Earth, Planets and Space

FRONTIER LETTER Open Access

COURSE: Cross-scale cOUpling pRocesses in the Solar–tErrestrial system—SCOSTEP's new program for 2026–2030

M. Laurenza[1*], K. Shiokawa[2], M. G. Molina[3,4,5], H.-L. Liu[6], N. A. Krivova[7], B. Funke[8], K. Kusano[2], J. B. Habarulema[9,10,11], D. Buresova[12], M. J. West[13], J. Chau[14], J. Zhang[15], H. Nesse[16], I. Usoskin[17], T. Alberti[5], L. Alfonsi[5], O. Coddington[18], S. Dasso[19,20], Shing F. Fung[21], Hisashi Hayakawa[2], Y. Miyoshi[2,22], R. Nakamura[23], M. Temmer[24], C. Stolle[14], Q.-G. Zong[25], C. Briand[26], N. Goplaswamy[27] and Jana Safranova[28]

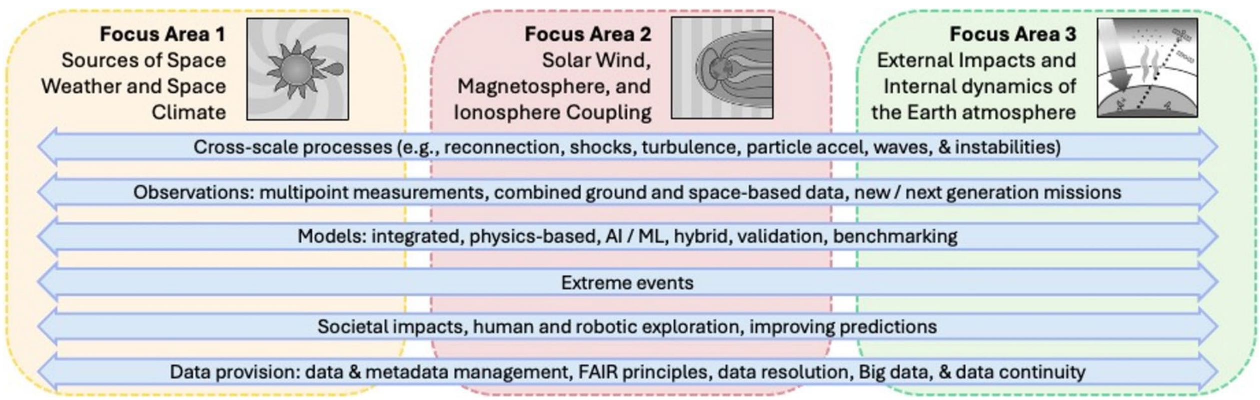
Abstract

The committee nominated to define the Scientific Committee on Solar–Terrestrial Physics (SCOSTEP) Next Scientific Program (NSP) has identified cross-scale coupling as the overarching theme for conducting and promoting coordinated research and outreach activities in the upcoming period 2026–2030. The program is called COURSE (Cross-scale cOUpling pRocesses in the Solar–tErrestrial system) and is organized in three main scientific focus areas: 1) sources of space weather and space climate; 2) solar wind, magnetosphere, and ionosphere coupling; and 3) external impacts and internal dynamics of the Earth atmosphere. For each Focus Area the NSP committee has identified: 1) long-standing goals, i.e., key questions persistent through SCOSTEP scientific programs and 2) objectives, i.e., precise outcomes that can be addressed over the 5-year program duration, which contribute to achieving the goals over the long term. Moreover, the committee envisions the implementation of the program through identified novel methods, including machine learning and Artificial Intelligence techniques; integrated models; new missions; the combination of multipoint in-situ data with ground observations; improved metadata; and adoption of Findable, Accessible, Interoperable, and Reusable (FAIR) principles.

Keywords Solar–terrestrial relationships, Cross-scale coupling, Sun, Solar transients, Solar wind, Galactic cosmic rays, Magnetosphere, Ionosphere, Earth's atmosphere

*Correspondence:
M. Laurenza
monica.laurenza@inaf.it
Full list of author information is available at the end of the article

Graphical Abstract



1 Introduction

The Sun is the primary driver of Space Weather and Space Climate, affecting the whole Heliosphere. Solar activity is variable over a wide range of spatial and temporal scales. Many processes in the solar–terrestrial system are coupled across different spatial, temporal, and energy scales, including: the generation of the solar magnetic fields in the solar interior through the interplay between the global dynamo (alpha-effect plus differential rotation) with the small-scale turbulent dynamo; the dynamical and radiative coupling of the solar interior with the surface, where magnetic flux emerges; the plasma and magnetic field motion and re-configuration in the solar atmosphere, involving different coupled scales, leading to transient eruptive events, such as coronal mass ejections (CMEs), flares, solar energetic particles (SEPs); the cross-scale coupling between the solar wind and its transient and corotating perturbations (interplanetary CME, stream interaction regions—SIRs, and corotating interaction regions—CIRs) with the magnetosphere and the ionosphere; cross-coupling across the geospace–atmosphere system.

Galactic cosmic rays (GCRs) are another important source of Space Weather and Space Climate and a proxy of interplanetary perturbations as well. The cosmic ray propagation in the Heliosphere down to the magnetosphere and the interaction with the atmosphere also involve several cross-scale coupled processes, such as small-scale diffusion and large-scale drifts.

Understanding the cross-scale coupled physical processes from the Sun to the Earth and those underlying the cosmic ray propagation is of primary importance for:

making significant advances in understanding solar–terrestrial Physics;

realizing a quality leap in our capabilities to predict Space Weather, address Space Climate effects, and ensure effective mitigation;

preparing for human exploration of space.

The SCOSTEP Next Scientific Program, called COURSE (Cross-scale cOUpling pRocesses in the Solar–tErrestrial system), aims at facilitating a comprehensive and interdisciplinary research through internationally coordinated efforts. COURSE will address the cross-scale coupling processes in the Sun–Earth system, i.e., in and between its different regions, plasma regimes, and particle populations, ranging from short-term (seconds to days) Space Weather timescales to long-term (decades to centuries) climate ones, a great variety of spatial scales from the plasma kinetic scales to many AUs, and a wide range of energies (1 eV to GeVs).

The program is organized in three focus areas: 1) sources of space weather and space climate; 2) solar wind, magnetosphere, and ionosphere coupling; and 3) external impacts and internal dynamics of the earth atmosphere.

For each focus area, the program contains scientific goals, indicating desired outcome of the research, that are persistent through subsequent SCOSTEP scientific programs, to set the direction and provide the overarching context for studying solar–terrestrial relationships. It then identifies objectives that are specific measurable outcomes that will contribute to achieving the goals. Objectives are narrower than goals and should be reached over the next scientific program. Moreover, for the main topics of each focus area, the following issues are discussed: the involved physical processes, with focus on the cross-scale coupling, the specific open questions, the needs, and the future directions.

The three focus areas are naturally interconnected through: 1) cross-scale coupled physical processes (e.g., reconnection, turbulence, waves, wave–particle interaction, shocks, and instabilities), common to the different regions of the solar–terrestrial system and 2) several other overarching themes (societal impacts, extreme events, human and robotic exploration, improving predictions) across the corresponding multiple disciplines.

The NSP also proposes the methodology, i.e., the approach or procedures used to conduct the research and help answer the scientific questions. Recommendations are provided to the community on what is missing to achieve the proposed objectives. In particular, the program highlights: 1) the promising techniques, tools, and processes employed to collect, analyze, and interpret data; 2) the necessity of developing integrated models and the need of their validation; and 3) the importance of new observations from next generation missions, multi-viewpoint observations, and combinations of space with ground-based observations.

The program urges the support and extension of ground-based networks, the continued practice of observing campaigns and preserving data, performance of cross-calibration of data, use of data standards, metadata systems, giving credit for data, and adoption of FAIR principles.

Finally, the program encourages synergies with existing national or international research programs. Figure 1 shows a scheme of the COURSE program.

2 Overarching focus area themes

Interdisciplinary studies across the different domains of solar–terrestrial physics, such as solar, heliospheric, magnetospheric, atmospheric physics, are essential for a comprehensive understanding of solar–terrestrial relationships, from the solar activity to the impacts on the interplanetary and terrestrial environments (e.g., Laurenza et al. 2023). Common physical processes spanning the different regions of the solar–terrestrial system as well as overarching themes across the multiple disciplines are identified and discussed in the following subsections.

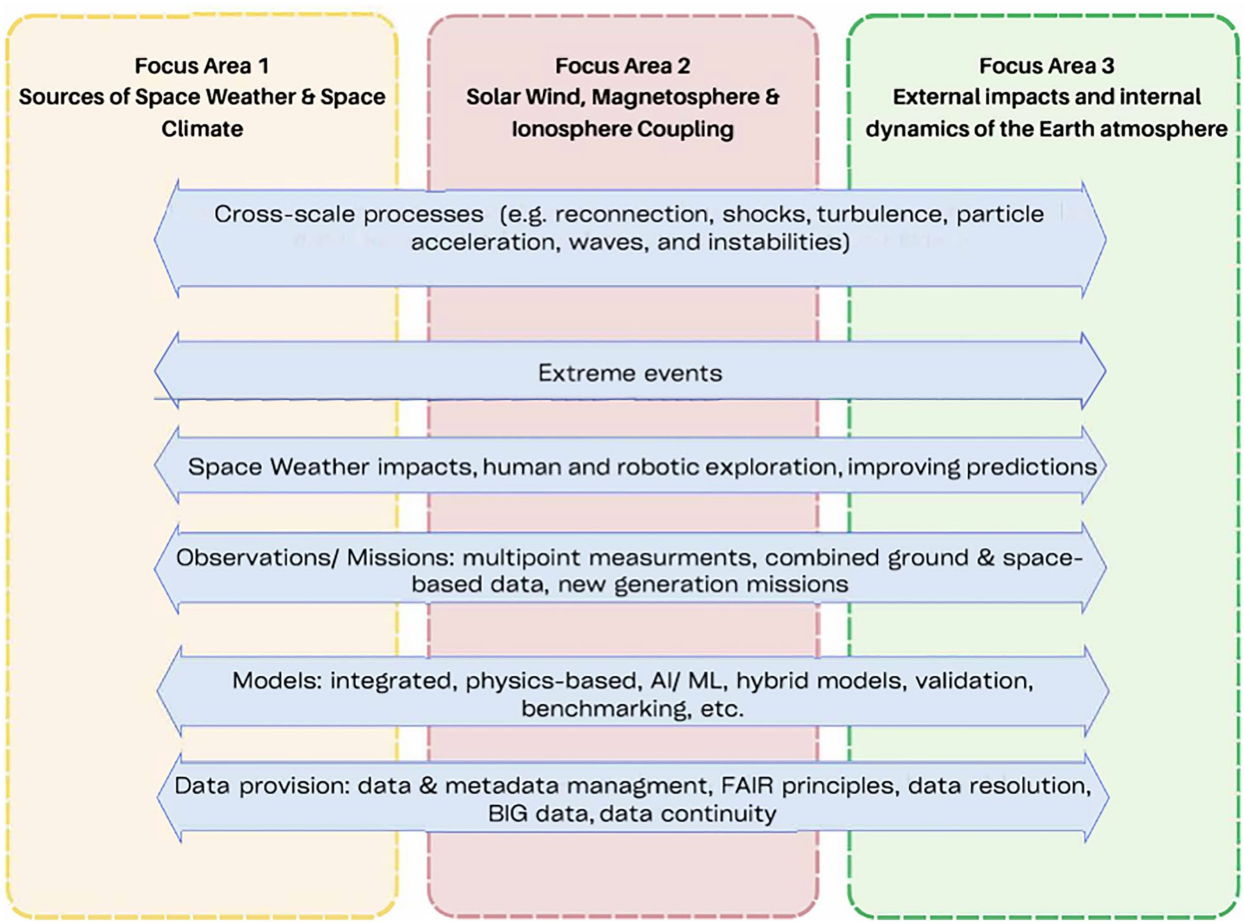


Fig. 1 Overall scheme of the three focus areas of the COURSE program. The light blue arrows show the main overarching topics to be addressed during the next five years to reach the detailed objectives of each focus area

2.1 Cross-scale processes

Most space plasmas can be far from equilibrium with each other. Reconnection, turbulence, waves, wave–particle interaction, shocks, instabilities are controlled by dynamic processes coupled on different spatial and temporal scales, including the electron kinetic, ion kinetic, fluid, global (e.g., heliosphere, sun, magnetosphere, and ionosphere), particle gyroradius, and wavelengths. The nonlinear interaction of 3D time-varying structures on such scales yields the variety of phenomena characterizing the solar–terrestrial system, such as flares, CMEs, SEPs, geomagnetic and ionospheric storms, including radiation belt electron acceleration. The resulting nonlinear dynamics provides different mechanisms for momentum and energy flow and redistribution. The Earth's atmosphere also includes tightly coupled photochemical, dynamical and electrodynamical processes, ranging from global scale waves and circulation processes, mesoscale waves and small-scale turbulence and chemical processes that can impact the meso- and global scales. Thus, understanding cross-scale coupling processes is the main overarching theme spanning the three focus areas.

2.2 Societal impacts

Beyond its importance for fundamental physics, solar–terrestrial research also has critical applied dimensions. These include assessing radiation hazards in space, forecasting disturbances across various domains—such as solar transients, and magnetospheric and ionospheric conditions—at multiple spatial and temporal scales, and evaluating the socio-economic consequences of Space Weather and Space Climate. These aspects are of growing significance, both for operational forecasting and for understanding long-term impacts on modern technological society.

Solar transients (see Sect. 3.3) are important Space Weather events as they produce nearly instant, powerful and sometimes spectacular repercussions on the whole heliosphere, and in particular on the terrestrial system. As a matter of fact, Space Weather events have a substantial impact upon spaceborne and ground-based critical infrastructures, human body and activities (Sects. 4.5, 5.4, 5.5). Their impacts affect more and more sectors of society. For instance, Space Weather events can have a noticeable impact on radio communications and navigation, enhance the radiation environment (Sects. 3.4, 3.9, 4.3, 4.5, and 5.5) and radiation dose rate to humans even at flight altitudes, and induce the onset of sharp increases in geoelectric fields and associated geomagnetically induced currents (GICs) leading to shorting of electrical power grids (Sect. 5.5).

In addition to Space Weather, solar variability on time scales of the solar cycle and longer, dealt with within the space climate field, is an important consideration in understanding the Earth's climate variability. Being far and away the dominant source of energy to Earth, the Sun creates conditions for life on it and affects its climate. Understanding the long-term changes on the Sun is also crucial for the assessment of the full potential range of solar activity, as the era of intense regular solar observations is negligibly short compared to the Sun's lifetime (see also Sects. 3.6, 3.7 and 3.8).

2.3 Extreme events

Extreme solar events are related to extremely strong solar eruptions and their consequences for the solar–terrestrial system. Such events are short (hours to days), rare (once per centuries–millennia), and strong (being the fluence of energetic particles or electromagnetic emission two–three orders of magnitude stronger than the instrumentally observed ones during the recent decades). Accordingly, their terrestrial impacts can be scaled up by orders of magnitude or even combined. Although never observed directly, such events, including extreme solar particle events or super-flares, have been identified indirectly in the past (Cliver et al. 2022). These events are rare (once per century to millennia), but are dangerous as they greatly expand the bounds of what can be expected from the Sun, and consequently exceed tolerances built into modern day technologies. Extreme events are studied in the framework of Space Climate and are discussed in detail in Sects. 3.6, 3.7 and 3.8.

2.4 Human and robotic exploration

Space exploration represents a frontier of great interest to major international players. Ambitious future missions beyond low Earth orbit (LEO) are being planned, targeting destinations, such as Mars, the Moon, and near-Earth objects. These missions are also preparatory steps toward resource utilization, human exploration, and sample return initiatives.

The challenges of interplanetary travel and long-duration space missions inherently involve risks associated with the unique characteristics of the space environment, including radiation exposure and altered gravity conditions.

Key priorities include: assessing the radiative environment in deep space and within space habitats (Sects. 4.3, 4.5, 5.5), particularly from galactic cosmic rays (Sects. 3.9) and solar energetic particles (Sect. 3.4); evaluating the effects of radiation exposure on robotic systems, biological systems, and human health;

developing strategies and technologies to mitigate damages caused by radiation.

Achieving these objectives requires advancements in knowledge, the development of effective countermeasures to limit the detrimental health risks and electronics damage induced by space radiation exposure (Fogtman et al. 2023), and innovative space infrastructures. It also necessitates the creation of new research and technological solutions to ensure that the expertise and capabilities needed for in-situ operations are accessible and effectively transferable.

2.5 Improving predictions

Predicting solar activity over both long-term (years, solar cycle and beyond) and short-term (seconds to months) timescales is crucial for addressing challenges in both Space Weather and Space Climate. To mitigate the impacts of Space Weather on the solar–terrestrial system, reliable predictions are needed for both the triggers of these events—such as solar eruptions—and the severity of their terrestrial effects. Similarly, predicting solar activity and the GCR intensity on timescales of solar cycle and longer is essential for understanding and mitigating its potential consequences for terrestrial climate change, as well as for long-term mission planning, particularly for human spaceflight.

However, accurately and reliably forecasting solar activity and its effects within the heliosphere remains notoriously difficult across all timescales (e.g., Pesnell 2012; Barnes et al. 2016, Whitman et al. 2022). At present, there is a significant gap between predictions and observed outcomes. Achieving reliable and accurate predictions requires a deeper understanding of the underlying physics (Sects. 3.1, 3.3, 4.2, 5.1, 5.3, 5.4). For instance, in explosive events, such as solar flares and coronal mass ejections (CMEs, Sects. 3.3, 3.7), the interaction between small-scale magnetic reconnection and large-scale magnetohydrodynamic instabilities is thought to play a pivotal role. Thus, understanding the cross-scale coupling between microscale and macroscale processes is vital to predict when, where, and how these events will occur.

Addressing these challenges calls for a complementary approach that integrates data-driven methods, leveraging diverse observational data sets (Sects. 6.3 and 6.4), with physics-based models (Sect. 6.2) that simulate the underlying processes and phenomena. Enhanced understanding of the cross-scaling of physical mechanisms and associated timescales also supports the development of relevant inputs for ionospheric empirical models, particularly during extreme Space Weather events such as geomagnetic storms. This advancement will enhance modeling, nowcasting, and forecasting capabilities to meet operational demands.

Predicting Space Climate trends presents even greater challenges, requiring a much deeper understanding of solar magnetism—especially the generation of magnetic fields through global and small-scale dynamo processes (see Sects. 3.1 and 3.2), as well as their interactions. Advances in understanding cross-scale coupling throughout the solar–terrestrial system are, therefore, critical to developing improved physics-based models for forecasting both Space Weather events and Space Climate trends.

The COURSE program proposed here, focusing on cross-scale coupling, is thus a natural extension of the previous PRESTO (Predictability of variable solar–terrestrial coupling) program that was focused on predictability (Daglis et al. 2021).

3 Focus area 1—sources of space weather and space climate

Focus area 1 addresses questions related to the cross-scale coupling processes involved in the generation and evolution of the Space Weather and Space Climate sources, in particular those related to the: solar dynamo, solar and interplanetary magnetic field, solar radiation, solar wind, solar and interplanetary transients, and galactic cosmic rays, over a variety of spatial and temporal scales. The main topics of focus area 1 are reported in Fig. 2.

Several fundamental questions still remain unsolved and represent a challenge for the next SCOSTEP programs, such as:

(G1.1) How are solar magnetic fields generated and transported from the interior through the solar atmospheric layers?
(G1.2) What processes control the transportation and conversion of solar energy over a wide range of time scales?
(G1.3) How does the solar wind originate and structure the heliosphere?
(G1.4) What triggers and drives solar eruptions, and dictates their evolution throughout the heliosphere?
(G1.5) What are the relative contributions from the different sources and mechanisms to the acceleration and transport of energetic particles on the Sun and in the Heliosphere (e.g., SEPs and GCRs)?

During the NSP the following objectives can be achieved:

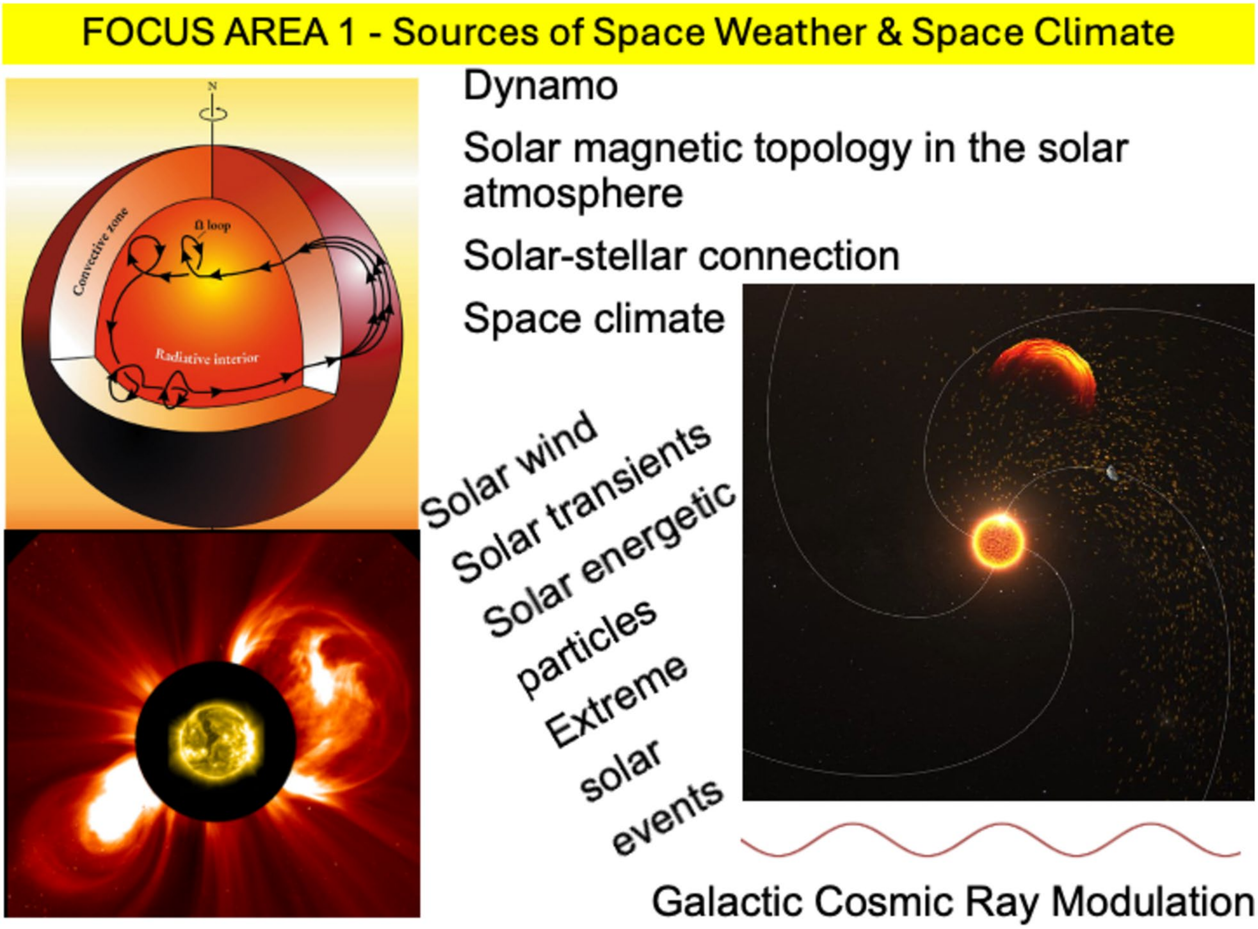


Fig. 2 Schematics of focus area 1 main topics

(O1.1) Constrain the location and mechanisms of magnetic field generation by comparing multiple dynamo models with observations.
(O1.2) Enhance understanding of long-term changes in solar activity through advanced physics-based modeling and validation with state-of-the-art observations and recovery of historical data.
(O1.3) Enhance understanding of the trigger and drivers of solar eruptions using improved observations and numerical simulations.
(O1.4) Constrain models of the evolution of interplanetary transients by exploiting new multipoint observations.
(O1.5) Assess accurately the radiation environment in interplanetary and near-Earth space by exploiting new calibrated data.
(O1.6) Develop new and enhance existing forecasting tools, also to work with the next generation of space weather instrumentation and observations.

3.1 Solar dynamo

The solar cycle is the primary cause of variability in heliospheric dynamics, making the understanding of its generation a fundamental problem in solar–terrestrial physics. While the solar cycle is widely believed to be governed by a dynamo mechanism within the solar interior—where kinetic energy is converted into magnetic energy—the precise processes responsible for the solar dynamo remain poorly understood. Numerous models have been proposed to explain the solar dynamo and its associated cycle activity (e.g., Charbonneau and Sokoloff 2023). Identifying the limitations and strengths of each model is critical for gaining a deeper understanding of solar dynamo processes over medium-to-long-term timescales. Achieving this requires integrating and comparing diverse observational data with advanced numerical simulations.

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of the solar dynamo:

1. Mechanisms of large-scale dynamics

- What mechanisms drive differential rotation and meridional circulation in the solar convection zone (Hotta et al. 2022)?

- What processes govern the polarity reversal of the Sun's magnetic field? (Jiang et al. 2014; Yeates et al. 2023).

2. Assessment of existing dynamo models

- What are the strengths and weaknesses of existing models and proposals, such as the dynamo wave model (Parker 1955), flux transport model (Wang et al. 1991, Choudhuri et al. 1995), the Babcock–Leighton dynamo model (Babcock 1961; Leighton 1969), and MRI-based model (Vasil et al. 2024)?

- Which model most closely aligns with observational data?

- What new observations are required to distinguish and validate these models?

3. Role of small-scale dynamo processes

- What role does the small-scale (short-term) local dynamo play in shaping the global magnetic field and driving the solar cycle (medium-to-long term)?

4. Improving solar cycle predictions

- Whether and how can the activity of the next solar cycle be predicted with greater accuracy, particularly for mission planning (Petrovay 2020)?

- How can ensemble solar dynamo models be developed to reconcile discrepancies between different model results?

Addressing these questions will require a concerted effort to bridge observational, theoretical, and simulation-based approaches, ultimately advancing our understanding of the solar dynamo and its implications for heliospheric dynamics. During the COURSE program, objective O1.1 can be reached.

3.2 Solar magnetic topology in the solar atmosphere

The topology of the solar magnetic field and the dynamic interplay between open and closed configurations, is an important factor in determining the energy release (flare) and eruptivity in active regions leading to CMEs. Likewise, closed and open magnetic field configurations generate slow and fast solar wind streams that interact with each other and form co-rotating interaction regions (CIRs), i.e., shaping the heliosphere. CIRs and CMEs are the main contributors to moderate-to-severe Space Weather effects when impacting Earth. Therefore, investigating the different magnetic field structures on the Sun, their dynamics across multiple spatial and temporal scales, as well as their relationship to solar activity is crucial in solar–terrestrial physics.

The first challenge is understanding the formation and evolution mechanisms of solar active regions and sunspots (G1.1). In particular, elucidating the formation mechanism of active regions producing eruptions (G1.2) is required for improving space weather forecasts (e.g., Cheung et al. 2010; Kaneko et al. 2022). Understanding the three-dimensional structure and topology of active region magnetic fields is crucial for this purpose. However, although many models for active region magnetic fields have been developed, the solutions from different models are not sufficiently well-converged (Toriumi et al. 2020). One reason for the inconsistency may be due to the non-force-free nature of the photosphere, so efforts should be made to develop a more realistic magnetic field model (e.g., Miyoshi et al. 2022) through careful verification based on the comparison with various observations of the photosphere, chromosphere, and the corona.

The second challenge is to clarify the cross-scale inter-relationship between the small and intermediate-scale magnetic fields in quiet and active regions and the global-scale magnetic field, such as dipoles or quadrupole components of the field (Mackay and Yeates 2012; Luo et al. 2024).

The challenge needs to be addressed through combined efforts in data analysis of (new) observations covering multiple spatial scales together with sophisticated models.

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of solar magnetic topology in the solar atmosphere.

1. Global magnetic field structure

- What determines the structure and evolution of coronal holes and how they relate to the open magnetic flux?

- How is the global magnetic field influenced by the magnetic field of active regions and small-scale magnetic field in the quiet regions of the Sun?

- What is the role of the polar regions of the Sun in relation to the global magnetic field structure (out-of-ecliptic SolO data)?

2. Active region magnetic field structure

- What determines when and where magnetic flux emerges through the solar surface (Weber et al. 2023)?

- What determines the amount of emerging magnetic flux and the flux emerging rate?

- What mechanism determines the hemispheric helicity rule? What disturbs this rule?

- What determines the free magnetic energy and magnetic helicity stored in active regions?

- How are the structure and topology of magnetic fields related to the productivity of flares, CMEs, and SEPs?

3. Small-scale magnetic field structure in the quiet region of the Sun

- How does the local dynamo (Buehler et al. 2013) contribute to the global magnetic field?

- How do the structure and strength of small-scale magnetic fields vary with latitude?

- How and how much does the small-scale magnetic field in the quiet region contribute to the formation of the solar atmospheric layers?

3.3 Solar transients

The magnetic energy stored in the corona can be released spontaneously, producing solar eruptions on a large scale that are manifested as a variety of observed phenomena known as solar flares, CMEs, filament eruptions and others (Green et al. 2018). The underlying mechanism of the eruptions involve the cross-coupling of physical processes in the spatial scales ranging from meters to tens of thousands of kilometers and in the temporal scales ranging from minutes to hours (and days for CME propagation). Magnetic reconnection, the primary process of converting magnetic energy into particle acceleration and plasma heating mostly within a thin current sheet, operates on the kinetic scale. However, the reconnection process is modulated by the magnetic structure and plasma flow on the scale of an eruption region. Ideal MHD instabilities, such as Torus Instability (TI) (Kliem & Torok 2006; Myers et al. 2016), which play an important role in initiating and driving the CME-forming magnetic flux rope (MFR), operate on a large scale (Torok et al. 2018; Jiang et al. 2021). However, the formation and expansion of MFRs are strongly modulated by the magnetic reconfiguration resulting from magnetic reconnection. Thus, investigating the coupling between non-ideal MHD and ideal MHD processes across the scales is compelling for understanding the mechanism of solar eruptions. The further propagation of CMEs is controlled by the ambient solar wind flow and interplanetary magnetic field (Temmer et al. 2017; Manchester et al. 2017; Zhang et al. 2021).

Recent high-resolution images of CMEs, provided by Parker Solar Probe (PSP) close to the Sun, show that interplanetary space is filled with small-scale magnetic structures. Especially, the boundaries of CMEs to the ambient solar wind show remarkable dynamics, which yet need to be understood. These new results also require comparison to the aerodynamic drag–force that is usually applied as an MHD analog in explaining the kinematical behavior of CMEs.

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of solar transients:

1. What is the initiation process of solar eruptions? What is the trigger of solar eruptions, the ideal MHD and non-ideal MHD process? How are the two processes coupled across the scale during the main phase of the eruption?
2. What is the primary magnetic configuration immediately prior to the eruption? What is the evolution track of the surface magnetic field leading to the formation of energy-carrying structure?
3. How do CMEs interact with the ambient solar wind and the preceding structure in the ambient heliosphere? What is the internal multi-scale structure within CMEs? How do these structures evolve in time and distance?
4. How to improve solar flare predictions using both ML/AI models and physics-based models, or physics-revealing explainable AI models using the latest deep learning technology?

New investigations are being facilitated by recent close-range observations of the Sun from the Solar Orbiter (SolO), Parker Solar Probe (PSP), and other heliospheric missions that form a multi-spacecraft constellation within the heliosphere. The combination of this unprecedented data and advanced numerical simulations enables the achievement of objectives O1.3, O1.4, and O1.6. In addition, the powerful ground-based 4-m Daniel K. Inouye Solar Telescope (DKIST) has entered its operational phase.

3.4 Solar energetic particles

Solar energetic particles (SEPs) are energetic particles that span a wide energy range, from tens of keV to relativistic energies exceeding 10 GeV. These particles are sporadically emitted from the Sun, typically during energetic events such as solar flares and coronal mass ejections (CMEs) associated with solar eruptions (Desai and Giacalone 2016). SEP events are hazardous radiation storms on Earth and in interplanetary space.

The acceleration of SEPs involves complex, coupled processes across multiple scales. At the flare site, particles could gain energy through electric fields generated by magnetic reconnection (e.g., Livtinenko 2006). Alternatively, acceleration may occur through stochastic mechanisms, such as resonant wave–particle interactions or turbulence-driven plasma waves (e.g., Aschwanden 2002). SEPs can also be accelerated by CME shocks (e.g., Reames 1999) through diffusive shock acceleration (e.g., Bell 1978), both in the solar corona and as the shock propagates through interplanetary space. This acceleration is part of a broader question regarding how shocks distribute incident bulk flow energy across fluid, ion, and electron scales. Variations in driving flows and instabilities at transition scales can significantly influence acceleration efficiency. Stochastic re-acceleration of energetic protons by enhanced Alfvenic turbulence in the downstream region of a quasi-perpendicular shock wave can also play a role (Afanasiev et al., 2018).

SEP events are often categorized into either impulsive, or gradual types. Impulsive SEPs are typically produced by flares, whereas gradual SEPs result from CME shocks accelerating solar wind particles. However, observations of flare-like properties in gradual SEP events challenge this simple dichotomy (e.g., Kocharov and Torsti 2002), so that the particle acceleration at > 10 MeV energies is still debated between flare and shock acceleration (see the review Zhang et al. 2021 and references therein).

The acceleration of relativistic SEPs remains particularly challenging to explain. These particles, capable of generating ground-level enhancements (GLEs) detected by neutron monitors, must be accelerated to GeV energies and reach Earth's atmosphere within approximately 10 min. Nevertheless, various acceleration mechanisms are expected to exhibit distinct characteristic timescales (Miroshnichenko and Perez-Peraza 2008; McCracken et al. 2012). Notably, many GLEs feature two components—prompt and delayed—distinguishable by their profiles and spectra. Especially prompt short pulses with rise times of just 3 to 5 min across all rigidities impose stringent constraints on any proposed acceleration mechanism (McCracken et al. 2008).

SEP propagation through interplanetary space is also determined by cross-scale coupling processes, including gyration around and streaming along interplanetary magnetic field (IMF) lines, focusing, adiabatic deceleration, spatial diffusion, self-generated waves, particle acceleration at traveling shocks, escape from shock regions, and the evolution of shocks in terms of orientation and strength (e.g., Lee 2012).

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of SEPs:

1. What causes the large event-to-event variations in SEP properties?
2. What are the relative contributions of flare-related processes and CME shocks to large gradual SEP events? What are the relative roles of flare-related magnetic reconnections-driven acceleration process, CME-shock associated diffusive shock acceleration, electric fields, and other mechanisms?
3. Do flares directly contribute high-energy particles? How are particles accelerated to GeV energies?
4. How do the origins, temporal variations, and spatial distributions of seed populations influence SEP properties?
5. What roles do ambient turbulence and self-generated waves play in trapping and releasing SEPs during acceleration and transport?
6. How do coronal and interplanetary structures, as well as IMF configurations, affect SEP energization, trapping, and escape? Is there a feedback mechanism limiting SEP flux, such as the "streaming limit" (Reames and Ng 1998)?

Ongoing missions such as SolO and Parker Solar Probe (PSP) are providing groundbreaking in-situ measurements of solar wind plasma, magnetic fields, waves, and energetic particles from approximately 10 solar radii to Earth's orbit. These observations are complemented by high-resolution imaging and spectroscopic data of SEP source regions from multiple vantage points. Over the next 5 years, these efforts, combined with data from upcoming missions (e.g., HENON, Sect. 6.3), advanced modeling techniques, and ground-based cosmic ray detectors, are expected to noticeably improve our understanding of SEP acceleration and transport. In addition, the availability of newly calibrated high energy particle data from the SPEARHEAD (SPEcification, Analysis and Re-calibration of High Energy pArticle Data) project, in the framework of the European Union's Horizon Europe program, will further support progress toward achieving objectives O1.3, O1.5, and O1.6.

3.5 The solar wind

The solar wind is a continuous outflow of charged particles from the Sun that permeates the heliosphere. It is composed of two primary components: the fast solar wind (> 500 km s^{-1}) and the slow solar wind (< 500 km s^{-1}) (e.g., McComas et al. 2000). The fast wind originates primarily from the interiors of coronal holes, particularly at higher latitudes, but also from low-latitude regions near the ecliptic plane. In contrast, the slow solar wind, highly structured and interspersed with fast wind streams near the ecliptic, remains less understood in terms of its source regions and driving mechanisms, presenting an enduring challenge in solar and heliospheric science.

Emerging evidence suggests that the slow solar wind arises from a spatially complex web of magnetized plasma structures within the middle corona. Persistent interactions and reconnections within this "coronal web" generate slow wind streams. Studies have shown that the observed coronal web is a manifestation of the underlying magnetic separatrix web (S-web; Higginson, 2017), which permeates the inner and middle corona. Reconnection dynamics within the S-web modulate and drive the structured nature of the slow solar wind (Chitta et al. 2023).

Solar Orbiter and Parker Solar probe have provided unprecedented measurements of the solar wind, boosting our knowledge on still unknown solar wind regions. PSP measurement at very close distance to the Sun (with 0.17 AU) reveals that the non-Maxwellian nature of the distribution of the electrons is observed much closer to the Sun than previously observed, which witnesses electron heating mechanism at close distance to the Sun (Whittlesey et al. 2020; Burch et al. 2020). In addition, solar orbiter has measured the abundances of ions, such as oxygen, carbon, and neon, which help to distinguish different solar wind types and reveal the sources of these wind streams. The spacecraft has shown that the solar wind is much more complex in terms of composition than previously thought, with significant differences in the proportions of these ions in the fast and slow solar wind (Müller et al. 2020).

The evolution of turbulence as the solar wind propagates outward from the Sun involves several key stages influenced by both the inherent properties of the solar wind and its interaction with the surrounding environment. Near the Sun, turbulence is forced by solar activity and remains in the inertial range, while the energy spectrum shows the steeper decay of the Kolmogorov cascade at larger distances (Bruno & Carbone 2013; DeForest et al. 2018; Chen et al. 2020). At larger distances (i.e., beyond 10AU or so), the turbulence becomes weaker and more isotropic. This evolution reflects a complex interplay between magnetic and velocity fields, challenging traditional models that assume weaker coupling between these fields farther from the Sun (Alberti et al. 2020; Alberti et al. 2022a) and the role played by wave–particle and wave–wave interactions.

Nonlinear interactions between magnetic and velocity fields are critical to understanding these processes. As solar wind propagates outward, these interactions evolve, influencing turbulence characteristics such as cross-helicity (Alberti et al. 2022b). Developing comprehensive frameworks to model this evolving coupling and intermittency is essential for describing solar wind dynamics across the heliosphere.

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of the solar wind:

1. What are the key differences in composition, origin, and behavior between the fast and slow solar wind?
2. How and where is the slow and fast solar wind accelerated?
3. What is the "coronal web," and how does it relate to the slow solar wind's origin?
4. What observational evidence supports the spatial complexity of the slow solar wind's source regions?
5. How does turbulence evolve as the solar wind propagates outward from the Sun?
6. How do nonlinear interactions between magnetic and velocity fields shape turbulence characteristics such as cross-helicity?

Synergistic observations from coordinated space missions are playing a pivotal role in advancing this field. Missions, such as Solar Orbiter and Parker Solar Probe, provide multi-point measurements that enable real-time tracking of solar wind evolution, these will be greatly enhanced with the Vigil L5 mission. Radial alignments and quadrature configurations can offer unprecedented insights into 3D turbulence structures, plasma heating, and the dynamic behavior of the solar wind. These multi-instrument observations also help disentangle spatial and temporal fluctuations, refining turbulence models and improving our understanding of solar wind properties (e.g., Alberti et al. 2022b). Ground-based radio telescopes, such as LOFAR and NenuFAR, provide also efficient way to measure properties of the solar wind, such as turbulence or magnetic field. Interplanetary scintillation and more recently intensity interferometry images have indeed been obtained to visualize the turbulent density structures during the passage of a CME (Fallows et al 2022). In addition, observation of pulsar from low-frequency radio–telescopes provides a reliable way for probing interplanetary magnetic field (You et al 2012; Tiburzi et al. 2021).

As observational capabilities continue to grow, novel approaches, e.g., combining statistical mechanics and ML with space plasma data, are advancing our understanding of scale-dependent turbulence. These methods aim to unravel energy transfer processes, including dissipation mechanisms at kinetic scales, offering a promising direction for future heliophysics research (Stumpo et al. 2023). By integrating these insights, we are poised to make significant strides in understanding the origins and dynamics of the solar wind.

3.6 Space climate

The era of regular and relatively intense solar observations using ground-based and space-borne instruments spans roughly a century. The only exception is telescopic solar observations, which date back to the seventeenth century. However, this period represents only a brief moment in the Sun's long lifespan. Relatively inactive at the beginning of the twentieth century, the Sun became increasingly temperamental by mid-century, experiencing what is known as a grand maximum, before its activity gradually returned to more moderate levels in the following decades. Solar activity on longer scales can only be studied using cosmogenic isotope data from dated ice cores and tree rings, which cover the Holocene–the past 12 millennia (Beer et al 2012). These studies suggest that the Sun occasionally undergoes extended periods of systematically higher or lower activity, known as grand maxima and grand minima, respectively (Usoskin 2023). Thus, modern observations alone do not capture the full range of possible solar activity.

To understand the Sun's behavior over longer time scales, including periods of activity beyond what has been observed in recent decades, we must rely on the following key factors: (1) a comprehensive understanding of the physical process governing the Sun at all scales, (2) sufficiently long-term proxies of past solar magnetic activity, and (3) robust models that incorporate cross-scale physics and are validated against the full range of modern observations. These aspects must be addressed by future studies.

Solar variability influences Earth's climate (Haigh 2007; Gray et al. 2010; Solanki et al. 2013). The potential mechanisms include: (1) variations in total solar irradiance (TSI), which regulate surface heating (bottom-up mechanism); (2) changes in spectral solar irradiance (SSI), primarily affecting heating and chemical balance in the middle and upper atmosphere (top-down mechanism); and (3) fluctuations in the flux of energetic particles reaching the upper atmosphere, including galactic cosmic rays (Sect. 3.9), SEPs (Sect. 3.4), and magnetospheric energetic particle precipitation (EPPs, Sect. 4.4), which impact atmospheric chemistry and dynamics (top-down mechanism). The driving force behind all these mechanisms is the solar magnetic field. The variability of solar irradiance on time scales longer than about a day is driven by the evolution of the solar surface magnetic field (Shapiro et al. 2017; Yeo et al. 2017). The GCR flux on Earth is modulated by solar magnetic activity (Potgieter 2013), while SEP fluxes are directly related to solar activity and EPP fluxes depend on dynamic processes in the magnetosphere (Pulkkinen 2007; Desai & Giacalone 2016).

Solar radiation provides over 99.96% of the energy in Earth's climate system (Kren et al. 2017). Direct space-based measurements reveal that TSI varies by approximately 0.1% on solar rotation and activity cycle timescales (e.g., Kopp 2016). However, variability over longer timescales remains uncertain, with estimates differing by an order of magnitude (e.g., Chatzistergos et al. 2023, 2024). The amplitude of the variability is strongly wavelength-dependent being 2–3 orders of magnitude higher in the UV compared to the visible and near-IR (e.g., Floyd et al. 2003; Harder et al. 2009). Even the phase of the near-IR variability relative to the solar cycle is heavily debated.

While the behavior of GCRs on secular timescales before the instrumental era is well-understood and studied using indirect but highly reliable cosmogenic isotope data from terrestrial archives (Beer et al. 2012; Usoskin 2023), the variability of other energetic particle components (SEP and EPP) cannot be directly reconstructed. Their past behavior is inferred through extrapolations based on statistical relations established for recent decades. However, this approach seems to overlook the occurrence of extreme solar particles events (ESPEs), which contribute to about half of the long-term averaged SEP flux (Usoskin et al. 2023a). Specifically, there is an observational gap between strong, directly observed SEP events with fluence of SEPs with energy > 200 MeV, $F200 < 2 \times 10^8$ cm^{-2}, and proxy-based ESPEs with $F200 > 3 \times 10^9$ cm^{-2} (Usoskin & Kovaltsov 2021), which needs to be filled using statistical methods. The full range of EPP variability in the past remains unknown.

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of space climate:

1. What is the full potential range of solar activity and variability?
2. How did the solar magnetic field change in the past, in historic and prehistoric times?
3. How strong is the secular irradiance variability?
4. How is the irradiance variability apportioned between different spectral intervals? What is the amplitude of the variability in the near- and mid-UV, and what is the magnitude and the phase of the variability in the near-IR?
5. Is the current instrumental-era statistic of energetic particles representative of longer time scales including grand minima of activity?
6. What are the patterns of SEP and EPP fluxes during grand minima and maxima of solar activity?

The most pressing uncertainties behind these questions relate to the lack of our understanding of the emergence, evolution and radiative properties of small-scale magnetic regions, such as faculae/plage and the network. While solar variability on the rotational time scale is sunspot-dominated, the role of the small-scale magnetic regions, such as faculae or plages (as observed in the photosphere or chromosphere, respectively), and the network, progressively bolsters at longer time scales, so that the secular variability is entirely dominated by them. In particular, understanding the extended periods of low activity with few or no sunspots, the so-called grand minima (see Usoskin 2023b), requires understanding of the evolution of the small-scale fields. This is closely related to understanding the relative roles and interplay between the global and local dynamos (see Sects. 3.1 and 3.2). To address this challenge and achieve objective O1.2, high-resolution (such as those from, e.g., Sunrise, DKIST, and EST) multiwavelength (e.g., Aditya/SUIT) and potentially multi-spacecraft (see, e.g., Albert et al. 2023) observations are required. At the same time, development of physically realistic 3D MHD and non-LTE radiative transfer simulations of the solar atmosphere is indispensable, as accurate, space-based solar irradiance observations have revealed limitations in empirical solar irradiance variability models.

In addition, appropriate long-running data and proxies of solar magnetic activity are required. The longest direct and most used records are instrumental sunspot observations dating back to 1607 (Clette et al. 2023; Hayakawa et al. 2024a). These records enable us to extend the sunspot number back to 1749, the sunspot group number to 1610 (Clette et al. 2023), and sunspot areas to 1874 (Mandal et al. 2020). Having a longer time series allows us to capture the extremity of space climatology, such as the Maunder Minimum in terms of sunspot records, eclipse records, and cosmogenic isotopes (Usoskin et al. 2015; Riley et al. 2015; Hayakawa et al. 2021, 2024d). However, these data sets suffer from progressively deteriorating quality and coverage when going back in time, as well as cross-calibration uncertainties. Even more critically, sunspot observations do not provide information on the small-scale magnetic regions. Historical observations of facular regions do exist, such as drawings or tabulations of white-light facular regions or full-disk photographs in Ca II K line (Chatzistergos 2022, 2024), but their processing and homogenisation require significant effort to make them usable for meaningful studies.

3.7 Solar–stellar connection

As discussed in Sect. 3.6, our knowledge about solar variability and activity is essentially based on a brief snapshot in the life of the Sun. The last several decades of intense solar observations do not capture the full range of its variability, making it challenging to assess how the Sun may have behaved in the past or how it might behave in the future. This challenge can be addressed by improving our understanding of the physical processes driving solar activity, variability and magnetism, as well as collecting all available direct and indirect proxies of solar magnetic activity over the longest possible timescales. Another approach is to study the variability of stars similar to the Sun. While the Sun is by far the best-observed and most-studied star, examining other stars provides countless snapshots of different episodes in stellar lives.

Solar–stellar variability comparisons have gained renewed attention over the past few decades driven by a series of unprecedented high-precision stellar photometric surveys conducted by planet-hunting missions, such as CNES CoRoT (Baglin et al. 2006), NASA's Kepler and TESS (Borucki et al. 2010; Ricker et al. 2014), and the forthcoming ESA PLATO mission (Rauer et al. 2014), complemented by ground-based observational programs (Lockwood et al. 2013). Observations of stellar photometric variability and solar–stellar comparisons have raised the rhetorical question of whether the Sun is truly a solar-type star, as it appears to be photometrically less variable than most other solar-type stars (e.g., Gilliland et al. 2011; Reinhold et al. 2020). This also poses the question of whether the Sun could at times exhibit higher variability and activity, reaching levels beyond those observed over the past century. The issue is also related to the question of whether the Sun is capable of producing superflares, as widely detected on other Sun-like stars.

An analysis of a sample of Kepler stars with temperatures and variability levels similar to the Sun suggests that superflares with energies exceeding10^{27} J may occur roughly once per century (Vasilyev et al. 2024). The frequency-energy distribution of stellar superflares appears to align with the extrapolation of the solar flare distribution, indicating a shared underlying physical mechanism. However, such extrapolation and direct comparisons remain highly uncertain, partly due to our limited understanding of the spectral energy distribution of flares. While most solar flares are observed in X-rays and EUV, stellar flare analyses rely on Kepler photometric observations in the visible spectrum.

Such superflares have not been observed on the Sun during the space era, although multiple flares with energies between 10^{25} and 10^{26} J have been recorded. The occurrence rate of superflares on Sun-like stars is also one to two orders of magnitude higher than that of extreme solar particle events (ESPEs, see Sect. 3.8), as inferred from terrestrial archives (Cliver et al. 2022). One reason for this discrepancy is the complex and not fully understood relationship between the occurrence rates and energies of flares and those of extreme particle events. Yashiro et al. (2006) reported a CME–flare association rate of about 89%, with higher energy flares being more frequently accompanied by CMEs. However, recent findings indicate that not all X-class flares are associated with eruptions due to strong overlying magnetic fields and insufficient free energy (so-called confined flares; see Sun et al. 2015; Thalmann et al. 2015; West & Seaton 2015). Magnetic confinement is also thought to be a key factor—along with observational limitations, such as insufficient spatial resolution and instrument sensitivity—in explaining why so few CMEs or eruptive filament/prominence signatures have been observed on stars (Vida et al. 2024). Analysis of sunspot magnetic flux and size, and related estimates of the Sun's capacity to produce superflares and extreme events also suggest a mismatch (Schmieder 2018).

Another important topic is the interaction between the Sun (or other stars) and their planets, which has important implications for the evolution of planetary atmospheres, atmospheric mass loss and habitability. Understanding these interactions builds on our knowledge of solar and stellar magnetism, radiative and energetic particle flux, and plasma winds in planetary systems, both with and without magnetospheres. This topic is of interest to scientists across multiple disciplines within the SCOSTEP community.

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of the solar–stellar connection:

1. What is the full range of solar variability and activity levels?
2. Do superflares on Sun-like stars represent the high-energy tail of the flare energy distribution observed on the Sun? Can the Sun produce a superflare?
3. Which and what fraction of stellar and solar (super-)flares are accompanied by CMEs and ESPEs?

3.8 Extreme solar events

Studies of the photometric variability of Sun-like stars have shown that these stars unleash so-called superflares with energies exceeding 10^{27} J—more than an order of magnitude stronger than any flare ever observed on the Sun (e.g., Maehara et al. 2012, Vasilyev et al. 2024; see also Sect. 3.7). Such energies lie beyond the range predicted by the standard solar flare model (Aulanier et al., 2013; Schmieder 2018; Cliver et al. 2022). Nevertheless, when restricting the stellar sample to stars with near-solar temperatures and variability ranges, Vasilyev et al. (2024) estimated that superflares could occur on such stars as frequently as once per century.

Indirect proxy data suggest that extreme solar particle events (ESPEs), one to two orders of magnitude stronger than any directly observed in recent decades, can occasionally occur on the Sun (Cliver et al. 2022; Usoskin, 2023b). The first ESPE was discovered by Miyake et al. (2012) as a remarkably large (~20 ‰) and rapid spike in radiocarbon relative abundance Δ14C within a Japanese cedar tree ring dated to 775 AD. This event was later demonstrated to have been caused by an extremely intense SEP event (Usoskin et al. 2013a, b; Mekhaldi et al. 2015), estimated to be 70 ± 30 times stronger than the largest directly detected SEP event of 23 February 1956 (GLE#5; Usoskin et al. 2020; Hayakawa et al. 2024b). Subsequent discoveries of additional ESPEs using various cosmogenic isotopes, indicate that, while rare, these events occasionally occur. Currently, five confirmed ESPEs and four candidates are known (Cliver et al. 2022), including the strongest recorded Δ^{14}C spike of ~40‰ (Bard et al. 2023) dated to 12,350 BC. The energy spectra of SEPs reconstructed for such events from multiple cosmogenic isotopes suggest that ESPEs resemble regular SEP events but exhibit fluxes 50–100 times higher (Mekhaldi et al. 2015; Koldobskiy et al. 2023). These events occur rarely, with an estimated rate of ~1 per 1,500 years, and follow an irregular pattern.

The apparent discrepancy between the occurrence rate of ESPEs on the Sun and superflares on Sun-like stars may partly be due to the poorly understood indirect relationship between the occurrence rate and energies of (super-)flares, CMEs and extreme particle events (see Sect. 3.7). Additional uncertainties arise from the extrapolation of solar flare data to higher energies, not well-characterized spectral distribution of flare energy or gaps in our understanding of the physical mechanisms driving such processes. At the time being, the poor statistics of such events and lack of appropriate models to describe them are the main challenges.

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of extreme solar events:

1. Are superflares and ESPEs manifestations of the same type of events or different phenomena?
2. Are such events consistent with the present paradigm of solar eruption, e.g., the standard solar flare model?
3. What is the upper limit on the strength of solar extreme events?
4. What could the consequences of such extreme events for modern technological society be?

These questions cannot currently be answered due to limited event statistics and the lack of appropriate models. To address this and breakthrough in understanding the nature of these extreme processes, the following steps are needed: (1) extending the timespan of precise cosmogenic–isotope measurements to improve the statistics of

ESPEs (Heaton et al. 2024); (2) developing a methodology for identifying Sun-like stars including different parameters (temperature, rotation rate, metallicity, type, etc.) to improve the stellar–solar projection (Vasiliev et al., 2022); (3) developing a model of SEP acceleration and transport under extreme conditions to understand the flare–ESPE relation and potential limitations on the SEP flux, including the streaming limit (Reames & Ng 1998; Desai & Giacalone 2016); and (4) joining efforts of solar–terrestrial and stellar communities to explore the physical connections between stellar superflares and terrestrial ESPEs.

3.9 Galactic cosmic ray modulation

Galactic cosmic rays represent an important source of Space Weather and Space Climate, as they are an important component of the radiation environment in the interplanetary and near-Earth space (Vainio et al. 2009) and have practical impacts. The Space Weather effects induced by GCRs span from damages to spacecraft and satellite electronics, instruments on board and data losses to radiation hazards for astronauts and aviation at high latitudes and altitudes. For long-duration missions (e.g., Moon and Mars), GCRs are the dominant radiation hazard because of the risk of stochastic effects due to long-term exposure to GCRs. During solar minimum, GCRs are basically the only source for aviation radiation exposure. The strength of such impacts varies with solar activity as explained below.

GCRs enter the heliosphere from the interstellar medium, are affected by the interplanetary magnetic field and solar wind, and undergo several cross-scale coupled processes over different spatial and temporal scales. The overall effect of particle propagation through the heliosphere is known as solar modulation. The intensity of the galactic cosmic radiation below a few tens of GeV is reduced significantly, with respect to the GCR energy spectrum outside the heliosphere, as they propagate in the heliosphere from interstellar space to the orbit of Earth (e.g., Potgieter 2013).

The physical processes causing GCR modulation include spatial diffusion at the small scales of the turbulent heliospheric magnetic field coupled with the particle drift gradient arising from the global curvature and gradients in the large-scale heliospheric magnetic field, as well as with convection and adiabatic deceleration in the expanding solar wind. Moreover, the strength and relative importance of these processes varies with the location in the heliosphere and with the 11 solar cycle and 22-year magnetic cycle.

The wavy heliospheric current sheet (HCS) plays a significant role in particle drifts and in establishing the features of the 22-year cycle in the solar modulation of GCRs (e.g., Kota and Jokipii 1983; Laurenza et al. 2014). Its effect depends on the latitudinal extension, varying during the solar cycle, being dominant during the decreasing and minimum phases of the solar cycles.

The behavior of cosmic rays during the years of the active Sun is quite different, and possibly much more complicated, when the Heliosphere is dominated by transient, diffusive propagating disturbances. Various types of merged interaction regions can lead to successive cosmic-ray decreases which by their cumulative effect may be the major cause of modulation. Moreover, time-dependent global changes in the heliospheric magnetic field over an 11-year cycle can also be responsible for medium and long-term modulation (Cane et al. 1999; Laurenza et al. 2012). GCR modulation over 11 and 22 year cycles are thought to be due to a combination of drifts with time-dependent HCS and global merged interaction regions (GMIRs; Le Roux & Potieger, 1995).

In the current scenario for GCR modulation, drifts are thought to be primarily responsible for long-term modulation during low to moderate solar activity, whereas HMF changes and global merged interaction regions play a dominant role during maximum solar activity, when the particle motion is more diffusive. Nevertheless, the quantitative contribution of different modulation processes remains uncertain and the transport parameters, the diffusion coefficients, and their spatial and temporal variations in the various regions of the heliosphere need to be better understood (related to G1.5).

The following questions within the SCOSTEP framework need to be addressed in the coming years to improve our understanding of GCR modulation:

1. What is the relative contribution of the diffusion and drift processes in GCR propagation?
2. How do they vary along 11 year and 22 years the solar cycles and in the Heliosphere?
3. What is the GCR longitudinal and radial gradient in the Heliosphere?
4. How do interplanetary perturbations affect the GCR propagation on short time scales (e.g., in Forbush decreases) across the Heliosphere?

4 Focus area 2—solar wind, magnetosphere, and ionosphere coupling

This focus area examines the cross-scale coupling of the solar wind with the Earth's magnetosphere and ionosphere. The main topics of focus area 2 are reported in Fig. 3. Despite significant progress made over the past decades through in-situ measurements from near-Earth plasma missions, our understanding of plasma energization and energy transport mechanisms in the solar wind–magnetosphere–ionosphere coupling system remains

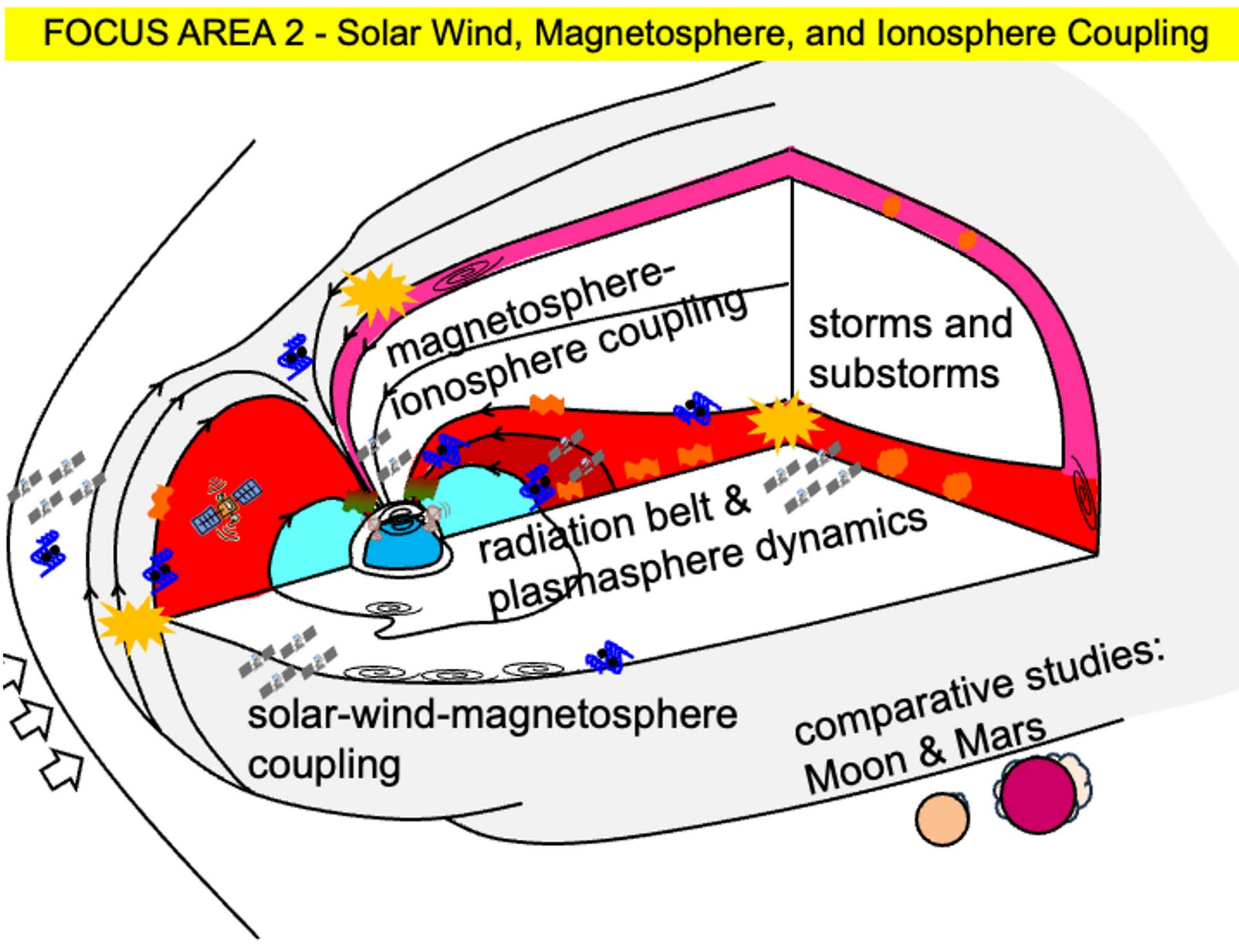


Fig. 3 Schematics of focus area 2 main topics

incomplete. These mechanisms are inherently governed by cross-scale coupling. In addition, the solar wind supplies momentum, driving plasma flows in both the magnetosphere and ionosphere. The key questions to address are as follows:

(G2.1) How is the magnetosphere coupled with the solar wind through cross-scale coupling processes?
(G2.2) How do magnetospheric disturbances develop through cross-scale coupling processes?
(G2.3) How is the magnetosphere coupled with the ionosphere and atmosphere at various scales?

During the NSP the following objectives can be achieved:

(O2.1) Enhance understanding of cross-scale coupling processes through coordinated multi-point measurements in space and on the ground.
(O2.2) Enhance understanding of particle acceleration and loss and global mass and flux transport and dissipation through cross-scale modeling efforts in the magnetosphere and coupling with the ionosphere.
(O2.3) Enhance the understanding of ionospheric and atmospheric consequences from magnetospheric disturbances.

4.1 Solar–wind–magnetosphere coupling

The plasma transport across the magnetopause is done by cross-scale coupling processes through magnetic reconnection, Kelvin–Helmholz (K–H) instability, finite Larmor effect, diffusion, impulsive penetration, and direct cusp entry. Multi-scale structures in the solar wind exist in the ICME sheath and contribute to control the solar–wind magnetosphere coupling (e.g., Kilpua et al. 2021). Furthermore, transient multi-scale processes around the bow shock and magnetosheath can modify the solar–wind and interplanetary magnetic field before it reaches the magnetopause. The dayside reconnection starts on a very small scale of kilometers, but it can make a big effect on the whole magnetosphere. These processes of cross-scale coupling are not yet well-understood. These magnetopause processes are accompanied by electromagnetic field disturbances and field-aligned current generation which can be mapped to the ionosphere, forming characteristic dayside aurora (e.g., Pritchett et al. 2012; Milan et al. 2020; Wang et al. 2024). However, how the dayside reconnection is connected to the ionosphere is still not clear.

The massive energy transport and particle energization becomes largest when fluid scales couple with smaller ion kinetic scales. For example, reconnection can also occur in the large-scale K–H vortex in the magnetopause boundary layer, changing significantly the transport efficiency of plasma across the magnetopause (e.g., Hwang et al. 2020). On the other hand, the chain of wave–particle resonances among different groups of waves and particles, such as ultra-low-frequency waves, electromagnetic–ion–cyclotron (EMIC) waves, manetosonic–whistler waves with ions and electrons, is an efficient mechanism for cross-scale energy transfer from macroscales to microscales., which could redistribute the kinetic energy and accelerate the particles in astrophysical and space plasmas (e.g., Liu et al. 2022; Li et al. 2025).

Dawn–dusk asymmetry is another characteristic feature in the solar–wind magnetosphere coupling processes (Walsh et al. 2014). In the foreshock region, ULF waves and jets at quasi-parallel shock side occur at dawn, while quasi-perpendicular shock becomes dominant at dusk. In the magnetosheath, dawnside is characterized by turbulent and dense plasma, while magnetic fields tend to be strong at dusk. The magnetopause becomes thicker at dawn, while larger current density develops at dusk. These dawn–dusk asymmetries contribute plasma and electromagnetic field disturbances in the magnetosphere and ionosphere, though their connection is still not well-understood.

Under these circumstances, the outstanding questions, connected to G2.1, on the solar–wind–magnetosphere coupling processes are:

1. How are particles energized in near-Earth space plasmas through cross-scale coupling processes?
2. Which processes dominate energy transport and drive coupling between different regions of the magnetospheric system?

These questions contain cross-scale coupling at reconnection, K–H instability and other particle and fluid dynamics in the magnetopause boundary layer. The solar–wind–magnetosphere–ionosphere coupling system contains various complicated plasma and field systems in it which are connected or disconnected from each other, forming the behavior of the whole system. Multi-point measurements in difference spatial and temporal scales, such as by THEMIS, Cluster, MMS, and future Plasma Observatory, are essentially needed. Coupled particle and fluid modeling and regional and global modeling are also essential to understand this system.

4.2 Geomagnetic storms and substorms

Geomagnetic storms and substorms are two major disturbances in the magnetosphere. The storms have a time scale of days and are related to long-lasting southward interplanetary magnetic field (IMF) and enhanced magnetospheric convection through dayside and nightside reconnection. The substorms have a time scale of hours and are driven by a storage-release scenario for which the magnetic flux from the dayside reconnection is once stored in the magnetotail (substorm growth phase) and then suddenly released through nightside reconnection.

4.2.1 Geomagnetic storms

Major geomagnetic storms in the magnetosphere and the ionosphere are caused by intense continuous southward interplanetary magnetic fields (e.g., Gonzalez et al. 1994; Kaidic et al., 2024). Thus, the understanding and prediction of geomagnetic storms are essentially connected to the mechanisms on how coherent magnetic structures are formed in the solar wind, such as magnetic clouds, interplanetary CMEs, CIRs, high-speed streams, and interplanetary shocks (e.g., Tsurutani et al. 2020). However, the magnetosphere–ionosphere coupled system does control the storm generation and intensity. For example, the role of cold heavy ions originated from the ionosphere is important for storm development, e.g., by controlling the tail reconnection efficiency (e.g., Chappell et al. 2021) as well as at the dayside producing asymmetries in the geosynchronous magnetopause crossing. Magnetotail reconnections occurring near the geosynchronous orbit significantly intensify storms (Angelopoulos et al. 2020). Particle energization and loss in the inner magnetosphere during storms occurs through adiabatic and non-adiabatic mechanisms. These processes are certainly through cross-scale coupling, but are not well-understood yet.

Severe geomagnetic storms have recently gotten more and more attention because of their significant consequences in space and on the ground. The severe storms include additional processes in the coupled magnetosphere and ionosphere system. By definition, such severe storms break out only infrequently. In this regard, recent severe storms such as those in May 2024 offer a unique opportunity to investigate the significant developments of the geomagnetic storms (e.g., Karan et al. 2024; Evans et al. 2024; Hayakawa et al. 2024c; Parker and Linares 2024). Besides, it is equally important to explore severe storms in the historical archival records and proxy records to learn from the past, to surpass the chronological limitation of the modern data sets. These records allow us to extend the chronology of geomagnetic storms to two centuries by geomagnetic measurements (Beggan et al. 2023, 2024), 3 millennia by records of candidate aurorae (Hayakawa et al. 2019; Van der Sluijs and Hayakawa 2023), and more than 10 millennia by cosmogenic isotope data (Usoskin et al. 2023a, b). These records are still under active investigations. Their case studies allow us to develop our understanding on the intensity and temporal evolutions of the severe geomagnetic storms beyond the coverage of the modern data sets.

The outstanding questions, connected to G2.2, of storm topic will be:

1. How do particle acceleration and loss through cross-scale coupling processes occur in the magnetosphere during geomagnetic storms?
2. How do background cold plasma and preconditioning of the magnetosphere affect the storm intensity?
3. How can we identify and predict the occurrence of extreme geomagnetic events?
4. What consequences happen in space and on the ground during extreme geomagnetic storms?

Simultaneous ground and satellite multi-point measurements and cross-scale coupled modeling are essentially needed to study these questions. Collecting information of past extreme storms in various ways, such as in historical records (e.g., Hayakawa et al. 2023a, b) and in cosmogenic isotopes (e.g., Miyake et al. 2012; Usoskin et al. 2013a, b, 2023a, b) will enhance our knowledge on characteristics and occurrence frequencies of extreme geomagnetic storms and its consequences on the modern society.

4.2.2 Magnetospheric substorms

As for the substorms, reconnection, dipolarization front, plasmoid, and related particle acceleration during substorms in the magnetotail have been extensively studied in recent years using multi-satellite missions, particularly, by Cluster, THEMIS, and MMS, as well as by fluid and particle simulations (e.g., Fu et al. 2020; Hwang et al. 2023; Fuseilier et al., 2024; Nakamura et al. 2024, and references therein). The substorm particle acceleration in the tail has been studied for both ions and electrons in large scale (e.g., Fermi and Betatron acceleration) and in micro scale (e.g., non-adiabatic, such as wave–particle interaction). However, the cross-scale couplings between ion and electron scales and between particle- and fluid-scale structures are still challenging topics in the magnetotail substorm studies, to understand particle energization and loss in the magnetosphere and to predict substorm disturbances in the space weather forecast.

These cross-scale couplings of substorm processes control substorm onset signatures observed on the ground and in space in various time/spatial scales. The short/meso-scale signatures are, e.g., Pi2 pulsations, ballooning and other near-Earth plasma instabilities and turbulence, localized tail reconnection, bursty bulk flow, auroral pseudo-breakups and beads, substorm current wedgelets (e.g., Ohtani et al., 2020; Forsyth et al. 2020; Gabrielse et al. 2023). The longer time/spatial scale signatures are, e.g., substorm current wedge, global reconnection, auroral electrojet currents, large-scale plasma convection, and particle injection at geosynchronous orbit. Cross-scale coupling of these substorm signatures in different time/spatial scales will be important to understand substorm energetics and predictability of substorm sizes, as well as their coupling to the ionosphere and atmosphere.

The preconditioning of the magnetosphere is another important topic to control the substorm onset timings and sizes. For example, Zong et al. (2021) pointed out that the preconditioning of the magnetosphere due to CME sheath structure with IMF Bz south and fast solar wind can cause supersubstorms of AE > 2000 nT with the effect of heavy oxygen ions originated from the Earth's atmosphere under disturbed conditions. In addition, strong substorms after the IP shock arrival are more likely to occur when IMF points toward (away from) the Sun around spring (autumn) equinox, which can be ascribed to the Russell–McPherron effect (Zong et al. 2021). Thus, the southward IMF precondition of an interplanetary shock and the Russell–McPherron effect can be considered as precursors of a strong substorm and/or super substorm triggered by IP shocks. Besides, substorms with longer durations often occur during solar maximum years and from May to July, likely due to the higher polar ionospheric conductivity and more sunward geomagnetic pole directions during summer in the northern hemisphere (Fu et al. 2025). In addition, there is an additional current wedge during intense substorms located near the dusk (Fu et al. 2021).

Considering these subjects, the outstanding questions for the substorm topics in the next 5 years will be:

1. How does cross-scale coupling occur between ion and electron scales and between particle- and fluid-scale structures? How do these couplings contribute to particle energization in the magnetosphere and the predictability of substorms in the space weather forecast?
2. How are the substorm signatures in different time/spatial scales coupled to form the overall substorms to determine their energetics and sizes and coupling to the ionosphere?
3. How does the preconditioning of the magnetosphere control the substorm onset timings and sizes?

Efforts should be necessary via multi-point coordinated measurements in space and on the ground and via cross-scale modeling efforts in the magnetosphere and their coupling to the ionosphere.

4.3 Radiation belt and plasmasphere dynamics

The dynamics of the Earth's radiation belts are governed by complex processes involving multiple wave–particle interactions and cross-scale, cross-energy, and cross-regional couplings (e.g., Reeves et al. 2003, Daglis et al., 2019 Rippole et al. 2020, Kanekal and Miyoshi 2021, Lejosne et al. 2022). Whistler-mode chorus waves and electromagnetic ion cyclotron (EMIC) waves play essential roles in the acceleration and loss of electrons in the inner magnetosphere. Nonlinear chorus waves accelerate sub-relativistic electrons to MeV energies, while EMIC waves scatter relativistic electrons into the atmosphere via pitch angle diffusion.

Ultralow-frequency (ULF) waves, primarily Pc3–5 pulsations, which are fast-mode MHD waves, drive the radial transport of trapped particles. By resonating with particles through drift resonance and drift-bounce resonance, these waves contribute to the redistribution and acceleration of electrons via cross-field transport (Zong et al. 2009). ULF waves also take part in magnetosphere–ionosphere coupling and thus play an essential role in regulating energy flow throughout the entire system (Zong et al. 2017). Generalized theory of drift and drift-bounce resonance with growth- or decay-localized ULF waves has been developed to explain in situ spacecraft observations. The wave-related observational features such as distorted energy spectrum "boomerang" and "fishbone" pitch angle distributions of radiation belt electrons, ring current ions and plasmaspheric plasma can be explained in the framework of this generalized theory (Zong et al., 2022).

In addition, cross-energy coupling is enhanced by wave–particle interactions. This involves the interplay between cold plasma (plasmaspheric plasma), medium-energy ring current/plasma sheet electrons (source populations for wave excitation), and sub-relativistic electrons (seed populations), ultimately generating MeV electron radiation belts. These processes operate across different spatial and temporal scales, linking localized wave–particle interactions to global radiation belt responses.

Wide energy observation of plasma/particles and wide frequency observations of field/waves by Van Allen Probes and Arase have contributed to the understanding of these phenomena (Mauk et al., 2013; Miyoshi et al. 2018).

Several key questions, connected to G2.2 and G2.3, about radiation belt dynamics remain unresolved, requiring interdisciplinary efforts to address. First, it is important to identify the dominant mechanisms for electron flux enhancement and loss. Specifically, what determines the relative contributions of external radial diffusion and internal local acceleration under varying geomagnetic conditions? Moreover, how do cross-scale processes adapt to changes in solar wind conditions and geomagnetic activity as well as long-term variations longer than the solar cycle? Answering these questions necessitates comprehensive multi-scale and high-resolution observations of the inner magnetosphere.

Another important question is the role of cross-energy coupling in controlling particle dynamics. Interplay between different plasma populations, such as cold plasmaspheric plasma, medium-energy ring current electrons, and sub-relativistic seed populations, are key to wave excitation and energy transfer of particles. In addition, the coupling between ULF, chorus, and EMIC waves significantly influences electron dynamics, requiring an integrated approach combining satellite and ground-based observations with advanced modeling and simulations. It has been demonstrated that nonlinear processes play a significant role in localized and short-term variations. However, it remains unclear whether long-term and global-scale phenomena can be adequately described using quasi-linear approximations. Achieving long-term and global simulation studies that incorporate the elementary processes of nonlinear dynamics is essential.

Finally, the coupling between the radiation belts and the atmosphere remains an open question. How does radiation belt electron precipitation impact upper and middle atmospheric chemistry? This requires interdisciplinary research linking space physics with atmospheric sciences to better understand the broader implications of these processes.

Comprehensive observations should make use of multipoint satellite missions, such as coordinated efforts between Arase, THEMIS, MMS, and other satellites to resolve spatial and temporal uncertainties in wave–particle interactions. Expanding ground-based observation networks will help provide a global perspective on ULF wave-driven radial transport/VLF chorus/Pc1 EMIC waves and support the interpretation of satellite data. The waveform measurements with high-temporal resolution of plasma waves are important to understand non-linear wave–particle interactions. The direct measurements of energy transfer between waves and particles (Shoji et al. 2017) are a powerful method to understand the causal relationship of wave–particle interactions. The common data format (like CDF) and common data analysis software such as SPEDAS/PyzSPEDAS (Angelopoulos et al.,2019) are essential for comprehensive data analysis using various kinds of observations/simulation data.

Interdisciplinary collaboration is also important, linking radiation belt studies with atmospheric and solar and interplanetary physics to investigate the broader effects of particle dynamics. Examining atmospheric impacts caused by precipitation by chorus, EMIC, and other waves as well as the field-line curvature deepen our understanding of space–atmosphere couplings. Advances in technology, such as a fleet of cubesats (small satellites), can provide a cost-effective way to increase measurement points and improve spatial/temporal coverage (Wu et al. 2024).

4.4 Magnetosphere–ionosphere coupling

The magnetosphere constitutes a complex environment with different populations of plasma and is coupled to the ionosphere via both energy and mass exchange in the form of, e.g., particle precipitation, ion-outflow, currents, and plasma waves. These are complex two-way processes, particularly important to understand the polar regions. For example, particle precipitation, visually represented by aurora, allows for mass exchange from the magnetosphere to the ionosphere. Ion-outflow facilitates mass exchange to the magnetosphere. Near-Earth plasma environment governs the plasma wave generation, propagation and interaction with particles which in turn impact the particle precipitation. The key to scientific progress on the MI coupling system requires both data and models to understand the cross-scale coupling in terms of time, space and energy.

Auroral dynamics visualizes cross-scale plasma coupling occurring in the magnetosphere. Transpolar auroral arcs in the high-latitude polar cap region reveal the coupling processes in the magnetotail (e.g., Zhang et al. 2020). In the auroral oval, poleward boundary intensifications, streamers, omega bands, and giant undulations are manifestations of plasma flows and instabilities in the nightside plasma sheet (e.g., Forsyth et al. 2020). Auroral beads occurring at substorm brightening auroras are likely visualizing the ballooning instability in the near-Earth plasma sheet (e.g., Motoba et al. 2012; Sorathia et al. 2020). Auroral pulsations show one-to-one correspondence with the ELF/VLF waves in the magnetosphere (e.g., Kasahara et al. 2018), so that the pulsating auroral patches indicate the spatial scale size of ELF/VLF wave–electron interaction region. At subauroral latitudes, Strong Thermal Emission Velocity Enhancement (STEVE) (Gallardo-Lacourt et al. 2018; Gillies et al. 2019; Nishimura et al. 2023), SAR arcs, and faint auroral arcs, show common features of equatorward detachment from the oval, suggesting penetration of small-scale localized structures in the inner boundary of plasma sheet (Yadav et al. 2021; 2022). Isolated proton auroras at subauroral latitudes show one-to-one correspondence with the electromagnetic ion cyclotron (EMIC) waves in the inner magnetosphere (Yahnina et al. 2000; Sakaguchi et al. 2007; Nakamura et al. 2022), indicating localized EMIC wave–ion interaction.

These recent achievements of auroral dynamics pose new challenging questions, related to G2.3.

1. How are these various localized auroral features created in the plasma sheet?
2. What kind of processes determine the localized scale sizes (~ 100 km in the ionosphere) of ELF/VLF/ULF wave–particle interaction regions, as indicated by pulsating patches and isolated proton auroras?

Moreover, not visible to the naked eye, medium (> 30 keV) and relativistic (> 500 keV) electron precipitation ionizing the D-region, is driven by wave–particle interactions in the magnetosphere. Wave–particle interactions have been studied with respect to their occurrences, radiation belt dynamics and case studies looking at the wave generation, local impacts on the particle populations and ultimately impacts on the atmosphere and ionosphere. Still, there is a discrepancy between the theoretical and statistical models and the associated loss to the atmosphere (e.g., Haas et al. 2023). Potential, but not well-explored ideas point to the role of cold plasma in plasma wave generation, propagation and diffusion in energy and pitch angle.

3. How do background cold plasma and preconditioning of the magnetosphere affect the energetic particle energy spectra?

To answer these questions, it is necessary to conduct multi-point coordinated ground-satellite measurements as well as fluid- and particle-scale coupled models.

Ion outflow from the atmosphere to space is another major topic for understanding the magnetosphere–ionosphere coupling system. The ion outflow can occur as cold ion refilling of the plasmasphere, polar wind from the high-latitude ionosphere, and suprathermal ions energized by wave–particle interaction or parallel potential acceleration (Yamauchi et al., 2019; Gronoff et al. 2020). The cold heavy ionospheric ions in the magnetosphere can significantly change plasma dynamics and instabilities as well as generation and propagation of plasma waves. The ion outflow study is also essentially important for understanding the evolution of planetary atmosphere (e.g., Jakosky et al. 2018). The current major and fundamental question still is (e.g., Ogawa et al. 2019) the following:

4. How does ion outflow respond to solar wind disturbances?

To understand the response, it is necessary to measure various physical parameters related to the ion outflow, i.e., outflow velocities and fluxes, plasma temperature, ion composition, heating and acceleration sources (electric fields and plasma waves), and combine these measurements with regional and global modeling. As such it might be possible to link the ion-outflow variability to its impact on the magnetosphere, e.g., in respect to storm, and substorm generation and subsequently particle precipitation (e.g., Toledo-Redondo et al. 2021).

In addition to the magnetospheric dissipation of kinetic energy flux by particle precipitation in the ionosphere, the magnetosphere dissipates electromagnetic flux through Joule heating. The role of neutral wind, turbulence, and unknown conductivities at small to medium scales still hinders an overall understanding of the total energy exchange (e.g., Heelis and Maute 2020). In addition, despite the SW control of magnetospheric dynamics, the Earth's rotation relative to Geospace provides a non-negligible and unresolved contribution to the Joule heating budget (Decotte et al. 2023).

As highlighted in Sect. 4.2, the Geomagnetic storms and substorms processes couples the magnetosphere–ionosphere system. While the ionospheric signatures of the substorms are well-described, there are several outstanding questions regarding how this coupling is shaped. Over the next 5 years, both EISCAT_3D and the satellite mission EZIE will, by observing the electrojets' medium- and small-scale structure and evolution, scientists can resolve outstanding mysteries about what shapes the electric circuit between Earth and space.

Moreover, exploring the three-dimensional structure of the ionospheric currents is also key to understanding how the magnetosphere dissipates electromagnetic flux in the ionosphere through Joule heating. Getting access to volumetric measurement of electron density and ion velocity vector together with model ion neutral collision frequency altitude profile can be used to calculate the E-region neutral winds affecting the Joule heating efficiency (McCrea et al. 2015). Understanding the role of small-scale structures, e.g., intense localized electric fields in the vicinity of auroral arcs, will provide a more accurate estimate of the magnetospheric energy dissipated into the ionosphere.

5. How do turbulence, neutral winds, Earth's rotation and small-scale conductivity variability affect the Joule heating energy budget?

With a better resolved ionosphere, it is also timely to ask:

6. What are the ionospheric signatures of magnetospheric energy conversion processes at different boundaries, magnetopause reconnection, Kelvin–Helmholtz waves, near-Earth magnetic reconnection and associated flow disturbances?

For example, the fastest field-aligned propagating disturbance is the accelerated electron beam followed by Alfven waves and ion flows (Wellenzohn et al. 2021). With an improved better resolved time scale, is it possible to identify the timing differences between the enhancement of the electron precipitation (conductivity gradient enhancement) vs. E-field enhancement? These questions can be addressed in near future with advanced ground-satellite conjugate measurements and coupled modeling of the solar–wind–magnetosphere–ionosphere system.

4.5 Comparative studies: moon and mars

This topic is related to all G2.1–G2.3. The Moon, with no significant atmosphere or global magnetic field, provides a unique environment for studying solar wind interactions. Solar wind plasma impinges directly on the lunar surface, forming the lunar wake and localized magnetic structures around remnant magnetic anomalies (Kurata et al., 2015). These interactions are governed by cross-scale couplings, where global solar wind dynamics influence local particle behavior and wave excitation. Such studies are essential for understanding plasma processes on airless bodies, which are fundamentally different from those in planetary magnetospheres (Zhang et al., 2023; Farrell et al. 2023).

Unlike Earth, Mars has no global magnetic field of internal dynamo origin and only a thin atmosphere, resulting in unique interactions with the solar wind. The solar wind interacts directly with the Martian atmosphere, creating an induced magnetosphere that dynamically responds to solar activity. This interaction drives atmospheric escape processes, such as ion pick-up and sputtering, which have shaped the climate evolution of Mars over geological timescales (Jakosky et al. 2018).

Understanding these couplings is crucial, because global variations in the solar wind (e.g., coronal mass ejections) influence localized processes, such as ionospheric heating and atmospheric ion loss (Green et al. 2022).

Research into the interactions between localized plasma environments and the global lunar environment provides important insights not only into lunar processes, but also into similar mechanisms on other celestial bodies. Understanding the effects of solar energetic particles (SEPs) and cosmic rays on astronaut safety and equipment reliability is essential for the success of long-term lunar missions. In addition, the study of mini-magnetospheres, how they form and protect the lunar surface from the solar wind, and the coupling between the lunar regolith and the solar wind plasma/SEPs is key to advancing the understanding of the interactions between solid bodies and the lunar surface.

On Mars, understanding the mechanisms that drive atmospheric escape remains a key challenge. Identifying the processes of ion and neutral loss under varying solar conditions is necessary to explain the planet's atmospheric evolution. Space weather events, such as SEPs and CMEs, have a significant impact on the Martian plasma environment and atmospheric stability, emphasizing the need for further research into their long-term effects.

In addition, linking space weather interactions to Martian climate evolution provides a broader perspective on Martian habitability. Continuous solar wind monitoring at Mars (such as Earth and L1 observations) and detailed in-situ observations of the Martian ionosphere and thermosphere are essential to improve models and advance our understanding.

In this context, the following open questions remain to be addressed by future research.

1. How do solar wind structures interact with lunar remnant magnetic anomalies and surface features, and how are these processes modulated on spatial and temporal scales?
2. What mechanisms govern the formation, stability and shielding effectiveness of lunar mini-magnetospheres?
3. How do SEPs and GCRs affect surface charging, dust mobilization and radiation levels on the Moon, especially under extreme space weather conditions?
4. What are the key processes and solar wind conditions that control the escape of ions and neutrals from the Martian atmosphere?
5. How do cross-scale couplings between global solar wind dynamics and local ionospheric/magnetospheric processes shape atmospheric loss and variability on Mars?
6. What monitoring systems and modeling approaches are needed to enable real-time space weather forecasting and early warning systems for the Moon and Mars?
7. How can comparative studies on Earth, Moon and Mars improve our general understanding of solar wind–plasma–atmosphere interactions?

Promoting research on the Moon and Mars is important not only for understanding these celestial bodies, but also for contributing to a more universal understanding of the Sun–Earth connection. With the increasing focus on human exploration of the Moon and Mars, it is even more important to advance space weather studies in these regions. These efforts deepen scientific understanding and support the safety and success of future human missions.

To better understand the lunar plasma environment and surface interactions, low-altitude orbiters and surface observatories will provide continuous monitoring of electric and magnetic fields, particle dynamics and radiation. The establishment of an unmanned multi-point observing network on the lunar surface is particularly important to capture spatial and temporal variations in the plasma/SEP environment and its interactions with the surface. Investigating areas of strong magnetic anomalies can provide important insights into the behavior of the mini-magnetosphere and how it protects the lunar surface. Combining research in plasma physics, lunar geology and space engineering will also help to assess the effects of the solar wind on surface features, human habitability and dust clouds, which could impact on exploration infrastructure.

Advanced modeling and simulation are also important for understanding the dynamic lunar environment. Hybrid and kinetic plasma models can simulate key processes such as wave–particle interactions and dust transport driven by electric and magnetic fields. Predicting and mitigating the effects of SEP events is essential to ensure the safety of astronauts and infrastructure on the Moon. The development of space weather forecasting systems with real-time monitoring and early warning capabilities will help protect missions and human activities. Working with international space agencies to share data and build a global lunar space weather database will further support safe and sustainable lunar exploration while contributing to broader heliophysics research.

Similarly, improved observations and models are essential for understanding and predicting space weather effects on Mars.

Space weather research is also key to supporting human exploration and settlement on Mars. A Mars space weather warning system to predict SEP events will

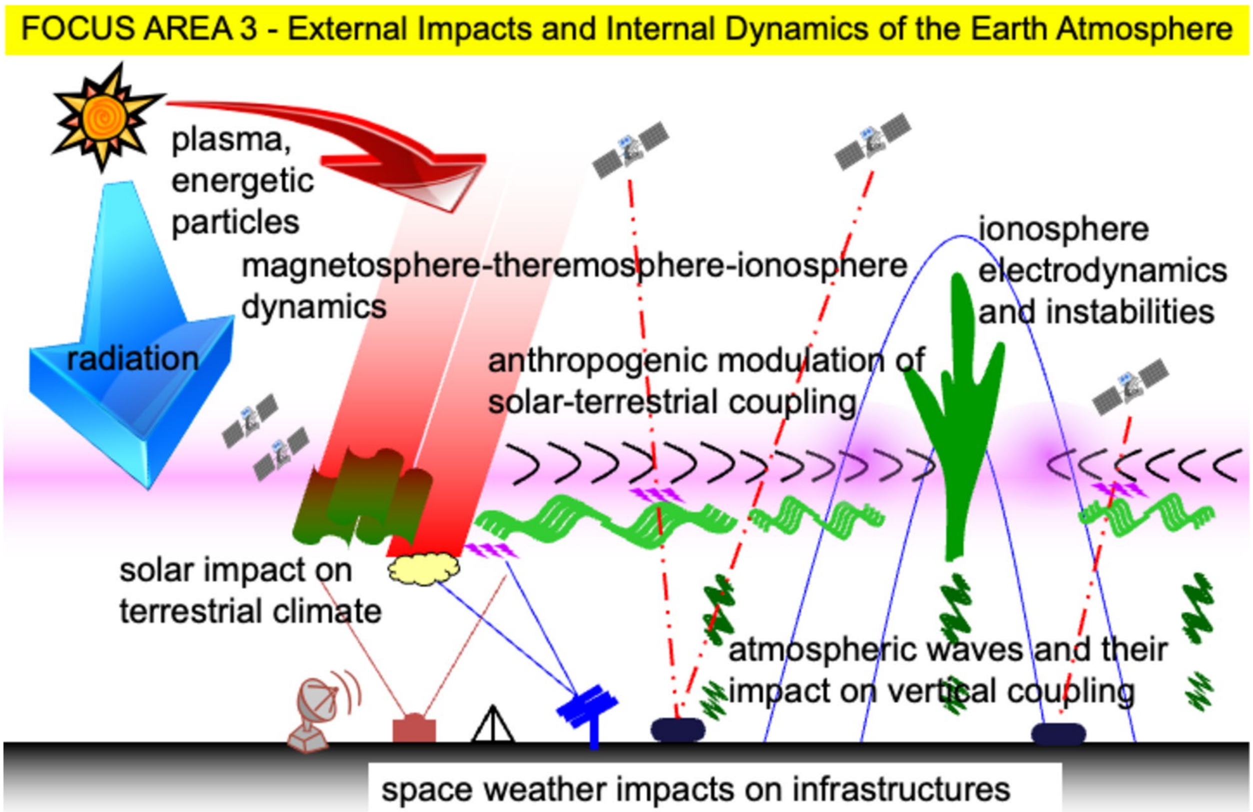


Fig. 4 Schematics of focus area 3 main topics

improve radiation monitoring and forecasting, ensuring the safety of astronauts and surface habitats. Simulation of extreme events, such as Carrington-class CMEs, will provide useful assessments of their impact on surface radiation and electrical systems. These efforts will support sustainable human missions to Mars and improve our understanding of the Sun–Mars system.

5 Focus area 3: external impacts and internal dynamics of the earth atmosphere

The Earth's middle and upper atmosphere is subject to strong forcing by the most energetic photons (e.g., X-ray and EUV), energetic particle precipitation and geomagnetic input. It is also an integral part of the Earth atmosphere system, where a broad spectrum of atmospheric waves from the terrestrial weather system grow to become increasingly dominant dynamically, and anthropogenic gases undergo long-term changes in tandem with the lower atmosphere due to upward transport. This region is, therefore, highly complex and intrinsically multi-scale, with interacting photochemical, dynamical and electrodynamical processes. Understanding and quantifying these cross-scale coupling interactions is a major goal of the SCOSTEP program. It is important for understanding the intrinsic predictability of the atmosphere–geospace system, and for advancing the space weather and space climate forecasts. Given its vast size, continuous monitoring of the system of all the interacting scales is challenging. Novel satellite missions, innovative ground-based observations, and fusion with advanced numerical models, data assimilation, and machine learning are essential for progress. The main topics of focus area 3 are reported in Fig. 4.

The main fundamental questions of this focus area are the following.

(G3.1) How do the external drivers and the internal dynamics interact in the middle and upper atmosphere?
(G3.2) What is the role of the middle and upper atmosphere in mutual coupling the Earth atmosphere and geospace system?
(G3.3) How do cross-scale interactions impact the middle and upper atmosphere?

(G3.4) How do couplings of different regions, drivers and scales impact the predictability of the middle and upper atmosphere system?

For the next phase of SCOSTEP we define the following research objectives:

(O3.1) Better understand and characterize the responses of the magnetosphere–thermosphere–ionosphere system to different types of solar storms, especially the hemispheric asymmetries of the response.
(O3.2) Quantifying atmospheric waves from planetary to meso-scales and their effects on the middle and upper atmosphere by taking full advantage of novel ground-based and space-based observations and high-resolution modeling capabilities.
(O3.3) Determine and quantify the driving of ionospheric variabilities by forcing from above and below and by multiscale dynamics.
(O3.4) Study the pathways of solar impact on the terrestrial climate system through the middle and upper atmosphere.
(O3.5) Achieve improved thermosphere–ionosphere forecast during extreme storm events by promoting data availability and advancing model capability with the goal to better protect the infrastructures.
(O3.6) Assess ramifications of projected anthropogenic climate change for solar–terrestrial coupling.

5.1 Magnetosphere–thermosphere–ionosphere (MTI) dynamics

5.1.1 Hemispheric asymmetries

Observations show hemispheric asymmetry in different parameters of the ionosphere and thermosphere particularly at high as well as mid and low latitudes. A better understanding of these asymmetries is important, because they can provide crucial clues for a better scientific description of the complex MTI system. Hemispheric asymmetries also represent a large-scale aspect of the Earth's response to space weather, which is important for understanding regional space weather.

5.1.1.1 Hemispheric asymmetries at high latitudes It is important to consider a large-scale asymmetry in the interhemispheric distribution of various electrodynamic parameters, as an impact of, for example, asymmetry in ionospheric conductance produced by solar UV radiation, seasonal changes in UV illumination, and variation caused by the offset between geographic and geomagnetic poles. Ionospheric conductance changes the properties of the plasma convection and affects the field-aligned currents (FAC) connecting the magnetosphere and ionosphere. The IMF By component affects electrodynamics in the magnetosphere, so that a voltage appears between the two magnetospheric lobes. Thus, it could be expected that a radial electric field and azimuthal plasma flow will form around the poles, which are oppositely directed in the Northern and Southern hemispheres. The magnitude of this effect seems to be dependent on the sign of the IMF Bz component. Penetration of the electric field to regions of closed geomagnetic field lines may be quite significant too, causing a mutual electrodynamic influence of the opposite hemispheres (Ridley 2007; Lukianova et al. 2008). Asymmetries on the response to solar perturbations of the geomagnetic field, atmosphere and ionosphere at high latitudes are reported in several papers (see, e.g., Alfonsi et al. 2022 and references therein). The understanding of the ionospheric plasma structuring, often following a cascade process from large- to meso- and small-scale sizes (from a GNSS perspective from thousands of kilometers to centimeters), is very challenging. For instance, the recent Mother's Day storm in May 2024 resulted in the so-called Tongue of Ionization (TOI) and the subsequent fragmentation described in Themens et al. (2024) through the combined use of GNSS receivers, Incoherent Scatter Radar and ionosonde observations.

5.1.1.2 Hemispheric asymmetries at mid and low latitudes The Equatorial Ionization Anomaly (EIA) parameters such as their strength, shape, intensity, and latitudinal positions are affected by the eastward electric field and effective meridional wind. The monthly variations in the EIA over two magnetic meridian sectors display a semiannual variation. The EIA crests were more symmetric in equinox than in solstice seasons. The intensities of the EIA crests also considerably decreased with solar descending phases. MTI coupling exerts influence on EIA structures through prompt penetration of electric field during geomagnetic storms. The combined effects of equatorial and high latitude origins at mid latitudes can make it challenging to disentangle the complex interactions during geomagnetically disturbed periods.

Understanding hemispheric asymmetries at all latitude regions involves thermospheric composition dynamics and vertical plasma motion with the latter consisting of contributions from ambipolar diffusion, horizontal neutral wind and vertical ExB drift. Comprehensive progress about this requires simultaneous presence of data and models to delineate the relative influence of each physical mechanism.

5.1.1.3 Ionospheric response to solar storms, storm time recovery and its predictability For both CME- and CIR-driven storms the ring current decays faster for events with short main phase durations in general, and it decays quickly for 1 day followed by a gradual long-lasting second-step recovery. Magnetic storms with longer main phase duration, on the other hand, exhibit a one-step slow and gradual recovery. Intense geomagnetic disturbances usually show two-step recovery (Ahmed, O., 2024). Although the storm recovery phase is characterized by an abatement of perturbations and a gradual return to the "ground state" of ionosphere, observations of disturbed ionosphere show significant departures from the climatology within this period. During recovery of intense storms ($Dst \leq -150$ nT) only the first initial phase (about 30%) of the period is perturbed, while during the weak-to-moderate CIR/CH HSS geomagnetic storms significant positive and negative deviations of the ionospheric main parameters (e.g., critical frequency of the ionospheric F2-layer *foF2* and height of the F2 layer *hmF2*) from their 27-day running means have been observed at middle latitudes for entire recovery period. A combination of numerical models and observations is desirable to explain ionospheric storm effects as there are sometimes data gaps from conventional instruments (such as ionosondes) arising from storm-induced processes (e.g., Habarulema et al. 2024; Molina et al. 2020).

There is a clear need for continued efforts to better understand the mechanisms, processes and ionospheric response during the recovery phase of geomagnetic disturbances induced by CMEs and CIRs, which will provide a solid basis for a reliable prediction of ionospheric variability under storm recovery conditions. This will also lead to improved ionospheric/space weather models as it is currently complicated (if not impossible) to model positive storm effects even retrospectively.

5.1.1.4 Ionospheric response to CIR/CH HSS-related storm-induced disturbances During the declining phase of the solar cycle and solar minima a number of other types of solar events dominate in which the coronal holes emerge from polar regions and extend in the equatorial regions. Because these hole regions are long-living, they co-rotate with the Sun. CIRs (co-rotating interaction regions), rather than the high-speed streams from coronal holes (CH HSS) alone, are responsible for recurrent geomagnetic activity. CIR/CH HSS-related magnetic storms usually are weak-to-moderate, and their effects on the middle latitude ionosphere (mostly positive) could be comparable with the effects of strong CME-related magnetic storms. The effect on the high latitude ionosphere is more significant. Compared to CMEs, traveling ionospheric disturbances (TID) activity and ionospheric disturbances associated with CIR/CH HSS have a longer duration (Buresova and Laštovička, 2017). The ionospheric response to CIR/CH HSS storms is not well-studied. The significantly increased medium scale TID (MSTID) activity during these storms affects the proper functioning of GNSS applications.

The above issues, related to G3.1, and objective O 3.1 could be addressed through:

1. Hemispheric asymmetry studies investigating development and drivers of ionospheric phenomena such as ionospheric storm effects and storm enhanced density (SED) during geomagnetic storms.
2. Quantification of contributions of relevant physical mechanisms to positive followed by negative storm effects (and vice versa) during storm period. Extending such studies in different latitude regions on long-term to establish trends.
3. Improved characterization of ionospheric storm effects on a statistical basis with the ultimate goal of developing/improving predictive models.

5.2 Atmospheric waves and their impact on vertical coupling

5.2.1 Mean circulation and composition

Atmospheric waves from the lower atmosphere, with horizontal scales ranging from tens of km to planetary scales, have been known to play a key role in the energetics, circulation, composition and variability of the middle and upper atmosphere (Liu 2016; Yiğit et al. 2016; Shiokawa & Georgieva 2021; Ward et al. 2021). There has been progress in quantifying the waves and their impacts in recent years, especially benefiting from the development of novel observation techniques, numerical models of the whole atmosphere system and with increasing spatial resolutions, and application of whole atmosphere data assimilation. A major challenge has been the poor understanding and quantification of cross-scale coupling processes, especially those involving mesoscale processes (e.g., gravity waves). The forcing by mesoscale gravity waves is the primary driver of the mesospheric and lower thermospheric circulation (Holton 1982, 1983), and it also contributes to the stratospheric quasi-biennial oscillation (QBO) (Baldwin et al. 2001), mesospheric semiannual oscillation (MSAO) (Dunkerton et al. 1982), and the thermospheric circulation and composition (Liu et al. 2024a). However, the quantification of these effects is severely limited by the difficulty in capturing the vastly different scales important for these processes in observations and in whole atmosphere models. In the latter the coarse resolution of the models and the poor subgrid scale parameterization schemes in representing the wave sources, propagation and the wave effects are major causes for biases and loss of model prediction skills on global scales, including the global winds, planetary scale waves (tides and planetary), and composition in the mesosphere and thermosphere (e.g., Pedatella et al. 2014a, b). The subgrid scale parameterization schemes also hinders the model capability in characterizing the cross-scale interactions. For example, the downward transport of nitric oxide produced in the lower thermosphere by EPP, especially following a stratospheric sudden warming, cannot be properly modeled with the current parameterization scheme (e.g.,Randall et al. 2015; Smith-Johnsen et al. 2022). Moreover, the underestimation of tides may result from excessive gravity wave drag. Consequently, diurnal tidal growth and breaking in the mesopause/lower thermosphere (Garcia 2023), which may provide important forcing for MSAO (Suclupe et al. 2024), cannot be properly simulated.

5.2.2 Middle and upper atmosphere weather

In addition to their key role in determining the mean circulation and composition as discussed in Sect. 5.2.1, atmospheric waves also cause large variability and drive the day-to-day weather of the middle and upper atmosphere. Studies of atmospheric tides (migrating and non-migrating), planetary waves, and gravity waves (including the generation of secondary waves due to body forces), as well as their interactions are of great importance. Tides propagating upward from the lower atmosphere could show considerable variability from day to day due to variations in tropospheric sources, middle atmosphere processes (e.g., vortex) intensifies such variations (Oberheide 2022; Pedatella & Harvey 2022), interaction with planetary waves (Lieberman et al. 2004, 2015; Pedatella, et al. 2016a) and interaction with the mean flow when propagating upward (Pedatella, et al. 2016b; Oberheide, et al. 2024). They strongly modulate the temperature and winds in the middle and upper atmosphere, and their day-to-day variability is a key contributor to the daily weather of the thermosphere and ionosphere (Miyoshi and Fujiwara 2003; Liu, 2013; Liu et al. 2013; Wang et al. 2021; Liu et al. 2018; Liu 2020). Tides also modulate the ionospheric E and F region dynamo (e.g.,Fesen et al. 2000; Immel et al. 2006). The predictability of the thermosphere and ionosphere daily weather (especially at low latitudes) is, therefore, strongly influenced by the predictability of the tidal weather. Of particular interest is the connection between the equatorial ExB vertical drift around dusk (the pre-reversal enhancement, PRE) and around midnight and tides (e.g.,Fesen et al. 2000; Liu 2020; Liu & Maute 2024) because of their importance in driving equatorial ionospheric irregularities.

At mesoscales, gravity waves play an important role in the dynamics and variability of the Earth's middle and upper atmosphere. Propagating through the thermosphere and interacting with the ionospheric plasma, gravity waves produce TIDs. Essential results of the TID studies were published in several papers (e.g., Hunsucker 1982; Hocke & Schlegel 1996; Shiokawa et al. 2007; MacDougall et al. 2009; Martinis et al. 2019; Chum et al. 2023). The main known sources of TID reaching ionospheric heights from the lower atmosphere are: intensive tropospheric events (drivers of meteorological origin, e.g., adjustment of unbalanced flows near jet streams and frontal systems, cold front passages, lightening, strong winds), orography, seismic activity (volcano eruptions, earthquakes), solar terminator, eclipses and anthropogenic sources (rocket launches, artificial explosions). MSTIDs with periods from 10 to 60 min tend to arise mostly from tropospheric jet streams and cold fronts (Vadas 2007) and the passages of the solar terminator (Cot & Teitelbaum 1980); and smaller scale TIDs are commonly associated with local convective activity, lightning strikes, and significant tropospheric disturbances propagating into the ionosphere (Hunsucker 1982). The gravity waves and TIDs probably provide the seeding for ionospheric irregularities, such as equatorial spread F (ESF) (discussed in 3.4), day-to-day variability under stable solar and geomagnetic forcing.

It is important, and feasible in our opinion, to make progress in better quantifying the atmosphere waves by deploying new observational instruments and developing new model capabilities in the next 5 years. An example of innovative ground-based instrument is the new multistatic meteor radars (e.g., Chau et al. 2021; Stober et al. 2022) combined with physics-informed machine learning approaches, provide 4D wind field measurements with horizontal scales of a few tens of kilometers (Urco et al. 2024, JGR Machine Learning). The NASA Atmospheric Wave Experiment (AWE) was launched in December of 2023, and it is making near global measurements of mesospheric gravity waves (GWs) with horizontal scales between 30 and 300 km, complementing earlier GW measurements by SABER in this region (Taylor et al. 2020). Assimilation of the observations using physics-based whole atmosphere models have been a powerful development in the past decade. It has been demonstrated that data assimilation (DA) helps mitigate the aforementioned model biases (Eckermann et al. 2009; Pedatella et al. 2014a, b; Koshin et al. 2020, 2021; McCormack et al. 2021).

The further development of high-resolution whole atmosphere models show promise in representing GW distribution, propagation, dissipation, generation of secondary/higher order GWs, and the wave effect on circulation and transport (e.g.,Becker et al. 2022; Liu et al 2024a, b). The high-resolution capability is important for capturing the cross-scale interactions. The high-resolution whole atmosphere simulations will also guide the development of scale-aware parameterization schemes (Liu 2019; Liu et al. 2024a,b; Plougonven et al. 2020). Extending to even smaller scales, instability induced by gravity waves and wave–turbulence interactions can now be simulated by direct numerical simulations (e.g., Fritts et al. 2024). Direct numerical simulations of rotating and stratified turbulence in the atmosphere in a flow regime similar to the mesosphere and lower thermosphere has led to new insights in the cascading processes (Alexakis et al 2024). Incorporating the knowledge gained from these high-resolution into subgrid scale parameterization, probably informed by machine learning, may be a fruitful pursuit to further advance the whole atmosphere model capabilities.

Specifically, our community will seek to address the following questions:

1. What are the major GW sources in the troposphere and stratosphere and what are their distribution and seasonal climatology?
2. How are the planetary scale waves modulated by the mesoscale waves and vice versa?
3. How do waves from mesoscales to planetary scales contribute to the circulation, transport and composition from the stratosphere to the thermosphere and ionosphere?
4. How to design a physically consistent, efficient and scale-aware parameterization schemes to represent the cross-scale processes in the middle and upper atmosphere?
5. What is the predictability of atmospheric tides and how does it impact the predictability of the ionospheric electrodynamics?
6. What are the relative significance of mesoscale gravity waves from the lower atmosphere and ionospheric instabilities in driving ionospheric TIDs?
7. What is the predictability of atmospheric gravity waves and how does it impact the predictability of the TIDs?
8. How are the atmospheric gravity waves and their predictability affected by their interaction with the stratified turbulence in the mesosphere and lower thermosphere?

5.3 Ionosphere electrodynamics and instabilities

High latitude ionospheric electrodynamics are predominantly influenced by processes of magnetospheric origin due to direct coupling of ionospheric currents to currents along magnetic field lines into the magnetosphere (Richmond and Thayer 2000). This is in addition to its mechanical coupling to the neutral atmosphere through collisions (Hatch et al. 2024). An important parameter used to describe magnetosphere–ionosphere coupling in high latitudes is the ionospheric conductivity and yet its measurements and estimates remain limited (Weimer and Edwards 2021; Hatch et al. 2024). Historically, there still exists a general imbalance in the observations used to estimate various parameters used in empirical and theoretical models in the southern hemisphere (SH) compared to the northern hemisphere (NH). This is an aspect that requires coordinated efforts for instruments' deployment in the SH to revisit previous assumptions of hemispherical symmetry. Currently it is relatively possible to accurately map polar ionospheric electrodynamics in NH (Landal et al., 2022), while a similar study is restricted by insufficient infrastructure in the SH.

Climatologically, the behavior of low latitude electrodynamics is relatively well-understood based on ground-based and satellite measurements. Complexities arise during periods of enhanced magnetic activity and other solar phenomena such as solar flares (Zhang et al. 2017; Chen et al. 2021). Storm time ionospheric electrodynamics in low latitudes are influenced by variations and orientations in solar wind interplanetary magnetic fields IMF Bz (e.g., Manucci et al., 2005; Huang et al. 2005), IMF By (Tsurutani et al. 2008; Tenfjord et al. 2015), substorms (Kikuchi et al. 2003), Sub-Auroral Polarization Streams (e.g., Forster and Vo, 2002). Broadly, electrodynamics in low latitudes during extreme space weather events are controlled by penetrating electric fields of magnetospheric origin (Kikuchi et al. 2008; Huang et al. 2005; Fejer et al. 2024) and Disturbed Dynamo Electric field (Blanch and Richmond, 1980; Heelis 2004). Most of the understanding of this topic (which is also a limitation) is based on observations from the Jicamarca incoherent scatter radar, TEC from GNSS and ionosondes located in equatorial regions. Currently, space missions such as GOLD or ICON have been used to study the effect of geomagnetic storms in the equatorial region in South America (Gonzalez et al., 2024). Recently, there have been studies highlighting higher vertical drifts in the American sector compared to the African sector and yet the latter experiences higher occurrences of ionospheric irregularities (e.g., Yizengaw et al. 2012). Numerical (e.g., Roble et al. 1988) and empirical (e.g., Fejer et al. 2008) modeling approaches have been advanced in simulating these effects at different time scales. Empirical models "suffer" from lack of sufficient data in all longitude sectors for comprehensive representation of localized effects, while theoretical/numerical models experience a similar problem especially for validation of the results. The future should involve deployment of low-cost instrumentation such as magnetometers for differential magnetometer approach (e.g., Anderson et al. 2002) and other such as coherent scatter radars (e.g., Patra et al. 2014) or ionosondes, improving modeling for accurate results and forecasting, providing temporal and longitudinal response of the electrodynamics to different drivers (e.g., Fejer et al. 2024) and identify a systematic way of isolating different effects to the entire system at different levels of the space weather event. These advancements would all benefit the all-time evolution and prediction of E region instabilities, F region Spread F and scintillation which are driven by changes in equatorial zonal eastward electric fields (e.g., Fejer et al. 2008, 2024).

Sporadic E layers (Es) are localized electron density enhancements at about 90–130 km heights in the ionosphere mainly at mid-latitudes, and predominantly in the summer hemisphere. The main physical mechanism for the Es layer development is related to the vertical wind shear process (Yamazaki *et al*., 2022). Other mechanisms, at low latitudes, may drive the occurrence of Es layer, such as EEJ plasma instabilities, particle precipitation at SAMA (South Atlantic Magnetic Anomaly), or gravity waves (Resende et al., 2023). Es layer is typically observed by ionosonde, thus, coverage in mid and low latitude sectors should be encouraged especially in the African sector. An aggregation of radio occultation Es information (Arras and Wickert 2018) and ionosonde observations can form a basis for the development of Es occurrence rate models to be integrated into a suite of space weather models for operational purposes.

Questions would include:

1. What is the temporal and longitudinal response of electrodynamics to different drivers? Answering this requires new networks of instruments in different longitude sectors to complement existing ones, thus facilitating analyses of these perturbations.
2. What is the role of DDEF and PPEF in initiating ionospheric irregularities?
3. How localized seeding of AGWs can improve the weather understanding and forecasting of such perturbations?
4. How can the knowledge of electrodynamics be improved by isolating/quantifying the contributions from forcing from below and from above? Which are the tools or models aiding such quantifications?
5. How can new observations and approaches help in obtaining ionospheric conductivity to better understand and describe the magnetosphere–ionosphere coupling in high latitudes?
6. At high latitudes, to which extent the auroral electrojet (AEJ) is modulated by current segments? and how to better understand the AEJ structure and evolution?

To answer some of these questions, a combination of ground and space-based data are needed to enhance model and forecasting capabilities. By enhancing ground-based instrument deployment and the upcoming satellite missions, in the near future the community can tackle most of these scientific questions.

5.4 Solar impact on terrestrial climate

Although solar variability is certainly not the main driver of recent climate change, a better understanding and quantification of its role is essential for reducing uncertainties in the assessment of future anthropogenic climate change. There are three mechanisms by which solar variability affects different layers of the Earth's atmosphere. The two most prominent and better understood ones are due to the radiative forcing by the solar electromagnetic radiation over the entire spectrum leading to a direct heating of the Earth's surface, and the radiation in the UV part of the spectrum, which heats the upper and middle atmosphere and affects ozone chemistry in the middle atmosphere. The third mechanism concerns the role of energetic particles, including SEPs and particularly particles coming from the Earth's magnetosphere (during solar-induced geomagnetic storms), which penetrate into the polar atmosphere, where they induce chemical and dynamical effects. The overall impact of energetic particle precipitation has long been neglected, but is now thought to be comparable to that of radiative forcing (Matthes et al. 2017).

Mechanisms of solar influence on the atmosphere and climate involve a large range of coupling processes connecting various scales (i.e., wave mean flow interactions) and domains (i.e., chemistry, radiation, atmosphere and magnetosphere dynamics). Current limitations include the assessment of the relative roles of solar forcing and internal variability under different background conditions and external forcings, i.e., past (no anthropogenic forcing) versus present and future (increasing anthropogenic forcing). Moreover, a reliable quantification of solar contribution to regional surface climate requires a better understanding of the middle atmosphere and its coupling with the troposphere, and of the atmosphere–ocean interactions. These issues are partially hampered by the lack of more comprehensive satellite and ground-based observations before the mid-twentieth century, and possible model limitations to capture the right climate responses to external forcings (e.g., an uncertainty of response of the North Atlantic Oscillation (NAO) to solar forcing; Mitchell et al. 2015; Chiodo et al. 2019; Kuroda et al. 2022).

Sub-seasonal to decadal timescales are considered relevant by policy makers and drive decisions in terms of, e.g., infrastructure investments or land use. To date, the middle atmosphere impact on the troposphere in subseasonal to seasonal prediction can be forecasted approximately 2 weeks ahead using numerical weather models (Domeisen, et al 2020). On the other hand, climate projections have been conducted by Earth system models on centennial scales (e.g., O'Neill et al., 2016). Bridging the gap in between, in particular from subseasonal to decadal scales, requires identification and understanding of sources of predictability, as well as its adequate representation in forecast models (Meehl et al. 2021). The solar impact on the middle atmosphere and the subsequent link to the troposphere integrates a complex array of components, some of them representing a promising source of predictability in subseasonal to decadal forecasts (Salminen et al. 2020). Better prediction of the solar UV and EPP forcing, with their inherent 11-year variations, improved understanding of the middle atmosphere–troposphere coupling, and a better representation in forecast systems represent major steps to improve predictability on subseasonal-to-decadal scales. This is a challenging goal, but if realized, they might bring added value to forecasts as "windows of opportunity", i.e., periods of enhanced predictability conditioned on skillful phenomena (Mariotti et al. 2020), with potential benefits to many sectors of society.

Relevant questions are:

1. What is the spatial and temporal variability of atmospheric ionization introduced by different types of energetic electron precipitation?
2. What is the (non-linear) interaction of solar forcing with internal variability modes? Where does it take place? (cross-scale coupling….)
3. How is solar influence on climate being modulated by anthropogenic forcing?
4. Can incorporating solar variability lead to better predictability of surface climate over subseasonal to decadal periods?
5. How can the solar signal be distinguished within the prevailing internal variability?

5.5 Space weather impacts on infrastructures

Space weather poses a significant threat to infrastructure resilience and is a source of risk, recognized by governmental agencies and corporations at the national and international level, in a wide range of impacts and scales (Eastwood et al. 2017).

Aviation and commercial space flights are subject to radiation hazards originating from SEP events and GCRs. In addition, relativistic electrons associated with the Van Allen radiation belts have been identified as potential sources of radiation level enhancement at commercial flight altitudes (Tobiska et al. 2016). Continuous radiation environment monitoring and modeling is a difficult task, not yet been achieved on regional or global scales. Recent studies have also developed modeling of the radiation dose of the flight altitude upon extreme SEPs, such as GLEs or the Miyake events (Dyer et al. 2018; Mishev et al. 2023; Asorey et al. 2023). These modelings will be further developed in combinations with historical measurements of radiations and data of historical extreme storms (e.g., Hands et al. 2022; Larsen and Mishev 2024).

Satellite drags are also of significant concern. Mass crushes of the Starlink Satellites occurred in 2022 (Berger et al. 2023; Baruah et al. 2024; Oliveira et al. 2025). Impacts of the satellite drags have been assessed for the modern storms (Parker and Linares 2024). Further extreme cases are modeled on the basis of recently recovered data for the extreme geomagnetic storms in the past (Oliveira et al. 2020).

Ionospheric density irregularities, i.e., regions of uneven distribution of electron density, are one of the primary space weather sources of interferences in radio frequency links producing nocive effects on radio waves propagation causing the degradation in performance of GNSS navigation and positioning or producing the scattering of HF radio signals. These irregularities may vary from 10 s meters to 10 s of Km and impact the HF systems increasing uncertainties in the ionospheric reflection point and fluctuations in signal-to-noise ratio (SNR), losses of signal lock, and increasing positioning errors due to fluctuations on the phase and amplitude of the received GNSS signals, whose diffractive effect is known as ionospheric scintillation.

Scintillation is especially relevant at high and low latitude regions affecting a wide range of socio-economic activities (naval shipping, digital farming, mining, etc.). In this context, the continuous monitoring and the increase of the sensor coverage can improve the capability for prediction and mitigation. Not only the deployment of GNSS receivers are important but also the heterogeneity of the sensors should be considered, because it may affect the capability of modeling and forecasting the occurrence of scintillation. Even if the scintillations can be monitored only with GNSS receivers capable of sampling the signals at high frequency (50–100 Hz), the exploitation of existing GNSS networks equipped with geodetic receivers are crucial to monitor TEC gradients. In this framework collaborative efforts with other communities (academic entities, service providers, mapping authorities, etc.) are already ongoing but need to be strengthened and consolidated. GNSS big data are now available from millions of mobiles all over the world, opening amazing opportunities of citizens in science activity that can be a valuable tool for scientists and space weather vulnerable users (Smith et al. 2024) The reconstruction of the temporal and spatial evolution of the ionospheric irregularities causing scintillations is the key to develop reliable forecasting models and this can be done only with a multi-instrumental and multidisciplinary approach based on the combination of ground- and space-based measurements supported by semi-empirical models and/or machine learning models of the upper atmosphere.

In addition, enhancements in the D-region electron density causing the increase of absorption, and F2-region electron density depletion (negative phase ionospheric storms) are two main space weather effects impacting HF radio communications. The first, occur because of energy particle precipitation producing three impacts: shortwave fadeout, auroral absorption, and polar cap absorption. While the latter, negative ionospheric storms, depend on the F region density response to geomagnetic storms producing the so-called post-storm maximum usable frequency depression (PSD) phenomena.

Geomagnetic induced currents (GICs) may cause negative impacts on the operations of power systems and depending on the severity of the geomagnetic storms the effects can vary from voltage fluctuations to power blackouts and severe damage to transformers. Recent studies have significantly developed modelings of regional GIC effects in various regions, such as the UK, the US, Canada, Finland, Sweden, and Japan (Viljanen et al. 2012; Love et al. 2016; Nakamura et al. 2018; Boteler et al., 2019; Beggan et al. 2021; Lanavere et al., 2024). Their effects on the train signal system have also recently been documented and modeled (Patterson et al. 2023). Efforts to more accurately assess the impact of GICs in the infrastructure include improving earth conductivity models, GICs forecasting models, mapping of the shock events as a function of the latitude, since there is evidence that in mid-latitudes the impact is also significant, enhanced continuous monitoring (e.g., increasing the deployment of magnetometers, direct or indirect continuous measurements on power grids, etc.) and better assessment of the risk and effects on power grids. Additional challenges arise due to the lack of information or reluctance to share information from the companies that in few cases are open to monitor and share data with the researchers.

It is worth mentioning that society has been paying attention to space weather because of the sighting of auroras around the globe, as recently happened during the 11th May 2024 storm (Spogli et al. 2024; Hayakawa et al. 2024c). This can be seen as a good opportunity to engage the public and to foster awareness, training and capacity building.

During the next 5 years, solar activity will be at its maximum or in the declining phase which favors the occurrence of more impactful events to modern society. The main questions to be answered are:

1. How is it possible to increase the forecasting horizon for the different space weather impacts?
2. How can Space Weather events (flares, SEPs, geomagnetic storms, CMEs) prediction be improved? and the advantages and limitations of physical models, IA models, statistical models, hybrid models, etc.?
3. How can extreme events impact assessments be improved?
4. How **can** real-time data availability be encouraged and facilitated to ensure better forecasting?
5. How **can** capacity building and efficient communication aid the R2O and O2R process?
6. What are the main user requirements that can drive the exploration of new research horizons?

5.6 Anthropogenic modulation of solar–terrestrial coupling

It is well-established that anthropogenic CO2 increase leads to upper atmosphere cooling and contraction from both numerical modeling simulations (Roble and Dickinson 1989; Qian et al. 2011; Liu, et al. 2020; Solomon et al. 2018; McInerney et al. 2024), and long-term monitoring of the mesosphere, thermosphere and ionosphere (Emmert et al. 2008; Emmert 2015; Laštovička et al., 2012; Ogawa et al. 2014; Zhang et al. 2016; Mlynczak et al., 2020). In recent years, the research community has started to explore the potential impacts of continuous CO2 increase on the middle and upper atmosphere using global models with different climate project scenarios (Cnossen 2022; Brown et al. 2024). In more pessimistic scenarios, the thermospheric temperature and density reduction due to the rapid increase of CO2 can be significant in comparison with historical trend. These changes are expected to have consequences on the drag on and lifetime of space vehicles and debris, ionospheric density, thermospheric waves and dynamics, ionospheric electrodynamics, MTI coupling, and thermospheric/ionospheric storm-time responses. Study of these questions will both give us new insights in the atmosphere–geospace coupling and enable critical assessment of the ramifications of climate change for the space weather and space climate. Whole atmosphere climate models have already been employed for projection studies, and they will continue to make a useful numerical tool for addressing these questions. To better quantify the geographical variability, local time dependence, and interaction with solar variability, it is important to realistically and self-consistently capture the terrestrial climate responses for the corresponding Shared Socioeconomic Pathways (SSP) scenarios, which would require the whole atmosphere simulations to have interacting ocean, land and ice components. It is also important to take into consideration the effects of long term changes in the geomagnetic field (Cnossen and Maute 2020).

A different aspect of anthropogenic impact on the geospace is the rocket emissions and debris from spacecraft falling out of orbit. They are having increasingly adverse impact on the global atmospheric chemistry (Shutler et al. 2022). Their modulation of metal layers and E and D region chemistry needs further investigation. Furthermore, according to climatology study for Europe (Rädler et al. 2019) the increase of frequency of severe thunderstorms occurrence is expected in the twenty-first century due to rising instability. As the convective environment is recognized to be an important source of gravity waves influencing the thermosphere/ionosphere, the contribution of gravity waves due to changing tropospheric conditions should be addressed.

Studies with projection simulations would help address the following questions:

1. What are the projected changes of mesosphere/thermosphere/ionosphere due to anthropogenic climate change under different SSP scenarios?
2. How do the middle and upper atmosphere dynamics, including waves from planetary to meso-scales, change under different SSP scenarios?
3. How do thermospheric density, satellite drag, lifetime of space vehicles and space debris/de-orbiting change?
4. How do ionospheric density, electric conductivities, electrodynamics and current system change?
5. How are the atmospheric chemistry, metal layers and ionospheric E/D region affected by human space flight launches and space debris?
6. How do the projected changes modulate the MTI system and their coupling?

6 Methodology, measurements and infrastructures

This chapter deals with four important aspects for the implementation of the COURSE program in terms of methodology, measurements and infrastructures to conduct the research, namely: 1) AI-based modeling and tools, 2) models, 3) observations, missions and instrumentation, and 4) data and metadata. These four aspects include novel techniques, tools and processes employed to collect, analyze, interpret the data, as well as recommendations for the community to achieve the proposed objectives within COURSE. These four aspects are transversally related to the three focus areas of the program.

6.1 AI-based modeling and tools

Research in the Solar–Terrestrial relationships field is no stranger to the rapid growth of machine learning (ML) techniques and other areas of artificial intelligence (AI). In recent years, the number of papers and research using these techniques have increased exponentially. Several aspects have contributed, including: a) the amount of available space and ground-based measurements that consistently is acquired, curated and added to persistent (and probably distributed) systems; b) the maturity of algorithms and techniques; c) capability of tackling complex problems, especially those dealing with multiple cross scales; d) the accessibility to efficient computing and new high level software tools; and e) the increasing usage of machine learning by researchers (especially at the early stages of their careers) creating a virtuous loop.

Nevertheless, machine learning is still a young field with many caveats, unknown potential, difficult to understand or not yet trustworthy among the researchers. Some ML applications include nowcasting/forecasting of different phenomena in different Solar–Terrestrial subdomains (Hu et al. 2023; Ren et al. 2023; Laurenza et al. 2024; Stumpo et al. 2024; Chierichini et al. 2024; Molina et al. 2024, amongst many more), using for monitoring or calibrations purposes (Acciarini et al. 2024; Torres Peralta et al. 2024; among others), analyzing patterns or even understanding some physical processes (Camporeale et al.2022; Panos et al. 2023; among others). In this context, several questions have been posed by the community that can be categorized as follows.

Scientific questions that can be aided by ML

1. How can we effectively use the machine learning technique for better understanding of physics behind predictability?
2. How can ML push the current boundaries of predictability? (e.g., forecasting scintillation, geomagnetic storms, solar flares, SEPs, etc.)
3. Can the multiple scales, present in Solar–Terrestrial physics, be tackled using ML?
4. How do we encourage/facilitate a synergy between ML and physics models?

Algorithms, tools, and techniques

1. How can some novel algorithms from other scientific fields be transferred/used in our community? Is it possible to develop tailored algorithms to fit the data and the problems in solar–terrestrial physics?

2. Which are the techniques/tools that better suit the Research to operations (R2O) and the operations to research (O2R) cycle?
3. Is it possible to implement scientific ML benchmarks, develop guidelines and best practices to aid the scientific community in successfully exploiting these ML methods?

Robustness and trustworthiness

1. How are biases treated in the data sets, the modeling or the deployment of the ML-based models?
2. How can a trained model be seamlessly deployed into operations?
3. Which is the role of Explainable Artificial Intelligence (XAI) methods to better understand the predictions?

Data sets

1. How is the unbalanced data set problem tackled/considered?
2. How to guarantee enough data (e.g., long data set's availability) to train more accurate models?
3. How should the data set's characteristics and availability need to be to fast develop, validate and potentially deploy ML models?

To answer these questions, in the near future, some recommendations include: enhance availability of data sets tailored for ML, including combined measurements (e.g., mixing ground and space-based data), provide ML models benchmarks and foster training/capacity building. ML/AI techniques are widely spread (in many research fields) fast arriving tools and sources publicly available (libraries, languages, data sets, frameworks, etc.) which may be overwhelming. Moreover, often, students or young scientists are prone to apply these methods with fast results but with less exhaustive validation or proper metrics. Encouraging advanced ML/AI training courses and capacity building, of the next generation of scientists, targeted especially for solar–terrestrial applications may significantly contribute to better use and development of ML/AI within the COURSE program.

6.2 Physics-based and hybrid modeling

As highlighted in the previous sections, in the solar–terrestrial system there are many phenomena in which the interaction between microscale and macroscale dynamics plays a key role. For example, in the magnetic reconnection in solar flares and magnetospheric substorms, the interaction between the kinetic effect in the local dissipation region and the large-scale magnetohydrodynamics is essential. Recently, algorithms have been developed to reproduce such phenomena accurately based on the first principles by embedding a microscale model into a macroscale model and interconnecting them (Sugiyama and Kusano 2007). Furthermore, to overcome the gap in micro and macro time scales, a new model has been developed to speed up computation using an implicit method (Daldorff et al. 2014). Applying such advanced cross-scale models will contribute to understanding and accurately predicting more complex multiscale phenomena (Lapenta et al. 2013).

Understanding the physical processes within the different subsystems on various scales (spatial, time and energy) and how they may trigger other processes or effects rely on the enhancement or improving of current/new physical models capabilities (e.g., physically realistic 3D MHD or modeling non-LTE radiative transfer of the solar atmosphere, e.g., Sect. 3.6). Some efforts to revise the current models, their limitations and perspectives have been made by the community already (Temmer et al. 2023; among others).

In many cases, such as simulating cross-energy dynamics and forecasting space weather, hybrid methods, that combine physics-based models with machine learning, can be more relevant in the next 5 years. It should be noted that achieving long-term and global simulation studies that incorporate the elementary processes of nonlinear dynamics is essential.

In some cases, such as to explain extreme SEP events, for example, there is a lack of models for both acceleration and propagation of the energetic particles.

Moreover, coupled models between different domains will play a key role in the next 5 years as they target the chain of processes within the solar–terrestrial system.

Coordinated modeling and benchmark efforts are encouraged, such as those implemented within the NASA CCMC, which allow models to be compared and verified against each other and observations, enabling access to state-of-the-art research models.

Finally, to fully achieve a proper model benchmarking better and objective metrics are needed.

The main questions to address in future modeling efforts are:

1. Which are the proper and more objective metrics to evaluate the models?
2. How should the community foster the continuous physics models development?
3. How integrated models can help the understanding of the linked cross-scale processes?
4. How to ensure data availability for proper validation?

Table 1 Ongoing missions relevant to address the FAs, their goals and objectives

Mission	Main Objective	Status	Related Focus Area (FA)/Goals (G)/ Objectives(O)
Advanced Composition Explorer (ACE)	In-situ observations of SW parameters, magnetic field, energetic particles Observation of Sun and Solar wind	Since 1997	FA1/G1.2,G1.4,G1.5/O1.2,O1.3,O1.4, O1.5
Aditya-L1	Solar upper atmospheric (chromosphere and corona) dynamics	Launched in 2023	FA1/G1.3, G1.4/O1.3, O1.6
Arase	study of Van Allen belts	Launched in 1016	FA3/G2.3
Atmospheric Waves Experiment (AWE)	Global characterization of atmospheric gravity waves (AGWs) that originate in Earth's lower atmosphere and affect space weather. Imaging temperature, atmospheric gravity waves in the MLT region	Launched in 2023	G3.1/G3.3
International Space Station—Alpha Magnetic Spectrometer (AMS)	Energetic particle physics experiment	Since 2011	FA1/G1.5/O1.5
Advanced Space-based Solar Observatory (ASO-S)	Observation of Sun	Since 2022	FA1/G1.1,G1.4/O1.3, O1.4
China Seismo-Electromagnetic Satellite (CSES)	Monitoring electromagnetic field and waves, plasma and particles perturbations of the atmosphere, ionosphere and magnetosphere	Launched in 2018	FA3/G3.1,G3.2/O3.1,O3.3
Geostationary Operational Environmental Satellites (GOES)	Monitoring the Sun and space weather: • solar ultraviolet imager (SUVI) • X-ray irradiance sensor (EXIS) • compact coronograph (CCOR-1) • Space environmental in-situ suite (SEISS) (energetic particles) • magnetometer	GOES-16 (2016) GOES-17 (2018) GOES-18 (2022) GOES-U (2024)—includes now a coronograph	FA1/G1.4,G1.5/O1.3, O1.4, O1.5 FA2/G2.1/O2.1
Global-scale Observations of the Limb and Disk (GOLD)	Measures densities and temperatures in Earth's thermosphere and ionosphere using UV imaging spectrograph	Launched in 2018	G3.1/G3.3
HINODE	Remote observation of the Sun at several wavelengths (optic, X-rays, and EUV) and magnetic field observations	Launched in 2016	FA1/G1.2, G1.3, G1.4, G1.5/O1.2,O1.3, O1.4
Parker Solar Probe (PSP)	Remote observation of Sun and in-situ observations of SW parameters, magnetic field, energetic particles	Since 2018	FA1/G1.3,G1.5/O1.4,O1.5
Proba-3	Sun's corona	launched in Dec 2024	FA1/G1.3, G1.4/O1.3, O1.4
Solar and Heliospheric Observatory (SOHO)	Remote observation of Sun and in-situ observations of SW parameters, magnetic field, energetic particles Observation of Sun and Solar wind	Since 1995	FA1/G1.1,G1.2, G1.3, G1.4, G1.5/O1.1,O1.2, O1.3, O1.4, O1.5
Solar Dynamics Observatory (SDO)	Remote observation of Sun	Since 2010	FA1/G1.1, G1.2, G1.3, G1.4, G1.5/O1.1,O1.2,O1.3, O1.4, O1.5

Table 1 (continued)

Mission	Main Objective	Status	Related Focus Area (FA)/Goals (G)/ Objectives(O)
Solar Orbiter (SO)	Remote observation of Sun and in-situ observations of SW parameters, magnetic field, energetic particles	Since 2020	FA1/G1.2, G1.3, G1.4, G1.5/O1.2,O1.3, O1.4, O1.5
Solar–TErrestrial RElations Observatory (STEREO)	Remote observation of Sun and in-situ observations of SW parameters, magnetic field, energetic particles Observation of Sun and Solar wind	Since 2006	FA1/G1.2, G1.3, G1.4, G1.5/O1.3, O1.4, O1.5
Sunrise-3	Balloon-borne solar observatory dedicated to the investigation of the key processes governing the physics of the magnetic field and the convective plasma flows in the lower solar atmosphere	June 16, 2024 completed 6.5 day flights	FA1/G1.1, G1.2/O1.1, O1.2
SWARM	Ionosphere, Earth' magnetic field, electric field in the atmosphere	Launched in 2014, extended until 2025	FA2/G2.3 FA3/G3.1
Thermosphere Ionosphere Mesosphere Energetics and Dynamics Mission (TIMED)	Study the physical and chemical processes acting within and upon the coupled mesosphere, lower thermosphere/ionosphere system between about 60 and 180 km	Launched in 2001	FA3/G3.2,G3.3,G3.4
Total and Spectral Irradiance Sensor (TSIS-1) mission	Measurement of total and spectral solar irradiance	Since 2018	FA1/G1.2/O1.2
WIND	Remote observation of Sun and in-situ observations of SW parameters, magnetic field, energetic particles Observation of Sun and Solar wind	Since 1994	FA1/G1.3,G1.4,G1.5/O1.4, O1.5

Table 2 Future missions relevant to address the FAs, their goals and objectives

Mission	Main Objective	Status	related Focus Area (FA)/Goals (G)// Objectives(O)
Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT)	Observe simultaneously from the middle troposphere to the lower thermosphere at high spectral resolution and with unprecedented horizontal and vertical resolution. With this, CAIRT will provide critical information on atmospheric gravity waves, circulation and mixing, as well as the coupling with the upper atmosphere, solar variability and space weather	Phase A Launch in 2032	FA3/G3.2, G3.3,G3.4
Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE)	Study interaction between solar wind and Mars' magnetic environment	To be launched in 2025	
EZIE	Image the auroral electrojets, utilizing Zeeman splitting of O2 emission. 2D structure of the electrojets will be available at higher spatial resolution than is possible from the ground	Launched March 2025	FA2/G2.3 FA3/G3.1,G3.3,G3.4
Geospace Dynamics Constellation (GDC/DYNAMIC)	Understanding of the processes that govern the dynamics of the Earth's upper atmosphere	To be launched in 2030	FA2/G2.3 FA3/G3.1,G3.2,G3.3,G3.4
HELIOSWARM	Simultaneous multipoint measurements across length scales, ranging from MHD (3000 km) to sub-ion (50 km) scales, in polyhedral and 3D configurations to study turbulence in the solar wind and the interplanetary magnetic field	To be launched in 2029	FA1/G1.3, G1.4/O1.4
Heliospheric Pioneer for Solar and Interplanetary Threats Defense (HENON)	Pathfinder mission launching a cubesat in deep space on a Distant Retrograde Orbit (including a period at about 0.1 AU upstream) to provide both near real time alerts of SEPs and geomagnetic storms and high resolution data for Space Weather Science	To be launched at the end of 2026	FA1/G1.3,G1.4, G1.5/O1.4, O1.5, O1.6
Plasma Observatory	Tailored to study plasma energization and energy transport in the Earth's Magnetospheric System through simultaneous measurements at both fluid and ion scales	Proposed in response to the ESA M7 call and selected for the Phase A study	FA1/G1.3, G1.4 FA2/G2.1, G2.2
PLATO	To study terrestrial exoplanets in orbits up to the habitable zone of Sun-like stars as well as variability of Sun-like stars	To be launched in 2026	FA1/G1.1,G1.2,O1.1,O1.2
PUNCH	Sun's corona and solar wind (from 1.5° (6 R⊙) to 45° (180 R⊙) from the Sun)	Launched March 2025	FA1/G1.3, G1.4/O1.3, O1.4
Solar wind Magnetosphere Ionosphere Link Explorer (SMILE)	X-ray imaging of dayside magnetopause. Sun–Earth connection by measuring the solar wind and its dynamic interaction with the magnetosphere	To be launched in 2025	FA2/G2.1,G2.2,G2.3

Table 2 (continued)

Mission	Main Objective	Status	related Focus Area (FA)/Goals (G)// Objectives(O)
SOLAR-C	Analyze the spectrum of the Sun's extreme UV radiation	In close collaboration with the US and European partnersparters, ISAS/JAXA and NAOJ are now developing SOLAR-C to achieve higher sensitivity and resolution than any previous EUV spectrometer, with the targeted launch of late 2020s https://solar-c.nao.ac.jp/en/	FA1/G1.3,G1.4/O1.3, O1.4
Vigil	Operational Space weather mission at L5	In development 2031?	FA1/G1.3,G1.4, G1.5/O1.4,O1.6 Target for new tools to be developed in preparation prior to launch (related to O1.6)
WINDCUBE	Study the influence of thermospheric winds on the earth's ionosphere	To be launched in 2025	FA3/G3.2,G3.3,G3.4

Table 3 Ground-based instruments and networks relevant to address the FAs, their goals and objectives

Collaboration/Network/instrument	Main Objective	Status/details	Related focus area (FA)/goals (G)/objectives(O)
All-Sky imagers (including MANGO network, etc.)	Optical monitoring of the ionosphere	Optical signatures of ionospheric disturbances	FA2/G2.1,G2.2,G2.3 FA3/G3.1
Antarctic Geospace and ATmosphere reseArch (AGATA)/SCAR	This scientific research program is a coordinated, worldwide effort to monitor, investigate and better understand the physics of the polar atmosphere and the impact of the Sun–Earth interactions on the polar regions	The program is foreseen to run from 2025 to 2032 AGATA ensures close interaction with COURSE, also in preparation to the next International Polar Year (2032–2033)	FA2. and 3
Continuous Doppler radar systems	propagation of AGWs/TIDs in the ionosphere	Since 2011 at different locations. Measure direction and velocity of TIDs/AGWs	FA2. and 3
DASI network	Distributed Array of Small Instruments	Program is designed to address the increasing need for high spatial and temporal resolution measurements to determine the local, regional, and global scale processes that are essential for addressing the fundamental questions in solar and space physics	FA1,FA2,FA3
DKIST Telescope	to observe and measure the basic magnetic structures (magnetic fibrils) at the solar surface and into the outer atmosphere	Since 2019	FA1/G1.1
EISCAT 3D and EISCAT Svalbard radar	Study polar ionosphere. Focus on the effects in the ionosphere of extreme solar events and geomagnetic field line vibrations (ULF waves)		FA2 FA3
European Solar Telescope (EST)	objective: to examine magnetic coupling in the solar atmosphere from the deepest layers of the photosphere to the highest layers of the chromosphere, to uncover the thermal, dynamic and magnetic properties of the Sun's plasma at high spatial and temporal resolution	planned for 2030–2031	FA1
Global Muon Detector Network (GMDN)	cosmic rays detection	Since at least 1992	FA1/G1.3, G1.4, G1.5/O1.4,O1.5 FA3/G3.1/O3.4, O3.5
GNSS networks	Monitoring the upper atmosphere conditions	Includes global/regional networks, cross-disciplinary networks (e.g., geodesy), citizen science (e.g., cellphone networks, among others	FA2 and FA3
GREGOR	1.5 m solar telescope producing high precision measurements of the solar magnetic field	installed at the Observatorio del Teide on Tenerife island since 2020	FA1
IceCube Collaboration	Ice Cherenkov Detectors	The main focus is the detection of high energy astroparticles	FA1/G1.3, G1.4, G1.5/O1.4,O1.5
Incoherent Scatter Radars (ISR)	Monitoring the ionosphere. The radar can measure the altitude dependence of a set of ionospheric observables, including the electron density, the electron and ion temperatures, and the ion bulk drift velocity		FA2. and 3

Table 3 (continued)

Collaboration/Network/instrument	Main Objective	Status/details	Related focus area (FA)/goals (G)/objectives(O)
IMCP (International Meridian Circle Program)	Project that aims to take full advantage of instrumentation to conduct all-weather observations and study the space weather and associated system sciences along approximately a meridian circle of 120°E/60°W passing through more than 10 countries and regions	Since 2006	FA3/G3.1,G3.2,G3.3,G3.4
Ionosondes	\HF pulsed radar, typically from 0 to 20 MHz, for monitoring the ionosphere	Distributed in different regions/countries. Able to observe the ionosphere at different heights	FA2.and 3
LAGO Collaboration—Water Cherenkov Detectors (WDC)	Detect GCR anisotropy and Forbush decreases from single WCDs	Continuous, operating since 2006 Detectors are spread along LatinAmerica (from Antarctica to Mexico)	FA1/G1.3, G1.4, G1.5/O1.4,O1.5
MAARSY	VHF radar to study the Arctic atmosphere from the troposphere up to the lower thermosphere with high spatio-temporal resolution	Since 2011	FA3
Magnetometers (ground)	Measurement of the geomagnetic field	Different networks: • International Real-time Magnetic Observatory Network (Intermagnet) • Embrace Magnetometer Network for South America • etc	FA2. G2 and G3 FA3. G1–G5
Neutron Monitor network neutron detectors	Observe the variations of the primary GCRs and to provide information the GCR and GLE spectrum	Continuous operating since 1951	FA1/G1.3, G1.4, G1.5/O1.4,O1.5, O1.6 FA3/G3.1/O3.4, O3.5
The Poker Flat Incoherent Scatter Radar (PFISR)	mission objectives usually involve auroral and polar middle- and upper-atmosphere research, phased array system consisting of 4,096 antennae across 128 panels designed to probe the ionospheric plasma	Since 2006	FA2, FA3
Sanya Incoherent Scatter Radar (SYISR 3D)	incoherent scatter radar (ISR) has recently been dedicated at Sanya (SYISR), China (geographic 18.34°N and 109.62°E) to detect the low-latitude ionospheric plasma by conducting continuous operation and electronic beam steering on a pulse-to-pulse basis	Since 2021	FA3
SIMONe (Multistatic meteor radars with MIMO technology)	to investigate mesosphere and lower thermosphere (MLT) dynamics	provide accurate horizontal winds with a reasonable time resolution (~ 1 h) for altitudes between 80 and 100 km	FA3
Solar Radio observatories	To monitor solar flares and other releases of energy from the sun		FA1

6.3 Observations: missions and ground-based instrumentation

Each focus area and their sub-domains rely on more accurate observations from both space and ground-based instruments.

A non-exhaustive list of current missions and their relation with the different focus areas are reported in Table 1.

Table 1: Ongoing missions relevant to address the goals and objectives of the focus areas.

Current and near-future solar and heliospheric missions will form an unprecedented multi-spacecraft constellation in the heliosphere, that over the next 5 years will provide the highest resolution data ever, that will allow, for example, to achieve O1.4 as well as O1.3, especially if combined with more advanced modeling, and O1.5 if combined with ground-based cosmic ray detectors.

New generation missions, including both approved and proposed ones, are summarized in Table 2.

Table 2: Future missions relevant to address the goals and objectives of the focus areas.

Long-term future missions which can allow to address the long-term goals identified in COURSE include: 1) NASA's Compact Solar Irradiance Suite (CSIS) constellation concept, which would provide continuous and daily TSI and SSI measurements over a decade-long period from CSIM and CTIM instruments integrated on a MicroSat platform; 2) Plasma Observatory which is an ESA M7 candidate mission, selected for phase A study, foreseen to be launched in 2037 in case of adoption, and would make multi-scale observations simultaneously to understand cross-scale coupling in the magnetosphere.

It is worth mentioning that data provided by missions already finished are especially relevant for the continuity of the research, specifically for climate or for comparisons with other missions/instruments. These missions/instruments include: The Ionospheric Connection Explorer (ICON), Solar Radiation and Climate Experiment (SORCE), etc.

Ground-based observations are essential to study the solar–terrestrial system. As a matter of fact, they even present some advantages with respect to missions, such as continuity, long lifetime and stability over the solar cycle.

Ground-based observations relevant for the solar–terrestrial relationships, especially for implementing the COURSE program, are reported in Table 3.

Table 3: Ground-based instruments and networks relevant to address the goals and objectives of the focus areas.

We highlight the urgency to support ground-based observations and networks (e.g., cosmic ray networks, WCDs, ionosondes, GNSS receivers, magnetometers, etc.) as they can both help to answer fundamental scientific questions and have societal aspects. For instance, the ground-based NMs have been continuously monitoring the intensity of the cosmic ray secondary nucleonic component for more than 70 years at cutoff rigidities of about 0.1–15 GV. The NM network includes more than 50 stations and as a whole, together with the geomagnetic field, represents a giant spectrometer, which allows one to observe the variations of the primary GCRs and to provide information about the GCR and GLE spectrum. The Neutron monitor database (NMDB) provides access to NM measurements from stations around the world. In addition to GCRs and relativistic SEP science, the NM network is crucial for the Space Weather applications and operations (e.g., for the GLE alert and AVIDOS applications at ESA—Space Situational Awareness program, Space Radiation Expert Service Center).

Networks of ground-based measurements will become increasingly valuable for studying multiscale processes and long-term, high-cadence monitoring of the middle and upper atmosphere (e.g., Bhatt et al. 2023; Sato et al., 2023). For example, it is demonstrated in an international joint project that global network of ground-based observations, in combination with targeted numerical modeling, can help elucidate the roles of both mesoscale gravity waves and large-scale waves in inter-hemispheric coupling (Sato et al., 2023).

It is essential to support these networks that are in danger of being depleted (as single stations might close) at the moment and eventually could disappear. Moreover, it is also a recommendation to increase coverage especially in under-represented areas such as the African sector or, when possible, in the oceans.

Moreover, it is important:

- to continue practice of observing campaigns, e.g., for different events such eclipses (e.g., Bravo et al. 2022; Shiokawa and Georgieva 2021);
- Recovery, preservation, processing of historical data (an example includes images from old ionosonde systems);
- Continuity of modern synoptic observations, irradiance, magnetograms, Ca II K observations among others.
- Encourage cross calibration of data.

6.4 Data and metadata

Observational data, models, model data, and analysis software are basic resources for supporting research in solar–terrestrial physics. To maximize opportunities for efficient discovery and usage of the data produced by missions and ground-based instruments, simulations, ML applications, etc., FAIR principles act as a guideline to guarantee the accessibility, interoperability and reuse of the digital resources (Wilkinson et al. 2016).

Data resources need to be readily available and accessible to a broad range of multidisciplinary researchers, from students to senior scientists, who then also need to be able to make use of the resources correctly to produce scientifically valuable results and to advance scientific understanding and knowledge. It is important to be reminded that data refers simply to the digital measurement records (often as a function of time) or some graphical representations of the measurements. All information about the data is collectively captured in metadata, which is not part of the data stream and would have to be provided by the data provider. This means that all information about, where data (or other types of resources) might be stored, how they might be accessed and used correctly, file format the date is produced and stored in, the time interval the data is available, etc., would have to be captured in metadata.

Solar–terrestrial physics is an inherently multidisciplinary field of research and spans across multiple sub domains. Due to the many different techniques and instrument types used to make ground-based and space-based measurements for investigating these different systems, data are diverse and complex such that students and sometimes even seasoned researchers are bewildered. Finding and accessing data from across different disciplines can be hampered by the lack of familiarity of the resources in different domains. Adopting a common or standard metadata model and associated data dictionary across all disciplines may provide a uniform information structure to describe diverse and heterogeneous resources uniformly, greatly reducing the steep learning curves typically associated with searching for and accessing multidisciplinary resources.

As an example, a fairly mature and extensive information model developed specifically for describing resources is the Space Physics Archive Search and Extract (SPASE) model (Roberts et al. 2018; SPASE Group 2021). As discussed in Fung et al. (2023), SPASE largely supports the FAIR principles making it potentially suitable for supporting the Open Science Initiative.

Another example on data management is the World Coordinate System (Greisen et al. 2002, Calabretta and Greisen 2002; Greisen et al 2006, Rots 2015). Metadata is critical for ensuring that diverse hemispheric data sets from different observatories, satellites, and instruments can be seamlessly integrated and analyzed. The WCS metadata included with data sets provides the spatial reference framework necessary for associating data points with real-world coordinates. In the heliospheric physics and space weather communities, this is particularly important given the variety of data sources, each employing different coordinate systems. Without standardized WCS metadata, scientists face significant challenges in aligning data sets, leading to errors in multi-instrument or cross-disciplinary studies.

Standards in WCS metadata allow for interoperability across data sets, which is especially crucial in cross-collaborative research. In the solar community, heliographic coordinates such as Heliographic Longitude and Latitude (HGC) are widely used. These coordinates describe positions on the Sun's surface or in its vicinity, aligned with the solar rotational axis. However, Earth-based systems often rely on geographic coordinates or Earth-centered celestial systems like the International Celestial Reference System (ICRS). The divergence in coordinate systems introduces complexities in connecting solar observations to Earth-based perspectives, especially when studying phenomena like solar storms that have their origins at the Sun and impact the Earth. Further divergences may be introduced with new data systems introduced from different viewing angles, such as data from Solar Orbiter and the future space weather missions, such as HENON and Vigil.

To bridge the gap between solar and Earth-based coordinate systems, transformations are required. Tools such as the IDL SolarSoft package (SSW), and Python Astropy and SunPy packages can provide transformations between coordinate systems. For instance, heliographic coordinates can be transformed into Earth-centered inertial coordinates using ephemeris data that account for the Sun–Earth orientation and solar rotation. This enables researchers to align data sets from solar observatories (e.g., SDO and SOHO) with terrestrial observatories or other Earth-based instruments. However, the set of transformations is not complete and requires user contributions.

To create unified, or compatible WCS's the space weather community needs to strengthen collaborations and establish unified standards for WCS metadata. A universal standard should be laid out, interoperable tools should be developed, and cross repositories or platforms, where researchers can access transformation tools, ephemeris data, and tutorials to connect data sets more effectively should be developed.

In summary, it is vital that data from different instruments/simulations, or data collected at different stages/dates by the same instrument, can be seamlessly used and accurately combined/compared to derive quantitative insights from observation data and maintain the scientific value of data archives. Thus, data calibration techniques and validation are essential. In many cases, this includes time consuming tasks (e.g., manually validation of ionograms, among many more). In this regard, SCOSTEP can provide a forum for international dialog on calibration and validation issues, to enhance coordination (in collaboration with other scientific organizations), to promote international cooperation and to focus activities in this field.

SCOSTEP has fostered actively different training and capacity building which can be also an important vehicle to foster best practices in data management and storage among researchers and students. Moreover, encouraging and supporting the creation and maintenance of databases from different research groups may facilitate the discovery and accessibility of the data.

Some important questions arise regarding the considerations on data handling in the near future:

1. How is data resolution linked to the scales involving the different processes?

2. How to enable data continuity (e.g., Sect. 3.6)?

3. How to foster or promote data and metadata standardization, especially in heterogeneous environments with uneven funding resources?

4. As historical data are key observations (e.g., Sect. 3.6), how can we facilitate their preservation and accessibility? How can we ensure their quality (e.g., for long term trends studies)?

5. How can SCOSTEP contribute to integration and optimal usage of observations: space- and ground-based? E.g., data assimilation and data sharing and challenges in international collaboration.

6. Complying with the FAIR principles is sufficient?

7. How can traditional data sets/databases be transferred/used in ML/AI development?

6.5 Implementation recommendation

To implement the program to address any one of the proposed questions, we recommend forming a core team composed of international experts to attack the question of interest consistently and persistently for a period between 3 and 5 years. Focus Area leaders have the flexibility of forming new teams or dismantling old teams as the program evolves. While "SCOSTEP/COURSE" provides the seed funding, the teamwork shall help the participants apply for research support (e.g., grants) from their home countries. In addition to in-person meetings, the virtual meetings shall facilitate the continuing collaborative efforts of the team members.

Acknowledgements
We acknowledge the following speakers invited to the NSP Committee meetings for their valuable inputs: Abadi Prayitno, Jian Lan, Groves Keith, Kwak Young-Sil, Kozai Masayoshi, Marcucci Maria Federica, Miyake Fusa, Munakata Kazuoki, Otsuka Yuichi, Karou Sato. We aknowledge the SCOSTEP Secretariat managed by the team at Boston College. ML acknowledges Scarabotti Matteo and the INAF-Istituto di Astrofisica e Planetologia Spaziali administration for aiding in the organization of the INGV meeting.

Author contributions
All authors contributed to conceptualization, writing, and review of this paper according to the order in the authors' list.

Funding
The COURSE program definition process has been supported by SCOSTEP, Institute for Space–Earth Environmental Research—Nagoya University, and the National Institute of Geophysics and Volcanology.

Data availability
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]INAF-Istituto Di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, 00133 Rome, Italy. [2]Institute for Space–Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan. [3]Tucumán Space Weather Center (TSWC), Facultad de Ciencias Exactas y Tecnología (FACET), Universidad Nacional de Tucuman (UNT), 4000 Tucumán, Argentina. [4]Consejo Nacional de Investigaciones Científicas y Técnicas, CONICET, Tucuman, Argentina. [5]Istituto Nazionale di Geofisica e Vulcanolgia, Rome, Italy. [6]High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO 80307-3000, USA. [7]Max Planck Institute for Solar System Research, Justus-Von-Liebig-Weg 3, 37077 Göttingen, Germany. [8]Instituto de Astrofísica de Andalucía, CSIC, Glorieta de La Astronomía S/N, 18008 Granada, Spain. [9]South African National Space Agency, Hermanus, South Africa. [10]Department of Physics and Electronics, Rhodes University, Makhanda, South Africa. [11]Centre for Space Research, North West University, Potchefstroom 2520, South Africa. [12]Institute of Atmospheric Physics, AS CR, Bocni II 1401, 14100 Prague 4, Czech Republic. [13]European Space Agency, ESTEC, 2201 AZ Noordwijk, The Netherlands. [14]Leibniz Institute of Atmospheric Physics at the University of Rostock, Kühlungsborn, Germany. [15]Department of Physics and Astronomy, George Mason University, 4400 University Dr., Fairfax, VA 220303, USA. [16]Department of Physics and Technology, University of Bergen, Bergen, Norway. [17]Space Physics and Astronomy Research Unit and Sodankylä Geophysical Observatory, University of Oulu, Oulu, Finland. [18]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, USA. [19]Instituto de Astronomía y Física del Espacio (IAFE), Laboratorio de Meteorología del esPacio (LAMP), CONICET - Universidad de Buenos Aires, Buenos Aires, Argentina. [20]Facultad de Ciencias Exactas y Naturales, Departamento de Ciencias de La Atmósfera y los Océanos (DCAO), Universidad de Buenos Aires, Buenos Aires, Argentina. [21]Ionospheric, Thermospheric, and Mesospheric Physics Laboratory, NASA Goddard Space Flight Center, Code 675, Greenbelt, MD 20771, USA. [22]Kyung Hee University, Swon, Korea. [23]Space Research Institute, Austrian Academy of Sciences, Graz, Austria. [24]Institute of Physics, University of Graz, 8010 Graz, Austria. [25]Peking University, 209 Chengfu Rd, Physics Building N412, Haidian, Beijing 100871, China. [26]LIRA/Observatoire de Paris, CNRS, Sorbonne Unviersité, Université Paris Cité, Université de Cergy, Paris, France. [27]NASA Goddard Space Flight Center, Greenbelt, MD, USA. [28]Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic.

Received: 5 May 2025 Accepted: 27 August 2025
Published online: 19 November 2025

References

Acciarini G, Brown E, Berger T, Guhathakurta M, Parr J, Bridges C, Baydin AG (2024) Improving thermospheric density predictions in low-Earth orbit with machine learning. Space Weather 22:e2023SW003652. https://doi.org/10.1029/2023SW003652

Afanasiev A, Vainio R, Rouillard AP, Battarbee M, Aran A, Zucca P (2018) Modelling of proton acceleration in application to a ground level enhancement. Astron Astrophys 614:A4. https://doi.org/10.1051/0004-6361/201731343

Ahmed O, Badruddin B, Derouich M (2024) Dynamics and solar wind control of the recovery of strong geomagnetic storms. Astrophys Space Sci 369:64. https://doi.org/10.1007/s10509-024-04325-3

Albert NA, Krivova J, Hirzberger J, Solanki SK, Moreno Vacas A, Orozco Suárez D, Albelo Jorge N, Appourchaux T, Alvarez-Herrero A, Blanco Rodríguez J, Gandorfer A, Gutierrez-Marques P, Kahil F, Kolleck M, Volkmer R, del Toro Iniesta JC, Woch J, Fiethe B, Pérez-Grande I, Sanchis Kilders E, Balaguer Jiménez M, Bellot Rubio LR, Calchetti D, Carmona M, Deutsch W, Feller A, Fernandez-Rico G, Fernández-Medina A, García Parejo P, Gasent Blesa JL, Gizon L, Grauf B, Heerlein K, Korpi-Lagg A, Lange T, López Jiménez A, Maue T, Meller R, Müller R, Nakai E, Schmidt W, Schou J, Sinjan J, Staub J, Strecker H, Torralbo I, Valori G (2023) Intensity contrast of solar network and faculae close to the solar limb, observed from two vantage points. A&a 678:A163. https://doi.org/10.1051/0004-6361/202346037

Alberti T et al (2020) On the scaling properties of magnetic-field fluctuations through the inner heliosphere. ApJ 902:84. https://doi.org/10.3847/1538-4357/abb3d2

Alberti T et al (2022a) Reconciling parker solar probe observations and magnetohydrodynamic theory. ApJL 940:L13. https://doi.org/10.3847/2041-8213/aca075

Alberti T et al (2022b) The "singular" behavior of the solar wind scaling features during parker solar probe–bepicolombo radial alignment. ApJ 926:174. https://doi.org/10.3847/1538-4357/ac478d

Alexakis A, Marino R, Mininni PD, van Kan A, Foldes R, Feraco F (2024) Large-scale self-organization in dry turbulent atmospheres. Science 383(6686):1005–1009. https://doi.org/10.1126/science.adg8269

Alfonsi L et al (2022) Review of environmental monitoring by means of radio waves in the polar regions: from atmosphere to geospace. Surv Geophys 43(6):1609–1698

Anderson D, Anghel A, Yumoto K, Ishitsuka M, Kudeki E (2002) Estimating daytime vertical ExB drift velocities in the equatorial F-region using ground-based magnetometer observations. Geophys Res Lett 29(12):37–41

Angelopoulos V et al (2019) The space physics environment data analysis system (SPEDAS). Space Sci Rev. https://doi.org/10.1007/s11214-018-0576-4

Angelopoulos V, Artemyev A, Phan TD, Miyashita Y (2020) Near-earth magnetotail reconnection powers space storms. Nat Phys. https://doi.org/10.1038/s41567-019-0749-4

Arras C, Wickert J (2018) Estimation of ionospheric sporadic E intensities from GPS radio occultation measurements. J Atmos Sol-Terr Phys 171:60–63

Aschwanden MJ (2002) Particle acceleration and kinematics in solar flares. Space Sci Rev 101:1–227

Asorey H, Suárez-Durán M, Mayo-García R (2023) Acorde: a new application for estimating the dose absorbed by passengers and crews in commercial flights. Appl Radiat Isot 196:110752. https://doi.org/10.1016/j.apradiso.2023.110752

Aulanier G, Démoulin P, Schrijver CJ et al (2013) The standard flare model in three dimensions. II. Upper limit on solar flare energy. Astron Astrophys 549:A66. https://doi.org/10.1051/0004-6361/201220406

Babcock HW (1961) The topology of the sun's magnetic field and the 22-YEAR cycle. Astrophys J 133:572. https://doi.org/10.1086/147060

Baglin A, Auvergne M, Boisnard L, Lam-Trong T, Barge P, Catala C, Deleuil M, Michel E, Weiss W (2006) CoRoT: a high precision photometer for stellar evolution and exoplanet finding. 36; 3749

Baldwin MP et al (2001) The quasi-biennial oscillation. Rev Geophys 39(2):179–229. https://doi.org/10.1029/1999RG000073

Bard E, Miramont C, Capano M et al (2023) A radiocarbon spike at 14 300 cal yr BP in subfossil trees provides the impulse response function of the global carbon cycle during the Late Glacial. Phil Trans R Soc A 381(2261):20220206. https://doi.org/10.1098/rsta.2022.0206

Barnes G, Leka KD, Schrijver CJ, Colak T, Qahwaji R, Ashamari OW et al (2016) A comparison of flare forecasting methods. I. Results from the "All-Clear" workshop. Astrophys J 829(2):89. https://doi.org/10.3847/0004-637X/829/2/89

Baruah Y, Roy S, Sinha S, Palmerio E, Pal S, Oliveira DM, Nandy D (2024) The loss of Starlink satellites in February 2022: how moderate geomagnetic storms can adversely affect assets in low-Earth orbit. Space Weather 22(4):e2023SW003716. https://doi.org/10.1029/2023SW003716

Becker E, Vadas SL, Bossert K, Harvey VL, Zülicke C, Hoffmann L (2022) A high-resolution whole-atmosphere model with resolved gravity waves and specified large-scale dynamics in the troposphere and stratosphere. J Geophys Res Atmos 127:e2021JD035018. https://doi.org/10.1029/2021JD035018

Beer J, McCracken KG, von Steiger R (2012) Cosmogenic radionuclides: theory and applications in the terrestrial and space environments. Phys Earth Space Environ. https://doi.org/10.1007/978-3-642-14651-0

Beggan CD, Richardson GS, Baillie O, Hübert J, Thomson AWP (2021) Geolectric field measurement, modelling and validation during geomagnetic storms in the UK. J Space Weather Space Clim 11:37. https://doi.org/10.1051/swsc/2021022

Beggan CD, Eaton E, Maume E, Clarke E, Williamson J, Humphries T (2023) Digitizing UK analogue magnetogram records from large geomagnetic storms of the past two centuries. Geosci Data J 10:73–86. https://doi.org/10.1002/gdj3.151

Beggan CD, Clarke E, Lawrence E, Eaton E, Williamson J, Matsumoto K, Hayakawa H (2024) Digitized continuous magnetic recordings for the August/September 1859 storms from London, UK. Space Weather 22:e2023SW003807. https://doi.org/10.1029/2023SW003807

Bell AR (1978) The acceleration of cosmic rays in shock fronts – I. Mon Not R Astron Soc 182:147–156

Berger TE, Dominique M, Lucas G, Pilinski M, Ray V, Sewell R, Sutton EK, Thayer JP, Thiemann E (2023) The thermosphere is a drag: the 2022 Starlink incident and the threat of geomagnetic storms to low Earth orbit space operations. Space Weather 21(3):e2022SW003330. https://doi.org/10.1029/2022SW003330

Bhatt AN, Harding BJ, Makela JJ, Navarro L, Lamarche LJ, Valentic T et al (2023) Mango: an optical network to study the dynamics of the Earth's upper atmosphere. J Geophys Res Space Physics 128:e2023JA031589. https://doi.org/10.1029/2023JA031589

Blanc M, Richmond AD (1980) The ionospheric disturbance dynamo. J Geophys Res 85:1669–1686

Borucki WJ, Koch D, Basri G et al (2010) Kepler planet-detection mission: introduction and first results. Science 327(5968):977. https://doi.org/10.1126/science.1185402

Boteler DH (2019) A 21st century view of the March 1989 magnetic storm. Space Weather 17:1427–1441. https://doi.org/10.1029/2019SW002278

Bravo M, Molina MG, Martinez-Ledezma M et al (2022) Ionospheric response modeling under eclipse conditions: evaluation of December 14, 2020, total solar eclipse prediction over the South American sector. Front Astron Space Sci. https://doi.org/10.3389/fspas.2022.1021910

Brown MK, Lewis HG, Kavanagh AJ, Cnossen I, Elvidge S (2024) Future climate change in the thermosphere under varying solar activity conditions. J Geophys Res Space Physics 129:e2024JA032659. https://doi.org/10.1029/2024JA032659

Bruno R, Carbone V (2013) The solar wind as a turbulent plasma. Living Rev Sol Phys. https://doi.org/10.12942/lrsp-2013-2

Buehler D, Lagg A, Solanki SK (2013) Quiet Sun magnetic fields observed by Hinode: support for a local dynamo. Astron Astrophys 555:A33. https://doi.org/10.1051/0004-6361/201321152

Burch JL et al (2020) The parker solar probe: first results on solar wind composition and its variability. Nat Astron 4:465–470. https://doi.org/10.1038/s41550-020-1046-7

Buresova D, Lastovicka J (2017) Differences in midlatitude ionospheric response to magnetic disturbances at Northern and Southern Hemispheres and anomalous response during the last extreme solar minimum. In: Fuller-Rowell T et al (eds) Ionospheric space weather longitude and hemispheric dependences and lower atmosphere forcing AGU geophysical monograph. John Wiley & Sons, Inc., Hoboken

Calabretta MR, Greisen EW (2002) Representations of celestial coordinates in FITS (paper II). Astron Astrophys 395:1077–1122

Camporeale E, Wilkie GJ, Drozdov AY, Bortnik J (2022) Data-driven discovery of Fokker-Planck equation for the Earth's radiation belts electrons using physics-informed neural networks. J Geophys Res Space Physics 127:e2022JA030377. https://doi.org/10.1029/2022JA030377
Cane HV, Wibberenz G, Richardson IG, von Rosenvinge TT (1999) Cosmic ray modulation and the solar magnetic field. Geophys Res Lett 26:565–568
Chappell CR, Glocer A, Giles BL, Moore TE, Huddleston MM, Gallagher DL (2021) The key role of cold ionospheric ions as a source of hot magnetospheric plasma and as a driver of the dynamics of substorms and storms. Front Astron Space Sci. https://doi.org/10.3389/fspas.2021.746283
Charbonneau P, Sokoloff D (2023) Evolution of solar and stellar dynamo theory. Space Sci Rev 219:1–27. https://doi.org/10.1007/s11214-023-00980-0
Chatzistergos T, Krivova NA, Ermolli I (2022) Full-disc Ca II K observations—A window to past solar magnetism. Front Astron Space Sci 9:336. https://doi.org/10.3389/fspas.2022.1038949
Chatzistergos T, Krivova NA, Yeo KL (2023) Long-term changes in solar activity and irradiance. J Atmos Sol Terr Phys 252:106150
Chatzistergos T, Krivova NA, Ermolli I (2024) Understanding the secular variability of solar irradiance: the potential of Ca II K observations. J Space Weather Space Clim 14:9. https://doi.org/10.1051/swsc/2024006
Chau JL, Urco JM, Vierinen J, Harding BJ, Clahsen M, Pfeffer N et al (2021) Multistatic specular meteor radar network in Peru: system description and initial results. Earth Space Sci 8(1):e2020EA001293. https://doi.org/10.1029/2020EA001293
Chen C et al (2020) The evolution and role of solar wind turbulence in the inner heliosphere. ApJS 246:53. https://doi.org/10.3847/1538-4365/ab60a3
Chen J, Lei J, Wang W, Liu J, Maute A, Qian L et al (2021) Electrodynamical coupling of the geospace system during solar flares. J Geophys Res Space Physics. https://doi.org/10.1029/2020JA028569
Cheung MCM, Rempel M, Title AM, Schüssler M (2010) Simulation of the formation of a solar active region. Astrophys J 720:233–244. https://doi.org/10.1088/0004-637x/720/1/233
Chierichini S, Liu J, Korsós M, Del Moro D, Erdélyi R (2024) CME arrival modeling with machine learning. Astrophys J 963:121. https://doi.org/10.3847/1538-4357/ad1cee
Chiodo G et al (2019) Insignificant influence of the 11-year solar cycle on the North Atlantic Oscillation. Nat Geosci 12:94–99. https://doi.org/10.1038/s41561-018-0293-3
Chitta LP et al (2023) Direct observations of a complex coronal web driving highly structured slow solar wind. Nat Astron 7:133–141. https://doi.org/10.1038/s41550-022-01834-5
Chum J, Šindelářová T, Koucká Knížová P, Podolská K, Rusz J, Baše J, Nakata H, Hosokawa K, Danielides M, Schmidt C, Knez L, Liu JY, Molina MG, Fagre M, Katamzi-Joseph Z, Ohya H, Omori T, Laštovička J, Obrazová Burešová D, Kouba D, Urbář J, Truhlík V (2023) Atmospheric and ionospheric waves induced by the Hunga eruption on 15 January 2022; Doppler sounding and infrasound. Geophys J Int 233(2):1429–1443. https://doi.org/10.1093/gji/ggac517
Clette F, Lefèvre L, Chatzistergos T, Hayakawa H, Carrasco VM et al (2023) Re-calibration of the sunspot number: status report. Sol Phys 298:44. https://doi.org/10.1007/s11207-023-02136-3
Cliver EW, Schrijver CJ, Shibata K, Usoskin IG (2022) Extreme solar events. Living Rev Sol Phys 19:2. https://doi.org/10.1007/s41116-022-00033-8
Cnossen I (2022) A realistic projection of climate change in the upper atmosphere into the 21st century. Geophys Res Lett 49:e2022GL100693. https://doi.org/10.1029/2022GL100693
Cnossen I, Maute A (2020) Simulated trends in ionosphere-thermosphere climate due to predicted main magnetic field changes from 2015 to 2065. J Geophys Res Space Physics 125:e2019JA027738. https://doi.org/10.1029/2019JA027738
Cot C, Teitelbaum H (1980) Generation of gravity-waves by inhomogeneous heating of the atmosphere. J Atmos Sol Terr Phys 42(9–10):877–883. https://doi.org/10.1016/0021-9169(80)90092-6
Daglis IA, Katsavrias C, Georgiou M (2019) From solar sneezing to killer electrons: outer radiation belt response to solar eruptions. Philos Trans A 377:2148
Daglis et al (2021) Predictability of variable solar–terrestrial coupling. Ann Geophys 39:1013–1035. https://doi.org/10.5194/angeo-39-1013-2021
Daldorff LKS, Toth G, Gombosi TI, Lapenta G, Amaya J, Markidis S, Brackbill JU (2014) Two-way coupling of a global Hall magnetohydrodynamics model with a local implicit particle-in-cell model. J Comput Phys 268:236–254. https://doi.org/10.1016/j.jcp.2014.03.009
Decotte M (2023) Auroral region morphology and the influence of Earth's rotation on geospace dynamics. Dissertation, University of Bergen. ISBN: 9788230849934. https://hdl.handle.net/11250/3131452
DeForest CE et al (2018) The highly structured outer solar corona. Astrophys J 862:18. https://doi.org/10.3847/1538-4357/aac8e3
Desai M, Giacalone J (2016) Large gradual solar energetic particle events. Living Rev Sol Phys 13:3. https://doi.org/10.1007/s41116-016-0002-5
Domeisen DIV, Butler AH, Charlton-Perez AJ, Ayarzagüena B, Baldwin MP, Dunn-Sigouin E et al (2020) The role of the stratosphere in subseasonal to seasonal prediction: 1. Predictability of the stratosphere. J Geophys Res Atmos 125:e2019JD030920. https://doi.org/10.1029/2019JD030920
Dunkerton TJ (1982) Theory of the mesopause semiannual oscillation. J Atmos Sci 39:2681–2690. https://doi.org/10.1175/1520-0469(1982)039%3c2681:TOTMSO%3e2.0.CO;2
Dyer C, Hands A, Ryden K, Lei F (2018) Extreme atmospheric radiation environments and single event effects. IEEE Trans Nucl Sci 65:432–438. https://doi.org/10.1109/TNS.2017.2761258
Eastwood JP, Biffis E, Hapgood MA, Green L, Bisi MM, Bentley RD, Wicks R, McKinnell L-A, Gibbs M, Burnett C (2017) The economic impact of space weather: where do we stand? Risk Anal 37:206–218. https://doi.org/10.1111/risa.12765
Eckermann SD, Hoppel KW, Coy L, McCormack JP, Siskind DE, Nielsen K, Kochenash A, Stevens MH, Englert CR, Singer W, Hervig M (2009) High-altitude data assimilation system experiments for the northern summer mesosphere season of 2007. J Atmos Sol Terr Phys 71:531–551. https://doi.org/10.1016/j.jastp.2008.09.036
Emmert JT (2015) Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag. J Geophys Res Space Phys 120:2940–2950. https://doi.org/10.1002/2015JA021047
Emmert JT, Picone JM, Meier RR (2008) Thermospheric global average density trends, 1967–2007, derived from orbits of 5000 near-Earth objects. Geophys Res Lett 35:L05101. https://doi.org/10.1029/2007GL032809
Evans JS, Correira J, Lumpe JD, Eastes RW, Gan Q, Laskar FI et al (2024) GOLD observations of the thermospheric response to the 10–12 May 2024 Gannon superstorm. Geophys Res Lett 51:e2024GL110506. https://doi.org/10.1029/2024GL110506
Fallows RA et al (2022) The scintillating tail of comet C/2020 F3 (Neowise). Astron Astrophys. https://doi.org/10.1051/0004-6361/202244377
Farrell W et al (2023) The dust, atmosphere, and plasma at the Moon. Rev Mineral Geochem. https://doi.org/10.2138/rmg.2023.89.13
Fejer BG, Jensen JW, Su SY (2008) Quiet time equatorial F region vertical plasma drift model derived from ROCSAT-1 observations. J Geophys Res 113:A05304
Fejer BG, Navarro LA, Chakrabarty D (2024) Recent results and outstanding questions on the response of the electrodynamics of the low latitude ionosphere to solar wind and magnetospheric disturbances. Front Astron Space Sci 11:1471140. https://doi.org/10.3389/fspas.2024.1471140
Fesen CG, Crowley G, Roble RG, Richmond AD, Fejer BG (2000) Simulation of the pre-reversal enhancement in the low latitude vertical ion drift. Geophys Res Lett 27(13):1851–1854. https://doi.org/10.1029/2000GL000061
Floyd L, Rottman G, DeLand M, Pap J (2003) 11 years of solar UV irradiance measurements from UARS. ESA SP 535:195–203
Fogtman A, Baatout S, Baselet B, Berger T, Hellweg CE, Jiggens P et al (2023) Towards sustainable human space exploration—priorities for radiation research to quantify and mitigate radiation risks. NPJ Microgravity 9:8. https://doi.org/10.1038/s41526-023-00262-7
Forsyth C, Sergeev VA, Henderson MG, Nishimura Y, Gallardo-Lacourt B (2020) Physical processes of meso-scale, dynamic auroral forms. Space Sci Rev. https://doi.org/10.1007/s11214-020-00665-y
Foster JC, Vo HB (2002) Average characteristics and activity dependence of the subauroral polarization stream. J Geophys Res 107:A12292
Fritts DC, Wang L, Lund T, Geller MA (2024) Kelvin-Helmholtz Instability "Tube" and "Knot" dynamics. Part III: extension of elevated turbulence and energy dissipation into increasingly viscous flows. J Atmos Sci 81:1147–1164. https://doi.org/10.1175/JAS-D-23-0085.1

Fu HS, Grigorenko EE, Gabrielse C, Liu CM, Lu S, Hwang KJ, Zhou XZ, Wang Z, Chen F (2020) Magnetotail dipolarization fronts and particle acceleration: a review. Sci China Earth Sci. https://doi.org/10.1007/s11430-019-9551-y

Fu H, Yue C, Zong Q-G, Zhou X-Z, Fu S (2021) Statistical characteristics of substorms with different intensity. J Geophys Res Space Physics 126:e2021JA029318. https://doi.org/10.1029/2021JA029318

Fu H, Yue C, Zong Q-G, Zhou X, Wang S, Liu J, Hu Z, Yang H (2025) Statistical analysis of substorms with different time durations. Earth Planet Phys. https://doi.org/10.26464/epp2025068

Fung SF, Masson A, Bargatze LF, King T, Ringuette R, Candey RM et al (2023) SPASE metadata as a building block of a heliophysics science-enabling framework. Adv Space Res 72:5707–5752. https://doi.org/10.1016/j.asr.2023.09.066

Fuselier SA, Petrinec SM, Reiff PH, Birn J, Baker DN, Cohen IJ, Nakamura R, Sitnov MI, Stephens GK, Hwang J, Lavraud B, Moore TE, Trattner KJ, Giles BL, Gershman DJ, Toledo-Redondo S, Eastwood JP (2024) Global-scale processes and effects of magnetic reconnection on the geospace environment. Space Sci Rev. https://doi.org/10.1007/s11214-024-01067-0

Gabrielse C, Gkioulidou M, Merkin S, Malaspina D, Turner DL, Chen MW, Ohtani S, Nishimura Y, Liu J, Birn J, Deng Y, Runov A, McPherron RL, Keesee A, Lui ATY, Sheng C, Hudson M, Gallardo-Lacourt B, Angelopoulos V, Lyons L, Wang CP, Spanswick EL, Donovan E, Kaeppler SR, Sorathia K, Kepko L, Zou SS (2023) Mesoscale phenomena and their contribution to the global response: a focus on the magnetotail transition region and magnetosphere-ionosphere coupling. Front Astron Space Sci. https://doi.org/10.3389/fspas.2023.1151339

Gallardo-Lacourt B, Nishimura Y, Donovan E, Gillies DM, Perry GW, Archer WE et al (2018) A statistical analysis of STEVE. J Geophys Res Space Phys 123:9893–9905. https://doi.org/10.1029/2018JA025368

Garcia RR (2023) On the structure and variability of the migrating diurnal temperature tide observed by SABER. J Atmos Sci 80:687–704. https://doi.org/10.1175/JAS-D-22-0167.1

Gillies DM, Donovan E, Hampton D, Liang J, Connors M, Nishimura Y et al (2019) First observations from the TREx spectrograph: the optical spectrum of STEVE and the picket fence phenomena. Geophys Res Lett 46:7207–7213. https://doi.org/10.1029/2019GL083272

Gilliland RL, Chaplin WJ, Dunham EW et al (2011) Kepler mission stellar and instrument noise properties. Astrophys J Suppl Ser 197(1):6. https://doi.org/10.1088/0067-0049/197/1/6

Gonzalez WD, Joselyn JA, Kamide Y, Kroehl HW, Rostoker G, Tsurutani BT, Vasyliunas VM (1994) What is a geomagnetic storm? J Geophys Res 99:5571–5792

González G, Wu Y-J, Gasque LC, Triplett CC, Harding BJ, Immel TJ (2024) Effects of storm-time winds on ionospheric pre-midnight equatorial plasma bubbles over South America as observed by ICON and GOLD. J Geophys Res Space Physics 129:e2024JA033111

Gray LJ, Beer J, Geller M, Haigh JD, Lockwood M et al (2010) Solar influences on climate. Rev Geophys 48:RG4001. https://doi.org/10.1029/2009RG000282

Green LM, Török T, Vršnak B, Manchester W, Veronig A (2018) The origin, early evolution and predictability of solar eruptions. Space Sci Rev 214:46. https://doi.org/10.1007/s11214-017-0462-5

Green JL et al (2022) Space weather observations, modeling, and alerts in support of human exploration of Mars. Front Astron Space Sci. https://doi.org/10.3389/fspas.2022.1023305

Greisen EW, Calabretta MR, Valdes FG, Allen SL (2006) Representations of spectral coordinates in FITS (paper III). Astron Astrophys 446:747–771

Gronoff G, Arras P, Baraka S, Bell JM, Cessateur G, Cohen O et al (2020) Atmospheric escape processes and planetary atmospheric evolution. J Geophys Res Space Physics 125:e2019JA027639. https://doi.org/10.1029/2019JA027639

Haas B, Shprits YY, Allison HJ et al (2023) A missing dusk-side loss process in the terrestrial electron ring current. Sci Rep 13:970. https://doi.org/10.1038/s41598-023-28093-2

Habarulema JB, Zhang Y, Matamba T, Buresova D, Lu G, Katamzi-Joseph Z et al (2024) Absence of high frequency echoes from ionosondes during the 23–25 April 2023 geomagnetic storm; what happened? J Geophys Res Space Physics 129:e2023JA032277. https://doi.org/10.1029/2023JA032277

Haigh JD (2007) The sun and the Earth's climate. Living Rev Sol Phys 4:2. https://doi.org/10.12942/lrsp-2007-2

Hands ADP, Lei F, Davis CS, Clewer BJ, Dyer CS, Ryden KA (2022) A new model for nowcasting the aviation radiation environment with comparisons to in situ measurements during GLEs. Space Weather 20:e2022SW003155. https://doi.org/10.1029/2022SW003155

Harder JW, Fontenla JM, Pilewskie P, Richard EC, Woods TN (2009) Trends in solar spectral irradiance variability in the visible and infrared. Geophys Res Lett 36:L07801. https://doi.org/10.1029/2008GL036797

Hatch SM, Vanhamaaki H, Laundal KM et al (2024) Does high-latitude ionospheric electrodynamics exhibit hemispheric mirror symmetry? Ann Geophys 42:229–253

Hayakawa H, Mitsuma Y, Ebihara Y, Miyake F (2019) The earliest candidates of auroral observations in Assyrian astrological reports: insights on solar activity around 660 BCE. Astrophys J Lett 884:L18. https://doi.org/10.3847/2041-8213/ab42e4

Hayakawa H, Lockwood M, Owens MJ, Sôma M, Besser BP, van Driel-Gesztelyi L (2021) Graphical evidence for the solar coronal structure during the Maunder minimum: comparative study of the total eclipse drawings in 1706 and 1715. J Space Weather Space Clim 11:1. https://doi.org/10.1051/swsc/2020035

Hayakawa H, Bechet S, Clette F, Hudson H, Maehara H, Namekata K, Notsu Y (2023a) Magnitude estimates for the Carrington flare in September 1859 as seen from the original records. Astrophys J Lett 954:L3. https://doi.org/10.3847/2041-8213/acd853

Hayakawa H, Cliver EW, Clette F, Ebihara Y, Toriumi S et al (2023b) The extreme space weather event of 1872 February: sunspots, magnetic disturbance, and auroral displays. Astrophys J 959:23. https://doi.org/10.3847/1538-4357/acc6cc

Hayakawa H, Ebihara Y, Mishev A, Koldobskiy S, Kusano K et al (2024) The solar and geomagnetic storms in May 2024: a flash data report. Astrophys J 959:47. https://doi.org/10.3847/1538-4357/ad9335

Hayakawa H, Carrasco VMS, Aparicio APJ, Villalba Álvarez J, Vaquero JM (2024a) An overview of sunspot observations in the early Maunder Minimum: 1645–1659. Mon Not R Astron Soc 528:6280–6291. https://doi.org/10.1093/mnras/stad3922

Hayakawa H, Koldobskiy S, Mishev A, Poluianov S, Gil A, Usoskina I, Usoskin I (2024c) Revision of the strongest solar energetic particle event of 23 February 1956 (GLE #5) based on the rediscovered original records. Astron Astrophys 684:A46. https://doi.org/10.1051/0004-6361/202348699

Hayakawa H, Murata K, Teague ETH, Bechet S, Sôma M (2024d) Analyses of Johannes Kepler's sunspot drawings in 1607: a revised scenario for the solar cycles in the early 17th century. Astrophys J Lett 970:L31. https://doi.org/10.3847/2041-8213/ad57c9

Heaton T, Bard E, Bayliss A, Blaauw M, Bronk Ramsey C, Reimer PJ, Turney CSM, Usoskin I (2024) Extreme solar storms and the quest for exact dating with radiocarbon. Nature 633:306–317. https://doi.org/10.1038/s41586-024-07679-4

Heelis RA (2004) Electrodynamics in the low and middle latitude ionosphere: a tutorial. J Atmos Sol-Terr Phys 66:825–838

Heelis RA, Maute A (2020) Challenges to understanding the Earth's ionosphere and thermosphere. J Geophys Res Space Physics 125:e2019JA027497. https://doi.org/10.1029/2019JA027497

Higginson AK et al (2017) Formation of heliospheric arcs of slow solar wind. Astrophys J Lett 840:L10. https://doi.org/10.3847/2041-8213/aa6d72

Hocke K, Schlegel K (1996) A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982–1995. Ann Geophys 14:917–940. https://doi.org/10.1007/s00585-996-0917-6

Holton JR (1982) The role of gravity wave induced drag and diffusion in the momentum budget of the mesosphere. J Atmos Sci 39:791–799. https://doi.org/10.1175/1520-0469(1982)039%3c0791:TROGWI%3e2.0.CO;2

Holton JR (1983) The influence of gravity wave breaking on the general circulation of the middle atmosphere. J Atmos Sci 40:2497–2507. https://doi.org/10.1175/1520-0469(1983)040%3c2497:TIOGWB%3e2.0.CO;2

Hotta H, Kusano K, Shimada R (2022) Generation of solar-like differential rotation. Astrophys J 933:199. https://doi.org/10.3847/1538-4357/ac7395

Hu A, Camporeale E, Swiger B (2023) Multi-hour-ahead Dst index prediction using multi-fidelity boosted neural networks. Space Weather 21:e2022SW003286. https://doi.org/10.1029/2022SW003286

Huang CM, Richmond AD, Chen MQ (2005) Theoretical effects of geomagnetic activity on low-latitude electric fields. J Geophys Res 110:A05312
Hunsucker RD (1982) Atmospheric gravity waves generated in the high-latitude ionosphere: a review. Rev Geophys 20:293–315. https://doi.org/10.1029/RG020i002p00293
Hwang KJ, Dokgo K, Choi E, Burch JL, Sibeck DG et al (2020) Magnetic reconnection inside a flux rope induced by kelvin-helmholtz vortices. J Geophys Res Space Phys. https://doi.org/10.1029/2019JA027665
Hwang KJ, Nakamura R, Eastwood JP, Fuselier SA, Hasegawa H, Nakamura T, Lavraud B, Dokgo K, Turner DL, Ergun RE, Reiff PH (2023) Cross-scale processes of magnetic reconnection. Space Sci Rev. https://doi.org/10.1007/s11214-023-01010-9
Immel TJ, Sagawa E, England SL, Henderson SB, Hagan ME, Mende SB, Frey HU, Swenson CM, Paxton LJ (2006) Control of equatorial ionospheric morphology by atmospheric tides. Geophys Res Lett 33:L15108. https://doi.org/10.1029/2006GL026161
Jakosky BM, Brain D, Chaffin M, Curry S, Deighan J, Grebowsky J, Halekas J et al (2018) Loss of the Martian atmosphere to space: present-day loss rates determined from MAVEN observations and integrated loss through time. Icarus 315:146–157. https://doi.org/10.1016/j.icarus.2018.05.030
Jiang J, Hathaway DH, Cameron RH et al (2014) Magnetic flux transport at the solar surface. Space Sci Rev 186:491–523. https://doi.org/10.1007/s11214-014-0083-1
Jiang C, Feng X, Liu R, Yan X, Hu Q, Moore R, Zhang J, Xu Y, Yang L (2021) A solar eruption driven by rapid flux emergence. Nat Astron 5:1126–1133. https://doi.org/10.1038/s41550-021-01423-8
Kajdic P, Blanco-Cano X, Turc L, Archer M, Raptis S, Liu TZ, Pfau-Kempf Y, LaMoury AT, Hao YF, Escoubet PC, Omidi N, Sibeck DG, Wang BY, Zhang H, Lin Y (2024) Transient upstream mesoscale structures: drivers of solar-quiet space weather. Front Astron Space Sci. https://doi.org/10.3389/fspas.2024.1436916
Kanekal S, Miyoshi Y (2021) Dynamics of the terrestrial radiation belts: a review of recent results during the VarSITI (Variability of the Sun and Its Terrestrial Impact) era, 2014–2018. Prog Earth Planet Sci 8:20. https://doi.org/10.1186/s40645-021-00413-y
Kaneko T, Hotta H, Toriumi S, Kusano K (2022) Impact of subsurface convective flows on the formation of sunspot magnetic field and energy build-up. Mon Not R Astron Soc 517:2775–2786. https://doi.org/10.1093/mnras/stac2635
Karan DK, Martinis CR, Daniell RE, Eastes RW, Wang W, McClintock WE, Michell RG, England S (2024) GOLD observations of the merging of the Southern Crest of the Equatorial Ionization Anomaly and Aurora during the 10 and 11 May 2024 mother's day super geomagnetic storm. Geophys Res Lett 51:e2024GL110632. https://doi.org/10.1029/2024GL110632
Kasahara S, Miyoshi Y, Yokota S, Mitani T, Kasahara Y, Matsuda S, Kumamoto A, Matsuoka A, Kazama Y, Frey HU, Angelopoulos V, Kurita S, Keika K, Seki K, Shinohara I (2018) Pulsating aurora from electron scattering by chorus waves. Nature 554:337–340. https://doi.org/10.1038/nature25505
Kikuchi T, Hashimoto KK, Kitamura T, Tachihara H, Fejer B (2003) Equatorial counter electrojet during substorms. J Geophys Res Space Phys 108:A11:1406
Kikuchi T, Hashimoto K, Nozaki K (2008) Penetration of magnetospheric electric fields to the equator during a geomagnetic storm. J Geophys Res 113:A062
Kilpua EKJ, Good SW, Dresing N, Vainio R, Davies EE et al (2021) Multi-spacecraft observations of the structure of the sheath of an interplanetary coronal mass ejection and related energetic ion enhancement. Astron Astrophys 656:A8. https://doi.org/10.1051/0004-6361/202140838
Kliem B, Török T (2006) Torus instability. Phys Rev Lett 96:255002. https://doi.org/10.1103/PhysRevLett.96.255002
Kocharov L, Torsti J (2002) Hybrid solar energetic particle events observed on board SOHO. Sol Phys 207:149–157. https://doi.org/10.1023/A:1015540311183
Koldobskiy S, Mekhaldi F, Kovaltsov G, Usoskin I (2023) Multiproxy reconstructions of integral energy spectra for extreme solar particle events of 7176 BCE, 660 BCE, 775 CE, and 994 CE. J Geophys Res Space Phys 128:e2022JA031186. https://doi.org/10.1029/2022JA031186
Kopp G (2016) Magnitudes and timescales of total solar irradiance variability. J Space Weather Space Clim 6:A30. https://doi.org/10.1051/swsc/2016025
Koshin D, Sato K, Miyazaki K, Watanabe S (2020) An ensemble Kalman filter data assimilation system for the whole neutral atmosphere. Geosci Model Dev 13:3145–3177. https://doi.org/10.5194/gmd-13-3145-2020
Kota J, Jokipii JR (1983) Effects of drift on the transport of cosmic rays. VI - a three-dimensional model including diffusion. Astrophys J 265:573–581
Kren AC, Pilewskie P, Coddington O (2017) Where does Earth's atmosphere get its energy? J Space Weather Space Clim 7:A10. https://doi.org/10.1051/swsc/2017007
Kurata M et al (2015) Mini-magnetosphere over the Reiner Gamma magnetic anomaly region on the Moon. Geophys Res Lett. https://doi.org/10.1029/2005G024097
Kuroda Y, Kodera K, Yoshida K, Yukimoto S, Gray L (2022) Influence of the solar cycle on the North Atlantic Oscillation. J Geophys Res Atmos 127:e2021JD035519. https://doi.org/10.1029/2021JD035519
Lanabere V, Dimmock AP, Rosenqvist L, Viljanen A, Juusola L et al (2024) Characterizing the distribution of extreme geoelectric field events in Sweden. J Space Weather Space Clim 14:22. https://doi.org/10.1051/swsc/2024025
Lapenta G, Pierrard V, Keppens R, Markidis S, Poedts S, Šebek O, Trávníček PM et al (2013) SWIFF: Space weather integrated forecasting framework. J Space Weather Space Clim 3:A05. https://doi.org/10.1051/swsc/2013027
Larsen N, Mishev A (2024) Relationship between NM data and radiation dose at aviation altitudes during GLE events. Space Weather 22:e2024SW003885. https://doi.org/10.1029/2024SW003885
Laštovička J (2012) On the role of ozone in long-term trends in the upper atmosphere-ionosphere system. Ann Geophys 30:811–816. https://doi.org/10.5194/angeo-30-811-2012
Laundal KM, Reistad JP, Hatch SM, Madelaire M, Walker S, Hovland AO et al (2022) Local mapping of polar ionospheric electrodynamics. J Geophys Res Space Phys 127:e2022JA030356
Laurenza M, Vecchio A, Storini M, Carbone V (2012) Quasi-biennial modulation of galactic cosmic rays. Astrophys J 749:167
Laurenza M, Vecchio A, Storini M, Carbone V (2014) Drift effects on the galactic cosmic ray modulation. Astrophys J 781:71
Laurenza M, Del Moro D, Alberti T, Battiston R, Benella S, Benvenuto F et al (2023) The CAESAR project for the ASI space weather infrastructure. Remote Sens 15:346. https://doi.org/10.3390/rs15020346
Laurenza M, Stumpo M, Zucca P, Mancini M, Benella S, Clark L et al (2024) Upgrades of the ESPERTA forecast tool for solar proton events. J Space Weather Space Clim 14:8. https://doi.org/10.1051/swsc/2024007
Le Roux JA, Potgieter MS (1995) The simulation of complete 11 and 12 year modulation cycles for cosmic rays in the heliosphere using a drift model with global merged interaction regions. Astrophys J 442:847–851
Lee MA, Mewaldt RA, Giacalone J (2012) Shock acceleration of ions in the heliosphere. Space Sci Rev 173:247–281. https://doi.org/10.1007/s11214-012-9932-y
Leighton RB (1969) A magneto-kinematic model of the solar cycle. Astrophys J 156:1. https://doi.org/10.1086/149943
Lejosne D, Ripoll JF, Boscher D, Watt CEJ (2022) Differentiating between the leading processes for electron radiation belt acceleration. Front Astron Space Sci. https://doi.org/10.3389/fspas.2022.896245
Li JH, Zhou XZ, Liu ZY, Wang S, Omura Y, Li L, Burch JL (2025) Direct observations of cross-scale wave-particle energy transfer in space plasmas. Sci Adv 11(6):eadr8227. https://doi.org/10.1126/sciadv.adr8227
Lieberman RS, Oberheide J, Hagan ME, Remsberg EE, Gordley LL (2004) Variability of diurnal tides and planetary waves during November 1978–May 1979. J Atmos Sol-Terr Phys. https://doi.org/10.1016/j.jastp.2004.01.006
Lieberman RS, Riggin DM, Ortland DA, Oberheide J, Siskind DE (2015) Global observations and modeling of nonmigrating diurnal tides generated by tide-planetary wave interactions. J Geophys Res Atmos 120:11419–11437. https://doi.org/10.1002/2015JD023739
Litvinenko YE (2006) Three-dimensional fan magnetic reconnection and particle acceleration in the solar corona. Astron Astrophys 452:1069–1074. https://doi.org/10.1051/0004-6361:20054324
Liu HL (2016) Variability and predictability of the space environment as related to lower atmosphere forcing. Space Weather 14:634–658. https://doi.org/10.1002/2016SW001450

Liu HL (2019) Quantifying gravity wave forcing using scale invariance. Nat Commun 10:2605. https://doi.org/10.1038/s41467-019-10527-z
Liu HL (2020) Day-to-day variability of prereversal enhancement in the vertical ion drift in response to large-scale forcing from the lower atmosphere. Space Weather 18:e2019SW002334. https://doi.org/10.1029/2019SW002334
Liu HL, Maute A (2024) Tidal control of equatorial vertical E × B drift under solar minimum conditions. Geophys Res Lett. https://doi.org/10.1029/2024GL108923
Liu HL, Yudin VA, Roble RG (2013) Day-to-day ionospheric variability due to lower atmosphere perturbations. Geophys Res Lett 40:665–670. https://doi.org/10.1002/grl.50125
Liu HL et al (2018) Development and validation of the whole atmosphere community climate model with thermosphere and ionosphere extension (WACCM-X 2.0). J Adv Model Earth Syst 10:381–402. https://doi.org/10.1002/2017MS001232
Liu H, Tao C, Jin H, Nakamoto Y (2020) Circulation and tides in a cooler upper atmosphere: dynamical effects of CO2 doubling. Geophys Res Lett 47:e2020GL087413. https://doi.org/10.1029/2020GL087413
Liu ZY, Zong QG, Rankin R et al (2022) Simultaneous macroscale and microscale wave–ion interaction in near-Earth space plasmas. Nat Commun 13:5593. https://doi.org/10.1038/s41467-022-33298-6
Liu HL, Lauritzen PH, Vitt F (2024a) Impacts of gravity waves on the thermospheric circulation and composition. Geophys Res Lett. https://doi.org/10.1029/2023GL107453
Liu HL, Lauritzen PH, Vitt F, Goldhaber S (2024b) Assessment of gravity waves from tropopause to thermosphere and ionosphere in high-resolution WACCM-X simulations. J Adv Model Earth Syst. https://doi.org/10.1029/2023MS004024
Lockwood GW, Henry GW, Hall JC, Radick RR (2013) Decadal variations of Sun-like stars. In: New Quests in Stellar Astrophysics III: A Panchromatic View of Solar-Like Stars, With and Without Planets, AIP Conf Ser 472:203
Love JJ, Pulkkinen A, Bedrosian PA, Jonas S, Kelbert A (2016) Geoelectric hazard maps for the continental United States. Geophys Res Lett 43:9415–9424. https://doi.org/10.1002/2016GL070469
Lukianova R, Hanuise C, Christiansen F (2008) Asymmetric distribution of the ionospheric electric potential in the opposite hemispheres as inferred from the SuperDARN observations and FAC-based convection model. J Atmos Terr Phys 70:2324–2335. https://doi.org/10.1016/j.jastp.2008.05.015
Luo Y, Jiang J, Wang R (2024) The sun's magnetic power spectra over two solar cycles. II. Cycle dependence of active regions, a magnetic network, and their relation. Astrophys J 970:76. https://doi.org/10.3847/1538-4357/ad5677
MacDougall J, Abdu MA, Batista I, Fagundes PR, Sahai Y, Jayachandran PT (2009) On the production of traveling ionospheric disturbances by atmospheric gravity waves. J Atmos Sol Terr Phys 71:2013–2016. https://doi.org/10.1016/j.jastp.2009.09.006
Mackay D, Yeates A (2012) The sun's global photospheric and coronal magnetic fields: observations and models. Living Rev Sol Phys 9:1–50. https://doi.org/10.12942/lrsp-2012-6
Maehara H, Shibayama T, Notsu S et al (2012) Superflares on solar-type stars. Nature 485:478–481. https://doi.org/10.1038/nature11063
Manchester W, Kilpua EKJ, Liu YD, Lugaz N, Riley P, Török T, Vršnak B (2017) The physical processes of CME/ICME evolution. Space Sci Rev 212(3–4):1159–1219. https://doi.org/10.1007/s11214-017-0394-0
Mandal S, Krivova NA, Solanki SK, Sinha N, Banerjee D (2020) Sunspot area catalog revisited: daily cross-calibrated areas since 1874. Astron Astrophys 640:A78. https://doi.org/10.1051/0004-6361/202037547
Mannucci AJ, Tsurutani BT, Iijima BA, Komjathy A, Saito A et al (2005) Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 "Halloween Storms." Geophys Res Lett 32:L12S02
Mariotti A, Ruti PM, Doblas-Reyes F et al (2020) Windows of opportunity for skillful forecasts S2S and beyond. Bull Am Meteorol Soc. https://doi.org/10.1175/BAMS-D-18-0326.1
Martinis C, Vadas SL, Baumgardner J, Pimenta AA, Medeiros AF, Medeiros RM, Lima LM (2019) First conjugate observations of medium-scale traveling ionospheric disturbances (MSTIDs) in the Europe-Africa longitude sector. J Geophys Res Space Phys 124:2213–2222. https://doi.org/10.1029/2018JA026018
Matthes K, Funke B, Andersson ME et al (2017) Solar forcing for CMIP6 (v3.2). Geosci Model Dev 10:2247–2302. https://doi.org/10.5194/gmd-10-2247-2017
Mauk BH (2013) Science objectives and rationale for the Radiation Belt Storm Probes mission. Space Sci Rev. https://doi.org/10.1007/s11214-012-9908-y
McComas DJ, Bame SJ, Barker P et al (2000) Solar wind observations over Ulysses' first full polar orbit. J Geophys Res Atmos 105:10419–10434. https://doi.org/10.1029/1999JA000383
McCormack JP, Harvey VL, Randall CE et al (2021) Intercomparison of middle atmospheric meteorological analyses for the Northern Hemisphere winter 2009–2010. Atmos Chem Phys 21:17577–17605. https://doi.org/10.5194/acp-21-17577-2021
McCracken KG, Moraal H, Stoker PH (2008) Investigation of the multiple-component structure of the 20 January 2005 cosmic ray ground level enhancement. J Geophys Res Space Physics 113:A12101. https://doi.org/10.1029/2007JA012829
McCracken KG, Moraal H, Shea MA (2012) The high-energy impulsive ground-level enhancement. Astrophys J 761(2):101. https://doi.org/10.1088/0004-637X/761/2/101
McCrea I, Aikio A, Alfonsi L et al (2015) The science case for the EISCAT_3D radar. Prog Earth Planet Sci 2(1):21. https://doi.org/10.1186/s40645-015-0051-8
McInerney JM, Qian L, Liu HL, Solomon SC, Nossal SM (2024) Climate change in the thermosphere and ionosphere from the early twentieth century to early twenty-first century simulated by the whole atmosphere community climate model—eXtended. J Geophys Res Atmos 129:e2023JD039397. https://doi.org/10.1029/2023JD039397
Meehl GA, Goddard L, Boer G et al (2021) Initialized earth system prediction from subseasonal to decadal timescales. Nat Rev Earth Environ 2:340–357. https://doi.org/10.1038/s43017-021-00155-x
Mekhaldi F, Muscheler R, Adolphi F et al (2015) Multiradionuclide evidence for the solar origin of the cosmic-ray events of AD 774/5 and 993/4. Nat Commun 6:8611. https://doi.org/10.1038/ncomms9611
Milan SE, Carter JA, Bower GE et al (2020) Dual-lobe reconnection and horse-collar auroras. J Geophys Res Space Physics 125:e2020JA028567. https://doi.org/10.1029/2020JA028567
Miroshnichenko LI, Perez-Peraza JA (2008) Astrophysical aspects in the studies of solar cosmic rays. Int J Mod Phys A 23:1–141. https://doi.org/10.1142/S0217751X08037312
Mishev A, Panovska S, Usoskin I (2023) Assessment of the radiation risk at flight altitudes for an extreme solar particle storm of 774 AD. J Space Weather Space Clim 13:22. https://doi.org/10.1051/swsc/2023020
Mitchell DM, Gray LJ, Anstey JA, Baldwin MP, Charlton-Perez AJ (2015) Solar signals in CMIP-5 simulations: the stratospheric pathway. Q J R Meteorol Soc 141:2390–2403
Miyake F, Nagaya K, Masuda K, Nakamura T (2012) A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan. Nature 486:240–242. https://doi.org/10.1038/nature11123
Miyoshi Y, Fujiwara H (2003) Day-to-day variations of migrating diurnal tide simulated by a GCM from the ground surface to the exobase. Geophys Res Lett 30:1789. https://doi.org/10.1029/2003GL017695
Miyoshi Y, Shinohara I, Takashima T et al (2018) Geospace Exploration Project ERG. Earth Planets Space. https://doi.org/10.1186/s40623-018-0862-0
Miyoshi Y, Shinohara I, Ukhorskiy S et al (2022) Collaborative research activities of the arase and van Allen probes. Space Sci Rev. https://doi.org/10.1007/s11214-022-00885-4
Molina MG, Zossi C, Brunini C, Meza A (2020) Consequences of a solar wind stream interaction region on the low latitude ionosphere: event of 7 October 2015. Sol Phys 295:173. https://doi.org/10.1007/s11207-020-01728-7
Molina MG, Namour J, Cesaroni C, Spogli L, Argüelles N, Asamoah E (2024) Boosting total electron content forecasting based on deep learning toward an operational service. J Atmos Sol Terr Phys 286:106427. https://doi.org/10.1016/j.jastp.2025.106427
Motoba T, Hosokawa K, Kadokura A, Sato N (2012) Magnetic conjugacy of northern and southern auroral beads. Geophys Res Lett 39:L08108. https://doi.org/10.1029/2012GL051599
Müller D, St Cyr OC, Zouganelis I et al (2020) Solar orbiter's first science results from the solar wind plasma and energetic particle suite (SWEAP). Sci Adv. https://doi.org/10.1126/sciadv.aay3480

Myers CE, Yamada M, Ji H, Yoo J, Fox W, Jara-Almonte J, Savcheva A (2016) A dynamic magnetic tension force as the cause of failed solar eruptions. Phys Plasmas 23(11):112102. https://doi.org/10.1063/1.4964481
Nakamura S, Ebihara Y, Fujita S et al (2018) Time domain simulation of geomagnetically induced current (GIC) flowing in 500-kV power grid in Japan including a three-dimensional ground inhomogeneity. Space Weather 16:1946–1959. https://doi.org/10.1029/2018SW002004
Nakamura K, Shiokawa K, Nosé M et al (2022) Multi-event study of simultaneous observations of isolated proton auroras at subauroral latitudes using ground all-sky imagers and the Van Allen probes. J Geophys Res Space Physics 127:e2022JA030455. https://doi.org/10.1029/2022JA030455
Nakamura R, Burch JL, Birn J, et al. (2024) Outstanding questions and future research of magnetic reconnection. arXiv:2407.09670
Nishimura Y, Dyer A, Kangas L, Donovan E, Angelopoulos V (2023) Unsolved problems in strong thermal emission velocity enhancement (STEVE) and the picket fence. Front Astron Space Sci. https://doi.org/10.3389/fspas.2023.1087974
Oberheide J (2022) Day-to-day variability of the semidiurnal tide in the F-region ionosphere during the January 2021 SSW from COSMIC-2 and ICON. Geophys Res Lett 49:e2022GL100369. https://doi.org/10.1029/2022GL100369
Oberheide J, Lu X, Aggarwal D (2024) A statistical study of the day-to-day variability of diurnal and semidiurnal tides in the ionospheric dynamo region from MIGHTI/ICON observations. J Geophys Res Space Physics 129:e2024JA032619. https://doi.org/10.1029/2024JA032619
Ogawa Y, Motoba T, Buchert SC, Häggström I, Nozawa S (2014) Upper atmosphere cooling over the past 33 years. Geophys Res Lett 41:5629–5635. https://doi.org/10.1002/2014GL060591
Ogawa Y, Seki K, Keika K, Ebihara Y (2019) Characteristics of CME- and CIR-driven ion upflows in the polar ionosphere. J Geophys Res Space Phys 124:3637–3649. https://doi.org/10.1029/2018JA025870
Ohtani S, Gjerloev JW (2020) Is the substorm current wedge an ensemble of wedgelets? Revisit to midlatitude positive bays. J Geophys Res Space Phys 125:e2020JA027902. https://doi.org/10.1029/2020JA027902
Oliveira DM, Zesta E, Hayakawa H, Bhaskar A (2020) Estimating satellite orbital drag during historical magnetic superstorms. Space Weather 18:e2020SW002472. https://doi.org/10.1029/2020SW002472
Oliveira DM, Zesta E, Garcia-Sage K (2025) Tracking reentries of Starlink satellites during the rising phase of solar cycle 25. Front Astron Space Sci 12:1572313. https://doi.org/10.3389/fspas.2025.1572313
O'Neill BC et al (2016) The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci Model Dev 9:3461–3482. https://doi.org/10.5194/gmd-9-3461-2016
Panos B, Kleint L, Zbinden J (2023) Identifying preflare spectral features using explainable artificial intelligence. Astron Astrophys. https://doi.org/10.1051/0004-6361/202244835
Parker EN (1955) Hydromagnetic dynamo models. Astrophys J 122:293. https://doi.org/10.1086/146087
Parker WE, Linares R (2024) Satellite drag analysis during the May 2024 Gannon Geomagnetic Storm. J Spacecr Rockets. https://doi.org/10.2514/1.A36164
Patra AK, Chaitanya PP, Otsuka Y, Yokoyama T et al (2014) Vertical ExB drifts from radar and C/NOFS observations in the Indian and Indonesian sectors: consistency of observations and model. J Geophys Res Space Phys 119:3777–3788
Patterson CJ, Wild JA, Boteler DH (2023) Modeling the impact of geomagnetically induced currents on electrified railway signaling systems in the United Kingdom. Space Weather 21:e2022SW003385. https://doi.org/10.1029/2022SW003385
Pedatella NM, Harvey VL (2022) Impact of strong and weak stratospheric polar vortices on the mesosphere and lower thermosphere. Geophys Res Lett 49:e2022GL098877. https://doi.org/10.1029/2022GL098877
Pedatella NM et al (2014a) The neutral dynamics during the 2009 sudden stratosphere warming simulated by different whole atmosphere models. J Geophys Res Space Phys 119:1306–1324. https://doi.org/10.1002/2013JA019421
Pedatella NM, Raeder K, Anderson JL, Liu HL (2014b) Ensemble data assimilation in the whole atmosphere community climate model. J Geophys Res Atmos 119:9793–9809. https://doi.org/10.1002/2014JD021776
Pedatella NM, Oberheide J, Sutton EK, Liu HL, Anderson JL, Raeder K (2016a) Short-term nonmigrating tide variability in the mesosphere, thermosphere, and ionosphere. J Geophys Res Space Phys 121:3621–3633. https://doi.org/10.1002/2016JA022528
Pedatella NM, Richmond AD, Maute A, Liu HL (2016b) Impact of semidiurnal tidal variability during SSWs on the mean state of the ionosphere and thermosphere. J Geophys Res Space Phys 121:8077–8088. https://doi.org/10.1002/2016JA022910
Pesnell WD (2012) Solar cycle predictions. Sol Phys 281:507–532
Petrovay K (2020) Solar cycle prediction. Living Rev Sol Phys. https://doi.org/10.1007/s41116-020-0022-z
Plougonven R, de la Cámara A, Hertzog A, Lott F (2020) How does knowledge of atmospheric gravity waves guide their parameterizations? Q J R Meteorol Soc 146:1529–1543. https://doi.org/10.1002/qj.3732
Potgieter MS (2013) Solar modulation of cosmic rays. Living Rev Sol Phys 10:3. https://doi.org/10.12942/lrsp-2013-3
Pritchett PL, Mozer FS, Wilber M (2012) Intense perpendicular electric fields associated with three-dimensional magnetic reconnection at the subsolar magnetopause. J Geophys Res 117:A06212. https://doi.org/10.1029/2012JA017533
Pulkkinen T (2007) Space weather: terrestrial perspective. Living Rev Sol Phys 4:1. https://doi.org/10.12942/lrsp-2007-1
Qian L, Laštovička J, Roble RG, Solomon SC (2011) Progress in observations and simulations of global change in the upper atmosphere. J Geophys Res 116:A00H03. https://doi.org/10.1029/2010JA016317
Rädler AT et al (2019) Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. Npj Clim Atmos Sci 2:30. https://doi.org/10.1038/s41612-019-0083-7
Randall CE, Harvey VL, Holt LA, Marsh DR, Kinnison D, Funke B, Bernath PF (2015) Simulation of energetic particle precipitation effects during the 2003–2004 arctic winter. J Geophys Res Space Phys 120:5035–5048. https://doi.org/10.1002/2015JA021196
Rauer H, Catala C, Aerts C et al (2014) The PLATO 2.0 mission. Exp Astron 38:249
Reames DV (1999) Particle acceleration at the sun and in the heliosphere. Space Sci Rev 90:413–491
Reames D, Ng C (1998) Streaming-limited intensities of solar energetic particles. Astrophys J 504:1002–1005. https://doi.org/10.1086/306124
Reeves GD, McAdams KL, Friedel RHW, O'Brien TP (2003) Acceleration and loss of relativistic electrons during geomagnetic storms. Geophys Res Lett 30(10):1529. https://doi.org/10.1029/2002GL016513
Reinhold T, Shapiro AI, Solanki SK, Montet BT, Krivova NA, Cameron RH, Amazo-Gómez EM (2020) The sun is less active than other solar-like stars. Science 368:518–521. https://doi.org/10.1126/science.aay3821
Ren X, Yang P, Mei D, Liu H, Xu G, Dong Y (2023) Global ionospheric TEC forecasting for geomagnetic storm time using a deep learning-based multi-model ensemble method. Space Weather 21:e2022SW003231. https://doi.org/10.1029/2022SW003231
Resende LCA, Zhu Y, Denardini CM, Chagas RAJ, Da Silva LA, Andrioli VF, Figueiredo CAO, Marchezi JP, Chen SS, Moro J, Silva RP, Li H, Wang C, Liu Z (2023) Analysis of the different physical mechanisms in the atypical sporadic E (Es) layer occurrence over a low latitude region in the Brazilian sector. Front Astron Space Sci 10:1193268. https://doi.org/10.3389/fspas.2023.1193268
Richmond AD, Thayer JP (2000) Ionospheric electrodynamics: a tutorial magnetospheric current systems. Geophys Monogr 118:131–146
Ricker GR, Winn JN, Vanderspek R et al (2014) Transiting Exoplanet Survey Satellite (TESS). Proc SPIE 9143:914320. https://doi.org/10.1117/12.2063489
Ridley AJ (2007) Effects of seasonal changes in the ionospheric conductance on magnetospheric field-aligned currents. Geophys Res Lett 34:L05101. https://doi.org/10.1029/2006GL028444
Riley P, Lionello R, Linker JA et al (2015) Inferring the structure of the solar corona and inner heliosphere during the Maunder minimum using global thermodynamic magnetohydrodynamic simulations. Astrophys J 802(2):105. https://doi.org/10.1088/0004-637X/802/2/105
Rippole J-F et al (2020) Particle dynamics in the Earth's radiation belts: review of current research and open questions. J Geophys Res. https://doi.org/10.1029/2019JA026735
Roberts DA, Thieman J, Génot V, King T, Gangloff M, Perry C et al (2018) The SPASE data model: a metadata standard for registering, finding,

accessing, and using heliophysics data obtained from observations and modeling. Space Weather. https://doi.org/10.1029/2018SW002038
Roble RG, Dickinson RE (1989) How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? Geophys Res Lett 16(12):1441–1444. https://doi.org/10.1029/GL016i012p01441
Roble RG, Ridley EC, Richmond AD, Dickinson RE (1988) A coupled thermosphere/ionosphere general circulation model. Geophys Res Lett 15:1325–1328
Rots A, Bunclark P, Calabretta M, Allen S, Manchester R, Thompson W (2015) Representations of time coordinates in FITS. Astron Astrophys 574:A36
Sakaguchi K, Shiokawa K, Ieda A, Miyoshi Y, Ogawa T, Connors M et al (2007) Simultaneous ground and satellite observations of an isolated proton arc at subauroral latitudes. J Geophys Res 112:A04202. https://doi.org/10.1029/2006JA012135
Salminen A, Asikainen T, Maliniemi V, Mursula K (2020) Dependence of sudden stratospheric warmings on internal and external drivers. Geophys Res Lett 47:e2019GL086444. https://doi.org/10.1029/2019GL086444
Sato K, Inoue J (2023) Ice cloud formation related to oceanic supply of ice-nucleating particles: a case study in the Southern Ocean near an atmospheric river in late summer. Geophys Res Lett 50:e2023GL106036. https://doi.org/10.1029/2023GL106036
Schmieder B (2018) Extreme solar storms based on solar magnetic field. J Atmos Solar-Terr Phys 180:46–51. https://doi.org/10.1016/j.jastp.2017.07.018
Shapiro AI, Solanki SK, Krivova NA, Cameron RH, Yeo KL, Schmutz WK (2017) The nature of solar brightness variations. Nat Astron 1:612–616. https://doi.org/10.1038/s41550-017-0217-y
Shiokawa K, Georgieva K (2021) A review of the SCOSTEP's 5-year scientific program VarSITI—variability of the sun and its terrestrial impact. Prog Earth Planet Sci 8:21. https://doi.org/10.1186/s40645-021-00410-1
Shiokawa K et al (2007) Ground observation and AMIE-TIEGCM modelling of a storm-time traveling ionospheric disturbance. J Geophys Res 112:A05308
Shoji M et al (2017) Ion hole formation and nonlinear generation of electromagnetic ion cyclotron waves: THEMIS observations. Geophys Res Lett. https://doi.org/10.1023/2017GL074254
Shutler JD et al (2022) Atmospheric impacts of the space industry require oversight. Nat Geosci 15:598–600. https://doi.org/10.1038/s41561-022-01001-5
Smith J, Kast A, Geraschenko A, Morton YJ, Brenner MP, van Diggelen F, Williams BP (2024) Mapping the ionosphere with millions of phones. Nature 635(8038):365–369
Smith-Johnsen C, Marsh DR, Smith AK, Tyssøy HN, Maliniemi V (2022) Mesospheric nitric oxide transport in WACCM. J Geophys Res Space Phys 127(3):e2021JA029998. https://doi.org/10.1029/2021JA029998
Solanki SK, Krivova NA, Haigh JD (2013) Solar irradiance variability and climate. Annu Rev Astron Astrophys 51:311–351. https://doi.org/10.1146/annurev-astro-082812-141007
Solomon SC, Liu HL, Marsh DR, McInerney JM, Qian L, Vitt FM (2018) Whole atmosphere simulation of anthropogenic climate change. Geophys Res Lett 45:1567–1576. https://doi.org/10.1002/2017GL076950
Sorathia KA, Merkin VG, Panov EV, Zhang B, Lyon JG, Garretson J, Ukhorskiy AY, Ohtani S, Sitnov M, Wiltberger M (2020) Ballooning-interchange instability in the near-Earth plasma sheet and auroral beads: global magnetospheric modeling at the limit of the MHD approximation. Geophys Res Lett 47:e2020GL088227. https://doi.org/10.1029/2020GL088227
SPASE Group (2021) Space Physics Archive Search and Extract (SPASE) Base Information Model. SPASE Group. https://doi.org/10.48322/E72C-5Y75. Accessed 14 Nov 2024
Spogli L et al (2024) The effects of the May 2024 Mother's Day superstorm over the Mediterranean sector: from data to public communication. Ann Geophys 67(2):PA218
Stober G et al (2022) Meteor radar vertical wind observation biases and mathematical debiasing strategies including the 3DVAR+DIV algorithm. Atmos Meas Tech 15(19):5769–5792. https://doi.org/10.5194/AMT-15-5769-2022
Stumpo M et al (2023) Relating intermittency and inverse cascade to stochastic entropy in solar wind turbulence. Astrophys J Lett 959:L20. https://doi.org/10.3847/2041-8213/ad1192
Stumpo M, Laurenza M, Benella S, Marcucci MF (2024) Predicting the energetic proton flux with a machine learning regression algorithm. Astrophys J 975:8. https://doi.org/10.3847/1538-4357/ad7734
Suclupe J et al (2024) On the abnormally strong westward phase of the mesospheric semiannual oscillation at low latitudes during March equinox 2023. Geophys Res Lett 51:e2024GL110331. https://doi.org/10.1029/2024GL110331
Sugiyama T, Kusano K (2007) Multi-scale plasma simulation by the interlocking of magnetohydrodynamic model and particle-in-cell kinetic model. J Comput Phys 227:1340–1356. https://doi.org/10.1016/j.jcp.2007.09.011
Sun X et al (2015) Why is the great solar active region 12192 flare-rich but CME-poor? Astrophys J 804:L28. https://doi.org/10.1088/2041-8205/804/2/L28
Taylor M, et al. (2020) Developing the NASA atmospheric waves experiment (AWE). AGU 2020 Fall Meeting. SA011–07
Temmer M, Thalmann JK, Dissauer K, Veronig AM, Tschernitz J, Hinterreiter J, Rodriguez L (2017) Magnetic configuration and non-potentiality of a solar active region from confined and eruptive flaring activity. Solar Phys 292(6):93. https://doi.org/10.1007/s11207-017-1119-7
Temmer M, Scolini C, Richardson IG, Heinemann SG, Paouris E, Vourlidas A, Bisi MM, Al-Haddad N, Amerstorfer T et al (2023) CME propagation through the heliosphere: Status and future of observations and model development. Adv Space Res. https://doi.org/10.1016/j.asr.2023.07.003
Tenfjord P, Østgaard N, Snekvik K, Laundal KM, Reistad JP, Haaland S et al (2015) How the IMF By induces a By component in the closed magnetosphere and how it leads to asymmetric currents and convection patterns in the two hemispheres. J Geophys Res Space Phys 120:9368–9384
Thalmann JK, Su Y, Temmer M, Veronig AM (2015) The confined X-class flares of solar active region 2192. Astrophys J 801:L23. https://doi.org/10.1088/2041-8205/801/2/L23
Themens DR, Elvidge S, McCaffrey A, Jayachandran PT, Coster A, Varney RH et al (2024) The high latitude ionospheric response to the major May 2024 geomagnetic storm: a synoptic view. Geophys Res Lett. https://doi.org/10.1029/2024GL111677
Tiburzi C et al (2021) The impact of solar wind variability on pulsar timing. Astron Astrophys. https://doi.org/10.1051/0004-6361/202039846
Tobiska WK et al (2016) Global real-time dose measurements using the automated radiation measurements for aerospace safety (ARMAS) system. Space Weather 14:1053–1080. https://doi.org/10.1002/2016SW001419
Toledo-Redondo S, Andre M, Aunai N, Chappell CR, Dargent J, Fuselier SA et al (2021) Impacts of ionospheric ions on magnetic reconnection and Earth's magnetosphere dynamics. Rev Geophys. https://doi.org/10.1029/2020RG000707
Toriumi S, Takasao S, Cheung MCM, Jiang C, Guo Y, Hayashi K et al (2020) Comparative study of data-driven solar coronal field models using a flux emergence simulation as a ground-truth data set. Astrophys J 890:103. https://doi.org/10.3847/1538-4357/ab6b1f
Török T, Downs C, Linker JA, Lionello R, Titov VS, Mikic Z, Riley P, Caplan RM, Wijaya J (2018) Sun-to-Earth MHD simulation of the 2000 July 14 "Bastille Day" eruption. Astrophys J 856:75. https://doi.org/10.3847/1538-4357/aab36d
Torres Peralta TJ, Molina MG, Asorey H, Sidelnik I, Rubio-Montero AJ, Dasso S et al (2024) Enhanced particle classification in water Cherenkov detectors using machine learning: Modeling and validation with Monte Carlo simulation datasets. Atmosphere 15(9):1039. https://doi.org/10.3390/atmos15091039
Tsurutani BT, Verkhoglyadova OP, Mannucci AJ, Saito A, Araki T, Yumoto K et al (2008) Prompt penetration electric fields (PPEFs) and their ionospheric effects during the great magnetic storm of 30–31 October 2003. J Geophys Res 113:A05311
Tsurutani BT, Lakhina GS, Hajra R (2020) The physics of space weather/solar-terrestrial physics (STP): what we know now and what the current and future challenges are. Nonlinear Process Geophys 27:75–92. https://doi.org/10.5194/npg-27-75-2020
Urco JM, Feraco F, Chau JL, Marino R (2024) Augmented four-dimensional mesosphere and lower thermosphere wind field reconstruction via the physics-informed machine learning approach HYPER. J Geophys Res Machine Learning Comput. https://doi.org/10.1029/2024JH000162
Usoskin IG (2023) A history of solar activity over millennia. Living Rev Sol Phys 20:2. https://doi.org/10.1007/s41116-023-00036-z

Usoskin IG, Kovaltsov GA (2021) Mind the gap: New precise 14C data indicate the nature of extreme solar particle events. Geophys Res Lett. https://doi.org/10.1029/2021GL094848
Usoskin IG, Kromer B, Ludlow F, Beer J, Friedrich M, Kovaltsov GA, Solanki SK, Wacker L (2013a) The AD775 cosmic event revisited: the Sun is to blame. Astron Astrophys. https://doi.org/10.1051/0004-6361/201321080
Usoskin IG, Kromer B, Ludlow F, Beer J, Friedrich M, Kovaltsov GA, Solanki SK, Wacker L (2013b) The AD775 cosmic event revisited: the Sun is to blame. Astron Astrophys Lett 552:L3
Usoskin IG, Arlt R, Asvestari E et al (2015) The Maunder minimum (1645–1715) was indeed a grand minimum: a reassessment of multiple datasets. Astron Astrophys 581:A95. https://doi.org/10.1051/0004-6361/201526652
Usoskin IG, Koldobskiy SA, Kovaltsov GA, Rozanov EV, Sukhodolov TV, Mishev AL, Mironova IA (2020) Revisited reference solar proton event of 23 February 1956: assessment of the cosmogenic-isotope method sensitivity to extreme solar events. J Geophys Res. https://doi.org/10.1029/2020JA027921
Usoskin I, Miyake F, Baroni M, Brehm N, Dalla S, Hayakawa H, Hudson H, Jull AJT, Knipp D, Koldobskiy S, Maehara H, Mekhaldi F, Notsu Y, Poluianov S, Rozanov E, Shapiro A, Spiegl T, Sukhodolov T, Uusitalo J, Wacker L (2023a) Extreme solar events: setting up a paradigm. Space Sci Rev 219:73. https://doi.org/10.1007/s11214-023-01018-1
Usoskin IG, Koldobskiy SA, Poluianov SV, Raukunen O, Vainio R, Kovaltsov GA (2023b) Consistency of the average flux of solar energetic particles over timescales of years to megayears. Astron Astrophys 670:L22. https://doi.org/10.1051/0004-6361/202245810
Vadas SL (2007) Horizontal and vertical propagation and dissipation of gravity waves in the thermosphere from lower atmospheric and thermospheric sources. J Geophys Res 112:A06305. https://doi.org/10.1029/2006JA011845
Vainio R et al (2009) Dynamics of the earth's particle radiation environment. Space Sci Rev 147:187–231. https://doi.org/10.1007/s11214-009-9496-7
Van der Sluijs MA, Hayakawa H (2023) A candidate auroral report in the Bamboo Annals, indicating a possible extreme space weather event in the early 10th century BCE. Adv Space Res 72:5767–5776. https://doi.org/10.1016/j.asr.2022.01.010
Vasil GM, Lecoanet D, Augustson K, Burns KJ, Oishi JS, Brown BP, et al. (2024) The solar dynamo begins near the surface, arXiv [astro-ph.SR]. http://arxiv.org/abs/2404.07740
Vasilyev V, Reinhold T, Shapiro AI, Krivova NA, Usoskin I, Monte BT, Solanki SK, Gizon L (2022) Superflares on solar-like stars: A new method for identifying the true flare sources in photometric surveys. Astron Astrophys 668:A167. https://doi.org/10.1051/0004-6361/202244422
Vasilyev V, Reinhold T, Shapiro AI, Usoskin I, Krivova NA, Maehara H, Notsu Y, Brun AS, Solanki SK, Gizon L (2024) Sun-like stars produce superflares roughly once per century. Science 386:1301–1305. https://doi.org/10.1126/science.adl544
Vida K et al (2024) Stellar flares, superflares, and coronal mass ejections—Entering the big data era. Universe 10:313. https://doi.org/10.3390/universe10080313
Viljanen A, Pirjola R, Wik M, Ádám A, Prácser E, Sakharov Y, Katkalov J (2012) Continental scale modelling of geomagnetically induced currents. J Space Weather Space Clim 2:A17. https://doi.org/10.1051/swsc/2012017
Walsh AP, Haaland S, Forsyth C, Keesee AM, Kissinger J, Li K, Runov A, Soucek J, Walsh BM, Wing S, Taylor MGG (2014) Dawn-dusk asymmetries in the coupled solar wind-magnetosphere-ionosphere system: a review. Ann Geophys 32:705–737. https://doi.org/10.5194/angeo-32-705-2014
Wang JC, Palo SE, Liu HL, Siskind DE (2021) Day-to-day variability of diurnal tide in the mesosphere and lower thermosphere driven from below. J Geophys Res Space Phys. https://doi.org/10.1029/2019JA027759
Wang CM, Huang SY, Yuan ZG, Zhou M, Jiang K, Xu SB, Xiong QY, Lin LT (2024) Small-scale field-aligned currents in the magnetopause boundary layer. Astrophys J 965:1
Ward W, Seppälä A, Yiğit E, Nakamura T, Stolle C, Laštovička J et al (2021) Role of the Sun and the middle atmosphere/thermosphere/ionosphere in climate (ROSMIC): a retrospective and prospective view. Prog Earth Planet Sci 8(1):47. https://doi.org/10.1186/s40645-021-00433-8
Weber MA, Schunker H, Jouve L, Isik E (2023) Understanding active region origins and emergence on the Sun and other cool stars. Space Sci Rev. https://doi.org/10.1007/s11214-023-01006-5
Weimer D, Edwards T (2021) Testing the electrodynamic method to derive height-integrated ionospheric conductances. Ann Geophys 39:31–51
Wellenzohn S, Nakamura R, Nakamura TKM, Varsani A, Sergeev VA, Apatenkov SV et al (2021) Remote sensing of magnetic reconnection in the magnetotail using in situ multipoint observations at the plasma sheet boundary layer. J Geophys Res Space Phys. https://doi.org/10.1029/2020JA028917
West M, Seaton D (2015) SWAP observations of post-flare giant arches in the long-duration 14 October 2014 solar eruption. Astrophys J Lett 801:L6. https://doi.org/10.1088/2041-8205/801/1/L6
Wilkinson M, Dumontier M, Aalbersberg I, et al (2016) The FAIR guiding principles for scientific data management and stewardship. Sci Data 3:160018. https://doi.org/10.1038/sdata.2016.18
Whitman K, Egeland R, Richardson IG et al (2023) Review of solar energetic particle prediction models. AdSpR 72:5161–5242. https://doi.org/10.1016/j.asr.2022.08.006
Whittlesey PL et al (2020) Solar wind composition from Parker Solar Probe. Astrophys J 895(1):45. https://doi.org/10.3847/1538-4357/ab8b35
Wu Y et al (2024) CORBES: radiation belt survey with international small satellite constellation. Adv Space Res. https://doi.org/10.1016/j.asr.2024.04.051
Yadav S, Shiokawa K, Oyama S, Inaba Y, Takahashi N, Seki K et al (2021) Study of an equatorward detachment of auroral arc from the oval using ground-space observations and the BATS-R-US - CIMI model. J Geophys Res. https://doi.org/10.1029/2020JA029080
Yadav S, Shiokawa K, Otsuka Y, Connors M (2022) Statistical study of subauroral arc detachment at Athabasca Canada: new insights on STEVE. J Geophys Res. https://doi.org/10.1029/2021JA029856
Yahnina TA, Yahnin AG, Kangas J, Manninen J (2000) Proton precipitation related to Pc1 pulsations. Geophys Res Lett 27(21):3575–3578. https://doi.org/10.1029/2000GL003763
Yamauchi M (2019) Terrestrial ion escape and relevant circulation in space. Ann Geophys 37:1197–1222. https://doi.org/10.5194/angeo-37-1197-2019
Yamazaki Y, Arras C, Andoh S, Miyoshi Y, Shinagawa H, Harding BJ et al (2022) Examining the wind shear theory of sporadic E with ICON/MIGHTI winds and COSMIC-2 radio occultation data. Geophys Res Lett 49:e2021GL096202
Yashiro S, Akiyama S, Gopalswamy N, Howard RA (2006) Different power-law indices in the frequency distributions of flares with and without coronal mass ejections. Astrophys J 650:L143–L146. https://doi.org/10.1086/508876
Yeates AR, Cheung MCM, Jiang C et al (2023) Surface flux transport on the Sun. Space Sci Rev 219(4):31. https://doi.org/10.1007/s11214-023-00978-8
Yeo KL, Solanki SK, Norris CM, Beeck B, Unruh YC, Krivova NA (2017) Solar irradiance variability is caused by the magnetic activity on the solar surface. Phys Rev Lett 119:091102. https://doi.org/10.1103/PhysRevLett.119.091102
Yiğit E, Knížová PK, Georgieva K, Ward W (2016) A review of vertical coupling in the atmosphere-ionosphere system: effects of waves, sudden stratospheric warmings, space weather, and solar activity. J Atmos Sol Terr Phys 141:1–12. https://doi.org/10.1016/j.jastp.2016.02.011
Yizengaw E, Zesta E, Moldwin MB, Damtie B, Mebrahtu A, Valladares CE, Pfaff RF (2012) Longitudinal differences of ionospheric vertical density distribution and equatorial electrodynamics. J Geophys Res 117:A07312
You XP et al (2012) Measurement of the electron density and magnetic field of the solar wind using millisecond pulsars. Mon Not R Astron Soc. https://doi.org/10.1111/j.1365-2966.2012.20688.x
Zhang SR, Holt JM, Erickson PJ, Goncharenko LP, Nicolls MJ et al (2016) Ionospheric ion temperature climate and upper atmospheric long-term cooling. J Geophys Res Space Phys. https://doi.org/10.1002/2016JA022971
Zhang R, Liu L, Le H, Chen Y (2017) Equatorial ionospheric electrodynamics during solar flares. Geophys Res Lett 44:4558–4565
Zhang QH, Zhang YL, Wang C, Lockwood M, Yang HG, Tang BB et al (2020) Multiple transpolar auroral arcs reveal insight about coupling processes in the Earth's magnetotail. Proc Natl Acad Sci USA. https://doi.org/10.1073/pnas.2000614117

Zhang J, Temmer M, Gopalswamy N et al (2021) Earth-affecting solar transients: a review of progresses in solar cycle 24. Prog Earth Planet Sci 8:56. https://doi.org/10.1186/s40645-021-00426-7
Zhang H et al (2023) Key questions of solar wind–Moon interaction. Space Sci Tech. https://doi.org/10.34133/space.0060
Zong Q (2022) Magnetospheric response to solar wind forcing: ultra-low-frequency wave–particle interaction perspective. Ann Geophys 40:121–150. https://doi.org/10.5194/angeo-40-121-2022
Zong QG, Zhou XZ, Wang YF, Li X, Song P, Baker DN, Fritz TA, Daly PW, Dunlop M, Pedersen A (2009) Energetic electron response to ULF waves induced by interplanetary shocks in the outer radiation belt. J Geophys Res. https://doi.org/10.1029/2009JA014393
Zong Q, Rankin R, Zhou X (2017) The interaction of ultra-low-frequency Pc3–5 waves with charged particles in Earth's magnetosphere. Rev Modern Plasma Phys. https://doi.org/10.1007/s41614-017-0011-4
Zong QG, Yue C, Fu SY (2021) Shock induced strong substorms and super substorms: preconditions and associated oxygen ion dynamics. Space Sci Rev. https://doi.org/10.1007/s11214-021-00806-x

Publisher's Note