SCOSTEP

Scientific Committee on Solar-Terrestrial Physics

## Committee for the definition of the Next Scientific Program (NSP)

# *PreSTo*: Variability and Predictability of the Solar-Terrestrial Coupling

NSP concept text prepared by the Committee for the SCOSTEP Next Scientific Program

### Overview

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

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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 Solar-Terrestrial System (PreSolTer), with the aim of triggering interest and receiving feedback on open scientific issues and needs of the solar-terrestrial community.

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 NSP; it furthermore combines the interests of different topical communities in a relevant way. PreSolTer 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 weather and 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 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 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. Space Weather

### 1.1. Predicting the occurrence and the properties of flares and CMEs, and the propagation of CMEs and arrival time at Earth

Predicting the arrival and properties of Earth-impacting coronal mass ejections (CMEs) and the occurrence of large solar flares is one of the major challenges of solar-terrestrial studies. The relevant time-scales vary from minutes related to the eruption of the CME and flares to days it takes for a CME to propagate from Sun to Earth. The occurrence and properties of CMEs and flares varies also in accordance with Sun's 11-year activity cycle and general solar activity level. While the occurrence and severity 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 solar cycle size. The formation of the eruptive structures at the Sun can take from hours to days, but their destabilization is a rapid process. Currently, the is no suitable mode to predict in near-real time when a flare and/or a CME might occur. This is particularly problematic from the space weather point of view, because energetic particles arrive to Earth within about ten-minute time-scales from the flare onset.

While substantial improvement has been made in predicting CME arrival using both simulations and semi-empirical models, we still lack capabilities to predict the magnetic structure of CMEs in advance. In particular, the accuracy of long-lead time (from about half a day to a few days) space weather predictions is still very modest and much of this arises from our inability to measure or model the magnetic field characteristics of the CMEs in the corona that later impinge the Earth. There are roughly two different phases in this prediction 1) Estimate the intrinsic magnetic field properties of CMEs (before or shortly after the eruption), and 2) Estimate how intrinsic magnetic field properties change as a CME propagates from Sun to Earth due to e.g., deformation, erosion, CME-CME interactions, deflection and rotation. Future attempts to improve this include using indirect solar proxies (based on EUV and X-ray observations and magnetograms), data-driven coronal modeling and heliospheric modeling (both using semi-empirical models and numerical simulations). One of the challenges is that CMEs can experience significant changes from their eruption on the Sun to their arrival at geospace.

Currently no model makes consistently accurate predictions of the CME arrival time at geospace. The drag force on ICMEs can vary substantially from case to case. Projection effects to properly estimate the real CME properties (e.g., speed and angular width), to know the properties of the ambient solar wind through which CMEs propagate from the Sun to the Earth, and the ICME - solar wind interaction, are still major problems to solve. Whether the ICME is encountered through the nose or through flank can also make significant difference in the predicted arrival time. Furthermore, the timing of the possible geomagnetic storm depends strongly on CMEs magnetic structures. Depending on whether the southward fields are in the leading or trailing part the ICME can make a difference of up to one day in advance storm warning.

### 1.2. Properties of CME sheath regions

Turbulent sheath regions ahead of CMEs are important drivers of geomagnetic disturbances, particularly at high latitudes, due to their large-amplitude magnetic field fluctuations and large dynamic pressure. Sheaths can also drive major storms independent of **whether the CME flux rope will be geoeffective**. Currently there is no practical way to estimate in advance the properties of CME sheath regions as they arrive to Earth. Plasma and field characteristics can also change considerably within a single sheath and their characteristics depend strongly both on the driver (CME and its shock) and on the ambient solar wind. Sheaths are not as well studied as CME flux ropes. A more comprehensive understanding of their statistical properties and correlation with CME, shock and ambient solar wind properties is required. We also need reliable estimates of the extent to which MHD models are capable of predicting properties of the turbulent sheath regions.

### 1.3. Solar wind-magnetosphere coupling and internal magnetospheric dynamics

Solar wind – magnetosphere coupling and internal magnetospheric dynamics play complex and crucial roles in geospace weather (magnetic storms and substorms and enhancements of energetic electrons in the radiation belts). Accurate and reliable predictions of geospace weather require the understanding of all aspects of the complex interplay of external and internal regulating factors operating over timescales ranging from minutes to days. Radiation belts, in particular, can experience drastic changes in timescales as short as a minute, while a substorm cycle last a few hours and a geomagnetic storm several days. The changes in magnetospheric/ionospheric current systems and in radiation belt electrons are governed by several physical processes operating at different time-scales, related e.g., to the transport, acceleration and loss of radiation belt and ring current particles. With regard to energy transfer from the solar wind into the magnetosphere system, recent studies have highlighted the importance of the transition of the solar wind through the bow shock and magnetosheath, as well as of internal, local and small-scale processes. Examples of relevant outstanding questions include: How do solar wind conditions dictate the saturation of the polar cap potential, how different large-scale solar wind structures (ICME flux ropes, sheaths, high-speed streams, slow-fast stream interaction regions) affect different regions in the magnetosphere/ionosphere and coupling efficiency; how solar wind conditions control the occurrence of foreshock transients (e.g., cavitons and spontaneous hot flow anomalies) and ULF waves. With regard to internal magnetospheric dynamics, some of the most pertinent open issues are: which electromagnetic waves are the most dominant for heating and losses of radiation belt electrons and what drives such waves; how substorm occurrence and ring current growth influence high-frequency waves (such as chorus whistlers), which are critical in radiation belt 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.

## 2. Solar activity and its influence on weather and climate

### 2.1. Understanding and predicting solar activity

The next five years in the run-up to Solar Cycle 25 provide an excellent opportunity for understanding solar cycle predictability and developing/assessing data-driven magnetohydrodynamic (MHD) dynamo models for solar activity. Decadal timescale activity is typically parametrized in variations of the sunspot number or surface magnetic flux that can be simulated by data driven solar dynamo models. Surface flux emergence and their evolution driven by flux transport processes govern the Sun’s polar field reversal and build up, 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 also be derived based on these dynamo model predictions.

Quasi-periodic bursts in solar activity, manifest in sub-annual to annual-scale seasonal variations 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.

On the monthly timescale, a memory exists in the large-scale coronal structure which may be used for predicting the evolution of the global coronal and heliospheric field up to a month or two ahead. This may allow a similar time window 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 the NOAA Space Weather Prediction Center (SWPC). These necessitate continuous measurements of vector magnetic fields of solar active regions (ARs) and exploring what properties relate to 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 the increase in computing power.

Large uncertainties remain in terms of a) Underlying assumptions in dynamo models and differing predictions (e.g., solar cycle 24), b) Prediction of the timing of solar eruptions and c) seamlessly bridging different timescales. Predictability beyond a decade also remains a major open question and challenge. Can this be done? How about speculation regarding an imminent Maunder minimum like phase; are we approaching one? Critical comparative assessment of theoretical-computational models of solar activity, testing their underlying assumptions, and their eventual coupling may lead to transformative progress in understanding and predicting solar activity in the next decade.

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 spectral irradiance variations over millennia timescale. How about solar driven regional, as opposed to global climate impacts? How about solar driven impacts on large scale atmospheric and ocean circulations? These questions need to be addressed to understand better and assess the impact of solar variability. A thrust should be on deciphering the physical pathways of Sun-Climate relationships, e.g., what physics of atmospheric systems is impacted by solar variability, instead of focusing simply on the global temperature - which is a net outcome of diverse factors.

### 2.2 Sub-seasonal to decadal variability of the Sun-Earth system

A grand challenge for predictions of the geospace environment is to bridge the gap between ~~the~~ 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, for example, 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 objective of the NSP. For space weather (see section 1.) the timescales are much shorter. However, 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 Sudden Stratospheric Warmings - SSWs) have timescales on the order of weeks and it has been shown that they affect the ionosphere, as that they affect the ionosphere, as well the troposphere and surface weather and climate, through their interactions with upward propagating waves. This driving should be integrated into ~~a~~ 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.

### 2.3 Centennial variability of the Sun-Earth system

Analysis of the Earth’s climate history suggests that solar activity variations significantly contribute to regional climate variability on centennial timescales. However, the magnitude of this influence and the key responsible mechanisms remain to be quantified. Several pathways are proposed to explain the solar variability influence 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 implies solar-induced changes in the middle atmosphere that in turn affect regional climate through stratosphere /troposphere couplings. While both pathways need to be accounted for, an accurate detection and attribution of their impact on climate remains to be achieved. In particular at centennial timescales, one of the main issue is to understand how low-frequency variations of solar activity influence, and/or interact with, the atmosphere-ocean-sea ice system which intrinsically varies at multi-decadal to centennial timescales through very complex processes.

The use of numerical models representing the complexness of the atmosphere-ocean-sea ice system is required to better understand and quantify the solar influence on climate. Nonetheless, 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, the model experiments need to be sufficiently long and repeated to insure the robustness of the results. While meeting all these requirements has long been nearly impossible, the permanent increase of computing power capacities and upgrade of climate models (e.g. climate models lid height and vertical resolutions are being expanded, geomagnetic activity fluctuations are now being accounted for, ...) offer many new and outstanding perspectives to explore solar-climate relationship more completely with regard to past climate (e.g. Maunder minimum, impact of De Vries/Suess cycles) but also future projection scenarios. Further progress will be made by coordinating efforts within the climate modeling community and by bridging climate modeling, paleoclimate, space weather and solar physics communities.

### 2.4 Multiscale Vertical Coupling and Feedbacks between atmospheric regions and space weather

The instances and mechanisms of upward and downward vertical coupling between atmospheric regions from the troposphere to the thermosphere and ionosphere are a section of continued interest. The results from the past decade have shown that events originating in the lower atmosphere such as tides and gravity waves generated by convection and latent heat release, SSWs in the middle atmosphere, as well as wave breaking and mixing in the mesosphere and lower thermosphere can have a significant and persistent effect on the variability and structure of the thermosphere and ionosphere – posing implications for radio propagation, as well as the low Earth orbit and reentry environments. Besides the mentioned upward coupling there is also downward wave coupling such as seen after SSWs. The scales of these phenomena can range from small scale gravity and acoustic waves on time scales of minutes, to tides and planetary waves with seasonal and interannual scales.

Recent developments in better understanding and quantifying the effects of such vertical coupling have led to the continued improvement and development of assimilative whole atmosphere models, as well as improvements in constellation observations of the middle and upper atmosphere through new satellites, as well as ground-based networks. As we move into the NSP, the aeronomy community continues to work on the development of the aforementioned infrastructure to explore new instances of vertical coupling produced by waves and tides, as well as the implications of global climate change and elevated levels of carbon dioxide throughout the climate system. Coordination and interaction between researchers examining phenomena at both large and small scales should also be encouraged.

### Graphic 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 ($10^8$ 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 ($10^8$ sec), while other phenomena, such as explosive events on the Sun and in near-Earth space (e.g., flares, 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.

### Acronyms used

CME: Coronal Mass Ejection
ENSO: El Nino Southern Oscillation
ICME: Interplanetary Coronal Mass Ejection
IPCC: Intergovernmental Panel on Climate Change
MJO: Madden-Julian Oscillation
MOC: Meridional Overturning Circulation
PDO: Pacific Decadal Oscillation
QBO: Quasi-Biennial Oscillation of tropical zonal mean winds in the lower stratosphere
SAO: Semi-Annual Oscillation of zonal mean winds around the tropical stratopause
SEP: Solar Energetic Particles
SSWs: Sudden Stratospheric Warmings