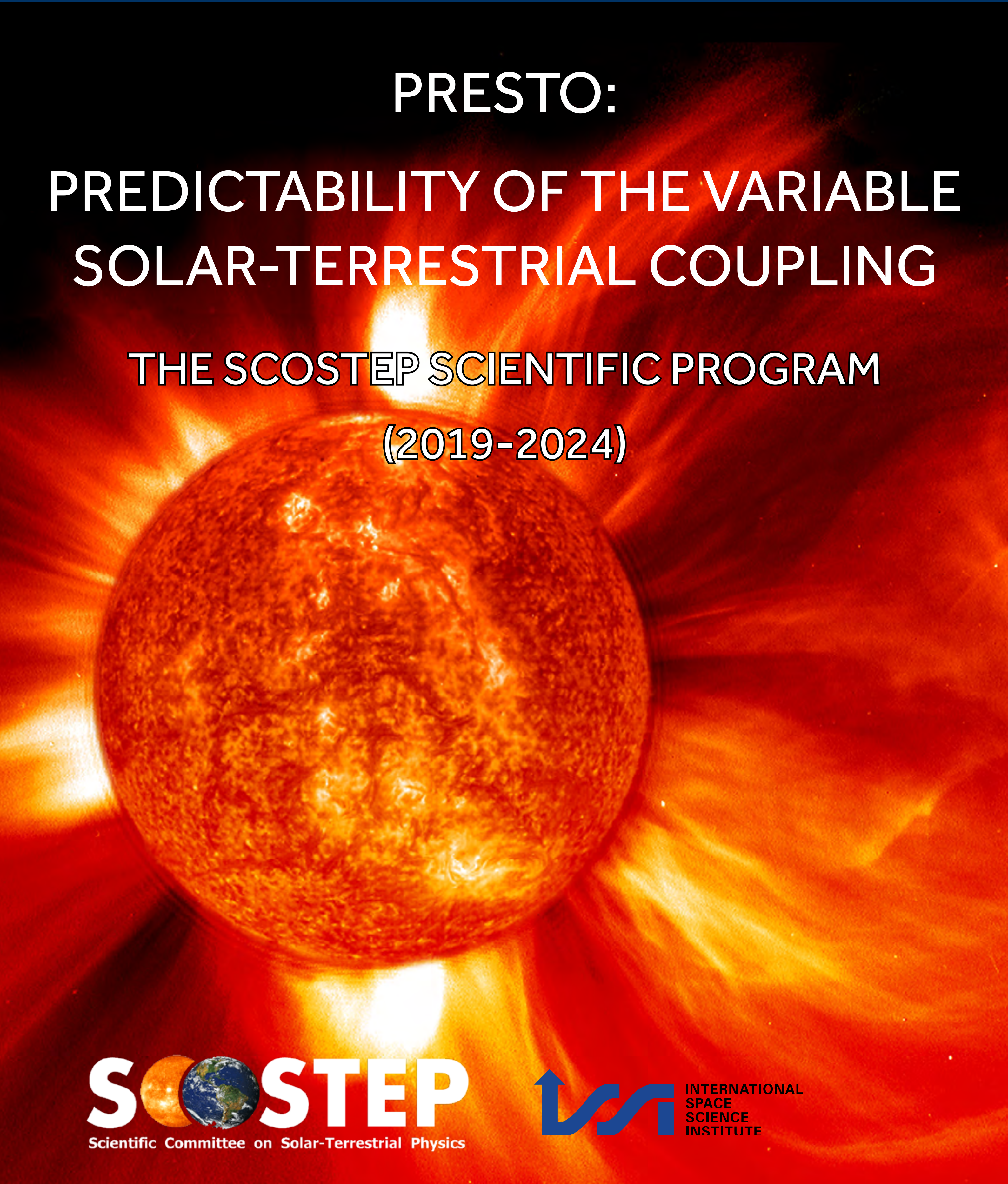
INTERNATIONAL SPACE SCIENCE INSTITUTE - BEIJING
国际空间科学研究所 - 北京

太空 | TAIKONG
ISSI-BJ Magazine
No. 13 June 2019

PRESTO:

PREDICTABILITY OF THE VARIABLE SOLAR-TERRESTRIAL COUPLING

THE SCOSTEP SCIENTIFIC PROGRAM (2019-2024)



SCOSTEP
Scientific Committee on Solar-Terrestrial Physics

INTERNATIONAL SPACE SCIENCE INSTITUTE

IMPRINT

太空 | TAIKONG
ISSI-BJ Magazine

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Front Cover

Coronal mass ejection. Credit: ESA/NASA/Soho

FOREWORD

The Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) was established in 1966 as an interdisciplinary body of ICSU, the International Council for Science. SCOSTEP is tasked with running long-term scientific program in Solar Terrestrial Physics, a topic closely aligned with several disciplines of the International Space Science Institute (ISSI). SCOSTEP is charged with seeking projects and programs that cross over traditional boundaries of physical regions and focused scientific disciplines. SCOSTEP's governing body is represented by five scientific unions (IAGA/IUGG, IAMAS, IAU, IUPAP, and URSI) and three interdisciplinary bodies (COSPAR, SCAR, and WDS) that have significant interest in solar-terrestrial relationship and its relevance to human society. SCOSTEP is a Permanent Observer to the United Nations Committee on Peaceful Uses of Outer Space (UNCOPUOS).

The formal interaction between ISSI and SCOSTEP started in 2012 based on an initial discussion between Professor Maurice Bonnet, the Executive Director of ISSI at the time and Dr. Nat Gopalswamy, the President of SCOSTEP during the COSPAR Assembly in Mysore India. The synergy between the two organizations was recognized and plans for cooperation was initiated.

SCOSTEP has three core activities: science, capacity building, and public outreach. Under science, SCOSTEP runs long-term scientific programs that focus on some aspects of the Sun-Earth system that are of current interest and address pressing questions. These programs are designed to be interdisciplinary and international in nature and carried out by scientists engaged in observations, theory, and modeling. The results are disseminated in symposia focused on the scientific programs. In addition, SCOSTEP has the tradition of the quadrennial solar terrestrial physics symposia that include topics over and above the current scientific program.

ISSI activities are also international and interdisciplinary in nature aimed at bringing observers, modelers, and theorists to tackle unsolved problems in space science. The scientific discipline of SCOSTEP is fully within the horizon of ISSI. This prompted SCOSTEP to establish the collaboration with ISSI in defining its long-term scientific programs after an ISSI forum dedicated for this purpose. Experts are identified from the scientific community and invited to the ISSI/SCOSTEP Forum where the final plan for the scientific program takes shape. The draft plan is then submitted to the SCOSTEP Bureau for consideration and implementation.

The successful SCOSTEP scientific program VarSITI (Variability of the Sun and Its Terrestrial Impact) that just concluded (2014-2018) was defined during the ISSI forum in May 2013 in Bern. In the current round, the SCOSTEP Forum has two parts; the first one was conducted in ISSI Beijing (ISSI-BJ) in order to facilitate scientists from the Asia region to participate in the deliberations. The second one is the current Forum at ISSI that finalized the next scientific program known as PRESTO (Predictability of the Variable Solar Terrestrial Coupling).

It is hoped that the interaction between ISSI, ISSI-BJ and SCOSTEP will continue in the form of international teams, working groups, and workshops that will be proposed to ISSI and/or ISSI-BJ as part of the implementation of PRESTO and enhance the science return.

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INTRODUCTION

Preamble

The Sun is a variable star and its variability influences the Earth's space environment. Furthermore, changing solar magnetic fields, radiative flux and energetic particle fluxes force the Earth's atmosphere and climate. Transient energetic events such as flares, coronal mass ejections (CMEs), interplanetary shocks, stream interaction regions (SIRs), corotating interaction regions (CIRs) and energetic particles adversely impact critical technologies based in space and on Earth that our society is increasingly dependent upon. At the same time, the middle and upper atmosphere/ ionosphere are impacted by processes originating at lower altitudes, e.g., by atmospheric gravity waves, tides and planetary waves and changes in radiatively active gases. With understanding of causal connections in the Sun-Earth system maturing over the last several decades, fueled by both observations and theoretical modelling, we are in a position to begin the transition of this understanding to predictions of the Sun-Earth coupled system of relevance to the society. PRESTO, the Next Scientific Program of SCOSTEP, aims at facilitating this interdisciplinary endeavor through focused, internationally coordinated efforts addressing predictability of the Sun-Earth system ranging across space weather and climate timescales. Synergies with existing national or international research programs are also encouraged.

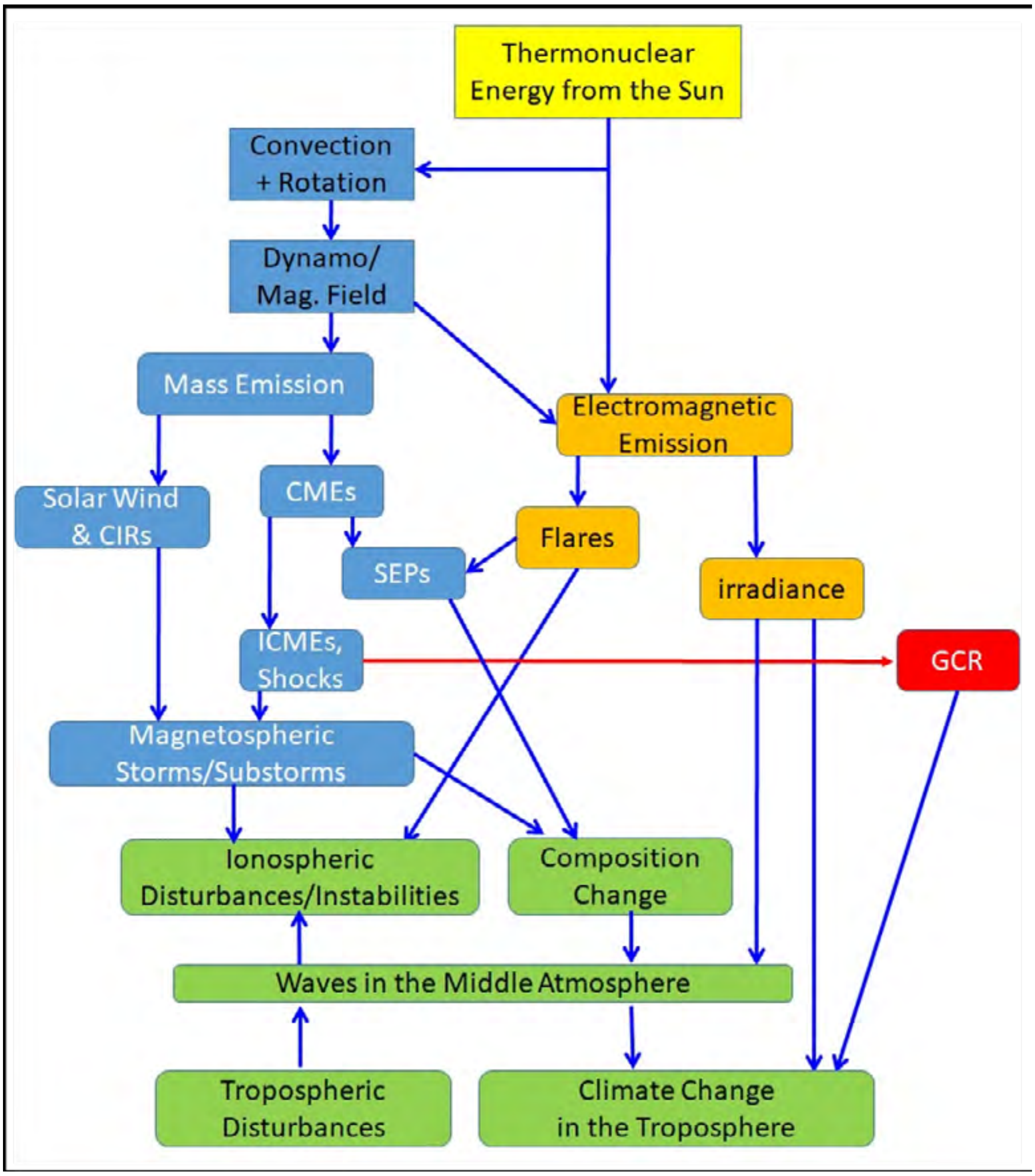


Figure 1: Four channels of energy flow in the solar-terrestrial system that SCOSTEP scientific programs generally address: mass (blue), electromagnetic (yellow/orange), Earth-to-space (green) and extra-heliospheric (red). CIR: corotating interaction region; CME: coronal mass ejection; SEP: solar energetic particle; ICME: interplanetary CME; GCR: galactic cosmic rays.

Executive Summary

The committee for the definition of the Next Scientific Program (NSP) for SCOSTEP has identified a theme of predictability as a unifying force for coordinating research and outreach activities for the period 2019-2024. The program would be named PRESTO: Predictability of the variable Solar-Terrestrial Coupling, and would be aligned along three pillars of research. What follows is a brief description of these pillars and of the key questions that need to be addressed over the duration of the next scientific program.

Pillar 1. Sun, interplanetary space and geospace

The properties of geoeffective solar events, such as CIRs, CMEs, and SEPs, the consequent solar wind – magnetosphere coupling and the internal magnetospheric dynamics play complex and intertwined roles in geospace weather. Accurate and reliable predictions of geospace weather (including the dynamics of all kinds of energetic particles and the terrestrial wave environment) require the understanding of the key aspects of the complex interplay of external and internal regulating factors operating over timescales ranging from milliseconds to days. In that respect, a major improvement for the long-term prediction of solar and interplanetary effects on geospace would be an advanced estimate of the geometry and nature of compression regions (fast/slow solar wind, CME sheaths) in addition to the magnetic structures embedded. However, there are still a lot of uncertainties in the observed parameters that are used to feed propagation and acceleration models, which need to be addressed.

Pillar 1 addresses the following overarching questions:

Q1.1 Under what conditions are solar eruptions, CMEs, and SEPs produced, and which indicators of pre-CME and pre-flare activity are reliable?

Q1.2 What are the required/critical model input parameters for most successfully forecasting the arrival of SEPs and the geoeffectiveness of CMEs, SIRs/CIRs and the consequences of the interactions between SIRs/CIRs and CMEs?

Q1.3 How are different magnetospheric disturbances and waves (which are critical for the ring current and radiation belt dynamics) driven by variable solar wind structures, and/or internal magnetospheric processes?

Q1.4 How can we improve the predictability of geomagnetic storms, substorms and radiation hazards, which impact the space environment and technological infrastructures (in space and on the ground)?

Pillar 2. Space weather and the Earth's atmosphere

The space weather of the middle and upper atmosphere (including ionosphere) is characterized by the variability occurring on timescales of minutes to weeks. This short-term variability is governed by several processes which partly originate at lower altitudes (e.g. planetary and gravity waves) but also come from outside the Earth's system (e.g. solar particles and radiation). The near-Earth space weather is of critical societal importance due to, e.g., its influence on communication and navigation operations. The second pillar of PRESTO aims at a better characterization, understanding and predictability of this variability.

The Space Weather and Earth's Atmosphere Pillar addresses the following overarching questions:

Q2.1 How does the thermosphere and ionosphere respond to various forcings from above and from below?

Q2.2 How do atmospheric waves and composition changes impact the middle and upper atmosphere?

Q2.3 What is the magnitude and spectral characteristics of solar and magnetospheric forcing, needed for accurate predictions of the atmospheric response?

Q2.4 What is the chemical and dynamical response of the middle atmosphere to solar and magnetospheric forcing?

Pillar 3. Solar activity and its influence on the climate of the Earth System

While we can make reasonably accurate predictions for weather and reproduce historical climate variability, there is a gap in our capability to make predictions over seasonal to decadal timescales. Better representation of the solar forcing (irradiance and particles) and the response of the atmosphere could be a pathway towards improved predictive skills to bridge the window between weather and climate. The third pillar seeks to improve the specification of forcing by translating our understanding of the solar interior to physics-based forecasting models of solar magnetic fields, total and spectral irradiance, solar open flux and solar particle flux variability across timescales relevant for the forcing of the Earth's atmosphere and climate. In addition, the program seeks to establish how solar signals are transmitted across various regions of the Earth's atmosphere with a view to identify causal connections across the Sun-Earth system. Accurate attribution of the observed Earth system variability to natural (with a focus on solar) and anthropogenic drivers is a concrete aim of this pillar. Trends in radiatively active gases and their role in changing the background state of the atmosphere and its capacity to alter solar driving are to be explored. Paleoclimate and solar activity reconstruction data are to be critically assessed with the aim of segregating natural and anthropogenic causes of climate change. Focus would be on both global and regional variability.

Pillar 3 addresses the following overarching questions:

Q3.1 How will future solar activity vary over timescales relevant for the forcing of the Earth's climate and atmospheric dynamics?

Q3.2 What is the role of coupling between atmospheric regions in the realization of the long-term solar influence on the Earth system?

Q3.3 How is the atmospheric response to the variable solar forcing affected by, and interacts with, increasing greenhouse concentrations?

Q3.4 How can solar activity predictions be used to improve atmospheric prediction on sub-seasonal to decadal timescales?

PRESTO - THE NEXT SCIENTIFIC PROGRAM OF SCOSTEP

Introduction

The predictability of the Sun-Earth System on timescales from a few hours to centuries seems to be a timely scientific topic for the next scientific program; it furthermore combines the interests of different topical communities in a relevant way. PRESTO will address the predictability of 1) space weather on timescales from seconds to days and months, including processes at the Sun, in the heliosphere and in the Earth's magnetosphere, ionosphere and atmosphere, 2) sub-seasonal to decadal and centennial variability of the Sun-Earth system, with a special focus on climate impacts and a link to the World Climate Research Program (WCRP) Grand Challenge Near-Term Climate Predictions as well as the IPCC.

A major motivation for the NSP is the desire to conduct fundamental research that has the promise to advance predictive capability with societal implications. Extreme events, i.e., Carrington event size solar eruptions and geospace storms, have attracted particular attention lately. They are rare but if they occur and impact the Earth, they can have potentially devastating effects on the modern technology infrastructure in space and on ground. On longer timescales, there is a pressing need to be able to separate natural from anthropogenic forcing of Earth's climate. Predicting the Sun-Earth system as a whole is highly challenging. Besides the different timescales discussed previously, this topic covers non-linear and multi–scale phenomena in highly different plasma and neutral fluid domains that are often coupled in a complex way from the Sun to the Earth's atmosphere and oceans. Furthermore, different communities in the field are often separate, and use different models, terminology and approaches in their studies.

It is hoped that by selecting predictability as an overarching theme for the NSP, it will encourage the SCOSTEP community to view the various sub-domains within solar-terrestrial physics as part of a chain within a coupled system, as illustrated in the attached graphic. By better understanding this chain and its various links we aim to improve prediction of phenomena that have significant

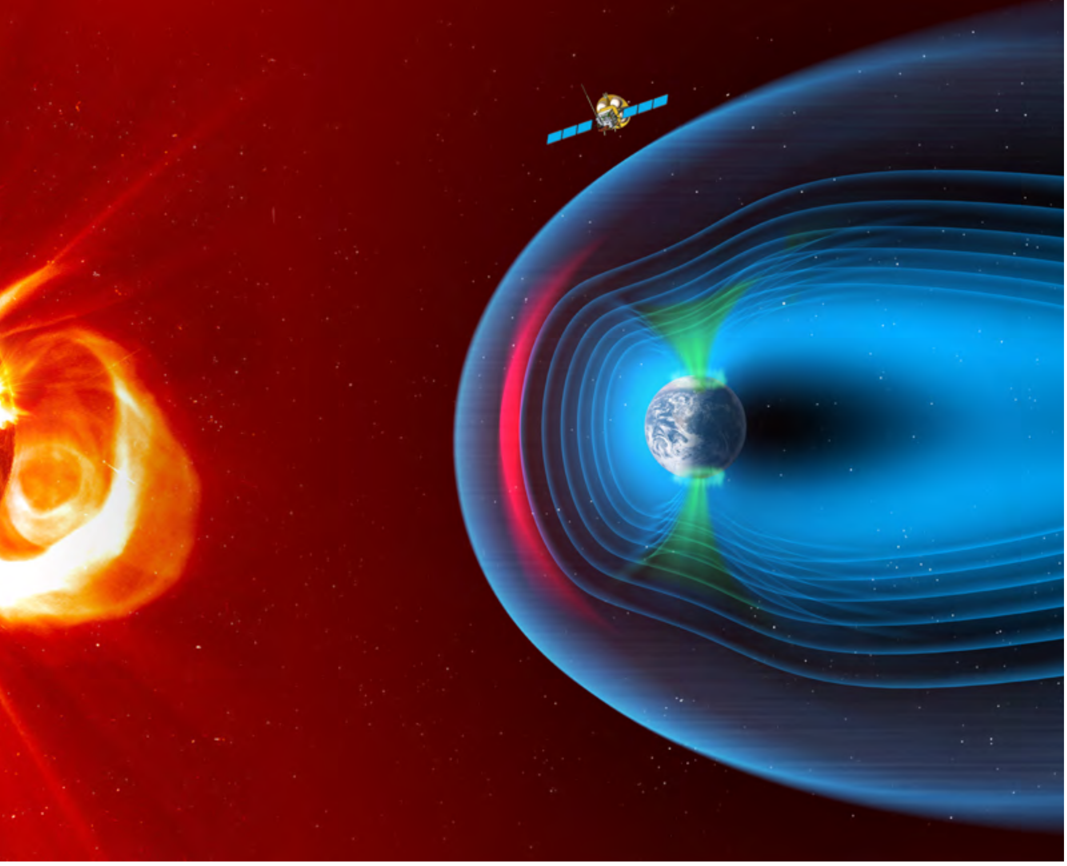


Figure 2: The Sun-Earth system can be severely disturbed by coronal mass ejections shown at the left part of the figure. CME-driven shocks accelerate particles to high energies. The shocks can also compress the magnetosphere sometimes exposing satellites to the solar wind. The CME magnetic fields can interact with the Earth's magnetic field causing geomagnetic storms (image credit: ESA)

societal relevance. Advancement in this area will require improved synthesis of observations and models, along with improvements in tools such as data assimilation and statistical analysis. It is hoped that viewing the problem in terms of timescales will foster a more interdisciplinary view and increase collaboration within SCOSTEP. Below, specific areas of scientific focus are listed where progress needs to be achieved to significantly improve our predictive skill of the solar-terrestrial system.

1. Sun, interplanetary space and geospace

This theme addresses the questions related to the properties and the predictability of solar eruptions, namely Coronal Mass Ejections (CMEs) and flares, large-scale heliospheric structures, including interplanetary CMEs (ICMEs), Corotating Interaction Regions (CIRs), interactions (CIR-CME, CME-CME), and Solar Energetic Particles (SEPs), as well as their consequences in geospace (substorms and storms, radiation belts and the ring current), including the complex coupling between different domains and populations.

1.1. Solar and Interplanetary Drivers

1.1.1. Predictability of Coronal Mass Ejections, flares, and SEPs

Predicting the occurrence of large solar flares and CMEs, and the arrival and properties of Earth-impacting CMEs, are major challenges of solar-terrestrial studies. The relevant time-scales vary from seconds/minutes/hours, for flares and the eruption of CMEs, to the several days it takes for a CME to propagate from the Sun to the Earth. The frequency and properties of CMEs and flares also vary in accordance with the Sun's 11-year activity cycle and overall solar activity levels. While the occurrence rate of flares and CMEs of moderate to strong size increases with increasing solar cycle strength, it is still an open question how the occurrence of the most extreme eruptions correlates with the solar cycle amplitude. Investigation of the solar flare spectral irradiance is also required to define better the input for ionospheric variability models and societal impact.

The formation of the eruptive structures at the Sun can take from hours to days, but their destabilization is a fast process, occurring when the energy stored in highly sheared or twisted field along magnetic photospheric polarity inversion lines (PILs) is rapidly released by some form of magnetic reconnection. In some cases, the eruptions result in geoeffective SEP events. The probability of flares and CMEs to occur depends on properties of sunspots and solar active regions, such as the degree of non-potentiality of the magnetic field and the amount of magnetic helicity (i.e. how twisted, linked and sheared the magnetic field lines are). It is a current consensus that magnetic flux ropes are an integral ingredient of erupting CMEs. There is however no suitable model yet to predict when a flare and/or a CME might occur, and we do not yet understand adequately the mechanisms that trigger and drive the eruption. This is particularly problematic from the space weather point of view, because X-ray/EUV emission and energetic particles arrive at Earth on a timescale of only minutes following flare onset.

The time needed for a CME to arrive at Earth varies from about half-a-day to days, depending on the initial speed of the CME and the speed of the ambient solar wind. Continuous direct observations of CMEs are available from the L1 Lagrange point, but from there it takes only from about 0.5-1 hours for CMEs and the solar wind to reach Earth. The accuracy of long-lead-time space weather predictions is still very modest. The key challenges in making such predictions for CMEs are:

1. To estimate realistically initial properties of CMEs (acceleration, speed, geometrical parameters, propagation direction, flux rope magnetic properties) from on-disk and off-limb observations, and from factors including coronal field structure in the neighborhood of the eruption.

2. To estimate accurately when and how CME properties will evolve during propagation from the Sun to the Earth, and when they will impact the Earth. This includes consideration of how CMEs can be altered during propagation through interactions with the ambient solar wind (e.g., high speed solar wind streams from coronal holes) and with other CMEs; such interactions can significantly deform, erode, deflect and rotate CMEs.

3. To predict the properties of the sheath regions of CMEs.

CME's kinematic and geometrical parameters and their propagation direction can be estimated from remote-sensing observations and related reconstruction techniques (e.g., reconstructions based on multi-spacecraft interplanetary observations in white light or ground based observations using radio interplanetary scintillation method), but the measurements are often subject to significant projection effects. It is well known that the directivity and flux rope magnetic properties of the resulting CME are strongly shaped by coronal magnetic structures of the erupting system and in its immediate vicinity. However, due to the lack of observations of the magnetic field in the CME and in the surrounding corona, determining these propagating CME properties is particularly challenging for forecasting ("Bz challenge").

Current attempts to estimate the magnetic field in CME flux ropes include using indirect solar proxies (based on EUV and X-ray observations and magnetograms) and data-driven coronal modeling. The magnetic field direction and strength dictate how effectively magnetic reconnection between the interplanetary and geomagnetic field develops. Because the timing of a geomagnetic storm depends on what part of the ICME holds the strongest southward magnetic field, the above-noted uncertainties in magnetic properties currently results in differences of up to one day in estimates of storm-occurrence times.

In recent years, there has been substantial improvement in predicting CME Earth-arrival times using MHD simulations (e.g., ENLIL, EUHFORIA, SUSANOO). There has also been progress in semi-empirical/analytical models (e.g., DBM), combined with observational techniques, such as interplanetary scintillation, wide-angle heliospheric imaging, and radio waves generated at the CME shocks, as well as some adaptive numerical methods. Much of these advances have benefited from dedicated "campaign studies," as well as real-time-prediction services, both of which rely upon close interaction and communication between modeling and observations. There is however no model yet that consistently makes accurate predictions of the ICME arrival times and impact details (i.e., whether a CME will make a direct hit or a glancing blow with Earth) and captures details of all major CME deformations. For example, the drag force of the ambient solar wind on CMEs can vary substantially from case to case, and numerical simulations are not yet routinely run with flux rope CMEs, thus lacking capability to predict accurately their magnetic properties. As a consequence of the evolution and interactions, ICMEs may have a highly complex structure. For example, a flux rope may not be present at all, or it might occupy only a part of a distorted ICME structure. Multiple CMEs can also merge to form "complex ejecta," where the characteristics of the individual CMEs are lost, or the following CME can strongly compress the field of the leading CME; the latter case can result in particularly severe space weather effects. Another recently highlighted important outstanding question for space weather is how coherent CME flux ropes are. Several studies suggest that the properties of a CME flux rope (e.g., their orientation) may change considerably over relatively small longitudinal separations (about a few degrees).

Regarding CME sheaths, the critical issue is their highly turbulent nature and strong internal variations. Sheaths can drive major geospace storms independent of whether the CME flux rope will be geoeffective, and they have particularly strong effects at high latitudes. Currently, there is no practical way to estimate in advance sheath properties. Also, required for accurate understanding of sheaths is a determination of whether magnetohydrodynamic (MHD) models are capable of predicting their turbulent properties, or if a kinetic/hybrid approach is required. Resolving in more detail the internal sheath structure, and determining how it depends on the driver (CME and shock) and the ambient solar wind may also help in predicting their space weather response.

Furthermore, SIRs/CIRS can drive interplanetary shocks (ISs). IS-magnetosphere interaction and IS geoeffectiveness is influenced by properties of the solar wind through which an IS propagates. The latter includes characteristics of turbulence and the IS interaction with various quasi-stable solar wind structures, i.e. other ISs, streams and the heliospheric current sheet (HCS). On the other hand, an IS itself generates a turbulent wake downstream, which is called the "sheath" in the ICME case.

Finally, some percentage of space-weather-relevant CMEs are not well observed, due to a lack of typical low-coronal pre-eruption and eruption-time signatures. These so-called "stealth CMEs" sometimes lead to "problem geomagnetic storms", which are storms for which the cause (in this case, the source stealth CME) is not obvious. Observational, theoretical, and numerical simulation studies are essential to understanding the mechanism(s) triggering stealth CMEs, and their propagation characteristics in the ambient solar wind.

1.1.2. Predictability of geoeffective structures of interplanetary space - CIRs/SIRs and fast solar wind streams

There are additional challenges in determining and predicting the structuring of interplanetary space and space weather effects resulting from corotating interaction regions (CIRs), which can repeat for several solar rotations, and of less-long-lived stream interaction regions (SIRs). Geoeffective CIRs/SIRs that bring compressed (dense) stream interface regions and subsequently fast solar wind plasma to the terrestrial magnetosphere, are formed as a result of the interaction of expanding high-speed flows from coronal holes (CHs) with slower ambient solar wind. Since CHs can appear at any time throughout the solar cycle, and because their shape is irregular and evolves with time, forecasting CIR/SIR encounter with the Earth's magnetosphere represents a particularly formidable task. Such forecasting however is critically important, as CIRs/SIRs and fast solar wind streams are the main triggers of geomagnetic storms in the absence of solar active regions and CMEs. They also represent a major source of energetic particles in the heliosphere during solar minima, and they are highly important for causing acceleration of electrons to relativistic energies in the Van Allen radiation belts; these are all crucial space weather considerations that cannot be ignored. Moreover, CHs often co-exist with active regions, especially around solar maximum, resulting in complex and poorly-investigated effects as streams from different sources interact, both in the corona and in the solar wind, on their way to the Earth. CMEs are also often compressed within CIRs/SIRs; these interactions can significantly enhance the geoeffectivity of both the CME and the CIR/SIR, leading to particularly strong geospace responses. CIRs/SIRs can also significantly change the path and/or orientation of CMEs in the heliosphere (cf. Section 1.1.1).

The internal structure of CIRs/SIRs is also a major open research question with significant space weather consequences. Recent studies suggest that CIRs/SIRs could frequently embed small-scale streamer-belt blobs and flux ropes. It is not known how the presence of these magnetic elements modify the SIR/CIR structure, and what consequences they imply for geoefficiency. Current coronal magnetic field models (numerical, analytical, and non-linear) use as boundary conditions photospheric field measurements (line-of-sight component averaged over a solar rotation, and/or actual vector magnetic fields). These measurements are then extrapolated to estimate/infer the 3D open/closed coronal and solar wind magnetic structure and the presence of high-speed streams. Refinements of these observational and modeling techniques are essential for improving space weather forecasting.

1.1.3. Predictability of interplanetary shocks and energetic particle flux enhancements

Solar energetic particles (SEPs) with energies overlapping with cosmic ray energies present a major space weather hazard. Predictability of the occurrence of solar radiation storms, characterized by severe enhancements of the solar energetic particle flux, strongly depends on the predictability of flares and properties of CMEs (see above). In addition to their critical role in local particle acceleration, interplanetary shocks (ISs) are highly geoeffective in terms of their interaction with the terrestrial magnetosphere. At the Earth orbit most ISs are forward shocks driven by CMEs. ISs are also formed at leading/trailing edges of CIRs/SIRs, but typically far from the Earth, at 2-3 AU. Consequent differences in propagation and inclination of shock fronts to the interplanetary magnetic field direction determine peculiarities of their geoeffectiveness and the efficiency of particle acceleration, which is still investigated insufficiently. Theoretical studies of the fundamental properties of shock waves in the solar wind plasma are needed.

Owing to the strong nonlinearity of processes of particle acceleration and IS-magnetosphere interaction, IS geoeffectiveness is impacted by properties of the solar wind through which an IS propagates. The latter includes characteristics of turbulence and the IS interaction with various quasi-stable solar wind structures, i.e. other ISs, streams and the heliospheric current sheet (HCS). On the other hand, an IS itself generates a turbulent wake downstream, which is called the "sheath" in the ICME case.

1.2. Solar-wind magnetosphere coupling, internal magnetospheric dynamics, and the predictability of substorms and geomagnetic storms

Solar wind–magnetosphere coupling and internal magnetospheric dynamics play complex and crucial roles in geospace weather. Accurate and reliable predictions of geospace weather require the understanding of all key aspects of the complex interplay of external and internal regulating factors operating over timescales ranging from milliseconds to days. Radiation belts, in particular, can experience drastic changes in timescales as short as minutes, while as mentioned above, a substorm cycle lasts a few hours and a geomagnetic storm several days.

While general interplanetary constraints for causing significant geospace storms are relatively well understood, e.g., the crucial importance of the interplanetary magnetic field (IMF) southward component and solar wind speed, there a several open questions related to the details the coupling. Some relevant outstanding questions include such as:

- How do various solar wind conditions (e.g. IMF components, speed, density, level of turbulence) and different large-scale drivers (see Sections 1.1 and 1.2) control coupling efficiency and energy/mass transfer from the solar wind to the magnetosphere?

- How do solar wind conditions control the occurrence frequency and location of magnetospheric waves?

With regard to internal magnetospheric dynamics, some of the most pertinent open issues are:

- How do electromagnetic waves of various modes in the inner magnetosphere (e.g., ULF, chorus, EMIC waves) influence acceleration, transport and losses of radiation belt electrons?

- How do both external and internal processes drive and regulate such waves and determine which mechanisms dominate for energetic particle dynamics?

- How do other plasma populations in the inner magnetosphere, such as the plasmasphere and ionosphere (including ion outflow), influence and contribute to energetic particle dynamics?

As these are key issues in the predictability of the geospace radiation environment, studies to address them using coordinated space-borne and ground-based instrumentation along with models are of essential importance (see also Section 4 on instruments).

Magnetospheric substorms and storms are the most important collective phenomena in geospace, dissipating the energy transferred by the solar wind to the magnetosphere. While a substorm cycle lasts approximately 2-3 hours, a storm may last from few hours even to weeks. Substorms with significant space weather effects can also occur without magnetic storms. Importance of storms/substorms for space weather relates to several aspects:

- They generate waves (through substorm-injected electrons and ring current ion anisotropies), that can accelerate electrons to relativistic energies, which are the causes of internal charging of satellites.

- They are responsible for geomagnetically induced currents (GICs), which are a serious threat for power grids

- They supply energetic electrons to the inner magnetosphere, which form the seed population for relativistic electrons in the outer Van Allen belt. Seed electrons pose themselves a threat to satellites through surface charging.

There have been several prediction models for Dst (storms, i.e. the intensity of the ring current) and AL (substorms, auroral electrojet currents). Due to the importance of both phenomena, the scientific community should continue the effort of improving such prediction models, e.g., understanding the substorm triggering mechanism, in particular, is a pertinent science research topic and should be taken into account in any prediction model. Key model items include the timing of substorm onset, and the intensity, spatial location and extent of the substorm.

The grand challenge questions identified for this pillar are:

- Q1.1 Under what conditions are solar eruptions, CMEs, and SEPs produced, and which indicators of pre-CME and pre-flare activity are reliable?

- Q1.2 What are the required model input parameters for most successfully forecasting the arrival of SEPs and the geoeffectiveness of CMEs, SIRs/CIRs and the consequences of their interactions?

- Q1.3 How are different magnetospheric disturbances and waves (which are critical for the ring current and radiation belt dynamics) driven by solar wind structures and variations, and/or internal magnetospheric processes?

- Q1.4 How can we improve the predictability of geomagnetic storms, substorms and particle radiation enhancements, allowing forecasting of their impact on both the space environment and on infrastructures on the ground and in space?

2. Space weather and Earth's atmosphere

This theme addresses the consequences and societal impacts of solar-induced effects and atmospheric variability. Coordination and interaction between researchers examining the phenomena at both large- and small-scales (days to seconds and global to millimeter) is encouraged to foster collaboration in achieving the scientific objectives.

2.1. Thermosphere and ionosphere response to various forcings from above and from below

The thermosphere and ionosphere are driven by both the upward coupling from waves originating in the lower atmosphere and downward coupling from solar and magnetosphere forcing. Understanding the response to these forcings is critical for specification and prediction of the thermosphere and ionosphere, and their impact on communication and navigation operations.

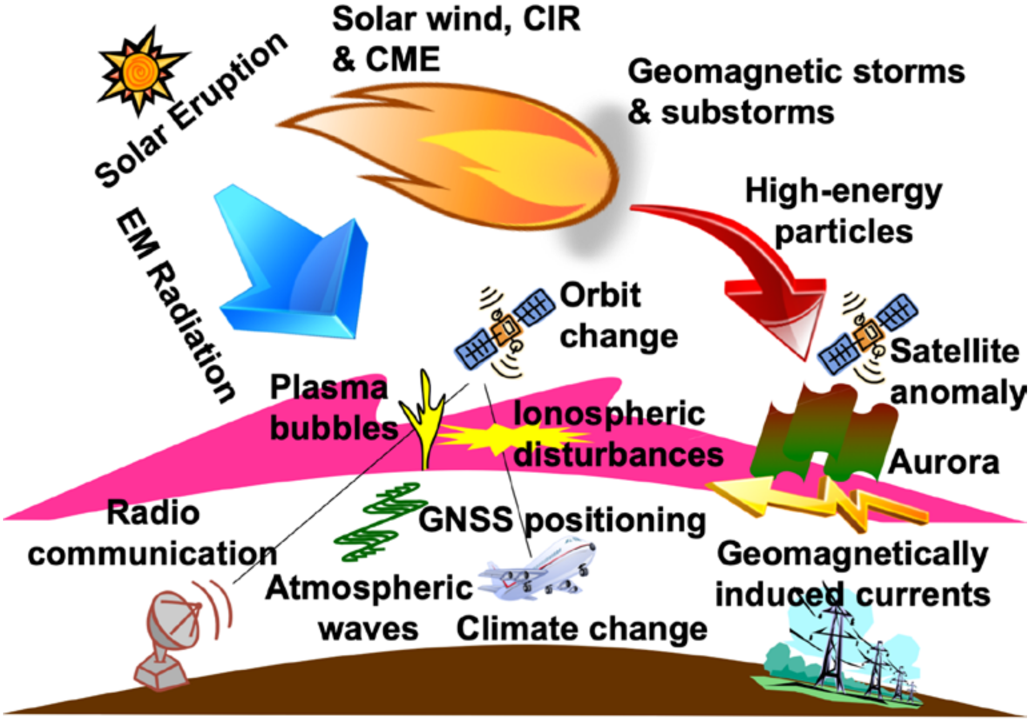


Figure 3: Space Weather in the vicinity of Earth is determined by solar mass and electromagnetic (EM) emissions. The mass emission is in the form of coronal mass ejections (CMEs) and the solar wind. Both carry magnetic fields with them. EM radiation during flares at X-ray and extreme ultraviolet wavelengths change the conductivity of the ionosphere, while microwaves from flares can drown signals from Global Navigation Satellite System (GNSS). GNSS signals are also affected by plasma bubbles and other ionospheric disturbances (Image credit: K. Shiokawa).

Recent ground and space-based observations, combined with the development of whole atmosphere models have led to increased understanding of how the thermosphere and ionosphere respond to forcing from above and below.

This area of research lies in better understanding of the internal variability and to improve the predictability of phenomena such as, particle precipitation, electric field penetration, Joule heating and Lorentz force at high latitudes, plasma irregularity, scintillations, travelling ionosphere/atmospheric disturbances, equatorial electrojet, equatorial ionization and temperature anomaly, Sq currents, polar mesospheric clouds, sudden stratospheric warmings, polar mesospheric summer echoes, and tropospheric convections. Specific questions related to this focus area include:

1) What is the response of the thermosphere and ionosphere to magnetospheric forcing?

2) What is the influence of the lower atmosphere on ionosphere and thermosphere dynamics?

3) What are the factors controlling the occurrence of equatorial plasma irregularities and what are their relative importance?

4) How and in what ways do solar flares modulate the terrestrial atmosphere?

5) What are the technological consequences (e.g., GNSS positioning and radio wave propagation) of ionospheric variability?

The community should continue to work on advancements of the aforementioned science issues in order to enhance understanding of vertical and horizontal coupling produced by factors from above and below the ionosphere/thermosphere region.

2.2. Impact of atmospheric waves and composition change on the middle and upper atmosphere

The results from the past decade have shown that wave sources originating in the lower atmosphere, such as tides, planetary and gravity waves can have a significant and persistent effect on the variability and structure of the middle and upper atmosphere. These sources can be generated by convection and jet streams in the lower atmosphere, SSWs (Sudden Stratospheric Warmings) in the middle atmosphere, as well as wave breaking and mixing in the upper atmosphere. These waves span a large spatial and temporal spectrum, ranging from small-scale gravity and acoustic waves with durations of minutes, to the global-scale tides and planetary waves which vary on daily, seasonal, and interannual time scales. As they propagate upwards, atmospheric waves can have a considerable impact on the middle and upper atmosphere. This is primarily through wave dissipation, but the waves themselves also represent an important source of variability in the middle and upper atmosphere. Of critical importance is understanding how the wave spectrum evolves with altitude, and its consequent impacts on the middle and upper atmosphere. Among the key questions to be considered are:

1) How do we quantify the effects of gravity waves, planetary waves, and tides (and their interactions) on the middle and upper atmosphere dynamics and chemistry?

2) What is the extent that SSWs couple the whole atmosphere, including effects on dynamics, composition, and chemistry?

3) Can gravity waves be better defined in terms of the mesoscale GW spectrum, amplitude, and vertical penetration into the thermosphere?

4) What is the predictability of atmospheric waves and their effects on the middle and upper atmosphere?

5) How do the various waves contribute to the global dynamics of the thermosphere and ionosphere?

Long-term changes in atmospheric composition (e.g., CO2, O3) may also have consequences for the short-term variability of the middle and upper atmosphere. This could either occur directly through changes in the wave forcing, or by changes in the mean flow which impact the wave propagation. The thermosphere is additionally radiatively cooled following geomagnetic storms by CO2. An increase in baseline CO2 levels thus has the potential to lead to a different response of the thermosphere to geomagnetic disturbances. Questions that may be addressed related to the role of changing composition on the middle and upper atmosphere variability include:

6) How does long-term changes in composition impact the wave spectrum in the middle and upper atmosphere?

7) To what extent do changes in CO2 influence the radiative cooling of the upper atmosphere?

2.3. Magnitude and spectral characteristics of solar and magnetospheric forcing

Earth's atmosphere and ionosphere are significantly affected by the increased energy deposition that occurs during solar and magnetospheric driven disturbances. Solar flares provide significant changes on the ionosphere and thermosphere. Geomagnetic disturbances, including storms and substorms, provide energy input into the high-latitude atmosphere which eventually propagate to lower latitudes. Various magnetospheric processes, such as plasma waves and pitch angle scattering, cause precipitation of the energetic particles from the magnetosphere to the ionosphere. These different sources of energy inputs into the ionosphere and thermosphere are complex, and modeling/observation efforts are necessary to improve specification of the energy inputs. Predictive skill of the mesosphere, thermosphere, and ionosphere depends upon accurate specification and prediction of the different solar and magnetospheric forcing. Critical areas to be addressed include:

1) What is the magnitude, spectra, and location of particle precipitation from the magnetosphere to the ionosphere and atmosphere?

2) What are the global electric currents and electric fields imposed from the magnetosphere to the ionosphere?

3) How to predict and quantify the likelihood of occurrence of solar flares and their spectral characteristics? (strong connection to section 1.1.1)

4) What is the uncertainty in specifications of solar and magnetospheric forcing, and the resultant response in the atmosphere?

2.4. Role of solar and magnetospheric forcing on the middle atmosphere

Energetic particle precipitation (EPP) from solar eruptions, galactic cosmic rays, and Earth's magnetosphere penetrate into the atmosphere. EPP deposit energy and trigger local ionization which perturbs the chemical and thermal structure of the middle atmosphere at high latitudes. Notably, EPPs induce a production of nitrogen oxides (NOx) and hydrogen oxides (HOx) that strongly contribute to ozone depletion in the mesosphere and stratosphere. Ozone changes could then affect the radiative balance which in turn would modulate the atmospheric dynamical state of the middle atmosphere. The resulting changes in the state of the middle atmosphere will affect the propagation of waves into the upper atmosphere, thus providing another pathway in which EPP could affect the upper atmosphere and ionosphere. Though EPP events are themselves relatively short-term processes, EPPs may introduce longer term variability due to the differences in particle forcing during solar maximum versus solar minimum. For this reason, EPPs have been recognized as one part of the solar-climate connection by the climate community, and has been included recently in the CMIP6 recommended solar forcing, and are important for Pillar 3 of PRESTO.

The source region of EPP generated NOx and HOx is the mesosphere and lower thermosphere (MLT, 70-150 km), an altitude region not included in most climate models. A better representation of the MLT is required in order to improve our understanding of the EPP effect on the middle atmosphere and climate. Although significant progress has been made in recent years, there remain discrepancies of an order of magnitude (or more) between modeled and observed NOx. Potential reasons of the model-observation discrepancy include inaccurate magnetospheric inputs, ionization rates, and underrepresentation of the downward transport. Evaluating the reasons for these discrepancies is critical for improving the representation of EPP in climate models. The complex chain of coupling processes that have an end result of dynamical changes in the lower-middle atmosphere are also not well understood.

The grand challenge questions identified for this pillar are:

Q2.1 How does the thermosphere and ionosphere respond to various forcings from above and from below?

Q2.2 How do atmospheric waves and composition changes impact the middle and upper atmosphere?

Q2.3 What is the magnitude and spectral characteristics of solar and magnetospheric forcing, needed for accurate predictions of the atmospheric response?

Q2.4 What is the chemical and dynamical response of the middle atmosphere to solar and magnetospheric forcing?

3. Solar activity and its influence on climate

3.1. Solar activity: Understanding the past and predicting the future

The next 5 years in the run-up to Solar Cycle 25 provide an excellent opportunity for understanding solar cycle predictability and assessing data-driven magnetohydrodynamic (MHD) dynamo models of the solar cycle. Decadal timescale activity is typically parametrized in variations of the sunspot

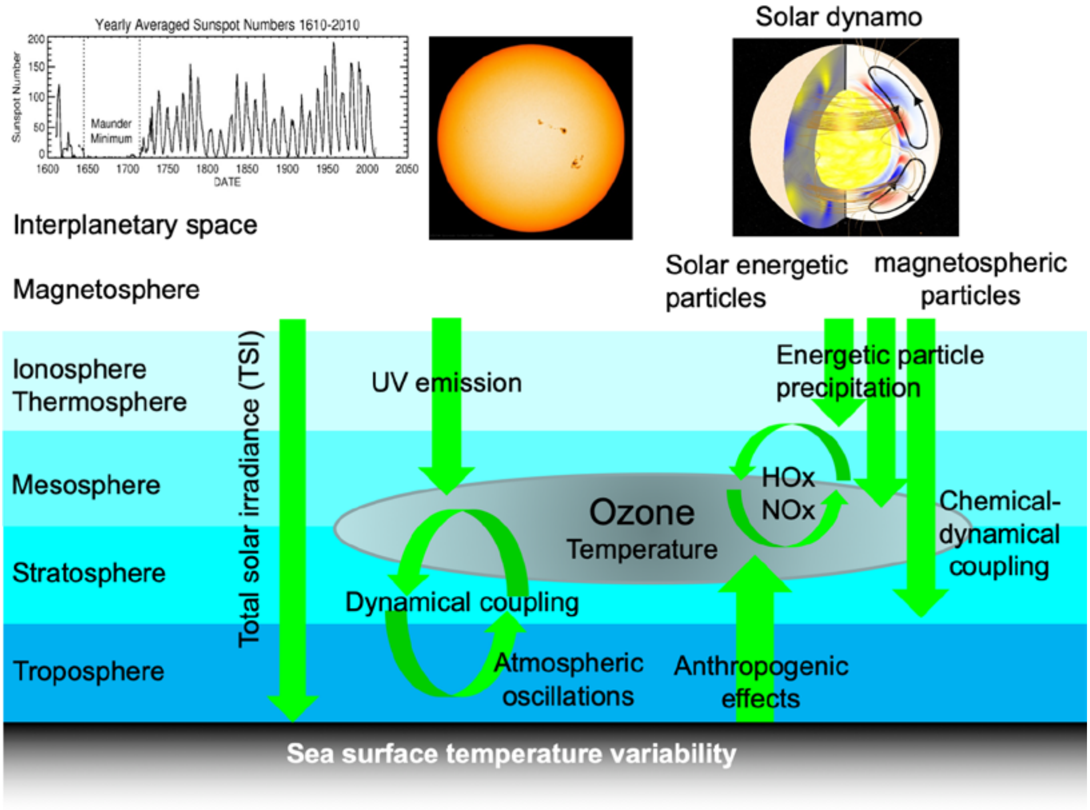


Figure 4: : Sunspots emerging from beneath the solar surface due to the solar dynamo and the variation of the sunspot number as a function of time. Particle and electromagnetic emission from the Sun affecting various layers of Earth's atmosphere. Sunspot number plot and solar image credit: NASA. The dynamo figure credit: A. Jaramillo-Muñoz. Schematic figure credit: L. Gray.

number or surface magnetic flux that can be simulated by data driven solar dynamo models. Surface flux emergence and its evolution driven by flux transport processes govern the Sun's polar field reversal, distribution of open and closed magnetic field lines and the large-scale structuring of the corona. These models are now capable of separately predicting the Northern and Southern hemisphere activities which may be used for assessing asymmetry related impacts on the heliosphere. Space weather and climate drivers, such as probable frequency of coronal mass ejections (CMEs) and flares, spectral and total irradiance variations, open flux variations and cosmic ray fluxes expected over decadal timescale may be derived from these dynamo and surface flux transport model-based predictions.

Quasi-periodic bursts in solar activity, manifest in sub-annual to annual-scale. Short-term fluctuations are also apparent in the sunspot time series which may have important space weather consequences. Understanding and predicting these quasi-periodic variations may therefore benefit short-term space weather and long-term space climate assessment. A dynamical memory on the order of solar rotation timescale exists in the large-scale coronal structure which may be used for predicting the evolution of global coronal and heliospheric field up to a month ahead. This may allow similar time windows for predicting the structure and strength of the solar wind, interplanetary (open) magnetic flux and cosmic ray fluxes.

On shorter timescale of days, both active region properties and MHD simulations are currently generating likelihood predictions of flares, CMEs and solar wind conditions, which are being used by operational space weather agencies, e.g., NOAA Space Weather Prediction Center (SWPC). These necessitate continuous measurements of vector magnetic fields of solar active regions (ARs) and exploring which near-Sun properties determine eruptive potential. Machine learning techniques are beginning to be applied to these data-based approaches. Computational approaches include data-driven coronal field modeling techniques that are becoming more complex and sophisticated with increasing computing power.

Uncertainties remain in terms of a) Underlying assumptions in dynamo models and differing predictions (e.g., solar cycle 24), b) Prediction of the timing and properties of solar eruptions and c) seamlessly bridging different timescales. Solar cycle predictability beyond a decade also remains a major open question and some studies indicate this is not possible. Would we have a solar cycle 25 or would there be an imminent slide to a Maunder minimum like phase? Critical comparative assessment of theoretical-computational models of solar activity, testing their underlying assumptions, and confronting them with past data may lead to transformative progress in understanding and predicting solar activity in the next decade. Such advance would enable accurate, physics-based inputs from the Sun to global climate models.

Assessing how solar activity models perform require their testing with historical datasets. Reconstruction of past solar activity and long-term climate variations (across centuries) also opens-up the possibility of segregating natural and anthropogenic causes of climate change. In the industrial and post-industrial era, anthropogenic forcing clearly dominates over natural climate drivers and thus going back to the pre-industrial era to establish the role of natural drivers is crucial; however large uncertainties remain. There are information gaps, e.g., for past solar spectral irradiance variations over millennia timescale and the floor of activity during the Maunder minimum. How about solar driven regional, as opposed to global climate impacts and solar driven impacts on large scale atmospheric and ocean circulations? These questions need to be addressed to understand and assess the system-wide impact of solar variability. Thrust should be on deciphering the physical pathways of Sun-Climate relationships, e.g., what physics of atmospheric systems is impacted by solar variability, rather than focusing simply on the global temperature - which is a net outcome of diverse factors.

3.2. Sub-seasonal to decadal variability of the terrestrial system

A grand challenge for predictions of the geospace environment is to bridge the gap between weather and climate timescales. The sub-seasonal to seasonal (S2S) to decadal timescales are of particular interest. These are the timescales that are considered most relevant by policy makers and drive decisions in terms of, e.g., infrastructure investments or land use. Forecast systems can already predict weather out to several weeks with reasonable accuracy and variations on centennial scales are well represented in climate models. It seems reasonable to assume that some progress can be made in the intermediate timescales if we can simultaneously improve the forcing of the Earth system as well as the understanding of its response. Better prediction of the solar and geomagnetic forcing, with their inherent 11-year variations, and improved characterization of the atmosphere-ocean response to that forcing could be one way to make progress, and one of the objectives of this program. For space weather (see section 1) the timescales are much shorter. Further, there are good reasons to believe improvements in geospace prediction (especially under quiet solar conditions) could come from better characterization of the forcing from below. For example, stratospheric vortex variations (such as SSWs) have timescales on the order of weeks and it has been shown that they affect the ionosphere, the troposphere and surface weather and climate through their interactions with upward propagating waves. This driving should be integrated into space weather forecast systems. Further progress can also be made via data assimilation to create improved initial states for forecast systems. It is critical to understand where the data and knowledge gaps are and try to address them. Expected societal benefit could be used to prioritize research efforts.

3.3. Solar activity and its influence on the climate of the Earth System

3.3.1. Solar influence on climate

Analysis of the Earth's climate history suggests that solar activity variations contribute to climate variability on decadal-to-centennial timescales. However, the magnitude of this influence and the key responsible mechanisms remain to be quantified. Several pathways are proposed to explain the influence of solar variations on regional climate. Among them, the "bottom-up" pathway refers to climate perturbations induced by fluctuations of the solar energy input which directly reaches the Earth's surface. Alternatively, the "top-down" pathway invokes solar-induced changes in the middle atmosphere (through solar UV irradiance changes or energetic particle precipitation) that in turn affect regional climate through stratosphere-troposphere couplings. Causal connections in both these pathways need to be explored and determined; accurate identification and attribution of their impact on climate remains elusive. One of the main challenges is to determine how low-frequency variations of solar activity influence, and/or interact with, the coupled ocean-atmosphere system which intrinsically varies at decadal-to-centennial timescales.

Adequate representation of the complexities of the coupled atmosphere-ocean-sea ice system in numerical models is required to better understand and quantify the solar influence on climate. In addition, these climate models should ideally resolve the entire middle atmosphere and calculate ozone chemistry interactively as both are key components of the "top-down" pathway. Finally, model experiments need to be sufficiently long and repeated to ensure the robustness of results. To date meeting these requirements has been nearly impossible. However, the increase of computing power, novel data mining and machine learning techniques, and improvements in climate models offer new opportunities to numerically explore the Sun-Climate relationship and make future projections. Transformative progress in these fronts may be achieved by coordinating efforts and bridging climate modeling, paleoclimate reconstructions, space weather and solar physics communities.

3.3.2. The impact of increasing radiatively active gases on the middle and upper atmospheric response to solar variability

The ITM system is evolving to a fundamentally new state due to the continued buildup of carbon dioxide in the atmosphere as a result of human activity. These changes, which are already becoming apparent, will have profound effects on the structure and composition of the ITM system, and potentially, on the long-term 'habitability' (i.e., the sustainability of its use) of low-earth orbit. Increasing carbon dioxide will ultimately cool the entire ITM system (as well as the stratosphere) and will result in density decreases approaching 5-8%/decade under solar minimum conditions at satellite altitudes. In addition, CO2 increases it will change the cooling rate of the thermosphere and the timescale by which the atmosphere dissipates solar storm driving (as described above). Both these processes will introduce a long-term trend in the way the atmosphere responds to space weather forcing. Finally, the effects of a cooler thermosphere on the chemistry of NO are also important given its production during geomagnetic storms and role in dissipating storm energy. Changes in the abundance of NO in a cooler thermosphere, its effects on storm dissipation times, and storm time thermospheric density are also crucial in the prediction of thermospheric variability.

Discerning the evolution of the ITM system is, in principle, a problem in trend detection, but one that is inherently tied to solar variability and solar-terrestrial physics, as well as to the variability of the lower atmosphere. This driving of the ITM system from "above" and "below" provides the natural variability (that is, 'noise') in the ITM system from which the trend signals must emerge to be detected. If we were to enter an extended period of weaker solar activity (as speculated in some quarters) this would reduce the natural variability of the ITM system. In addition, long-term changes in the troposphere may alter the variability of the ITM system due to forcing from below. Understanding the effects of the natural forcing, and how they will influence the detection and prediction of long-term change in the ITM system, is a daunting problem in solar-terrestrial science.

Prediction of long-term ITM changes is more than just a pure scientific interest. As density changes at satellite altitude, lifetimes of all orbiting objects, including debris, increase significantly. With the projected launch of thousands of satellites over the next decade debris will proliferate, posing a threat to the habitability of regions of low earth orbit. Predicting the long-term temperature and density changes resulting from trends in greenhouse gases and the dependency of those trends on the solar cycle will influence international space policy for the rest of this century and beyond. It will be a major factor in the satellite insurance and re-insurance industry.

The grand challenge questions identified for this pillar are:

- Q3.1 How will future solar activity vary over timescales relevant for the forcing of the Earth's climate and atmospheric dynamics?
- Q3.2 What is the role of the coupling between atmospheric regions in the realization of the long-term solar influence on the Earth system?
- Q3.3 How is the atmospheric response to the variable solar forcing affected by, and interacts with, increasing greenhouse concentrations?
- Q3.4 How can solar activity predictions be used to improve atmospheric prediction on sub-seasonal to decadal timescales?

4. Tools

4.1. Current missions and observations of interest to PRESTO

It is important to identify assets that can be used to monitor the Sun-Earth system. The required observational data can be provided by current and upcoming space missions (e.g., SDO, STEREO, SOHO, Hinode, WIND, ACE, Solar Orbiter, DSCOVR, Geotail, MMS, Cluster, Swarm, THEMIS, Van Allen Probes, Arase/ERG, DSX, GDC, COSMIC, GOLD, ICON, TIMED, COSMIC-2, FORMOSAT-5), by cubesats, and by balloon and sounding rocket campaigns. In addition, new constellation-class missions will be required to properly and fully quantify the variability in the entire solar-terrestrial chain. Collaborative studies combining spacecraft measurements, ground-based observations and models should be pursued by the scientific community and encouraged by funding agencies, to synergistically exploit their potential for resolving the open questions addressed by PRESTO.

4.2. Future missions concept development

Observations from space and ground are crucial in predicting effects of CIRs/SIRs, fast streams and CMEs, and related SEPs. They can be used as such to give early warnings, in various reconstruction techniques and they are critical boundary conditions for various semi-empirical models and first-principle simulations. An optimal solution would be using multi-spacecraft observations with spacecraft located not only on the Sun-Earth line (or near-Earth space) but also beyond, e.g., Sun-Earth Lagrange points 4 and 5 (L4, L5) and out of ecliptic orbits. A space weather monitor at L5 could provide direct observations of CIR/SIR and fast streams before the source rotates to the Earth-facing zone, also allowing cross-sectional views of CMEs with white-light imagery. This would allow estimating CME properties without significant projection effects and monitoring the evolution of potentially dangerous active regions, with e.g., magnetograph and EUV observations.

Ground based and satellite observations of the near-Earth space environment are necessary to understand the dynamics of the magnetosphere-ionosphere system. Higher resolution measurements of particles, fields, and waves are necessary to improve the predictability of the fluxes of trapped and precipitating energetic particles. Multipoint observations in geospace are particularly encouraged, as they are essential to discriminate spatio-temporal variations and to understand different phenomena at different magnetic local times, latitudes, and L-shells. In addition to large-scale missions, alternative measurement platforms, such as cubesats, sounding rockets, and balloons, should be explored as a cost-effective way to monitor the geospace system.

In addition, ground based and satellite observations of the winds, temperature and composition of the atmosphere are necessary to understand the response of the upper atmosphere and ionosphere to forcing from above and below. New, higher resolution measurements are needed to study multi-scale phenomena (e.g., the interaction between gravity waves and global scale waves) to better understand the coupling between atmospheric regions. Having sufficient sampling to disentangle spatial and temporal variability is also critical. To determine long-term changes, there is a need to continue to monitor the dynamical and compositional state of the atmosphere and its response to decadal solar variability and anthropogenic climate change.

4.3. Ground-based observational networks

International networks of ground-based observations are crucial for space weather forecast. Some of these observations cover several decades which allows to study solar induced effects as well as long term trends. Solar monitoring from ground is regularly performed since the late 1940s covering white-light, H-alpha (filaments), Ca II K (magnetic field and irradiance), magnetograph, etc. image data. These are important backups for actual space-borne data and also serve as historic databases to study mid- to long-term trends of solar activity. Observational techniques are continuously improved in terms of temporal/spatial coverage, precision, and coverage of physical processes. Therefore, they play an important role in PRESTO in order to characterize variability on a large range of scales including trends and solar cycle impacts.

Regarding the ground-based measurements of middle and upper atmosphere and ionosphere, various IS and coherent radars contributed for developing our understandings of this region. EISCAT_3D radar, which is currently under construction, will contribute significantly to quantify the energy input from the magnetosphere to the high-latitude ionosphere. Ground-based multi-point networks of GNSS receivers, small-scale radio and optical sounders (such as ionosondes and lidars), NLC/PMC observations, airglow imagers and interferometers, magnetometers, and ULF/ELF/VLF wave receivers, are growing activities at various national and international projects including those at developing countries in Asia and Africa. Efforts for coordinating these networks, such as the Network for the Detection of Mesospheric Change (NDMC), is also going on. These networks provide insights into global (latitudinal and longitudinal) characteristics of propagation of atmospheric and ionospheric waves and disturbances, as well as visualizing magnetospheric disturbances imposed on the ionosphere.

4.4. Models and methodology

For the inter-comparison between different models/ methods and validation purposes the communities among all disciplines are encouraged to define standard metrics and to provide benchmarks to refine existing and/or develop new models and methods. Solar signals in observations and/or model studies are, and have been for a long time, usually attributed using various versions of two statistical methods: multiple linear regressions (MLR) or superposed epoch analysis (or "compositing"). These methods, however, are not always appropriately justified, and their inherent limitations are usually barely discussed, if at all. Although these methods are appealing due to their simplicity and high physical explanatory power, they can present substantial caveats which may lead to erroneous conclusions, such as signal misattribution. The assessment of analytical methods used to retrieve solar signals in observations, reanalysis data, as well as single- or multi- model results is needed. The goal is essentially to help SCOSTEP community to apply and/or design statistical methods as robust and suitable as possible to detect and attribute Earth's system response to solar forcing.

Data driven computational models using L5 magnetograms as boundary conditions would provide an additional perspective. It is also important in the future to better incorporate a larger variety of observations for standard space weather prediction purposes, e.g., heliospheric imagery, ground observations of interplanetary scintillations, and radio observations. Since the number of spacecraft operating in the solar wind is very limited, several important aspects of geoeffectiveness of different solar wind structures are still investigated insufficiently. This also stresses the importance of using and developing modelling techniques for prediction purposes. In that respect, we would also like to stress the importance of combined modeling-observational approaches, either through dedicated campaign event studies and/or real-time service development (research to operations - R2O). Cooperation with COSPAR, International Living with a Star Program, ISWI, ISES, etc. is encouraged.

4.5. Database construction and development of community data analysis tools

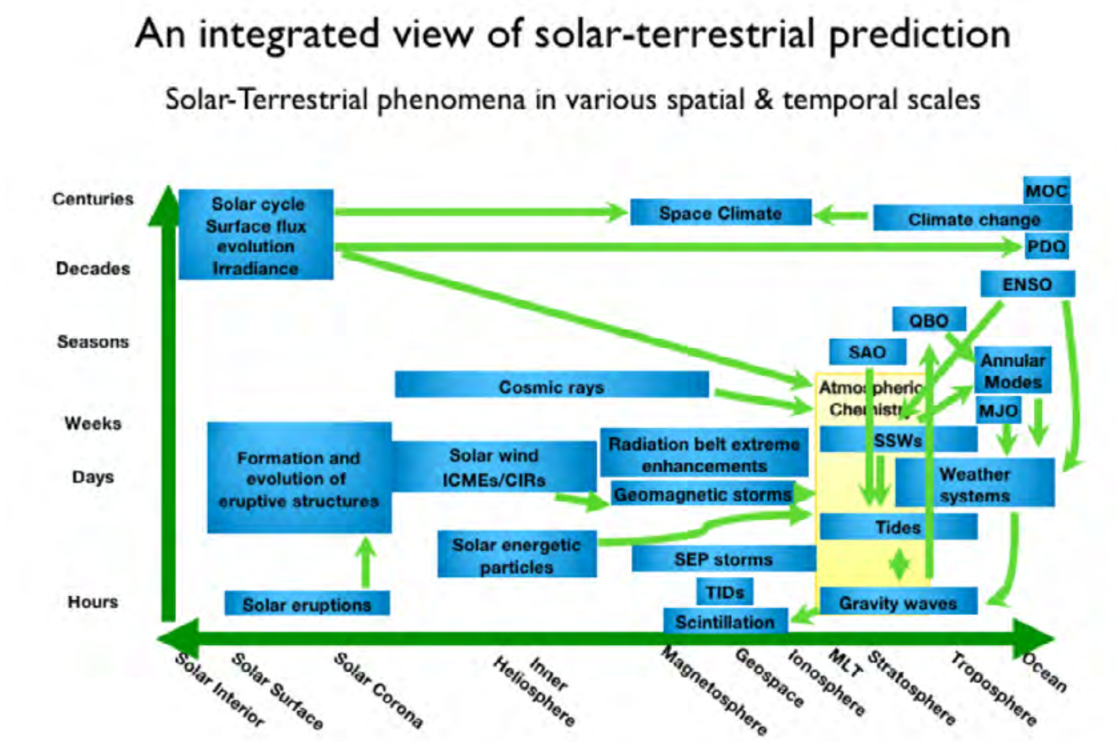
The study of Sun-Earth connection requires the combination of various types of data obtained by satellites, ground-based instruments, and modeling.

Thus, it is essentially important to encourage open data policy and develop open databases that are visible and user friendly. Development of community data analysis tools is critical for data sharing. Research driven by Big Data and Artificial Intelligence will also become important to improve and evaluate the predictability of various disturbances in the Sun-Earth system. PRESTO should also collaborate with the WDS community to support and enhance centralized data facilities, in order to use long-term data records for the predictability of the Sun-Earth system.

5. Chart of events, regions and scales in the solar-terrestrial system

The solar-terrestrial system is the largest complex system that mankind can study by in-situ observation. It involves dimensions ranging from 1 AU (108 m) to the radius of charged particle motions as they spiral around magnetic fields, which can be only a few centimetres (10-2 m).

On the temporal scale, solar activity varies on the sunspot cycle of 11 and 22 years (108 sec), while other phenomena, such as explosive events on the Sun and in near-Earth space (e.g., flares, a substorm onset), require study on time scales of seconds. We have designed a graphic showing the overlap of various Solar-Terrestrial phenomena with various spatiotemporal scales.



6. Implementation

The PRESTO program will focus on fundamental research that has the promise to advance predictive capability with societal implications. PRESTO, like previous SCOSTEP scientific programs, will consider the short and long-term variability of the Sun-Earth system including space weather and climate impacts with an emphasis on predictability. PRESTO activities will have relevance also to the World Climate Research Program (WCRP) Grand Challenge Near-Term Climate Predictions as well as the Intergovernmental Panel on Climate Change (IPCC). The objectives of such a large program can be achieved only by global cooperation involving scientists from many countries that have diverse expertise.

It is envisaged that the implementation of the PRSETO program will involve the solar terrestrial physics community in the form of a steering committee with Program co-chairs, Pillar co-leaders, Focus-area leaders, and Working group leaders (see Figure 5). The implementation plan will include multiple symposia, ISSI Working Groups, special sessions during major scientific meetings, special issues of journals, and capacity building.

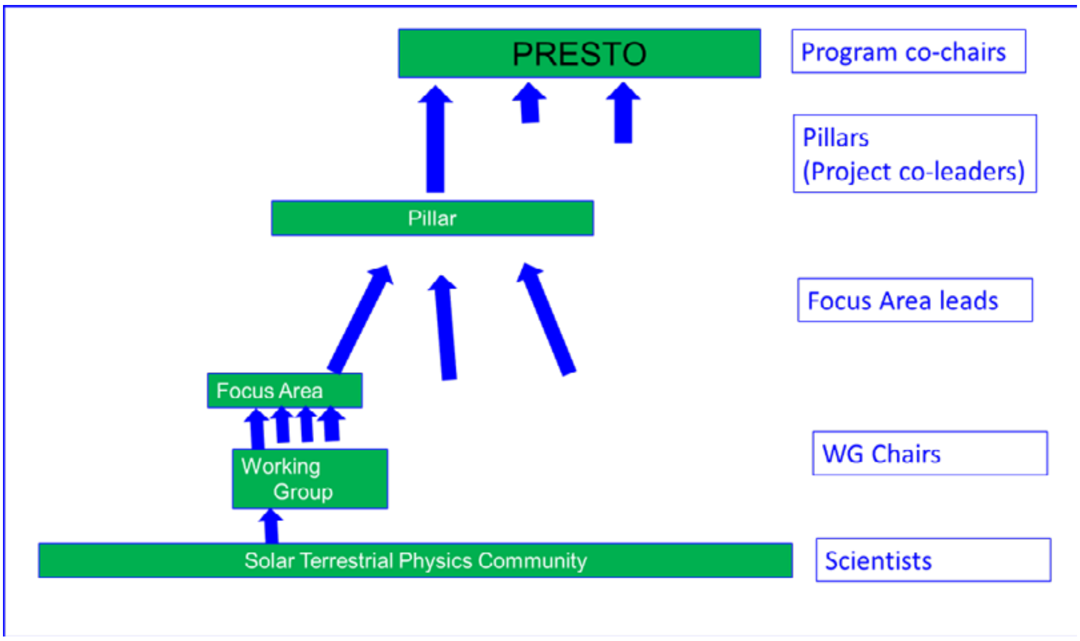


Figure 5: Schematic of the simple organizational structure of SCOSTEP/PRESTO

APPENDICES

Appendix 1

In October 2017, the SCOSTEP Bureau established a committee for the design of SCOSTEP's Next Scientific Program (NSP) from 2019 to 2022. The NSP committee comprised the following members:

Ioannis A. Daglis, Chair (National and Kapodistrian University of Athens, Greece)
Loren Chang (National Central University, Taiwan)
Sergio Dasso (Universidad de Buenos Aires, Argentina)
Olga Khabarova (IZMIRAN, Russia)
Emilia Kilpua (University of Helsinki, Finland)
Daniel Marsh (National Center for Atmospheric Research, USA)
Katja Matthes (GEOMAR and Christian-Albrechts Universität, Germany)
Dibyendu Nandi (IISER Kolkata, India)
Annika Seppälä (University of Otago, New Zealand)
Rémi Thiéblemont (Univ. Pierre et Marie Curie, France)
Qiugang Zong (Peking University, China)

Over the course of 5 months, the committee deliberated through a series of teleconferences and email exchanges and prepared a draft text for the Next Scientific Program under the general concept of the "Predictability of the variable Solar-Terrestrial System" (PRESTO), with the aim of triggering interest and receiving feedback on open scientific issues and needs of the solar-terrestrial community.

On November 14-16, 2018, a Forum on the SCOSTEP NSP was held at ISSI Beijing. NSP committee members and external invited experts (see Appendix 2) gave presentations on open issues in solar-terrestrial physics and discussed about the structure and the contents of PRESTO. The discussions formed the basis for the revision of the first draft of this document.

On February 25-27, 2019, a second Forum on the SCOSTEP NSP was held at ISSI Bern. NSP committee members and external invited experts (see Appendix 3) gave presentations on open issues in solar-terrestrial physics and discussed about the structure and the contents of PRESTO. Following the discussions, the PRESTO document reached its final form.

Appendix 2

Figure 6: Group picture of the participants of the Forum in 2018.

On November 14-16, 2018, a Forum on the SCOSTEP NSP was held at the International Space Science Institute - Beijing (ISSI-BJ), with the following participants:

Amal Chandran, Nanyang Technological University, Singapore
Ioannis A. Daglis, NSP Committee Chair / National and Kapodistrian University of Athens, Greece
Sergio Dasso, NSP Committee Member / IAFFE, Argentina
Katya Georgieva, VarSITI / Bulgarian Academy of Sciences
Nat Gopalswamy, SCOSTEP Bureau / NASA GSFC, USA
Mamoru Ishii, NICT, Japan
Olga Khabarova, NSP Committee Member / IZMIRAN, Russia
Kanya Kusano, Nagoya University, Japan
William Liu, National Space Science Center, CAS, China
Shinobu Machida, Nagoya University, Japan
Takahiro Obara, Tohoku University, Japan

Duggirala Pallamraju, Physical Research Laboratory, India
Marianna Shepherd, SCOSTEP Bureau / York University, Canada
Kazuo Shiokawa, VarSITI / Nagoya University, Japan
Nandita Srivastava, Udaipur Solar Observatory, India
Chi Wang, National Space Science Center, CAS, China
Yuming Wang, Univ. of Science and Technology of China, China
Yihua Yan, National Astronomical Observatories, CAS, China
Qiugang Zong, NSP Committee Member / Peking University, China

Appendix 3

Figure 7: Group picture of the participants of the Forum in 2019.

On February 25-27, 2019, a Forum on the SCOSTEP NSP was held at the International Space Science Institute (ISSI) in Bern, with the following participants:

Seth Claudepierre, The Aerospace Corporation and UCLA, USA
Ioannis A. Daglis, NSP Committee Chair / National and Kapodistrian University of Athens, Greece
Patricia Doherty, Boston College, USA

Katya Georgieva, VarSITI / Bulgarian Academy of Sciences
Nat Gopalswamy, SCOSTEP Bureau / NASA GSFC, USA
Olga Khabarova, NSP Committee Member / IZMIRAN, Russia
Emilia Kilpua, NSP Committee Member / University of Helsinki, Finland
Petra Koucká Knížová, Czech Academy of Sciences
Vladimir Kuznetsov, SCOSTEP Bureau / IZMIRAN, Russia
Franz-Josef Luebken, SCOSTEP Bureau / IAP, Germany
Daniel Marsh, NSP Committee Member / NCAR, USA
Dibyendu Nandi, NSP Committee Member / IISER Kolkata, India
Nick Pedatella, UCAR, USA
Eugene Rozanov, PMOD and ETH, Switzerland
Marianna Shepherd, SCOSTEP Bureau / York University, Canada
Kazuo Shiokawa, VarSITI / Nagoya University, Japan
Alphonse Sterling, NASA MSFC, USA
Manuela Temmer, University of Graz, Austria
Rémi Thiéblemont, NSP Committee Member / IPSL, France
Qiugang Zong, NSP Committee Member / Peking University, China

Acknowledgment:

The PRESTO definition was truly a community effort because of the continuous and innumerable contributions from the community. The dedicated work done by the NSP committee contributed enormously to the development of the PRESTO document presented here. The ISSI Fora helped bring focus to the document by involving experts from all over the world. The financial and logistics support provided by ISSI, ISSI-BJ, and the National Space Science Center of the Chinese Academy of Sciences are gratefully acknowledged.

LIST OF ACRONYMS

AR: Active Region
Bz: The southward component of the IMF
CIR: Corotating Interaction Region
CH: Coronal Hole
CME: Coronal Mass Ejection
CMIP6: Coupled Model Intercomparison Project Phase 6
DBM: Drag Based Model
DSA: Diffusive Shock Acceleration
ELF: Extremely Low Frequency
EMIC: Electromagnetic Ion Cyclotron
ENLIL: Name of a numerical MHD code for modeling solar wind disturbances
ENSO: El Nino Southern Oscillation
EPP: Energetic Particle Precipitation
EUHFORIA: European heliospheric forecasting information asset
EUV: Extreme Ultraviolet
GDC: Geospace Dynamics Constellation
GICs: Geomagnetically Induced Currents
GNSS: Global Navigation Satellite System
HCS: Heliospheric Current Sheet
HOx: Hydrogen oxides
ICME: Interplanetary Coronal Mass Ejection
IMF: Interplanetary magnetic field
IPCC: Intergovernmental Panel on Climate Change
IS: Interplanetary Shocks
ITM: Ionosphere-Thermosphere-Mesosphere
MHD: Magnetohydrodynamic
MJO: Madden-Julian Oscillation
MLR: Multiple linear regression
MLT: Mesosphere & lower thermosphere
MOC: Meridional Overturning Circulation
NLC: Noctilucent Clouds
NOx: Nitrogen oxides
NSP: Next scientific program
PDO: Pacific Decadal Oscillation
PILs: Polarity Inversion Lines
PMC: Polar Mesospheric Clouds
PRESTO: Predictability of the variable Solar-Terrestrial Coupling
QBO: Quasi-Biennial Oscillation of tropical zonal mean winds in the lower stratosphere
S2S: Sub-seasonal to seasonal
SAO: Semi-Annual Oscillation of zonal mean winds around the tropical stratopause
SCOSTEP: Scientific Committee On Solar-TErrestrial Physics
SEPs: Solar Energetic Particles
SIR: Stream Interaction Region
SPEDAS: Space Physics Environment Data Analysis Software
SWPC: NOAA Space Weather Prediction Center
SSWs: Sudden Stratospheric Warmings
SUSANOO: Space-weather-forecast-Usable System Anchored by Numerical Operations and Observations
SWPC: Space Weather Prediction Center
ULF: Ultra Low Frequency
VLF: Very Low Frequency
WCRP: World Climate Research Program

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太空 | TAIKONG

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