CHALLENGE 3

SPACE OPPORTUNITIES AND THREATS FOR SOCIETY: PREDICTING THE SPACE-EARTH INTERACTION

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1. INTRODUCTION AND GENERAL DESCRIPTION

Earth and human life are exposed to a highly variable space environment. Space weather driven by impulsive phenomena in the solar corona induces short-term variation from minutes to weeks in the upper atmosphere and ionosphere, impacting technology and human health. Solar activity variations on decadal to centennial time scales influence Earth's climate. The influx of extra-terrestrial material on Earth, mainly in the form of interplanetary dust, meteoroids, asteroids and comets, has relevance in many different aspects: from the creation of metal layers in the upper terrestrial atmosphere to the potential local damage caused by Megaton-class impacts to even the destruction of the civilization from large impacts capable of causing massive extinctions and temporal modification of climate. On the other hand, anthropogenic climate change is expected to alter the near-space environment populated by low-orbiting satellites and space debris.

This challenge deals with Space-Earth interactions, from space weather phenomena to the Earth's surface, with the mediating role of the upper and middle atmosphere, where these phenomena are felt the most and their signals can subsequently propagate to the Earth's surface.

Integrated understanding of this complex system, in particular coupling of the middle atmosphere with the troposphere, is key for future climate projections and enhancing skills of subseasonal-to-seasonal and potentially decadal climate predictions. In addition, they would further enable anticipation and preparedness to environmental and technological hazards by extreme events caused by extreme space weather and worst-case events such as asteroid impacts or solar superstorms.

1.1. Space weather

The Sun is not a static body, but the amount of energy emanating from it varies with time. Impulsive phenomena in the solar corona expel huge amounts of energetic solar material into interplanetary space, substantially increasing the density and velocity of the solar wind. Under these conditions, a great variety of phenomena such as geomagnetic storms, auroral and substorm activity, or thermospheric and ionospheric storms does occur.

Space weather (SWe) refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health. Space weather deals with phenomena involving ambient plasma, magnetic fields, radiation, particle flows in space and how these phenomena may influence man-made systems. Because our society is becoming increasingly dependent on those technological systems, the ionosphere, its electrodynamics, and its coupling with the lower atmosphere, the neutral upper atmosphere and the magnetosphere are a matter of intensive research. This research seeks to determine to what extent valid predictions of those phenomena and their effects can be made [e.g. Richmond, 1996]. In addition to the Sun, non-solar sources such as galactic cosmic rays (GCRs) can be considered as space weather elements since they alter space environment conditions near the Earth.

Solar processes and interplanetary space

Most space weather phenomena are ultimately driven by the Sun. More specifically, solar coronal mass ejections (CMEs) and co-rotating interaction regions (CIRs), which are at the root of most severe geomagnetic storms have a solar magnetic field origin. The same occurs with flares, medium to high radiative energy releases that alter the conditions of the interplanetary medium and the solar wind, triggering, for example, solar energetic particles (SEPs) fluxes. These are also driven by borrowing energy from magnetic fields. Twisting and subsequent reconnection of magnetic fields are thought to be the energy supply for all those solar phenomena relevant to space weather. Indeed, the magnetic field shapes and couples the various atmospheric layers from the photosphere to the corona and gives rise to the so-called solar activity. That solar activity and magnetic field entangling vary at all spatial scales from the smallest observable (0."1 - 0."2) and shorter times (of the order of less than 1 min; e.g., Requerey et al. 2017) to the whole solar disk and years.

The still insufficient knowledge of the solar magnetic fields and their variability hampers our capability to predict flares, CMEs, CIRs, SEPs, and other space-weather phenomena. A better characterization of the Sun's magnetic field, in particular, of its outermost layers, the chromosphere and the corona, is mandatory to understand the essential building blocks of space weather.

Impacts on magnetosphere, ionosphere and MLT atmospheric composition

During extreme Space Weather events (SWe), solar flares abruptly release huge amounts of energy that promptly change the ionospheric structure in the sunlit hemisphere. The intense ultraviolet and x-ray radiation, after a propagation time of about 8 minutes, hits the dayside of the Earth and is absorbed by atmospheric constituents, raising them to excited states and knocking electrons free in the process of photoionization. The low-altitude ionospheric layers (D and E regions) immediately increase in electron density over the entire dayside, a process known as sudden ionospheric disturbances (SIDs). Short radio waves (in the HF range) are absorbed by the increased particles in the low altitude ionosphere, causing a complete blackout of radio communications. In the higher latitudes, the solar wind energy dissipation triggers geomagnetic storms and consequently, ionospheric storms following gradually the impact of geoeffective phenomena of solar surface origin: CMEs and "coronal holes" that emit high-speed solar wind streams (HSSs) and CIRs under the interaction of HSSs with preceding low-speed solar wind. Numerous experimental and theoretical studies show that the behaviour of the ionosphere during geomagnetic storms is greatly influenced by the coincident thermospheric storm. The changes in neutral air winds and composition result in changes to rates of production and loss of ionization. The modified electron densities in turn alter the ion drag on the neutrals. Disturbed neutral winds also cause F region electric fields by the disturbance dynamo mechanism. These electric fields redistribute the plasma, affecting production and loss rates. Apart from large scale ionization enhancements or depletions, the storm-related electric fields may also destabilize the plasma, producing irregularities. Spread F condition, particularly at the equatorial and at high latitudes, and bubbles in the equatorial zone lead to additional perturbations in the electron density, which are more pronounced as the ionospheric electron density increases.

Atmospheric gravity waves launched by high-latitude sources such as Joule heating, Lorenz forces, or intense particle precipitations, are detected in the form of Large Scale Travelling Ionospheric Disturbances (LS-TIDs), propagating from high to middle latitudes. The solar proton events (SPE) cause abnormal ionization in the ionospheric D-region that absorb radio waves in the HF and VHF bands, the so-called polar cap absorption (PCA) events.

This complex physical system is the source of many scientific, operational, societal, and environmental challenges that affect the smooth and uninterrupted operation of technological systems such as radio communication and geolocation systems, ground and satellite-based augmentation systems, and space-based communications as well as communications between the Earth and ground stations (or rovers) at Moon, Mars, and other planets, low-frequency radio astronomy and Synthetic-Aperture Radars.

Currently, the available ionospheric models provide forecasts of large-scale effects in the critical ionospheric characteristics up to few hours, i.e. only when the solar wind characteristics at L1 are known. The forecast of irregular structures is even more uncertain, because of their local character. Irregularities such as scintillations, bubbles and travelling ionospheric disturbances (TIDs), can be only nowcasted or forecasted by 1 hour ahead. In general, current ionospheric forecasting capabilities severely lag behind users' requirements. There are two reasons: a) the complexity of the physical mechanisms acting in the ionosphere and the regional character of ionospheric perturbations; and b) the very short-term notice given for the expected perturbations in the characteristics of the solar radiation environment and solar wind plasma, and in the interplanetary magnetic field (from minutes to few hours) that drive the ionospheric forecasting models.

Worst case events

Worst case SWe events may cause severe impacts on the Earth environment. Several such events are known historically, as the strongest white-light flare and geomagnetic storm of 1859 (Carrington event) and the solar radiation storm of 775 AD, which may serve as an upper estimate of solar events (Usoskin et al. 2017). So far, possible future extreme events of this magnitude have not been considered in climate assessments and only a limited number of studies deal with the potential technological impacts of such worst case events. Despite the rather low probability, their consideration is relevant due to the expected magnitude of socio-economic impacts. A comprehensive assessment of the occurrence probability is still missing due to the difficulty to reconstruct past extreme events from proxy data. The study of bright flares on other Sun-like stars (Maehara et al., 2012) could be a way to make progress in the future.

1.2. Influence of solar activity on climate

Together with volcanic activity, solar activity variations are an important source of naturally forced climate variability. On timescales of years to decades, relevant solar variations include the 11-year solar cycle and sustained periods of anomalously high and low solar activity, known as grand solar maxima and minima, respectively. Solar effects in the middle atmosphere, particularly those related to the 11-year solar cycle are well documented, whereas near-surface impacts are more controversial and subject to debate. Uncertainties and challenges include the limited observational record of solar forcing changes, discrepancies in their reconstruction over the pre-satellite era, the generally small radiative forcing associated with recent solar variations, and our limited understanding of the mechanisms whereby solar signals in the middle atmosphere could propagate to Earth's surface and its representation in climate models.

Past, present, and future solar activity

Solar activity on decadal and longer timescales is driven by the solar dynamo, by which the dynamical interactions of flows and magnetic fields in the solar convection zone lead to cyclic reversals of polarity of the solar magnetic field with a quasi-static period of 11 years. One of its consequences is the emergence of regions with enhanced magnetic fields, namely sunspots, whose numbers are the most widely known proxy of solar activity for the last centuries. Sunspots provide reliable estimates of Total Solar Irradiance (TSI), which is key for quantifying the solar contribution to past climate variability as well as for constraining the evolution of future solar activity and associated climate impacts. Changes in TSI, such as those associated with the 11-year solar cycle, do not distribute uniformly through the solar spectrum. Instead, they involve larger irradiance variations in short wavelengths (e.g. ultraviolet, UV) than over the visible part of the spectrum. Quantification of these spectral solar irradiance (SSI) changes is of paramount importance to elucidate the pathways of solar influences on climate. Observational-based assessments of the last solar cycle suggested larger SSI variations in UV wavelengths than previously thought. However, instrument sensitivity drifts and unrealistic ozone responses to these UV changes have also been reported. Due to the limited availability of accurate satellite measurements, SSI variations are often inferred from empirical models (e.g. Matthes et al. 2017 and references therein). While TSI variations since the 1970s are relatively well known from direct spaceborne observations and, to a lesser extent, from ground-based observations since the late 19th century, their reconstruction for the past centuries from sunspots, is rather complicated and uncertain. On longer timescales, solar variability can only be reconstructed using cosmogenic isotope proxies (mostly ^{14}C and ^{10}Be in natural stratified archives), allowing estimates of the solar modulation of cosmic rays, ultimately driven by solar magnetic activity. Geomagnetic activity, i.e. disturbances of the magnetosphere, caused by solar transients and solar wind, are monitored by ground-based magnetometers since the mid-19th century or by qualitative historical auroral records for several centuries, but should be reconstructed on longer time scales. Isotope-based reconstructions of sunspots are fed in solar irradiance models to retrieve a suite of solar forcing reconstructions of TSI and SSI for the last millennia (Jungclaus et al. 2017), in support of the IPCC. Notable discrepancies (one order of magnitude) exist in long-term variations of solar activity, with e.g. TSI relative changes from the Late Maunder Minimum (LMM, 1675-1715 CE) to present days ranging from 0.06% to 0.25%.

Despite recent advances of physical models of the solar magnetic dynamo, "true" predictions of solar activity are currently not possible beyond one cycle. Estimates of future solar activity are thus restricted to probabilistic assessments based on the present conditions and statistics of past variations, which suggest that the recent solar activity decline will continue during the upcoming decades. Plausible future scenarios based on such statistics are included, for instance, in recent recommendations of solar forcing for climate model projections informing the upcoming IPCC assessment report (Matthes et al. 2017), which includes a best-guess future scenario of solar forcing, as well as an extreme scenario of low level of solar activity during the 21st century, comparable to the Maunder Minimum. Single modelling studies have also quantified the effects of a near-future grand solar minimum in climate change projections, using a considerable spread of solar forcings, which allows testing the sensitivity of the response to the amplitude of solar variations. However, a complete probabilistic evaluation of the possible range of future solar forcing is to date still missing.

In summary, despite recent progress, significant uncertainties remain in understanding and modelling solar irradiance variations. The most critical issues are the variability of solar irradiance in the UV part of the spectrum between 200 and 400 nm and the lack of reliable constraints on the magnitude of the centennial variations.

Climate impacts

Direct heating of the Earth's surface by solar radiation in the Visible and Infrared represents the most obvious mechanism by which solar energy enters the climate system. Although the variability of the TSI hardly exceeds 0.1% over the 11-year solar cycle, several studies have suggested different mechanisms whereby this small signal can be amplified. The so-called bottom-up mechanism involves heating of the subtropical sea surface temperatures (SSTs) from solar variations in visible wavelengths, amplified by air-sea coupling in the tropical Pacific. Another mechanism is associated with well-known temperature variations in the upper tropical stratosphere induced by ozone absorption of UV radiation. According to this mechanism, the ozone-induced warming of the upper tropical stratosphere during solar maxima strengthens the climatological circumpolar westerly winds of the winter stratosphere (stratospheric polar vortex) through enhanced meridional temperature gradient, thereby promoting stratosphere-troposphere coupling (see below). This interaction between radiation, chemistry and dynamics is also referred to as the top-down mechanism, and has been suggested to propagate solar signals from the polar winter stratosphere downwards to the extratropical troposphere and the ocean, being particularly important for regional climate variability. Both, top-down and bottom-up solar mechanisms may work in tandem to amplify solar signals, which complicates the attribution and quantification of their relative impact on climate.

In addition, recent studies have paid attention to potential impacts of energetic particle precipitation (EPP) on climate. EPP is strongly linked to the solar cycle, either directly by CMEs producing sporadically large fluxes of solar energetic particles or, indirectly, by the quasi-continuous impact of the solar wind on the Earth's magnetosphere, as well as by the shielding of GCR fluxes by the solar magnetic field (see, e.g. Mironova et al., 2015, for an overview). EPP-induced ionization initiates the production of odd nitrogen and odd hydrogen, both of them destroying ozone via catalytic cycles.

SPEs caused by CMEs are particularly frequent around the maximum of the solar cycle and produce transient alterations of the chemistry in the polar mesosphere and stratosphere. Energetic electron precipitation is associated with geomagnetic storms and occurs mainly in the polar auroral and sub-auroral regions. Such geomagnetic perturbations occur throughout the solar cycle with an intensity being largest about 2 years after the maximum of the solar cycle, in phase with the acceleration of the solar wind. Processes that occur in the outer radiation belt typically generate mid-energy electron (MEE) precipitation affecting the atmosphere at altitudes of 50–100 km. Auroral electrons, originating principally from the plasma sheet, affect the lower thermosphere (95–120 km). Odd nitrogen produced by precipitating electrons is long-lived during polar winter and is regularly transported down from its source region in the mesosphere and lower thermosphere into the stratosphere, to altitudes well below 30 km (e.g., Funke et al., 2014) where it interacts with the ozone layer. Satellite observations of the last two decades have provided a clear picture of this EPP indirect effect occurring regularly during polar winters. Between the surface and 25–30 km, cosmic rays are the main source of atmospheric ionization, exhibiting highest levels during solar minima. GCR-induced ozone alterations have been postulated by several model studies, although, no observational evidence has been provided to date.

EPP-induced ozone changes are thought to modify the thermal structure and winds in the stratosphere, which, in turn, modulate the strength of the Arctic polar vortex. The introduced signal could then propagate down to the surface, introducing significant variations of regional climate, particularly in the Northern Hemisphere (NH; see, e.g. Sinnhuber and Funke, 2020, for a recent review). However, despite the recent advances in the investigation of EPP impacts on the middle atmosphere and their potential climate impacts, many open questions and issues still remain. Most of them are related to current limitations of available observations and climate model capabilities. Others are caused by the lack of process understanding, particularly of processes related to the possible mechanisms that could lead to energetic electron impacts on regional surface climate.

The climate system exhibits a wide spectrum of persistent internal modes of variability such as the dominant atmospheric circulation patterns in the NH and Southern Hemisphere (SH), i.e., the annular modes (Northern Annular Mode, NAM, and Southern Annular Mode, SAM, respectively), and their regional manifestations (i.e. the North Atlantic Oscillation, NAO). Other examples include the coupled atmosphere-ocean circulation patterns like the El Niño Southern Oscillation (ENSO) phenomenon, and SST modes of variability, such as the Atlantic Multidecadal Variability (AMV). All of them play a substantial role in regional weather and climate. Natural forcing from the decadal-scale solar cycle has been proposed to synchronize the NAO, the inter-to multi-decadal variability in the Atlantic and Pacific oceans, and the ENSO-related Pacific Walker circulation. However, convincing and systematic evidence is still missing. An intense topic of recent research has focused on the influence of the 11-year solar cycle on the winter NAO, which largely dictates climate anomalies over the Euro-Atlantic sector. Several studies have argued that positive phases of the NAO, associated with warmer and wetter winters in northern Europe, are more likely during solar maxima, therefore representing a window of opportunity for decadal predictability in extratropical regions of the NH. Modelling evidence supports a lagged response of the NAO to the solar cycle, although this is often weaker than in the observations and is not robust across models. A more recent study reports the absence of any solar signal prior to the mid-1960s in various observation-based datasets and suggests that internal variability alone is capable of generating decadal NAO variations as those observed in the more recent period. Current limitations to detect robust regional solar signals include the assessment of the relative roles of solar forcing and internal variability under different background conditions and external forcings, i.e. past (no anthropogenic forcing) versus present and future (increasing anthropogenic forcing). Moreover, a reliable quantification of solar of solar effects in regional regional surface climate requires a better understanding of the middle atmosphere and its coupling with the troposphere, and of atmosphere-ocean interactions. These issues are partially hampered by the short length of dense observations before the mid-20th century, and the model ability to capture the climate responses to external forcing (e.g. an apparent underestimated response of the NAO to solar forcing, see also Challenge 2 in Volume 7).

The Space-Earth system integrates a complex array of components, some of them representing a promising source of predictability in subseasonal to decadal, with potential benefits for both weather and space weather predictions.

In particular, substantial skill in subseasonal-to-seasonal (S2S) forecasts arises from atmospheric coupling of the lower, middle and upper atmosphere. This coupling is evidenced in wintertime with a strongly perturbed boreal stratospheric polar vortex or just the opposite, strong vortex events. The most salient examples associated with weakening of the stratospheric polar vortex are Sudden Stratospheric Warmings (SSWs), extreme phenomena characterized by an abrupt temporary warming of the polar winter stratosphere (see also Challenge 5 in Volume 7). Their effects propagate above and below the stratosphere, materializing as extensive changes of the whole atmosphere, even across both hemispheres. For example, the strong negative anomalies of the NAM in the middle stratosphere produced by SSWs propagate downwards to the troposphere, thereby causing temperature and precipitation anomalies persisting from weeks to months. Moreover, SSWs eventually lead to polar winter elevated stratopauses formed at mesospheric altitudes, that alter the upward propagation of atmospheric waves to the thermosphere. They also produce considerable variations of the thermosphere and the ionosphere across the globe, i.e., appreciable reductions of upper-thermospheric density, low-latitude electron density anomalies with a magnitude similar to those caused by moderate geomagnetic storms or tidal variations affecting the equatorial electrojet and the current system.

The S2S predictability skill associated with stratosphere-troposphere coupling is mainly confined to periods of SSWs, being otherwise low. The modulation of the stratospheric polar vortex and SSWs by internal modes of atmospheric variability may further extend predictability of the stratosphere (see Challenge 5 in Volume 7). However, this requires that prediction models simulate adequately these phenomena, their teleconnections to the polar stratosphere and the whole atmosphere coupling.

Traditional model limitations to the predictive skill from the stratosphere include low model tops, poor vertical resolution, the lack of internally-generated QBO, unrealistic gravity wave parameterizations and tropospheric biases. In order to further improve predictions In order to further improve predictions and to extend them to the whole atmosphere, there is also a need for i) a better modelling of stratospheric ozone as an additional source of predictibility, ii) improved data assimilation for initialization, and iii) a comprehensive knowledge of vertical coupling processes.

Major sources of seasonal-to-decadal (S2D) predictability in current forecast systems mainly rely on SST anomalies that are predictable beyond a season, such as ENSO and AMV. As discussed above, decadal solar variations may also excite stratosphere-troposphere coupling and influence internal modes of variability on these time scales, therefore providing additional skill in S2D forecasts. However, realizing this potential predictability will require better understanding of the response of stratosphere-troposphere coupling to solar variations and the separation of this externally forced signal from internal variability.

1.3. Meteoroid population

The Zodiacal Dust Cloud (ZDC) is a circumsolar debris disk centered at the ecliptic plane, composed by dust particles originated from the collision of asteroids and disintegration of comets. ZDC particle accretion constitutes the dominant source of interplanetary material to the inner Solar System planets. In contrast to the relatively fresh cometary trails originating well-known meteor showers, the orbital characteristics of zodiacal particles have evolved significantly since ejection, which makes it impossible to establish a direct link to their specific parent bodies. However, they can be generally classified in relation to a source family using ground-based radar and optical observations of atmospheric entry events.

The so-called Sporadic Meteor Complex (SMC) consists of six directional enhancements of the meteor radiants. These apparent sources are known as the North and South Apex, composed mainly of dust from long period comets; the Helion and Anti-Helion, originating from short period comets; and the North and South Toroidal, which have been linked to Halley-family comets (Janches et al. 2017 and references therein). Dynamical models of dust evolution from different cometary families have been constrained with spaceborne impactor data (LDEF) and infrared dust emission observations (IRAS and Planck). These modelling efforts indicate that the ZDC is dominated by small (~10 μg) and slow (<15 km s^{-1}) particles, originating mainly from the Jupiter family of comets (JFC) (Nesvorný et al. 2010).

Coupled orbital dynamics and atmospheric entry modelling has been used to interpret a wealth of ground based observations, including the micrometeorite record population, high performance-large aperture radar meteor rates, accumulation rate of meteor smoke particles (MSPs) in ice cores and lidar density measurements of the mesospheric Na, Fe and Ca layers. This has enabled estimating the interplanetary dust input to Earth to be around 40 tons day^{-1} and to derive also estimates for Mars and Venus (Carrillo-Sánchez, 2020).

These estimates are broadly consistent with the independent interplanetary meteoroid flux density model by Grün et al. (1985). Nevertheless, important discrepancies regarding some key ground-based observations remain, which points to an incomplete understanding of the physics of atmospheric entry.

1.4. Climate change impacts on the upper atmosphere and geospace

While man-made greenhouse gas emissions trigger global warming in the troposphere, a cooling response has been observed in the middle atmosphere. This is thought to be related to increased carbon dioxide (CO_2) concentrations in the middle and upper atmosphere that have been recently reported. If the mesosphere - lower thermosphere (MLT) region cools down, then atmospheric contraction reduces the density in the thermosphere. The underlying picture is further entangled by the modulation of such contraction by the solar cycle, and also by hemispheric asymmetries and additional horizontal inhomogeneities.

The lower and middle atmosphere further affect the upper atmosphere via the upward propagation of atmospheric waves, including planetary waves, atmospheric tides, and gravity waves. As these waves propagate upward, their amplitudes grow due to the decreasing density with height, until they eventually break and deposit their energy and momentum into the ambient atmosphere, driving large-scale circulations. This might be observed also in the variability of the Earth's ionosphere which can be caused by both solar/geomagnetic activity and meteorological effects (Altadill and Apostolov, 2003). Both the excitation of atmospheric waves in the lower atmosphere, and their upward propagation through the middle atmosphere, are dependent on the conditions in the background atmosphere and are therefore likely to be affected by climate change. A long term increase in gravity wave forcing of the upper atmosphere would result in additional cooling and cause more turbulent mixing, thereby enhancing the downward transport of thermospheric atomic oxygen and thus amplifying the reduction of mass density.

All objects in low Earth orbits experience an atmospheric drag which is proportional to the ambient atmospheric density. This drag acts to lower the object's orbit and will eventually cause it to fall back to the Earth's surface. This is the main way in which space debris is removed from the near-Earth space environment. Any long-term change in the density of the upper atmosphere will therefore have a significant impact on the time evolution of the space debris population.

Also the meteoroid environment influences the upper atmosphere. The atmospheric processing of Fe, Mg and Si atoms ablated from micrometeoroids results in re-condensation of meteoric material as nm-sized MSPs. These act as condensation nuclei of noctilucent clouds (NLCs), which were reported for the first time in 1885 and have been since growing brighter and spreading to lower latitudes. NLCs appear at the high latitude summer mesopause (around ~85 km), where the temperature falls below 150 K and water vapour then spontaneously forms ice particles. NLCs are a long-term indicator for climate change due to the increase of H_2O in the middle atmosphere resulting from the oxidation of anthropogenic methane. The occurrence frequency and brightness of NLCs may be impacted on decadal time scales by changes in H_2O and O_3, and in the dominant meridional circulation in the mesosphere. Temperature is crucial too, although there is no clear evidence of a temperature decrease at the particular altitude of the mesopause due to increased CO_2.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

2.1. Towards an integrated understanding of the Space-Earth system

A major expected impact is to interconnect Spanish and international research communities addressing solar physics, minor bodies of the Solar system, atmospheric and ionospheric physics, and climate sciences to jointly advance our understanding of the entire impact chain of Space-Earth interactions in a holistic manner and generate new integrated knowledge. This implies the coordinated development of synergistic space mission concepts and observational strategies, as well as the generation and sharing of multidisciplinary datasets and community data analysis tools addressing all aspects of the Space-Earth system. The joint effort of presently disconnected disciplines is expected to enhance the CSIC visibility and leadership in the international basic science panorama.

The designing and provision of an organized access to experimental facilities, Findable, Accessible, Interoperable, Re-usable (FAIR) data, standardized data products, and training and innovation services will impact in the progress of basic science and in societal benefits. This, in turn, will drive the way for new observing technologies, procedures and tools for the end-to-end transition of research models to applications tuned to meet the requirements of the technologies concerned, and linking best-in-class facilities to provide seamless multi-technology services.

2.2. Societal benefits of enhanced predictability

Space weather forecasts

Monitoring and forecasting space weather in an accurate and timely manner is important to protect critical infrastructures from interruptions or indeed long-term damage by adverse SWe. The implications of space weather on numerous aspects of life in our planet, including socio-economic activities of developing countries, are well-known and recognized. Some examples follow:

- The total electron content (TEC) of the ionosphere may increase substantially during strong ionospheric storms, causing variability in the propagation conditions of electromagnetic waves. SPEs, for instance, can cause episodes of enhanced absorption of radio waves in the Earth's polar caps (PCA events), thereby restricting (if not disabling) transpolar high-frequency (HF) radio communications. Commercial airlines are potentially affected by these disruptions when they overfly the polar zones, being obliged to deviate from their projected shortest routes towards lower latitudes.
- The accuracy of single frequency receivers signals of Global Navigation Satellite Systems (GNSS) can also be affected by intense TEC enhancements and ionospheric scintillations produced by irregularly structured regions, as these signals suffer from unknown delays and scattering.
- High-energy SPEs and GCRs can also expose astronauts to radiation levels above the safety limits, especially those working in the exterior of their spacecraft or in unprotected areas, due to lack of atmospheric shielding. Particle solar radiation can also incur damages in satellite-borne equipment.
- Temperature-induced inflation of the thermosphere during geospheric storms can cause low Earth orbit (LEO) satellites to reduce its speed and even fall prematurely due to enhanced drag with this part of the upper atmosphere.
- Strong currents flowing at the ionosphere of relatively high magnetic latitudes during geomagnetic storms and substorms produce strong and highly variable magnetic fields at the Earth's surface, giving rise to induced electric fields in the solid earth. Because electrical power grids are grounded, these electric fields act as a voltage source for the

high-voltage power transmission grids, thus introducing a substantial direct current (DC) signal in the network. The related currents, known as geomagnetically induced currents (GICs), may disrupt or damage the transformers of those grids, which are set up for alternating current (AC) flow, thus potentially affecting the final user. This is perhaps the space weather threat of most concern in our era. At lower latitudes, the main mechanism of GIC generation is rather related to the direct impact of the solar wind onto the magnetosphere, namely the sudden impulse (SI) in the magnetic field produced by the abrupt increase of the magnetopause currents caused by the bulk of incoming solar plasma. Although one generally expects that at those latitudes the magnitude of GICs is one order of magnitude lower than that at high latitudes, recently there has been a great wealth of studies on the vulnerability assessment at those middle to low latitude grids. To be efficient, such vulnerability analyses must benefit from the following: i) the knowledge of the geomagnetic field variations at each node of the grid; ii) the knowledge of the Earth's geoelectrical structures beneath the network. Abrupt site-to-site differences in the derived geoelectric field can show geographically distributed differences up to a factor of 1000; iii) the knowledge of the topology and the relative resistances of the power grid elements in the precise instant of the geomagnetic storm.

- There also exists evidence that intense GICs can hamper rail traffic by disturbing signaling and train control systems. Such a threat concerns long railway segments and is primarily caused by high-latitude geomagnetic disturbances driven by the auroral electrojet, but also by SI and pulsations, which can affect a higher range of latitudes.

Reliable and accurate monitoring and forecasting requires large heterogeneous data sets, detailed theoretical models and advanced data processing techniques. Recent advances in machine learning now offer great potential to uncover the characteristics of the Sun-Earth system, to use this knowledge to predict solar activity and its terrestrial impacts on timescales ranging from hours to days, and to improve the accuracy of interplanetary propagation models.

Climate projections and sub-seasonal to decadal prediction

Sub-seasonal to decadal timescales are considered most relevant by policy makers and drive decisions in terms of, e.g., infrastructure investments or land use. As to date, weather forecast systems exhibit reasonable skills out to several weeks. On the other hand, climate variations are well represented in Earth system models on centennial scales. Bridging the gap in the intermediate timescales requires identification and understanding of sources of predictability, as well as its adequate representation in forecast models.

Better prediction of the solar and geomagnetic evolution, with their inherent 11- year variations, improved understanding of the mechanisms whereby they affect weather and climate, and a better representation in forecast systems represent major steps to assess the benefits from these potential sources of predictability in subseasonal-to-decadal scales. If realized, they might bring added value to forecasts as "windows of opportunity", i.e. periods of enhanced predictability conditioned on skillful phenomena, with potential benefits to many sectors of society.

Regarding climate projections on longer timescales, one of the current limitations concerns the lack of probability estimates of future solar forcing variations, which limits the design of model sensitivity experiments within the Coupled Model Intercomparison Project (CMIP) that supports the IPCC. Although recent progress has been made regarding the consideration of plausible and extreme future solar forcing, they do not represent the full range of scenarios and even less the occurrence of low-probability worst-case events. A better quantification of solar impacts on global and regional climate would also represent an important step to improve knowledge of past climate, and hence to better constrain climate sensitivity, which represent a key source of uncertainty in the climate projections that ultimately guide the measures required to meet the ambitious global surface temperature targets agreed under the COP21 Paris Agreement.

2.3. Adaptation to extreme events

Extreme SWe

Intensive efforts are presently dedicated to forecasting GIC with some lead time in order to benefit decision making. When it comes to evaluate the performance of a given model, one is faced with the question of what is the most suitable method to compare it with real observations (in the case of GIC in power grids, the currents measured directly in the transformer neutrals by using Hall effect transducers; or those indirectly obtained by differential magnetometry under power lines). The broader community studying extreme SWe impacts is actively discussing how to evaluate model performance across a variety of prediction domains. This includes predictions of the ground magnetic perturbations leading to GIC. Efforts are done also to develop warning and mitigating capacities of SWe effects in the ionosphere: a) to detect and track ionospheric disturbances that might degrade technological systems based on radio-telecommunications in order to provide warnings and to create strategies to mitigate such a deleterious effects; b) to develop back-up communications systems to maintain the flow of critical information under failure of other communications systems that might be caused by natural or anthropogenic threats; and c) to prove the integrity of radio-communication systems technologies under the effects of certain scenarios.

Meteor showers

The detection of large bolides should concentrate monitoring efforts in order to identify the sources of hazard to humans. In the lower range of particle diameters, cometary meteoroid streams and younger dust trails encountering the Earth can produce a significant fraction of millimeter- to centimeter-sized projectiles that could require palliative measurements to avoid satellite impact hazard.

The dynamic linkage between a meteoroid orbit and that of a comet or asteroid has been also reinforced using powerful backward integrators like e.g. Mercury 6. As a consequence, the links are established on the basis of a long temporal scale comparison between the orbits of the parent bodies and that of each meteoroid. Such a procedure avoids false associations with meteoroids belonging to the sporadic background, casually showing similarity at the epoch of their encounter with Earth.

A close encounter with a comet is very unlikely, but the atmospheric consequences of a comet flyby similar to Siding Spring's passage near Mars (140000 km) would cause an increase of the input of extra-terrestrial dust to the upper atmosphere, which would perturbate significantly both atmospheric chemistry and dynamics. The consequences would range from destruction of ozone and water in the middle atmosphere to a perturbation of stratospheric aerosol as a result of the injection of cometary sulfur (Gómez Martín et al., 2017). Besides climate impacts, such an encounter would have a large impact on the ionosphere, creating a metal ion E layer with the potential of disrupting space-to-ground communications. Encounters with long period comets are difficult to predict, e.g. Siding Spring was observed for the first time about 20 months before its encounter with Mars.

Adaptation to climate change impacts on geospace

Predicting the middle and upper atmosphere 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 reinsurance industry, particularly when considering that monitoring the location of all known space debris objects to avoid collisions, even when no avoidance manoeuvres are needed, comes at considerable cost to satellite operators.

3. KEY CHALLENGING POINTS

3.1. Observational challenges

Sun and interplanetary space

Polar observations of the Sun: Seen from Earth or Earth-bound orbits, the poles of the Sun are hardly accessible to observation but are responsible for the large scale structure of the coronal magnetic field. In this sense, efforts to exploit the results coming from the excellent vantage point provided by ESA's Solar Orbiter will be key during the next 10 - 15 yr to understand the changes of solar activity at the poles of the Sun. The unique orbit of Solar Orbiter, inclined from the ecliptic up to 32 degree, will provide an unprecedented view of polar magnetic fields. Solar Orbiter is going to provide another unique observational capability, namely, the observation of the whole-Sun magnetic field by combining the PHI (Polarimetric and Helioseismic Imager) magnetographic data with those coming from the Earth (or Earth-bound orbit) when the spacecraft and our planet are in opposition with respect to the Sun. These global measurements will be key to gauge the prediction capabilities of current models of solar activity variability that have never been checked observationally.

Synergistic operational monitoring of the solar corona, the solar wind and the interplanetary magnetic field is key for early and reliable predictions of arrival times and characteristics of space weather events. ESA has recently initiated Phase-A studies for Lagrange, a mission concept specifically devoted to space weather. Designed to monitor the Sun from the Lagrange's L5 point, it will be the greatest herald of space-weather, Earth-directed phenomena with due time advance, thanks to the 60 degree angle that the spacecraft and Earth form as seen from the Sun. Among its payload, as is currently normal in every space weather effort, a magnetograph is included. PMI (Polarimetric and

Magnetic Imager) will hence provide crucial 24/7 monitoring of the photospheric magnetic field. When combined with proper extrapolations, its measurements will increase our forecasting capabilities of CMEs, CIRs, SEPs and flares.

Accurate and extended satellite measurements of SSI variations, covering the 11-year solar cycle, are of paramount importance to quantify solar effects in climate and unveil the underlying mechanisms. Observations of the last solar cycle showed larger SSI changes in UV wavelengths than hitherto believed, and climate models prescribing them revealed stronger climate responses to solar cycle, with regional climate impacts that were promising for subseasonal-to-decadal forecasts. These observations were later suggested to be biased by drifts in satellite instruments. Current estimates of SSI changes employed in climate models are based on empirical or semi-empirical irradiance models, with substantial differences in the magnitude of SSI changes over the 11-year solar cycle, which prevent more definitive answers on the controversial debate about solar impacts in climate.

High spatial resolution measurements of the solar magnetic fields are expected to benefit from the state-of-the-art features of the DKIST, which has recently seen first light at Haleakala Observatory, in the Hawaiian island of Maui, and EST (European Solar Telescope) to be erected in one of the Canarian observatories. Those telescopes, and the third edition of the Sunrise stratospheric mission, will provide new capabilities for observing the chromosphere and the corona.

However, a *global picture of the coronal magnetic field* does not appear in the plans of space agencies, although we only know the properties of the Sun's global photospheric and chromospheric field. If high resolution is crucial to understanding the detailed physics, global, moderate-resolution observations of the corona are paramount to predict the arrival of CMEs to Earth. A long term goal would be to pursuing the development of a space mission devoted to monitoring the global coronal magnetic field.

Magnetosphere and ionosphere

Spectrally and pitch angle resolved measurements of electron fluxes. A good knowledge of the vertical shape of the atmospheric ionization profile is crucial for constraining direct and indirect atmospheric impacts of energetic electron precipitation. This is particularly relevant in the MLT region, where dynamical factors such as the interplay between diffusion and advection induce huge variations of the magnitude of particle-induced composition changes as a result of only small variations in the vertical distribution of ionization. The existing MEPED instrument on POES suffers from poor energy resolution, directly translating into poor vertical resolution of the derived atmospheric ionization. Further issues of these instruments are contamination by medium-energy protons and uncertainties in terms of the fraction of precipitation observed. Current instrumentation has also poor coverage of relativistic electrons (>1 MeV), resulting in poor knowledge of direct EPP impacts in the upper stratosphere. Furthermore, there is a lack of pitch angle resolved measurements over a wide angle range, which prevents from a true measurement of the fluxes of all electrons precipitating into the atmosphere. These issues need to be addressed in future space mission concepts.

Detection and tracking of ionospheric irregularities caused by Space Weather is key for the study of ionospheric irregularities phenomena, expanding the understanding of the dominant energy distribution and momentum transfer mechanisms in the ionosphere and thermosphere, and, in turn enabling the development of advanced warning and mitigation applications for systems relying on predictable ionospheric radiowave propagation. For this purpose, ground-based networks of sensors probing the ionosphere are mandatory. However, even denser networks of sensors are needed for a more accurate and precise detection and tracking of ionospheric irregularities (e.g. Altadill et al., 2020). Moreover, although significant advances in our understanding of ionospheric irregularities have been made to date, a complete picture is yet to emerge. This is why research into ionospheric disturbances phenomena remains an important topic for the ionospheric community. New observational methods, both from Space and ground, will be key for future progress.

Atmosphere

Continuous monitoring of the dynamical and compositional state of the atmosphere. The "Golden Age" of spaceborne Earth observation of the past two decades has offered a unique opportunity to advance our knowledge of naturally and anthropogenically forced atmospheric composition changes and associated dynamical variations. However, roughly two decades of observations are not sufficient for capturing long-term changes of both, the direct chemical impacts (caused by changes of the irradiance and ionization levels related to decadal and secular variations of the Sun) and the dynamical coupling of these impacts to the stratosphere (due to changing circulation patterns as consequence of greenhouse gas forcing). Perspectives for the future are not promising: several space missions targeting middle atmosphere observations have recently ended or are phasing out in the next few years, with no replacements planned in the near future. As a consequence, an observational gap is expected that will seriously harm the continuity of long-term observational records of ozone and related chemical agents, temperature, and dynamical tracers such as water vapor, carbon monoxide and methane. The promotion of future space instrumentation targeting the continuation of the monitoring of middle atmospheric key variables is thus of utmost importance.

Generation of consistent long-term climate records. Multi-decadal climate data records from combined satellite datasets and their integration in numerical models are key for the detection and attribution of long-term trends in the atmosphere. Improved and extended datasets are also required for the evaluation of Earth System Models as well as for verification of hindcasts in subseasonal-to-decadal forecasts. Mandatory steps include the critical assessment of methods for merging, homogenising and testing disparate measurement series, as well as the implementation of ways of providing quantitative and traceable uncertainties of merged datasets and their systematic comparison. Standardised products for community use need to be developed and improved, including tools to access the merged datasets, for its use in data assimilation schemes employed in reanalyses, and forecasts whose skill strongly depends on initialization state.

The thermosphere is the poorest known atmospheric region, despite its importance for linking Geospace with the atmosphere where we live. Remote sensing observations of the thermosphere are extremely difficult to perform with current instrumentation and, as a consequence, temperature and CO2 measurements in this region are sparse. Atomic oxygen, a key parameter that largely controls the energy budget of this region through chemical recombination, as well as its cooling by CO2 and NO emissions, has never been measured globally. As the thermosphere is expected to be significantly affected by increasing CO2 concentrations which, in turn, has unforeseen effects on the LEO satellite orbits and space debris, the future continuous monitoring of its CO2 and atomic oxygen concentrations and temperature are fundamental for understanding the future evolution of the Space-Earth system.

High resolution observations of critical chemical parameters in the MLT region: Trace gas measurements in the middle atmosphere are difficult, particularly in its upper part, where most of the solar-induced composition changes occur. Except for isolated in situ measurements by instrumentation on rockets this region is accessible only by remote sensing techniques from space and ground. Limitations of these techniques with respect to spatial sampling, dependence on illumination, and vertical resolution often make it difficult to draw robust and/or quantitative conclusions about the magnitude and spatial variability of chemical changes. This is particularly the case for nitric oxide observations in the MLT region because of its large vertical gradients and its pronounced variability caused by energetic particle precipitation. Future progress in sensor technology and miniaturization, together with the development of new observational strategies (e.g., satellite constellations), is hoped to overcome current limitations.

Meteoroid and asteroid environment

New fireball networks have been created during the last few decades using new high-sensitive digital cameras. As a consequence, the atmospheric volume monitored has increased, and applying new detector techniques, including digital CCD and video imaging (Trigo-Rodríguez et al., 2013), have allowed the discovery of new sources of meteoritic activity. Such an effort has ended in 112 recognized meteoroid streams, plus a working list of 685 additional streams that remain to be confirmed (https://www.ta3.sk/IAUC22DB/MDC2007/). Most of these meteor showers are associated with comets, but others are linked with asteroids or transitional objects in near-Earth space. The later are more challenging as they might contain meter-sized rocks that can produce meteorite falls, or even excavate small craters like e.g. Carancas.

Additional effort is required to understand the ability of these challenging meter-sized bodies to penetrate in Earth's atmosphere. The development of new mathematical approaches is the key to decipher the implications of m-sized meteoroids in impact hazard (Moreno-Ibáñez et al., 2020). To quantify and identify the effects it is needed to increase the fireball monitoring effort using high-resolution temporal and spatial detector systems. Increasing astrometric measurements will get better quality of orbital parameters.

New technological developments are also required to enable *interplanetary dust collection devices* to be deployed on board of orbital platforms for in situ analysis or return missions that do not involve altering the collected samples by high-speed collisions. Further afield, evidence of micrometeorites on the Martian surface and cometary return missions analogue to Osiris-REX would be highly desirable.

3.2. Models and methodological developments

Sun and interplanetary space

In spite of recent advances, our current understanding of the solar cycle progression is still poor. Improved magnetohydrodynamic (MHD) modeling of the solar dynamo is needed to allow for solar activity forecasts beyond the ongoing solar cycle and as a tool for SWe event prediction. Still more important are the techniques for combining those forecasts with future observational data (in particular those from Lagrange). Further, an effort to use our current good knowledge of the past to extrapolate the future is needed.

Space weather and Ionosphere:

Most current forecasting techniques of SWe effects on Earth are based on empirical models driven by solar wind data or by solar/geomagnetic activity indices which are able to warn for a few hours or fractions in advance. This is a significant gap for SWe products. In addition, ionospheric forecasting products, which can be tailored for a given region, as Europe, or to provide global forecasting, have a forecast horizon limited from minutes to few hours ahead. Therefore, it is needed to forecast ionospheric perturbations triggered by SWe much earlier in advance. To improve this, a better knowledge and more accurate storm-time electrodynamics is needed to be able to better forecast ionospheric irregularities. The analyses and exploration of additional physical magnitudes which can serve as proxies of plasma clouds arrival, in order to anticipate a SWe event much earlier in advance, are the key challenges for providing improved forecasting techniques and models capable of extending the forecasting horizons of disturbances caused by SWe up to several days.

While many ionospheric models are based on the linear regression approach and dependent on a limited number of variables, the correct relation between drivers and response parameters is still a state-of-art solution. The main advancement of contemporary models is the introduction of delayed reaction of ionosphere to the driver forcing. Moreover a progress is needed from predicting climatology to describing the real-time weather conditions in the ionosphere.

Atmosphere and Climate:

Parameterized processes in climate modelling. The dynamics of the mesosphere and lower thermosphere is driven largely by small scale waves, which are not explicitly considered in most climate models owing to limitations of horizontal resolution. Although resolved planetary waves are critical for the stratosphere, its circulation is also strongly sensitive to small scale waves, in particular orographic and non-orographic gravity waves. Parameterizations are often implemented to account for the impact of such waves in climate models and forecast systems. Deficiencies of these parameterizations are, for instance, the likely cause of the mismatch between modeled and observed NOx descent during dynamically perturbed NH winters, and an important factor of current model biases and the spread of future climate projections in the stratosphere. Currently, large efforts are being made to improve these parameterizations. Future progress will also benefit from the growing computing power, allowing the increase of horizontal model resolution, and hence, possibly allowing for explicit simulation of small scale waves and their propagation through the entire atmosphere.

High vertical resolution and climate model lid height. Recent progress in modelling and computing facilities has allowed higher vertical resolution and extending vertically the upper boundary of climate models above the stratopause. This has fostered international initiatives evaluating the beneficial role of an explicit well-resolved representation of stratospheric dynamics (the so-called high-top models; e.g. SPARC), and interactive chemistry (e.g. CCMI). The latter is of paramount importance for future projections foreseeing competing and interactive effects between the expected recovery of the ozone layer and increasing concentrations of greenhouse gases. Benefits have been tremendous, including an improved representation of stratosphere-troposphere coupling, the spontaneous simulation of internally-generated phenomena (e.g. the QBO), reduction of model biases, or an enhanced skill in subseasonal-to-seasonal forecasts. However, there are still large avenues for further improvements to fully exploit the added value of the middle atmosphere in upcoming generations of climate models. While there is no theoretical understanding regarding minimum requirements for the vertical resolution and model lid heights, coupling of the stratosphere with upper layers of the atmosphere is still not fully understood, as well as their potential benefits, which represents an endeavour to integrate in a holistic way the Space-Earth system and simulate their interactions.

Advanced statistical analysis methods. Solar signals in observations and/or model studies have been usually attributed using statistical methods such as multilinear regression, optimal fingerprints or superposed epoch analysis. These have a strong explanatory power, are easy to implement and have allowed advances in detection and attribution of climate change to climate forcing with large signal to noise (e.g. greenhouse gases concentrations or volcanic eruptions). However, the assumptions required for these standard methods (e.g., linearity, normality of the error distribution, regressor orthogonality, and so forth) are often not fulfilled in the climate system, which may result in biases or may even lead to erroneous conclusions. Currently, a robust detection and attribution to solar forcing is often elusive, particularly in paleoclimate, where additional uncertainties add to those of solar forcing reconstructions. As such, the attribution of past climate changes to solar variations is inconclusive even on hemispheric scales and for periods of well-known solar variations such as the Maunder minimum. Advances in statistical learning analysis methods developed in other fields may have the potential to overcome the aforementioned limitations and need therefore to be explored. Machine learning has recently been successfully employed in climate problems to e.g. uncover cause-effect relationships in this nonlinear highly complex system (so-called causal networks). Promising results can be anticipated for the identification of skilful predictors in statistical forecasts and the separation of superposing drivers of stratosphere-troposphere coupling that suffer from aliasing effects (e.g., solar vs. volcanic forcing)

Meteoroid and asteroid environment

Meteoroid ablation models need to implement the new insights into the composition and structure of cometary dust obtained by the Rosetta mission. Fragmentation of micrometeoroids as a result of vaporization of the interstitial organic matter is possibly the clue to reconciling apparently diverging ground observations. The potential of remote spectro-photo-polarimetric observations of the Zodiacal Cloud to determine the different dust populations should be fully developed. This involves a better understanding at a fundamental level of the interaction between radiation and particulate matter, and identifying light scattering spectro-photo-polarimetric features that may assist in quantifying the relative contribution of different populations, e.g. asteroidal vs cometary.

Meteoroid engineering models and atmospheric entry models require a better characterisation of the sporadic meteoroid complex regarding composition, structure, density, and tensile strength. Recent space missions to comets like e.g. Stardust (NASA) and Rosetta (ESA) have provided a significant insight into the heterogeneous nature of mm-sized meteoroids associated with comets. These particles initially forming meteoroid streams are fragile aggregates that fragment over time due to solar irradiation, and also suffer non-gravitational effects and collisions that make them lose progressively dynamical affinity with their parent bodies. We know that in time-scales of tens of thousands of years they are fragmented into micron-sized dust that forms the Zodiacal Dust. To increase the fireball monitoring effort using a multidisciplinary approach could be the key to increase our knowledge in these areas.

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