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EDITED AND REVIEWED BY
Joseph E. Borovsky,
Space Science Institute (SSI), United States

*CORRESPONDENCE
Yi Wang,
wingwy@mail.ustc.edu.cn
Boyi Wang,
bywang08@gmail.com

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Editorial: Variability in the solar wind and its impact on the coupled magnetosphere-ionosphere-thermosphere system

Yi Wang[1,2]*, Boyi Wang[1,2]*, Andrey Samsonov[3], Nithin Sivadas[4], Yulia Bogdanova[5] and Guram Kervalishvili[6]

[1]State Key Laboratory of Solar Activity and Space Weather, School of Aerospace, Harbin Institute of Technology, Shenzhen, China, [2]Shenzhen Key Laboratory of Numerical Prediction for Space Storm, School of Aerospace, Harbin Institute of Technology, Shenzhen, China, [3]Mullard Space Science Laboratory, University College London, Dorking, United Kingdom, [4]Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, United States, [5]RAL Space, Science and Technology Facilities Council, United Kingdom Research and Innovation, Rutherford Appleton Laboratory, Didcot, United Kingdom, [6]GFZ Helmholtz Centre for Geosciences, Potsdam, Germany

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Editorial on the Research Topic
Variability in the solar wind and its impact on the coupled magnetosphere-ionosphere-thermosphere system

Introduction

The inherent variability of the solar wind, from large-scale structures to kinetic-scale fluctuations, drives a cascade of energy transfer and plasma processes throughout the coupled Magnetosphere-Ionosphere-Thermosphere (M-I-T) system. Understanding these multiscale interactions is critical not only for advancing fundamental heliophysics but also for developing effective mitigation strategies against the hazards space weather poses to our technologically dependent society. This Research Topic confronts this grand challenge by integrating *in situ* observations, theoretical analysis, and numerical modeling to elucidate the causal chain that links microscopic plasma mechanisms to their large-scale terrestrial consequences. By consolidating findings across four complementary areas of study, this Research Topic aims to contribute to a more predictive, physics-based understanding, laying a stronger foundation for enhancing forecasting capabilities.

Solar wind and magnetosheath dynamics

Some space plasma and magnetic field structures hitting the magnetosphere result from the interaction between the Interplanetary Magnetic Field (IMF) discontinuities and the bow shock. Lu et al. studies an event in which they identified both a hot flow anomaly [1] and a foreshock bubble [2] using THEMIS and MMS data near the subsolar bow shock. Their observations confirm the previously published hybrid simulation results, which show that these two phenomena can coexist. The authors emphasize the importance of multiple spacecraft observations to reveal the full scope of foreshock transients.

Madanian et al. presents another interesting event in which a density structure within the magnetic cloud impacted the Earth and caused significant variations in the magnetopause and bow shock locations. The most interesting feature of the event is a sunward flow [3] in the inner magnetosheath near the subsolar point following the solar wind dynamic pressure decrease. The authors find that the sunward flow is formed due to magnetosheath expansion and is driven by the magnetic pressure gradient force.

Chen et al. presents a theoretical investigation into the fundamental problem of three-dimensional, time-dependent magnetic reconnection. Its principal contribution is the first-ever analytical demonstration that steady-state plasma outflows can theoretically exist within a time-varying magnetic field, resolving an apparent contradiction between observations of quasi-steady reconnection in turbulent environments [4] and the intuition that a dynamic field should drive a dynamic flow.

Villante comments on the analysis of solar wind density fluctuations (0.45–4.65 mHz) by Di Matteo et al. [5]. The author refers to the previous papers [6], which showed only 50% agreement between frequencies of fluctuations observed by two spacecraft in the solar wind. They point out that these results suggest compressional solar wind modes may drive magnetospheric fluctuations. However, there are analysis challenges due to spatial variability and methodological differences that may alter the results of the data analysis.

Magnetospheric phenomena

Chen et al. analyzes an interplanetary shock event that reveals two simultaneous electron acceleration processes in Earth's radiation belts. They find that shock-induced impulsive electric fields instantly energized relativistic electrons near dusk, creating energy-dependent drift echoes. The authors emphasize the important role of the modulations by an azimuthally confined ultralow frequency [7] wave in this energization process.

The review by Archer et al. examines magnetopause MHD surface waves [8] as a critical mediator of the solar wind-magnetosphere interaction. The authors highlight how the magnetopause can act as a dynamic resonator, forming standing eigenmodes whose frequencies are directly governed by upstream solar wind conditions. This mechanism effectively filters, accumulates, and guides turbulent solar wind energy into geospace. The paper concludes that overcoming current theoretical challenges is essential for understanding this global energy transfer and for interpreting data from future space missions.

Xie et al. presents the first report of electron cyclotron harmonic waves [9] responding to an interplanetary shock. They find that shock compression boosted >0.1 keV electron fluxes by 30%–50%, providing free energy for wave growth. This confirms a direct solar wind-magnetosphere coupling pathway where shock-induced electron injections drive wave instability within minutes.

Leveraging high-resolution MMS data, Wei et al. investigates the electron firehose instability [10] in the magnetotail, revealing that this phenomenon, typically associated with reconnection outflows and depolarization fronts, can also arise in the pristine plasma sheet. Their analysis further implicates this instability as a potential driver for magnetotail flapping motions and the generation of associated sub-ion scale Alfvénic fluctuations.

Ionospheric and thermospheric responses

Davidson et al. examines the delay in the response time of ion-neutral wind in the high-latitude ionosphere to substorm onsets [11]. Using data from Scanning Doppler Imagers (SDI) and the Poker Flat Incoherent Scatter Radar (PFISR) of 23 substorms, they find the average neutral wind response time to be 16 min. Their analysis shows that a southward turning of IMF 1.5 h before the substorm onset and large electron densities in the ionosphere lead to faster response time.

Li et al. conducts a simulation-based study comparing the ionospheric total electron content (TEC) between the South Atlantic Anomaly (SAA) and the Indian Ocean (IO) at solar maximum. The authors apply the empirical orthogonal function (EOF) method to analyze the spatial and temporal variations in both regions. The results show clear differences in the structure and behavior of the equatorial ionization anomaly (EIA) between the two areas, influenced by geomagnetic field deviations and tidal effects.

Space weather impacts

The impact of the extreme geomagnetic storm [12] of May 2024 on the re-entry of a Starlink satellite from very low-Earth orbit is studied in Oliveira et al. In comparison with the previous observations of the satellites' re-entries during a variety of geomagnetic conditions, it is shown that a sharp altitude decay starts at the start of the storm main phase, and that severity of the storm increases a speed of the satellite altitude decay and the time difference between the predicted and observed re-entry dates. The physical reasons behind the enhanced drag effects during the increased geomagnetic conditions have been discussed, as well as a need for a more detailed investigation of the causal relationship between storm occurrence and satellite orbital decay.

Li et al. studies an interplanetary coronal mass ejection [13] that triggered intense geomagnetic activity, severely degraded GNSS positioning performance in low-latitude Hong Kong. The study reveals that magnetospheric compression during the storm's initial phase caused more pronounced ionospheric scintillation [14] than that during the main phase. They also examines the accuracies of different GNSS positioning techniques. Overall, the authors attempt to establish a chain from solar wind dynamics to ionospheric turbulence and GNSS degradation, which contributes to enhancing space weather monitoring.

Space radiation poses a serious risk to crewed missions, especially to future missions to Mars, with the Galactic Cosmic

Rays (GCR) being a main contributor to the radiation dose on those missions [15]. Song et al. developed the Space-Dependent Energetic cosmic ray Modulation using MAgnetic spectrometer (SDEMMA) model, which models Galactic Cosmic Ray dynamic beyond 1.0 AU, covering the inner heliosphere between Earth and Mars. This novel model explicitly resolves radial gradients under diverse heliospheric conditions. The application of the model in the calculation of the dose equivalent rate is demonstrated.

The perspective by Wang et al. presents a paradigm-shifting argument that fundamentally reframes the role of space weather in aviation science [16]. In a critical departure from decades of research that treated space weather impacts as isolated phenomena largely confined to specific risks in polar regions, this work provides a systemic, global link between space weather events and widespread flight delays and cancellations. The authors are the first to quantitatively establish that space weather is not merely a technical concern but a significant and previously underestimated contributor to the performance degradation of the entire air transportation network.

Author contributions

YW: Writing – review and editing, Writing – original draft. BW: Writing – review and editing, Writing – original draft. AS: Writing – review and editing, Writing – original draft. NS: Writing – review and editing, Writing – original draft. YB: Writing – original draft, Writing – review and editing. GK: Writing – review and editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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