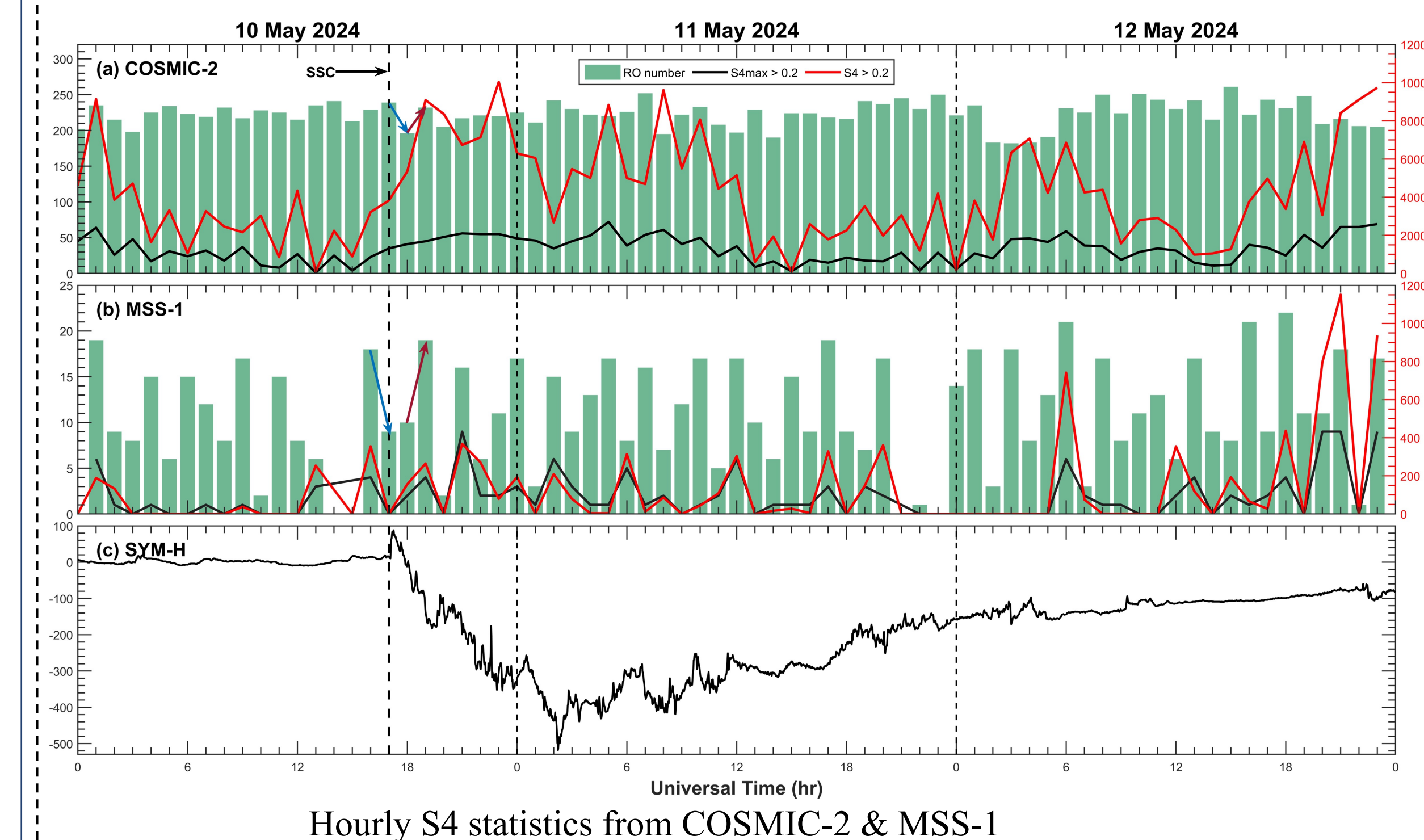
Distribution of GNSS stations and RO tangent points on May 10, 2024: (a) ~1,740 GNSS stations (red dots); (b) COSMIC-2 S4max tangent points; (c) MSS-1 full-profile tangent points. Colorbar shows UT time.

Data Sources



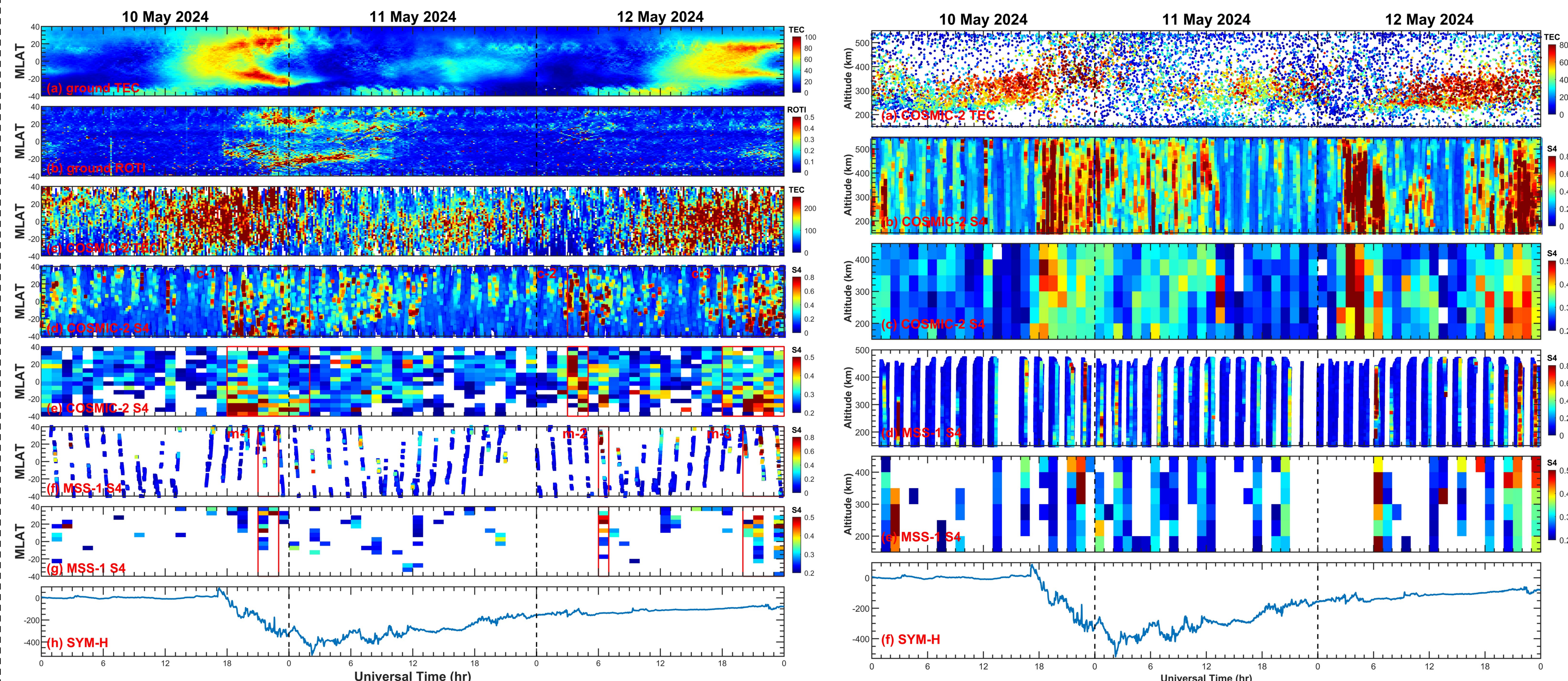
Observations

Ionospheric Scintillation Evolution



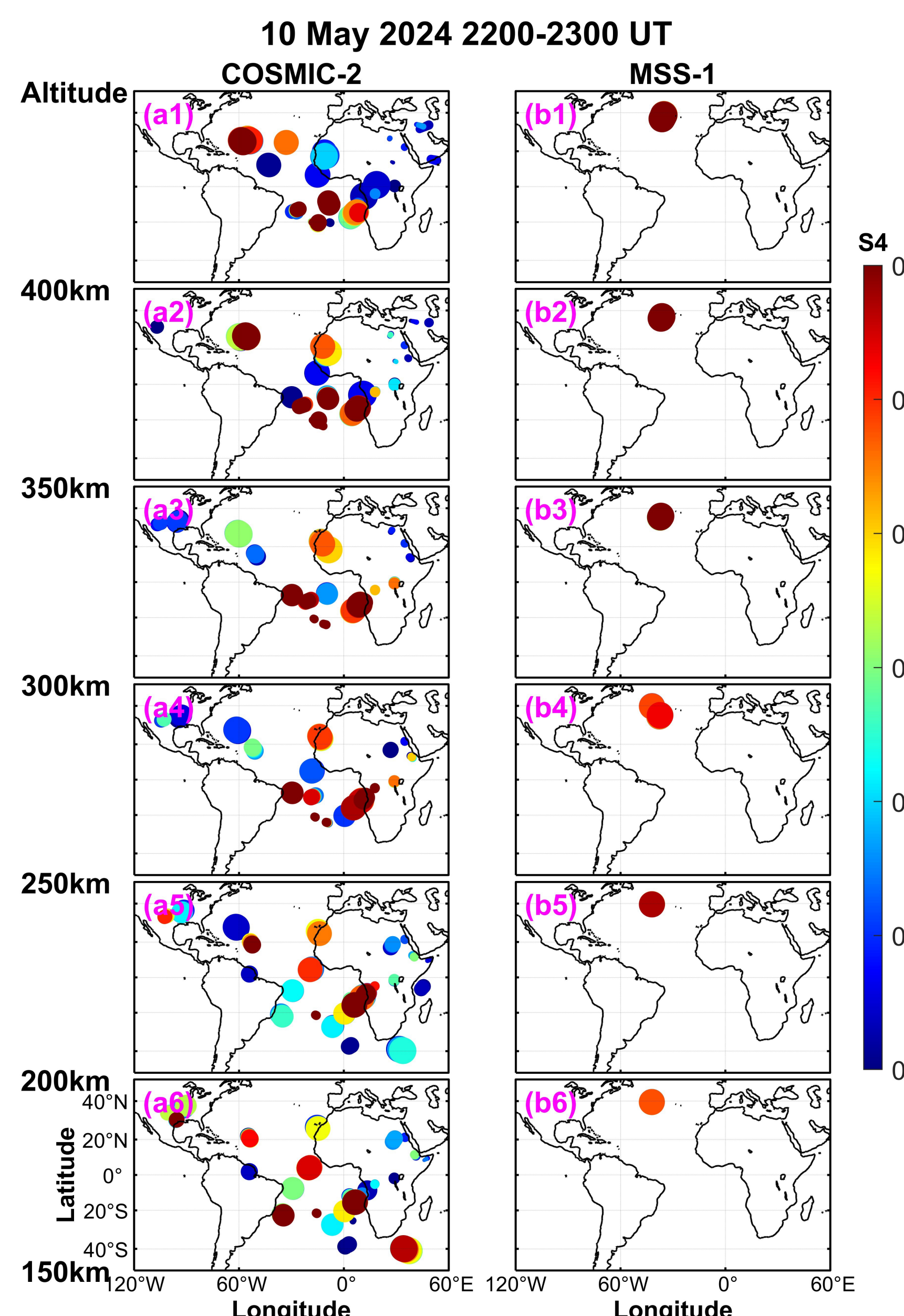
Hourly S4 statistics from COSMIC-2 & MSS-1

Spatiotemporal Ionospheric Responses



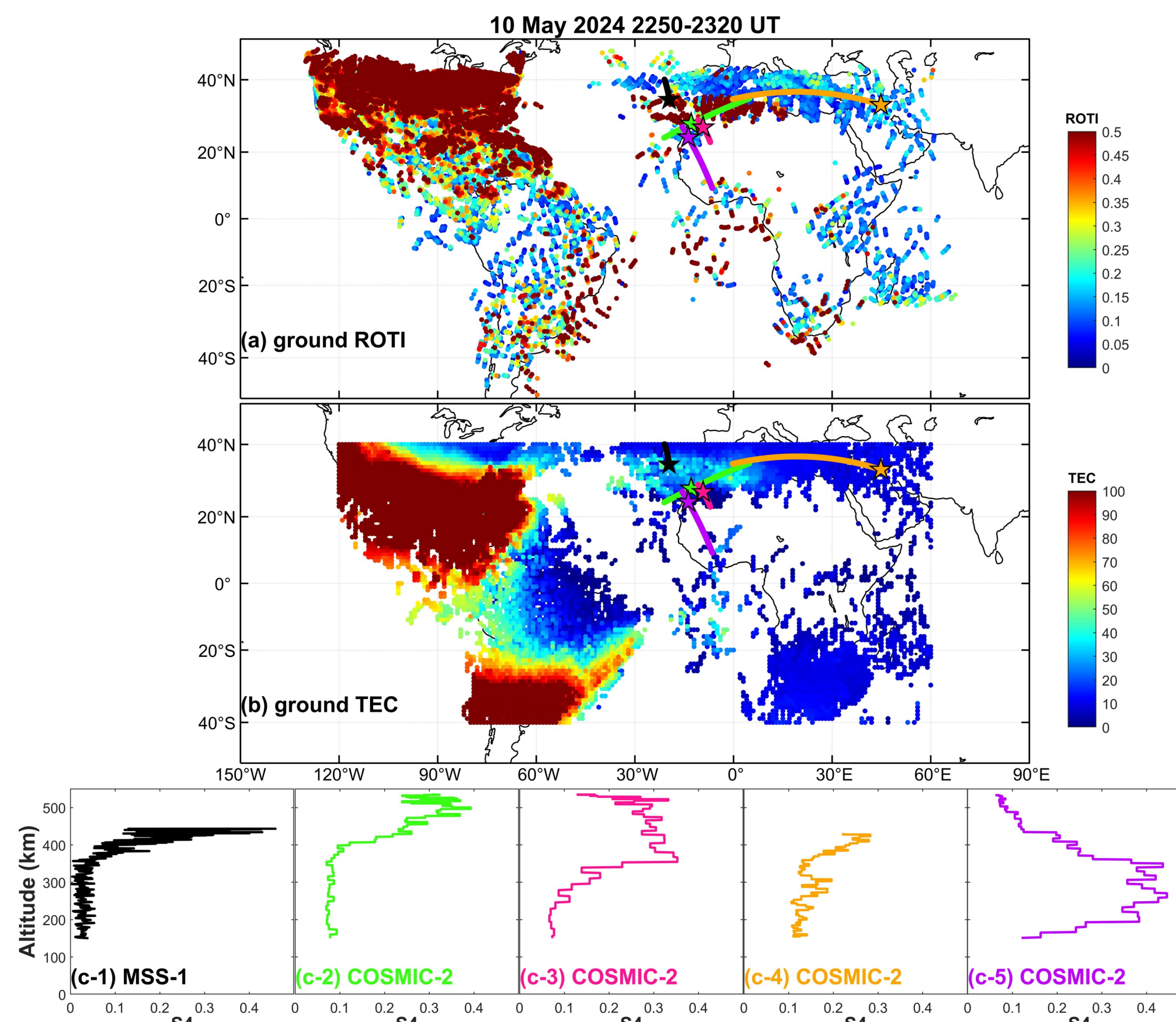
Multi-Source observations of ionospheric variations as a function of UT and MLAT

Observations as a function of UT and ALT



S4 tangent point maps (150–450 km) from COSMIC-2 & MSS-1

Case Study: Scintillation Event near 23UT on May 10



Ground & RO profile-based TEC/ROTI/S4 case study

Conclusion

This study utilized unique radio occultation data from MSS-1, complemented by COSMIC-2 satellite observations and ground-based GNSS TEC/ROTI measurements, to investigate the ionospheric response within the SAA region during the G5 geomagnetic storm on May 10, 2024. The key findings are:

- A prompt positive ionospheric storm developed immediately after the SSC (17:00 UT), with significant TEC enhancement lasting from the main phase through midday on May 11;
- The EIA peaks expanded to higher latitudes and altitudes, and a super plasma fountain was detected by MSS-1 and COSMIC-2 in SAA region. This phenomenon was driven by PPEF induced by a rapid southward turning of the IMF Bz component.
- 3D occultation profiles revealed intense scintillation at higher altitudes over the Atlantic Ocean, with both occurrence rate and intensity increasing with altitude;
- This study highlights the importance of multi-platform observations in advancing our understanding of ionospheric dynamics, improving ionospheric modeling, and enhancing space weather forecasting capabilities.

References

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- NOAA Space Weather Scales: <https://www.swpc.noaa.gov/noaa-scales-explanation>

Acknowledgments

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