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"Assessment and Recommendations for a Consolidated European Approach to Space Weather – as Part of a Global Space Weather Effort"

European Space Weather Assessment and Consolidation Committee – ESWACC
Report (Full Version – August 30, 2019)

authored by

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European Space Weather Activities

Assessment and Recommendations for a Consolidated European Approach to Space Weather – as Part of a Global Space Weather Effort

European Space Weather Assessment and Consolidation Committee – ESWACC

Report (Full Version – August 30, 2019)

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(NOTE: the ex-officio representatives are not co-authoring this report, but have given valuable comments and advice throughout the process of meetings and discussions)

A report commissioned by the European Space Science Committee ESSC, of the European Science Foundation ESF in May 2017.

Process

Starting with a first meeting at ESOC in Darmstadt in June 2017, ESWACC has held four face-to-face meetings, at ROB in Brussels, at ESA-ESTEC in Noordwijk, and at the UN in Vienna.

This report was completed following a number of teleconferences also to prepare slides with preliminary findings and recommendation as requested by the EU / DG-Growth in February 2018 and another set of slides with the final ESWACC findings and recommendations for the DG of ESA, Dr. Jan Wörner at ESA HQ in February 2019.

The next-to-final report was presented to the ESSC Plenary Meeting in Amsterdam on May 9-10, and after further iteration and helpful comments from Profs. Dan Baker, LASP, Boulder, USA, Ian Mann, U. of Alberta, Canada, Tim Fuller-Rowell, CIRES, U. of Colorado and NOAA, USA, and Karel Schrijver, Lockheed Palo Alto (retired), USA.

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Executive Summary

Over the last 10-20 years there has been an ever-increasing international awareness of risks to modern society from adverse and potentially harmful – and in extreme cases even disastrous – space weather events. Many individual countries and even international organisations like the United Nations (UN) have begun to increase their activities in preparing for and mitigating effects of adverse space weather. As in the rest of the world there is also in Europe an urgent need for coordination of Space Weather efforts in individual countries as well as in and among European organisations such as the European Space Agency (ESA) and the European Union (EU). This coordination should not only improve our ability to meet space weather risks, but also enable Europe to contribute to on-going global space weather efforts. While space weather is a global threat which needs a global response it also requires tailored regional and trans-regional responses that require coordination at all levels.

This report discusses on-going European SWx (in the following we will adopt the US standard abbreviation "SWx" for Space Weather) efforts and issues, and gives recommendations for future coordinated and better consolidated activities. We have found that these issues can be broken down into 6 activities where coordination at European level will be required.

<u>This report makes recommendations in these six areas - as defined by:</u>

1. **Area 1: Enabling critical science to improve our scientific understanding of SWx:**
   Our overall description of the coupled Sun-Earth system in the space age still contains critical gaps in the scientific understanding of several mechanisms through which space weather couples from space all the way down to Earth. While significant progress can and will be made using existing scientific infrastructure including existing multi-spacecraft missions and ground-based networks, support must urgently be provided for the next generation space missions and the replacement of ageing ground-based infrastructure.

2. **Area 2: Development and coupling of advanced models by applying a system-science approach which utilises physics-based modelling**:
   Develop better physics-based models and also define metrics that facilitate assessment of different models and to encourage their transition to operations.

3. **Area 3: Assessment of risks at National, Regional and European levels:**
   European States should regularly assess their exposure to SWx risks and coordinate and combine their studies at regional and European level to cover the interdependency of technological infrastructures. This requires close cooperation between decision makers, SWx scientists, service providers, and end-users.

4. **Area 4: Consolidation of European User Requirements**
   European SWx user requirements should be (re-)assessed and prioritised taking into account regional and societal differences and needs, also addressing different needs of various infrastructure systems. This should be done on a regular basis, e.g. every 5 years, also to facilitate the exchange of information among European SWx actors.

5. **Area 5: Support to R2O (and O2R)**
   The best available knowledge and models should be used in future SWx service organisations. Such transition from Research to Operations should be guided by

teams of scientists all over Europe - following the distributed ESA Expert Service Centre approach. In addition, a structure to enable models that have been transitioned to operations to be improved (O2R) should be established.

6. **Area 6: Define and implement an operational network for future SWx observations**
   Based on our present scientific understanding and the above assessments of risks and user requirements we need to define an *operational* space- and ground-based network that measures essential space weather parameters which in turn can drive the SWx predictions required to protect our society's infrastructure.

Other Issues requiring attention:

A first analysis of our knowledge, observational gaps and requirements for an appropriate SWx warning system with special consideration of European SWx vulnerabilities and weaknesses, but also taking into account European strengths has been carried out by the Expert Groups in the ESA SSA Space Weather Service Network and the results of the analysis have been reviewed by the European Space Weather Working Team. However, continuous elaboration of the analysis including assessment of space weather risks on European infrastructure and understanding of the user needs will be required because of the constantly evolving end user landscape and European SWx competencies.

We find that the presently ongoing SWx efforts in Europe are to a large degree uncoordinated and also mostly unsustainable. This is probably at least partially due to the fragmentation of funding responsibilities in Europe. Apart from the ESA and the EU, individual states and many different agencies also fund space weather activities.

The **ESA** is presently developing pre-operational SWx-services in the framework of its Space Situational Awareness (SSA) Programme with 19 out of ESA's 22 Member States participating in the SWx segment. However, the ESA SSA programme is optional and the participating member-states contribute very diverse voluntary annual contributions, not always reflecting Net National Income. Also the scope of the services, established within this programme, is currently limited to testing, verification and validation.

The **EU** had – and still has - scattered H2020 (FPx) SWx calls, reoccurring every other or sometimes even only every third year. Even if the EU funding to SWx activities adds up to a considerable amount of approximately 60 M€ over the last 10 years, the funding offered in each call is sub-critical to develop sustainable science and service activities, and did not match the European needs. Many of these calls were (and still are) aimed primarily at the prototyping of services with relatively little regard for the scientific foundations, which are required for such services to become reliable. Most of the work required for the scientific underpinning of SWx, especially the science and data exploitation activities (see our findings below), fall into the general EU-calls, where they compete with basic science.

Additional funding provided by individual European states is fragmented, localised, un-coordinated, and also mostly insufficient to satisfy the growing societal needs, for both the advancement of knowledge and the provision of services. Also it is difficult to build transnational and regional efforts on national funding.

Moreover, the private sector is recently becoming more and more active in space, and realises its exposure to SWx-threats. However - and yet again - the funding emerging from such sources is often too directed and topically far too narrow to satisfy SWx needs.

We would like to stress that while this diversity in funding is currently often seen as a European weakness, it could be turned into a strength, if it were coordinated according to the principle **„Let those do the work who are best at it“.** We strongly advocate a dedicated Europe-wide coordination of SWx activities. This could be done in a similar manner to how the COPERNICUS programme deals with Earth Observations.

Current European SWx services rely on data from ageing infrastructure such as ESA‘s SOHO spacecraft, which is rapidly approaching its 25th anniversary, having thus substantially exceeded its design lifetime of 2 years. While ESA is indeed discussing with the US about a coordinated development of a common space weather monitoring system, there is no consolidated plan yet for the successor for SOHO. The current scientific space infrastructure is not able to provide near-real time 24/7 operational data for future SWx warning systems.

The presently available fleet of space- and ground-based assets, which observe the sun, geospace, and the region of space between these two, the inner heliosphere, offer the current and unique opportunity to increase our scientific understanding of SWx. As this infrastructure continues to age beyond its operational lifetime, and given the increasing funding pressures, progress in the scientific understanding of SWx can, and needs to be made now, requiring adequate, coordinated, and reliable funding.

Europe is, of course, not alone in its recognition of the importance of SWx science and services. European agencies and researchers have long recognised the importance of international coordination of scientific efforts, information exchange on space weather events and their mitigation, national, regional and over-regional risk analysis and assessment of user needs. This coordination should be understood to encompass the currently scattered, uncoordinated, short-term, and often insufficient funding of European SWx activities and should lead to an increase in funding of SWx activities to a level that allows an operational European SWx system to be established, operated and maintained. These activities should cover both the scientific foundations of SWx as well as the development and provision of SWx services for society.

Purpose of this document

The **E**uropean **S**pace **S**ciences **C**ommittee (**ESSC** - www.essc.esf.org) of the European Science Foundation (ESF) is an independent committee that regularly provides expert advice to European and National research funding and research performing organisations that support space sciences in Europe. The members of the ESSC are drawn from experts active in all fields of space research on the basis of scientific expertise and recognition within the community, they are nominated *ad-personam* and therefore do not represent any organisation or country.

The ESSC covers the whole spectrum of space sciences; it is structured around panels (Astronomy and Fundamental Physics, Earth Sciences, Life and Physical Sciences, and Solar System and Exploration). The mission of the ESSC is to facilitate and foster space sciences at the European level by providing unbiased, expert advice on European space research and policy via recommendations or reports. Furthermore, ESSC provides a unique focal point to assist European national councils and agencies to achieve optimal science return and harmonise strategic priorities in space activities.

The ESSC **Panel of Solar System and Exploration** has in the recent past frequently been asked to give advise in questions concerning the **Policy and Science of Space Weather**, which is a fast growing area of concern for our highly technological society both in Europe and around the world. In 2015 COSPAR and the Inter-Agency initiative International Living with a Star (ILWS) have published an international roadmap [54] concerning a global approach to understand and mitigate effects of adverse space weather and to shield our society. This roadmap document has ever since been adopted and used as the guiding-document for the planning of a global coordination effort by the Committee for Peaceful Use of Outer Space (COPUOS) of the United Nations. It has also triggered the formulation of space weather activities and mitigation plans in many countries, most pronounced maybe in the USA in the form of a detailed National Space Weather Action Plan (https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf).

In the recent years also most European countries have recognised the potential challenges and risks to our modern society, potentially emerging from adverse or even extreme space weather. Almost every individual country has in some way increased their national awareness and potential preparedness for harmful SWx effects. On European level both the ESA and the EU are preparing overarching programs to increase Europe's ability to meet the emerging threats from our space environment.

In response to such growing interest and the increasing international awareness about potential threats from adverse space weather to our modern society the ESSC has both been asked and decided by itself to look into a consolidated advice concerning a European approach to Space Weather risk assessment and parallel scientific and service activities, by creating the **European Space Weather Assessment and Consolidation Committee, ESWACC.**

The aim of this new Committee was to prepare detailed recommendations for a consolidated and strategic approach to SWx - for Europe as a whole and also as a part of the global SWx effort as advocated by the UN-COPUOS.

The situation of SWx today is that we do understand the underlying principles of Sun-Planet interactions, but we are still far from an operational system for SWx predictions as we know them from Earth weather forecasts.

While our community is learning how to make more accurate predictions about such SWx impacts, we are – and should be - continuously learning more about the underlying physics of the coupled Sun-Earth System, in order to improve our models. At the same time the driving societal needs are constantly developing - and changing.
A future SWx system or service function needs be built in a way that it constantly can adapt to such changing requirements. Societal SWx risks – and prediction requirements - are different in different European regions - thus different solutions will be needed for different places and also for different assets in space and on the ground.

A promising approach to develop the required future European space weather activities and services can best be described as an iterative loop, in which there should exist a continuous iteration and feedback between:

a) new improved science understanding and supporting observations
b) evolving requirements of European end-users and infrastructure providers, and
c) improved potential to deliver SWx products (based on recent science findings)

where b) and c) should also address particular national and trans-national requirements, and eventually feed back into new challenges for the science efforts under a).

The ESWACC has during the recent two years explored the challenges and monitored the approaches being taken in Europe and around the globe for advancements in SWx research and services. In this document the ESWAC-WG has prepared a number of detailed recommendations for a consolidated and strategic European approach to SWx, within which we try to identify the appropriate efforts and investments that need to occur in all parts of the above described SWx “iteration loop” in a timely and coordinated fashion.

We find that one carefully needs to balance **long-term efforts** as e.g. investments in basic science, **short-term efforts** like investments in applied science and **immediate efforts** and investments in general infrastructure resilience, survival potential and related recovery measures.

Our recommendations recognise efforts already undertaken by national and international organisations in Europe. The committee has also closely collaborated and coordinated its activities with the existing ESA SSA-SWE program to recommend a path forward towards the establishment of a long-term European space weather effort and closely linked tailored SWx-service functions for Europe.

1. Introduction

The impacts of energetic events at the Sun (and outside our solar system) on near-Earth space - and consequently on technological infrastructure on and around our planet - are generally referred to as Space Weather (short SWx). Policy-makers in governments around the world are presently widely engaged in discussions about the potential risks posed by SWx (see e.g. [36] on recent UN Efforts; or the US Space Weather Action Plan). Similarly various national and international organisations are assessing the adverse impacts of space weather events on critical infrastructure and advanced technological services, and what kind of information (benchmarks, nowcasts, forecasts) the user communities would require to mitigate space weather impacts. This report focusses on European SWx vulnerabilities, opportunities, and ongoing and future efforts required to reduce European SWx exposure.

The socio-economic impacts of SWx events are increasingly being studied in their entire breadth and in their full depth [45, 46]; a cost-benefit analysis of the European Space Agency details the importance of preparing for SWx [1]. Such studies have established that extreme SWx events pose a High Impact Low Frequency (HILF) threat. Such HILF-threats pose a challenge to science to estimate their occurrence rates reliably, and to science, politics, insurance companies, and society as a whole to assess their potential damage. Estimating their occurrence rate is crucial because the related damage is potentially so large that efforts need to be made now to mitigate SWx risks to ensure the well-being of modern civilisation.

Space weather has not only been recognised as a global challenge for society, it also remains a major challenge for the scientific community itself. While there is a considerable, urgent and constantly growing need to strengthen the reliability of technological systems in space and on the ground and their ability to respond to the impact of adverse SWx, there is unfortunately still a considerable lack of essential understanding of the Sun-Earth system and the very complex and highly dynamic physical coupling between the vastly different plasma regimes on the Sun, in the heliosphere and in the near-Earth space, i.e. the magnetosphere, ionosphere and upper atmosphere. Of course, it is crucial to understand these processes if we want to protect society from them, but at the same time, we can not afford to wait for a complete scientific understanding of SWx before we develop and implement SWx services for society. Thus it is critical to ensure a continuing feedback loop between all SWx actors: scientists, developers, service providers, governments, and end users. With the currently limited scientific understanding both of the causes and effects of SWx, efforts today need to focus on how governments should invest into knowledge and methods to forecast space weather and mitigate its adverse effects in the same way as policy-makers invest in methods to mitigate the risks posed by other natural hazards (see e.g. 19). What makes Space Weather risks unique is that **the threat is truly global**, affecting large parts of the globe for major solar storms while **the detailed impacts vary at regional and trans-national levels**. In other words, SWx-event can be very different from country to country, depending primarily on the latitude of the country's geographical coverage,, but also depending on the event itself, on whether the longitude of the region is at night-, day, dawn- or dusk-side, the details of particular vulnerability and connectivity of national and (trans-) regional infrastructures, and the economic interconnections between nations and regions. Space weather is a modern risk, it affects our modern and inter-connected society in ways for which we have no historical experiences to teach us how to cope with it. Space weather events can create damage beyond the ground-based infrastructure in the affected region or country itself by adversely affecting space and aeronautical assets, or other external infrastructure like international transport on water and land. In Europe this interconnectedness is complicated by the fact that there are varied national interests, particular vulnerabilities and specific abilities, all of which determine each country's individual approach to SWx.

In this spirit, two European organisations, the ESA and the EU have both - in partnership with other global players - recognised the SWx risk for Europe as a whole. But at present both organisations are working more or less independently in preparation of initial European SWx prediction services as well as trans-national mitigation efforts. Both organisations support research for an improved understanding of SWx processes and impacts, and of the

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[1] *"A cost-benefit analysis of the SSA programme", 29 September 2016. Presentation available from the Global Space Economic Forum section of the European Space Agency website (www.esa.int/).*

underlying space physics, in addition to, and largely uncoordinated, with already ongoing national efforts. Moreover, as has been noted before, there are different priorities and attitudes toward SWx research and services in Europe. While research funding organisations in some countries prefer to invest in so-called "curiosity-driven" research, others rather choose to invest in more directed work aimed at practical solutions. Some countries already invest in both avenues; Space weather is a typical scientific problem area where both – curiosity-driven and result-oriented – research efforts are needed.

Progress in reducing space weather risk for Europe as a whole requires that the guidance and funding given by the ESA and the EU are closely coordinated also with national efforts to establish a good balance and synergy between all economic and cultural aspects. This would ensure strong links and close connections between efforts funded in Europe and thus contribute to solutions based on the particular needs of the European infrastructure, and also account for particular European strengths and weaknesses in science and technology.

Furthermore we should note that the effects of space weather are not only restricted to our own planet, but do affect the entire heliosphere. As both European and world-wide space exploration has been extended throughout the solar system, Heliospheric Weather can be a threat for any present and future human asset or activity on other planets, for spacecraft orbiting planets, cruising in the wider solar system - or even crossing the boundary to interstellar space. The protection of these high-cost and high-value assets outside our closest geo-space environment is a growing future goal of SWx activities as well.

1.1. Background - Space weather as a global challenge

Following the approach defined by the Committee on Space Research (COSPAR) and International Living With a Star (ILWS) SWx Road-Map document [54] the effects of space weather on technological infrastructure can broadly be defined in terms of different impact pathways:

- geomagnetically induced currents, impacting on power and transport infrastructures;
- radiation effects leading to ageing and malfunctions of space, aviation and in severe cases even ground assets, including direct impacts on radio wave and other communication transmissions,
- and combined effects of both radiation and current flow effects, leading to ionospheric disturbances of navigation and communication systems, increased satellite drag and thus decreased satellite lifetime, as well as inaccurate assessments of satellites' orbits, which in turn could increase collision risks with space debris, as a secondary SWx impact.

Until today the largest potential socio-economic SWx impacts have arisen from SWx-driven geo-magnetically induced currents (GICs) in electrical power networks. Examples include the voltage collapse of the Hydro-Québec power network in Canada during a space storm in 1989 and, more recently, the failure of the power network in Malmö, Sweden, in 2003. The main risk from SWx on the electrical power grid is a voltage collapse (as caused by loss of reactive power and/or tripping of safety systems due to harmonics), which can occur with only limited damage to infrastructure. Heating due to repetitive GICs can lead to ageing of transformers as we discuss below. Even more significant and worrying are the potential down-stream impacts of such "traditional" SWx effects, which include the loss of services that rely on the availability of electricity, which, in the interconnected economy of the twenty-first century could quickly lead to extreme impacts. Such loss of power can thus result in extensive damage to property and infrastructure, as well as loss of life.

There is also growing evidence that the cumulative effects of everyday space weather (e.g. low levels of GIC) have significant impacts on electric power systems, impacts that degrade long-term economic performance rather than cause short-term disruptions. For example, there is evidence that everyday space weather contributes to the "wear and tear" that limits the working life of transformers [23] and maybe a significant increase in insurance claims associated with failures of electrical systems [53, 54]. There is also a significant body of economic evidence showing that electricity markets are affected by everyday space weather [20, 21, 22].

Today global reliance on space-based assets is rapidly increasing in communication and positioning services, as well as for Earth observation and all their down-stream applications. Space radiation during severe space storms can damage satellite systems and even cause their total loss, either immediately at impact or eventually through increased ageing. Even temporary loss of services from global navigation satellite systems (GNSS) due to ionospheric disturbances would have an impact on numerous economic sectors. A remarkable example is given by the global financial system which relies on highly accurate timing. While such timing is often taken from GNSS signals, most of the banking sector today is aware of the associated SWx risk and has already developed solutions for these SWx-sensitive timing signals.

Storm-time ionospheric effects may disturb or even interrupt communications and navigation satellites and high-frequency communication signals through upper atmospheric irregularities in the electron density, which manifest themselves as scintillation and thermospheric effects, travelling ionospheric disturbances and ionospheric bubbles. This can occur not only at high latitudes (in the auroral zone and near the poles), but also at middle latitudes and close to the equator as a result of a solar flare or the dynamics of ionospheric plasma bubbles. Such disturbances have impacts on any services or safety mechanisms that rely on accurate position information or the integrity of communication pathways, affecting for example airline operations, but also satellite-based augmentation systems, HF geolocation and communication operations. Space Weather even impacts scientific observational systems such as the LOFAR and SKA radio astronomy telescopes. There is now increasing awareness that during quieter geomagnetic conditions, when the Sun is not active, space weather disturbances are still active, particularly at low latitude. For instance, ionospheric irregularities can be present at anytime, and can impact ground and space based communication and navigation systems.

Already now and even more so in the future, space-based monitoring from satellites is a critical aspect of numerous Earth-observation applications, including monitoring the effects of global climatic change, for ground- and space-based situational awareness, for coordinating responses to natural disasters and, more generally, for safety and security. With the recent rapid growth in the number of space actors in both space-faring nations and emerging space nations, and especially from the private sector, there is also a pressing need for increased reliability of satellite-provided services and infrastructure in space and on ground. In particular, when building completely new infrastructure in emerging nations in e.g. Africa or Asia, one should keep adverse SWx impacts in mind from the very beginning, and design and construct new infrastructure taking potential SWx risks and their optimal mitigation into account.

It is important to develop scenarios outlining the likelihood and the impact of severe - or even extreme - space weather on the Earth and on human activities. An example of how vulnerable our modern society has become is studied by Baker et al. [6] focused on the large CME which was launched from the Sun in July 2012, and was detected by NASA's Stereo-A spacecraft. Those authors found that the 2012 event could have had enormous technological impacts on Earth, perhaps even greater than the famous 1859 Carrington storm; luckily, the event missed Earth by about a week's worth of solar rotation. Other recent studies [52, 14] found that the likelihood of a similar very severe space storm on Earth in the next decade could be as large as ~3–10 per cent. Such recent studies have led some countries to develop appropriate national responses to the threats posed by space weather, i.e., to the development of appropriate national action plans and protocols for the protection of critical infrastructure. Because of the global scale of space weather threats, such scattered and individual efforts need to be expanded into a wider European context and eventually into a coordinated global effort. Europe must prepare to contribute and provide its part of that global effort.

In summary, our modern society's strong reliance on technology and its increasing interconnectedness have significantly increased society's vulnerability to space weather effects. Thus, impacts arising from the natural hazard of severe or extreme space weather require a coordinated response from the international (European and global) community.

A recent report from the United Nations Expert Group on Space Weather [2] points out that scientific research, detailed socio-economic and technical impact assessment studies as well as preparatory activities within civil protection administrations are needed to ensure that states and regions **know what to do** to protect their infrastructure. Accurate and actionable space weather warnings are needed so states will **know when to act**. The new and unprecedented global and interlinked nature of space weather threats means that authorities (and the public) need to **know how to act** through new and different kinds of information chains than they have become used to dealing with in traditional civil protection.

1.2. Past and on-going European SWx activities and their position in the international framework

Throughout the entire last century European research groups have done pioneering work on several aspects of SWx, in particular by developing and utilising ground-based observation technologies to probe and understand geo-space phenomena, most of which today are of utmost relevance for dedicated space weather research. Many of the original techniques are still at use today both in SWx operations and in SWx enabling science, such as, e.g., magnetometers, ionosondes and coherent scatter radars, which all have been invented in Europe.

On the spacecraft side Europe has led a number ground-breaking missions, which have paved the way to our modern understanding of how space plasma processes are associated with and cause space weather. Missions like Helios, ISEE, Ulysses, AMPTE, GEOS, SOHO, Cluster and Swarm have been extremely productive in gaining increased SWx understanding. The first truly three-dimensional 4-spacecraft ESA Cluster mission can be considered as a pioneering effort in designing a set-up of coordinated multi-point measurements in space at

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[2] *UN Committee of Peaceful Use of Outer Space (COPUOS), Scientific and Technical Subcommittee (STSC) Report: Thematic Priority 4. International Framework for Space Weather Services, UN-OOSA, A/AC.105/1171, 2018.*

a variety of scales, in coordination with ground-based instruments to support the scientific program, with Earth being “the fifth satellite of the mission”. The same approach towards dedicated ground based instrument coordination has been successfully and formally adopted later in the NASA THEMIS mission operation, and has by now become a constant part of all on-going geo-space missions around the globe.

Despite of their virtues in science, none of the above listed European missions (maybe with the exception of the ageing, and now 24 year old SOHO satellite) can qualify as a true **“space weather observatory”**. None of the other missions is capable to deliver 24/7 near real time data about the activity state or the complete dynamics of any of the coupled space plasma regimes between the Sun and Earth. Probably this has been one factor motivating ESA member countries to expand the agency’s activities from its science program – which since long has served as the *primus motor* in SWx exploratory missions - also to the realm of more operational activities under the auspices of the Directorate of Operations.

The European Space Agency (ESA) started the Space Situational Awareness (SSA) Programme in 2009, after the ESA Member States had approved the Programme Declaration in the Ministerial Council meeting in 2008. Space Weather is one of the three segments in the SSA Programme. The other two segments are Near Earth Objects (NEO) and Space Surveillance and Tracking technology (SST). In 2009 the Programme issued a Space Weather Customer Requirements Document (CRD) that has become the baseline document for the development defining the user needs. All space weather development activities within the programme address the requirements in the CRD and target new capabilities to fulfil the end-user needs. Although SSA is an optional programme, 19 out of the 22 ESA Member States participate in the space weather activities in the Programme.

The Space Weather System under development in the framework of the SSA Programme comprises an initial Space Weather Service Network and the measurement systems that are providing data for the space weather services. In more detail the Space Weather Service Network consists of the following main elements:

- SSA Space Weather Coordination Centre (SSCC);
- Five Expert Service Centres (ESCs) for Solar Weather, Heliospheric Weather, Space Radiation, Ionospheric Weather, and Geomagnetic Conditions, in Belgium (ROB), the UK (RAL), Belgium (BIRA), Germany (DLR) and Norway (UoBergen), respectively;
- SSA SWE Data Centre.

In 2009 – 2019 the SSA Space Weather Segment has been developing, testing and validating the products and pre-cursor services from the system. The SSA network of Space Weather Expert Service Centres (ESCs) includes more than 40 Expert Groups representing leading space weather expertise in Europe. These Expert Groups are responsible for over 200 data products that are coordinated at the ESC level and combined into 25 precursor services which are provided to the end users by the SSA SWE Coordination Centre (SSCC). This structure follows the SWE System business model consolidated during SSA Period 3. The available space weather services address critical service and user domains including power grid operations, aviation, satellite navigation and manned space flight. All available space weather products and applications have either already gone through a rigorous validation of the service content or are in the process of doing that. At the same time development activities for new capabilities focussing particularly on improvements in space weather nowcasting, forecasting and physics-based modelling are being carried out. The modelling activities in 2016-2019 have particularly been focussing on forecasting of solar flares, heliospheric modelling and MHD modelling of the solar wind interaction with the Earth’s magnetosphere and upper atmosphere. Space Weather ESCs are continuously engaging with the European end users to test all space weather products and service elements and to collect feedback for continuous elaboration of the user requirements within the Programme.

The measurements currently utilised by the SSA Space Weather System come from science and technology demonstration missions (e.g. SOHO, ACE, Proba-2), ground based measurement systems (e.g. the MIRACLE network, networks of GNSS receivers, ionosondes, neutron monitors, etc.) and operational space weather monitoring missions (e.g. GOES, DSCOVR). The Programme has launched its first hosted payload mission in December 2018 (SOSMAG magnetometer onboard GEO-KOMPSAT-2A satellite) and the second mission will be launched in July 2019 (NGRM radiation monitor onboard EDRS-C) (for more details and access to the SWx data you can register for SSA at: http://swe.ssa.esa.int/web/guest/asset-database)

To further ESA's contribution to the expressed European goal to "ensure European autonomy in accessing and using space in a safe and secure environment", ESA intends to put forward an optional Space Safety Programme at the next Council meeting at Ministerial level in November 2019. The new programme will be addressing the three segments of: Space weather; Planetary defence; and Debris and Clean Space and build upon the success of ESA's SSA Programme. Space Weather segment activities in the Space Safety Programme will continue development of the Space Weather System including space and ground based measurement systems and networking of European space weather assets and expertise. The Space Safety Programme will also continue the elaboration of the European end user requirements and support infrastructure sensitivity studies including a space weather Cost Benefit Analysis (CBA).

The start up of the ESA SWx programme is a very promising development, but we still seem to struggle with several Europe-specific obstacles hampering fast and further progress. While European research institutes are, indeed, building and running several interesting and important observation programmes for upper atmospheric and magnetospheric research, directly or indirectly enabling the future development of space weather services, we have to acknowledge the fact that the North American countries and Japan are today ahead of Europe in the combined use of ground and space experiments for a holistic view on spatio-temporal evolution of space weather phenomena. It seems that the traditional European approach, where ground-based observations are funded in national programs and space-based missions by separate multi-national programmes or by ESA, is not as favourable for modern coordinated measurement concepts as some other non-European national programmes have been. As many emerging countries are presently making fast progress in the field as well, Europe should take prompt action for more agile, coordinated observation programmes in order to maintain its position as a credible and - more importantly - reliable partner in leading-edge space weather enabling research.

Major efforts to establish a permanent SWx monitoring function in parallel to the exploratory scientific fleet of heliophysics missions are at present more or less restricted to the US (NASA and NOAA). When it comes to more global coordination of "space weather enabling science" missions, the International Living With a Star (ILWS) initiative has for the past 10-15 years paved the way for a continuous scientific gap analysis and has fostered international partnership in enabling science missions for growing space weather needs. However, there is still no truly global process to coordinate SWx missions of different agencies around the world into one future global space weather programme, with 24/7 observational capabilities in the prime regions and regimes of space weather processes. There is ample room and reason to continue global international partnerships (as demonstrated by the ILWS) also for missions meeting more operational SWx needs. Europe should express its ambition and consequently strive to become a leading partner in such a future global effort on SWx.

The presently on-going discussion between ESA and NOAA to place two coordinated monitoring missions at both the L1 and L5 points is a good start of such global activities, but beyond these primary near-Earth monitoring points there are strong requirements for coordinated observations both closer to the sun and at many locations in Geospace. The entire fleet of required spacecraft for a global space weather service will go far beyond the capabilities of any one space agency in the world. Thus Europe should, in partnership with other agencies, agree to supply missions and assets to a global network, keeping in mind both European expertise, capabilities and requirements. Thus any European activities in this field should be seen as part of a global effort. This approach has particularly been emphasised in the ILWS/COSPAR Space Weather Roadmap [54], which has consequently been adopted as the baseline for global space weather efforts as pursued and closely monitored by the UN-COPUOS Expert Group on Space Weather.

Any such future European contribution to future global SWx efforts should also reflect on how economic interconnections will make most countries vulnerable to space weather impacts on other parts of the world, i.e., that there are significant mutual benefits arising from global cooperation in space weather risk mitigation. We note that the SWx roadmap [54] mostly addresses such global activities, and while it may need to be updated in some parts, we nevertheless consider it a good starting point for a tailored European plan for sustainable space weather research and operations. Therefore, our recommendations below are in many cases based on the recommendations of the roadmap.

On a separate website (http://www.essc.esf.org/studies-and-publications/eswacc-report) we have compiled – to the best of our knowledge – a present day description of and reference to past and on-going European Space Weather activities, funded by ESA, EU and national member state organisations.

1.3. Other Remaining Challenges

It is important to keep the entire coupled system of solar terrestrial events in mind when analysing SWx processes. Much of the radiation originating from Solar Flares and Coronal Mass Ejections (CME's) reaches Earth within a few minutes, introducing mostly ionospheric and atmospheric effects and constitutes the Radiation and SEP pathways of Schrijver et al. [54]. However, the CME pathway has a different temporal characteristic, as it takes the plasma cloud and the surrounding magnetic field structure about 1-3 days to propagate form the Sun to Earth. Only upon arrival of the CME at the Earth's outer magnetic barrier does the interaction of the disturbed solar wind with the Earth's magnetosphere start a whole chain of coupled processes of storage, transfer, and release of huge amounts of energy (see details below). Further complications come from the interaction between electrically charged and neutral particle populations in the atmosphere, which appears as a myriad of chemical reactions and waves affecting particle densities, temperatures and velocities. Planetary waves, tides, and gravity waves propagate upward from the lower atmosphere, deposit momentum into the mean thermospheric circulation, and generate electric fields via the dynamo mechanism in the lower ionosphere. Dynamo electric fields are also created by disturbance winds. Neutral winds and electric fields from these combined sources redistribute plasma over local, regional, and global scales and sometimes create conditions for instability and production of smaller-scale structures in neutral and plasma components of the system.

The above described coupled interactions of the entire "Geo-space System" is presently not understood in sufficient detail to predict the **time and location** of those very strong disturbances in upper atmospheric electrodynamics. We only know that major complications in ground and space-based technology may happen, with a short advance notice of few hours. While we do understand enough about the physics of the coupled Sun-Earth system to know what kind of disturbances can and will follow from a certain space weather event, we are still far from being able to predict the "**where and when**" and the "**how bad**" of every consequent disturbance. Depending on the rotation-position of the globe under the day- and night-side of the magnetosphere any error in the "**when**" will shift the "**where**" by an amount larger than the longitudinal extent of some countries or even continents. Also the degree of magnetic coupling between the solar wind and the Earths magnetosphere can shift the auroral zone in latitude by more than 500 km and in some cases even more than 1000 km. As we often will not not know which latitudinal and local time areas will be suffering from any such SWx impacts, the value of any detailed regional warnings may become compromised. The resulting narrower forecasting window may then not be sufficient for the users to develop efficient mitigation procedures.

2. Findings and Recommendations

The challenges stated above, which are imposed by the Sun-Heliosphere-Geospace system itself, imply the following basic and overarching principles of a future European SWx architecture - yet-to-be-developed:

- Predictions of space weather events require a deep understanding of the underlying science and rely on the availability of a variety of different - often scientific - datasets. These data sets need to be combined, modelled, analysed, and assimilated into networks of models and datasets. This complex flow needs to be constantly improved.
- Observations and the processing of corresponding and other relevant data from Sun to Earth must be available in near real time.
- Coordinated observing capability between all space- and ground-based monitors must be improved.
- Regional ground-based networks of sufficient station density need to be coupled to allow the understanding, now-casting, and prediction of - amongst others - magnetospheric disturbances (substorms and spikes in storms) and ionospheric irregularities (scintillations, sporadic E layers, travelling ionospheric disturbances) that have a mostly regional impacts.
- Instruments for observing the upper atmosphere, magnetosphere, heliosphere and the sun need to be calibrated and inter-calibrated, to enable both long-term observations and intercomparability. This recurring activity requires coordination and oversight.
- Standardised procedures for data archiving, preservation and open access need to be developed and implemented. This also applies models and model results.
- Modelling of SWx phenomena needs a very strong effort on the physical interactions and feedback mechanisms in the Sun-Earth system in a coordinated, and coherent manner.
- Such modelling should cover not only the Earth-Sun system, but also the inner heliosphere to allow better validation by using measurements by existing and future deep space missions and to support (and prepare for human) exploration of the solar system.

In the following we will present our detailed findings and make recommendations to meet the requirements for an improved European space weather program - structured under six main themes, which were already introduced in the previous chapters:

- **Area 1: Imminent Need for Critical Research with Dedication to Enable Space Weather Understanding and Prediction**
- **Area 2: Support to system-science approach with Coupled Physics-based Modelling: Sun / Solar Wind / Magnetosphere / Ionosphere / Atmosphere**
- **Area 3: Consolidation of National, Regional and European Risk Assessments**
- **Area 4: Consolidation of European User Requirements**
- **Area 5: "R2O" and "O2R" or how can SWx scientists interface with candidate organisations for SWx services – in Europe and globally**
- **Area 6: Define and implement a network of space and ground-based assets for future SWx observations**

2.1. Area 1: Imminent Need for Critical Research with Dedication to Enable Space Weather Understanding and Prediction

A science-driven approach to the mitigation of space weather effects increases confidence in the assessments of risk and socio-economic impacts and in the accuracy of their results. As discussed, for example, in the COSPAR/ILWS roadmap [54], and despite very significant recent improvements in the understanding of the drivers of extreme space weather, scientists are still a long way from being able to offer high quality forecasting of impending severe space weather that provides concrete benefits to users.

The complexity of SWx phenomena has led to a distinction being made between high quality forecasting and high precision forecasting. SWx forecasts need to distinguish between amplitude and timing of the phenomena [49], especially because the ubiquitous process of magnetic reconnection, which underlies much of SWx, is highly unlikely to be predictable in the deterministic sense. While high precision probabilities of the amplitudes of such events may be possible in the future, we do not expect to be able to predict their onset times are in the coming decades [48, 29]. We may ultimately have to embrace uncertainty as a fundamental part of space weather forecasting (see also [44]).

Findings:

Research in the past decades has led to substantial progress in our understanding of the overall big picture of the Sun-Earth SWx chain. Nevertheless, this research has also taught us how complex and interconnected the Sun-Earth system is. At present we still lack critical understanding of: the solar activity cycle itself, of the origin of solar eruptions, of how heliospheric transients propagate into, interact with and, evolve in the solar wind, the detailed mechanisms of energy storage, transformation and release in the magnetosphere/ionosphere system, and of how this is released into the atmosphere and the Earth’s conducting crust. This insufficient understanding currently limits our capability to meet the expectations emerging from most present – and still increasing - user requirements.

The network of space- and ground-based assets, which formed the basis for our present scientific understanding of the SWx chain, is ageing and in danger of turning insufficient to provide the reliable input needed for a realistic operational SWx system. Despite the large visibility in the public of space-based assets, at present there is no indication that we will have a similar fleet of spacecraft at our disposal in the near future. Networks of the much less prominent ground-based stations are presently operated on decreasing, often uncoordinated and unstable national or even institutional budgets. Such networks require the efforts of scientists and engineers for their continued maintenance through grass-roots efforts, which in many cases is becoming ever-more unsustainable. Nevertheless, most present-day Space Weather services rely on such networks, which may suddenly disappear with a loss of their funding. Examples of such networks are magnetometers, geo-electric field sensors, ionospheric radars, optical imagers, ionosondes, multi-frequency radio-observations of the sun, solar imaging (in the visible, and H-Alpha) as well as neutron monitors, observations of radio-scintillation and Faraday-rotation in the solar wind, and so on.

To achieve an optimum exploitation of space science data from existing space assets it will furthermore be necessary both to maintain the existing coverage - and to close some glaring gaps - of present day ground-based space science observing instrument networks in Europe, as part of a European contribution to the required global network.

Furthermore, at the European level, we lack a coordinated effort to combine the results of past, ongoing, and future SWx-enabling research into a SWx prediction framework. We also lack a coordinated European science effort to combine the results of individual SWx-enabling research activities. On a global scale this is presently attempted by the COSPAR Panel for Space Weather (PSW) through the establishment of so-called International Space Weather Action Teams (for I-SWAT see https://ccmc.gsfc.nasa.gov/psw/)

The “Bureaucracy Load” presently existing at both ESA-SWE and the EU H2020 grant and project management is very high especially for university science leaders. ESA, and to same extent the EU, need to recognise that such leaders of science teams are generally directly involved in the scientific work of the studies funded by ESA and the EU. Unlike in industry, there is not a separate layer of management in scientific institutions. The contract management process for science teams needs to reflect this, striking a balance between that process and the need to make scientific and technical progress. Science leaders need time to do their scientific work between project meetings and reporting. A failure to respect that will divert already scarce resources away from scientific work and is likely to delay the important progress in technical and scientific progress.

General Recommendations for Area 1:

1. ***Sustained and adequate financial support to a directed SWx-enabling research effort*** *in solar, heliospheric and magnetospheric/ionospheric/atmospheric physics to build a better knowledge base for future SWx services.*

2. ***Exploitation of existing SWx datasets*** *for near Geo-space (e.g. SWARM and other LEO and GEO satellites,…), in the magnetosphere (e.g. Cluster, Themis, MMS, Van Allen Probes,…), in the Heliosphere and for the Sun (e.g. SOHO, ACE, Wind, SDO, Hinode, Parker Solar Probe,…) should be lifted out of future general H2020 data exploitation calls by creating a "dedicated funding line" for space weather enabling science,* ***with the declared goal to improve SWx forecast reliability and in order to stimulate the "harvesting of low hanging fruits”!***

3. ***Efforts to combine data and results from connected regimes (system science) should be encouraged.***

4. ***Any such funding should be on a long-term and regular, and continuous basis to make best use of the European assets.***

5. ***Foster collaboration both within Europe and with similar efforts around the world.***

Additional Recommendations with respect to ground-based efforts:

6. ***Dedicated and, if at all possible, coordinated financial support, both at national and European level, to ground-based network efforts*** *which support SWx-enabling research in the physics of the Sun, heliosphere, magnetosphere, ionosphere, atmosphere, and solid Earth physics in order to build a better knowledge base for future SWx services. This support is needed for the continuation and maintenance of such networks and to close gaps.*

7. ***Encourage member states to see funding of national instrument assets (often parts of networks) as a global subscription for access to all data from wider European and global programs*** *of similar instruments and as a critical national contribution to a wider and important pan-European SWx observing network.*

8. ***Efforts should be supported to combine and coordinate any European assets concerning such instrumentation into regional and global networks,*** *to enable improved collaboration and data-sharing with other space-based SWx assets.*

9. ***It is important to decrease the "Bureaucracy Load" presently existing at both ESA-SWE and the EU H2020 grant and project management.***

One of our recommendations above addresses the term **"low hanging fruits"**, by which we mean outstanding scientific questions of SWx-enabling relevance that could and should be addressed now by utilizing past and present data and information from existing missions, instruments and models. A unique - albeit somewhat ageing - fleet of spacecraft is presently observing the Sun, the solar wind and the near Earth environment and a globe-spanning network of ground-based instruments measures the impacts of SWx on Earth. We doubt that such an opportunity for frontier-advancing science including several multi-spacecraft missions, and well-developed ground-based networks will re-occur within the foreseeable future of SWx observations. This offers a unique opportunity to combine basic and applied science efforts for the benefit of knowledge advancement in SWx science. Similar approaches have also been recommended in the US National Academy 2013-2024 Decadal Survey for Heliophysics (2012).

In the next paragraphs we will, for each regime, summarise some of the most urgent scientific questions concerning the fundamental physical processes that cause extreme space weather and how they could be addressed in a timely manner to advance our knowledge about the processes underlying SWx.

Sun

Space weather phenomena are strongly related with the solar dynamo, which generates the variable magnetic field of the Sun. This variability is characterised by the 22-year solar magnetic cycle that modulates the number of sunspots on the solar disc. Higher up in the solar atmosphere, in the solar corona, groups of these sunspots are part of so-called active regions, composed of predominantly closed magnetic loops that connect sunspots of different polarity. In "coronal holes" the magnetic field expands outwards and fills and structures interplanetary space with the (fast) solar wind. The Sun rotates around its axis in roughly 27 days as seen from the Earth, with the solar poles taking a few days longer for a complete rotation than the solar equator. Following this rotation, the magnetic field, which is imbedded in the solar wind is swept around much like fire-hose streams. The solar wind from similar source regions passes by the Earth with a 27-day recurrence.

The solar activity cycle is determined by the concurrent interplay of the dynamo mechanism, the latitudinal and radial differential rotation and the inner meridional plasma motions, whose dynamics are difficult to model and predict. The chaotic behaviour resulting from the combination of these processes makes it impossible to predict both sunspot emergence and clustering, as well as the sunspot group magnetic topology and evolution. In turn, this affects the possibility to predict whether, when and how an activity centre will flare, what will be the outcome, and the energetics to be expected. With increasing complexity, the magnetic active regions in the solar corona tend to become unstable to so-called magnetic reconnection, leading to energy release in terms of particle acceleration and heating, producing energy emissions, called solar flares, which are observed over the entire electromagnetic spectrum. Solar flares are categorised, e.g., according to their emission in soft X-rays using a logarithmic scaling. The most violent class of flares (X-class) amount to an increase by a factor 10000 in solar X-ray emission with respect to the background level (A-class) observed on quiet days. The same magnetic instability process can lead to coronal mass ejections (CMEs) whereby a large (typically 10^{12} kg) volume of gas is expelled from the solar atmosphere into the solar wind. If the propagation of the CME is faster than that of the ambient solar wind, then the CME fronts can steepen into shock waves. CME's are extremely variable in all properties (magnetic field, plasma density, mass, size and velocity). This results in a wide range of effects on Geospace, from mainly causing beautiful auroras in mild events to devastating impacts on technological infrastructure in rare extreme events.

In the wake of solar flares or CME shock waves, solar plasma particles can be accelerated to near-relativistic speeds. The particles escape away from the Sun into space. Moving through space, these electrically charged particles (electrons, protons, and heavier ions) are forced to follow the magnetic field dragged into space by the solar wind. These fast particles are called 'Solar Energetic Particles' or in short SEPs. Their velocities can approach the speed of light, their energy can be sufficient to penetrate spacecraft, affect electronics, and lead to accelerated aging of space assets. They can be critical for manned space missions, and in rare cases they can even reach and affect infrastructure on the Earth's surface.

In recent times, many techniques, including machine learning, have been applied to flare forecasting, but the confidence level of the results is still unsatisfactory for a reliable SWx prediction chain. Notwithstanding the continuous search for effective precursors, very few of them have been identified and their statistics are not robust enough (e.g., sigmoidal configurations, pre-flare microwave emissions, etc.) for forecasting purposes. Similarly, only now-casting is possible for prominence eruptions that lead to CMEs. Furthermore, it is difficult to predict the magnetic structure and polarity of CMEs. Remarkably, even the exact relation between flares and CME's is presently unclear. In addition, the formation and evolution of the solar wind from coronal holes and other regions has not been successfully modelled to date.

The Sun thus drives space weather with its 27-day rotation, coronal holes, and with irregularly occurring events such as flares, CMEs and SEPs. Its activity varies with an overall 22-year magnetic cycle, which in turn is modulated by longer-term cycles of stronger or weaker maxima.

Since the launch of SOHO (1995, ESA/NASA), significant advances have been made in understanding how these solar signatures and events propagate throughout the heliosphere. Contemporary and upcoming solar missions in space (NASA's SDO and Parker Solar Probe, ESA's Solar Orbiter) and observatories on the ground (DKIST, EST) promise to shed light on the many still open questions, such as:

- How does the solar dynamo work and can we understand the variations in the magnetic field and their consequences?
- Can the strength of the next solar maximum be predicted?

- Can the emergence of complex active regions be anticipated?
- How can we measure and identify magnetic instabilities in the solar corona before they erupt as flares or CMEs?
- Why is there a corona at all and what are the respective roles of nanoflares, turbulence or waves in the heating of the corona, and how can this be predicted?
- How is the corona connected to the heliosphere? Where are the foot points on the solar surface of the heliospheric magnetic field lines? Where does the solar wind come from?

Heliosphere

There are still a number of unsolved problems in our understanding of the development of a CME on its way from ejection at the Sun to 1 AU or rather the Earth-Sun Lagrange Point L1. Remote sensing observations from L1 do not give a very good picture of the CME geometry (only the CME "halo" is visible), and thus the initialisation of the CME structure and its ejection velocity can generally not be included correctly in state-of-the-art models and assimilations. In addition the development of both the CME and the shock driven by it strongly depends on the CME itself, and the solar wind, through which the Interplanetary CME (ICME) has to make its way towards Earth. Thus the internal (magnetic) structure of the CME and the structure of the background solar wind have an important impact on estimates of ICME arrival time and structure at L1.

Multi-viewpoint satellite data (as e.g. from STEREO, VEX, MESSENGER, MAVEN, etc.) could help a lot to improve our knowledge and understanding of the 3D geometry and propagation behaviours of ICMEs, however, there are still many parameters that are less well covered, which prevents us from improving forecasts. The basic question if a CME hits Earth or not is to know the directivity of a CME. As we observe a line-of-sight integrated intensity from image data, even though having multi-spacecraft data, the directivity is still strongly affected by uncertainties. The propagation direction has large impacts on estimating the actual arrival time, impact speed and geomagnetic effects. CME flank hits are usually related to milder Space Weather effects compared to apex hits as the compression of the magnetic field is strongest at the CME nose. In general, single events are easier to forecast compared to multiple events, which lead to CME-CME interactions, or interactions of CMEs with large-scale structures in the solar wind such as stream interaction regions (SIRs). A series of recent studies concerning the so called 2015 St Patrick's Day storm (*"Geospace system response to the St. Patrick's Day storms in 2013 and 2015"*, JGR special section, Febr. 2016) give evidence that multiple, interacting or combined events may be more effective drivers of severe SWx impacts at Earth.

To forecast the arrival times and speeds for those CMEs that are identified to possibly hit the Earth magnetosphere, we need to derive the drag force acting on it. The drag force acting on an ICME in interplanetary space, as we understand it today, mainly depends on the relative speed between the ICME and the ambient solar wind, and their relative densities as well as the size of the ICME. This implies we need to be able to simulate the background solar wind structures (especially high-speed solar wind streams) and their characteristic parameters. There are only few observational data points available for solar wind parameters in interplanetary space: Only very few spacecraft at extremely scarce selected positions can monitor the in situ solar wind; from Earth, interplanetary scintillation (IPS) radio measurements are sometimes available from e.g. EISCAT and LOFAR, but only cover the plane of the sky. LOFAR may become available more continuously through a recently funded EU H2020 funded project, LOFAR4SW. For a general assessment of current capabilities to predict CME arrival see e.g. [31].

Based on such observations we are currently able to model the solar wind speed to a certain degree of reliability, but other parameters, above all magnetic field, but also density and temperature are not well understood in order to successfully drive physics-based models. Furthermore, we need to have better estimates of ICME density, hence mass, and a better understanding of how the mass is distributed within the CME, and how it evolves as the CME propagates in interplanetary space. Moreover, we also know that in our applied approach of MHD drag, currently the magnetic field, which is supposed to have effects on the propagation of a CME, is not at all taken into account.

In fact, the magnetic field topology of the ICME itself is another issue, representing the "holy grail" in solar and heliospheric physics. The magnetic field of the CME and all relevant models for heliospheric simulations are to-date fed by a single magnetic field measurement taken at the photospheric level. The coronal field, in fact, the atmospheric layer of the Sun that actually is the major component of a CME eruption, cannot yet be measured, even if efforts are under way to achieve such measurement in the future. Usually, models are used to estimate the magnetic field in the corona and also in interplanetary space, implying many assumptions because of many unknown parameters.

Thus we see that, based on current observational data and computational methods, we have to accept large uncertainties in our predictions at the level of around 12 hours [42]. This could, however, be considerably improved e.g. by an additional solar wind observing asset at L5. Techniques to handle uncertainties in IMF forecasts via downscaling are being developed [see 47]. A promising approach to improve predictions despite these large uncertainties is the use of so-called ensemble models [1, 48]. Rather than giving absolute values for arrival times, impact speeds, etc., probabilities can be given for parameters that cause Space Weather effects. Such ensemble models run many samples of input data sets, which cover the existing uncertainty margins. They require substantial computational power and the appropriate IT-infrastructure [see e.g., 40, 48, 1]. This is not affordable for every scientific research group. Community centres like the ESA/VSWMC in Belgium or the NASA/CCMC still require better and more continuous financial support and closer collaboration to provide a platform for models to be tested and actually used. Such platforms can also potentially become the future driveway for R2O activities (see Chapter 2 and 5), where scientists and users meet.

We have identified most present gaps in our observational data. Closing them should lead to ground-breaking scientific results, which in turn will feed into improved operational SWx services. Most of the instruments needed for measuring the coronal or interplanetary magnetic field have already been described in the scientific literature. The necessary networks of ground-based observatories for H-alpha, IPS, and radio waves have also been clearly identified and they do exist in initial stages. For instance, LOFAR4SW, an EU/H2020 project, is a promising first step. On the downside, we still require continued and sufficient financial support for these identified needs. History has taught us that we can make tremendous progress by combining theory with observations, long-term observations with science, and that this is driven by new instruments as well as new methods.

Key topics that need to be investigated using past and present ground-based and satellite data:

- Improve models of the structured background solar wind to derive more reliable forecasts for CME propagation.
- Derive better 3D estimates of CME geometry and mass that both strongly affect ICME arrival time and impact speed.
- Reliably connect observational/modelling results for magnetic field orientation at the Sun with those measured in situ.

- Understand how the interaction between IMF and CME changes the magnetic field and with that the geo-effectiveness of ICMEs and their sheaths.
- Effectively connect and exploit data of existing networks of ground based observations (e.g., magnetographs, H-alpha, IPS, radio,…) and satellite missions.

Magnetosphere

Once the solar wind (be it in the form of normal variable solar wind, Co-rotating Interaction Region (CIR), or ICME) reaches the terrestrial bow-shock and magnetopause, it begins to influence and modulate the coupled system of plasmas in the various regions of the magnetosphere and upper atmosphere. These interactions often appear as plasma waves with great variability in their properties and propagation paths. We have a basic understanding of the fundamental processes by which energy is transferred from the solar wind into the coupled geospace system. The same may also largely be said for the processes that control the subsequent transport, storage, and release of energy in the coupled system. This knowledge has in general been derived using normal solar wind fluctuations; for example the processes active in magnetospheric substorms have been studied intensively for over 50 years. Nevertheless, the exact timing and magnitude of sporadic and very rapid night-side magnetospheric energy releases remain unclear, and only the directly driven magnetospheric processes are reasonably well understood and thus to some degree reasonably predictable. Also the main features in the statistical occurrence of different plasma waves in various magnetospheric regimes are known, but there are still many open questions in the interaction of different wave modes and their linkage with the dynamics of electric currents and particle populations. Fundamentally, how these multiple processes combine and couple together in the global system is still poorly understood. Since these processes are also tightly coupled, the result is that it remains extremely challenging to accurately predict the overall response of the coupled system to incoming solar wind driving conditions, even if the characteristics of the upstream solar wind drivers are known perfectly. To a large degree, the larger and more long-lasting the driving, the more complex and un-predictable the overall response of the coupled system becomes.

Both sporadic and directly driven processes and the related wave activity are all strongly coupled to the ionosphere below. During extreme space weather the resulting so-called geomagnetic storms contain a yet unknown mixture of driven and sporadic energy coupling processes, which makes the entire picture hard to both understand and predict. Statistically we do understand how multiple substorm injections build up the large storm time current systems and populate the energetic particles in the ring current, how the auroral zone moves to much lower latitude, and how the overall growing auroral and magnetospheric current systems connect to the ionosphere below, causing detrimental SWx effects on technological infrastructure. Recent NASA missions in the near-Earth space such as the Van Allen Probes have enhanced our understanding on wave-particle interactions as sources and losses for particles in the near-Earth magnetosphere. Similarly, the NASA MMS and THEMIS missions, and the ESA/NASA Cluster mission, have all improved the process level understanding of many aspects of solar wind-magnetosphere coupling, and nightside energy transport and release during storms and substorms. With their advanced and high-resolution instrumentation these missions are able to provide more versatile information than their predecessors, but unfortunately the system level response is still poorly understood. The understanding of extreme conditions is also hampered by the fact that more recently launched missions have yet to experience extremely strong storm conditions due to the current relatively quiet of solar conditions.

We have so far much less knowledge about how the system responds to extreme solar wind drivers, as other instabilities may be triggered in extreme conditions and the coupled system may respond non-linearly to such drivers. Substorm-like features do still exist in storms, but are known to behave much more erratically and also more violently during magnetic storms. Via extremely localised short-lived three-dimensional current systems, consisting of both field-aligned magnetospheric currents and ionospheric currents, such sporadic energy releases cause the geo-magnetically induced currents, which affect electric power-lines, and transformers in the electric power grid, railways and any other conducting technological infrastructure below. Also the connection of extreme magnetospheric driving to instabilities and irregularities in the upper atmosphere through large currents and electric fields (setting up large plasma convection velocities) is as of yet poorly understood.

The main reason for this poor system level understanding is that sufficiently high quality data from extreme SWx conditions are scarce, and despite multiple missions operating simultaneously the coverage of the vast regions of geospace remains relatively sparse. Also - for obvious reasons – many times very extreme conditions are not selected for study during the initial phase of space science missions, since these complex responses are hard to fully understand. Also most of the geo-space satellites and ground-based systems of today are located at places where their data is most-useful to address and solve science questions during periods of moderate space weather characterised by more normal magnetospheric dynamics. As a consequence, we have had very few missions which have addressed extreme conditions. Such conditions are relatively rare, such that missions are usually not designed to spend long-periods of mission life there. What we have observed is typically derived by fortuitous passes through such locations. One critical region, which couples the active plasma flows in the magnetotail to the response in the nearer-Earth magnetosphere and ionosphere is at the extreme inner edge of the night-side plasma-sheet, in the transition region between dipole-like and tail-like magnetic fields. However, prior missions have only poorly sampled this region, with the exception of fortuitous transits by the NASA THEMIS satellites.

There is only one notable exception for a mission in that location - the Combined Release and Radiation Effects Satellite (CRRES) mission of NASA, as there are only few Keplerian orbits allowing spacecraft to stay in that region for extended periods of time. In order to really understand the storm time inner edge of the plasma sheet one should go back to the dataset of the CRRES mission.

In order to define and derive future proxy measurements, i.e. essential space weather parameters that describe the physical and dynamical state of the plasmasheet, one would also have to go back to data from past polar imaging missions like e.g. Polar and Image, in order to relate various kinds of auroral activity to plasma-sheet processes, which we now better understand thanks to recent results from Cluster, MMS and Themis. Data from the Van Allen Probes could also inform the design of future ring current ENA imaging missions as will be described in Chapter 6 (Future operational fleet) in more detail. Besides the need to extend the ground-based networks to lower latitudes with sufficient spatial density, it will be important to pay special attention to the quality of measurements. Extreme events will challenge the new instruments both in their time resolution and dynamic range. International networks are beginning to adapt to such new space weather needs, but the funding is mostly national, sporadic and uncoordinated even on a regional, let alone global level.

European highlights in future magnetospheric research are the recently adopted SMILE mission, and new operational modes of Cluster configurations since the spring of 2019, where the Cluster 1 spacecraft acts as a just-upstream solar wind monitor, whilst the other three spacecraft observe the dynamics of the magnetosheath and magnetopause.

Examples of questions that should be investigated using past and present ground-based and satellite data:

- How does the magnetosphere modulate the spatio-temporal appearance of activity driven by CMEs or high-speed solar wind streams through the magnetosphere-ionosphere coupling?
- How does the impact of a single CME differ from the impact by a sequence of several CMEs in the magnetosphere and ionosphere, i.e. how strong is the magnetospheric "hysteresis" effect?
- Which processes in the magnetosphere generate rapidly varying currents in the ionosphere, and are these processes externally driven, and then by which solar wind drivers?
- Which factors in the magnetosphere can have a significant impact on the geomagnetic storm duration, once the solar wind driving stops?
- How do magnetosonic waves, propagating across the magnetic field, couple with field-aligned wave modes, and how does this affect the generation of magnetic disturbances related to geomagnetically induced currents in ground infrastructure?
- How are plasmasheet disturbances and plasma flows coupled to the inner magnetosphere, and what controls the efficiency of energy and plasma transport?
- How do various magnetospheric waves control the plasma exchange, energy transport, coupling, and field-aligned currents, which flow between the magnetosphere and ionosphere?
- Do magnetospheric processes cause ionospheric irregularities, and if so which ones and how?

Ionosphere and thermosphere

The ionosphere appears at the end of the chain of SWx plasma processes. This is the transition zone between the collisionless plasma of the magnetosphere above and the collisional neutral atmosphere below. The name for the zone comes from the fact that there a significant part of the atmospheric gas, also known as the thermosphere, is ionised. Spatial and temporal variability in the ionosphere are controlled by the Sun, both directly in the form of radiation and in-directly by processes in the magnetosphere as well as through coupling to the neutral atmosphere (thermosphere). The response of the ionosphere-thermosphere system to solar forcing varies according to latitude, not just because of the variation in illumination, but also due to Earth's magnetic field topology. A significant fraction of the quiet-time ionosphere and thermosphere variability is also driven by wave and momentum sources from the lower atmosphere. Furthermore, it is important to note that the interactions between electrically charged and neutral particles in the ionosphere are not controlled only by physics, but also by chemistry where complicated chain reactions are involved.

The above-described processes cause variations in the ionospheric electron content, which control the spatial distribution and intensity of electric currents and radio wave propagation conditions in the upper atmosphere. Magnetospheric processes as the primary cause for rapid current variations are described above in the Magnetospheric Section. Much of the energy by these processes is deposited in the ionosphere through a variety of different mechanisms, such as Joule heating or energetic particle precipitation. Joule heating results from enhanced collisions between the ions and neutrals due to the imposition of electric fields moving the ions and not the neutrals. Such heating results in changes in global thermospheric circulation, upwelling of the neutral gas and changes in neutral composition, which can lead to enhanced recombination (the so-called "negative phase" of an ionospheric storm) and significant reductions in the electron density. Particle precipitation, on the other hand, enhances ionization and causes heating of ionospheric electrons by collisions at high latitudes. Enhanced ionization implies enhanced conductivity and thus stronger currents in those regions. Significant increases in plasma density can also occur at mid-latitude, the exact causal mechanism of which is an active area of research. These mid-latitude increases are often referred to as storm enhanced density (SED). They appear to be associated with times of significant expansion of the high-latitude convection pattern into mid-latitudes in regions of sunlight and solar ion production.

Joule heating, auroral precipitation, and SEDs can cause strong gradients in the electron density and the creation of ionospheric irregularities, both of which affect radio wave propagation. A further consequence of the atmospheric heating is that there is general expansion of the atmosphere to higher altitudes, thereby affecting the orbits of spacecraft and space debris by enhanced air drag. As a separate case from magnetosphere-ionosphere coupling direct impact of solar activity can appear as precipitation of very energetic particles in the polar cap regions. Such precipitation can enhance the ionospheric electron density to levels that radio signals in the HF-regime (3-30 MHz) are severely attenuated or even totally absorbed.

At mid- and low latitudes the impact of solar X-ray and EUV bursts on electron content is largest in the dayside ionosphere. Strong bursts are likely to cause similar problems in the HF communication as in the cases of polar cap absorption events. During geomagnetic storms significant amounts of energy from the high-latitude processes get redistributed to mid and low latitudes through wave activity. Such waves appear as large scale travelling ionospheric disturbances that can serve as platforms for small-scale plasma irregularities disturbing radio wave propagation similarly as auroral precipitation or Joule heating at high latitudes. Another example of a phenomenon building steep electron density gradients and thus favouring build-up of irregularities are so called sub auroral polarization streams that are latitudinal narrow structures associated with high plasma drift velocities and significant reductions in the electron density. Sharp turnings of the solar wind magnetic field southwards can create situations where the associated electric field penetrates promptly to the equatorial ionosphere and enhances the plasma drift and uplift and electric currents there significantly. Consequently strong spatial gradients in the electron density build up and generation of plasma irregularities gets enhanced at the sunset longitudes. An additional complication of the appearance of SWx phenomena at low and mid-latitudes comes from the variability in the shield against solar activity which the terrestrial magnetic field provides. This shield is attenuated in some longitudinal sectors due to the internal magnetic field topology. The most widely known region of exceptional magnetic field configuration is the Southern Atlantic Magnetic Anomaly at the eastern coast of South-America, where SWx disturbances appear systematically more frequently than elsewhere at the same latitudes.

Due to reasons described above, characterizing the upper atmospheric conditions comprehensively with one unified global model is challenging. Global magnetohydrodynamic simulations describe quite nicely large and mesoscale features (scales >100 km) in magnetosphere-ionosphere interactions at high-latitudes, but they are not applicable at mid- and low latitudes. On the other hand, global circulation models can solve thermosphere-ionosphere interactions self consistently at sub-auroral latitudes, but their interactions with the magnetosphere are typically described with simplified empirical models. Yet, in reality upper atmospheric phenomena at these two latitude regimes are coupled with each other and, as mentioned above, this coupling is particularly prominent during strong SWx storms. Furthermore, the ionosphere is often modelled as an infinitely thin sheet, especially when its electrodynamic interaction with the magnetosphere is studied. The sheet approximation easily leads to a view where the upper-atmosphere is only a passive mirror of magnetospheric dynamics. This simplistic view is challenged in studies on extended periods of storm activity, when energy and momentum exchange between ionosphere and thermosphere can modify the atmospheric response to magnetospheric driving. Ion velocity measurements as a function of altitude would be helpful in quantifying these feedback interactions, but they are currently available only locally by incoherent scatter radars. The electric currents connecting the magnetosphere to the auroral ionosphere have also been investigated for centuries with the simplification of height-integrated currents in the ionosphere. At large scales this simplification yields reasonable results, but in the key region of substorm activity the real current system can be quite different, composed of partial current closures inside the ionosphere. Comprehensive understanding of regional current systems is important, because recent studies have revealed their crucial role in generating high ground induced currents (GICs).

The altitude range from 50 to 400 km, where many interesting magnetosphere-ionosphere-thermosphere coupling processes take place, is difficult to reach with in-situ measurements. Traditional, long-term satellite missions are not feasible due to the air drag issue, and rocket or balloon campaigns can provide only sporadic data sets. Forthcoming small satellite missions are envisaged to improve the situation, with remote sensing by ground-based instruments continue to play an essential role in providing homogeneous data sets to support modellers. The value of magnetometer networks, optical measurements and probes using radio waves either passively or actively (ionosondes and radars) is increasing with advancements in data analysis methods. However, for big leaps forward we would need coordinated Sun-Earth observatory systems, where models' forecasting capabilities are improved by systematic space and ground-based data incorporation and ensemble runs. Synergies between meteorological and space weather data assimilation are envisaged to be useful particularly for upper atmospheric models, where dynamics are strongly controlled by the given initial conditions, similarly as in the models for lower parts of the atmosphere.

The advantage of observing upper-atmospheric space weather phenomena in three dimensions (3D) has been acknowledged in Europe. The EISCAT Association of four European member countries has started to build a next generation incoherent scatter radar system, which will be able to measure ionospheric key parameters - including ion velocity vectors - in a 3D volume. Also the three ESA Swarm satellites on Low-Earth-Orbits at altitudes of 450 and 530 km can be considered as a mission towards multipoint measurements in the upper parts of the ionosphere. Besides observing systems devoted to space science, the European research community harvests data also from other global networks, the Global Navigation Satellite Systems (GNSS) dual-frequency receivers being the most prominent example. Observing the ionosphere has been able to take advantage of the rapidly growing availability of GNSS data both from ground-based networks and from space in the form of radio occultations (RO). GNSS data are mostly used to generate maps of Total Electron Content (TEC), which are useful to show ionospheric structure and gradients, such as SEDs, which affect satellite navigation. The same data can also be used to map ionospheric irregulaties, either as maps of the rate-of-change-of TEC (ROTI) or through amplitude and phase fluctuations (S4 and sigma phi, respectively). GNSS maps have also been used to detect medium-scale ionospheric disturbances (MSTIDs from lower atmosphere forcing) and for detecting large scale travelling ionospheric disturbances (LSTIDs from high latitude auroral and Joule heating sources). Furthermore, GNSS receivers with high sampling rates have appeared to be a valuable asset in the research of ionospheric irregularities, which occasionally cause scintillation in GNSS signals. Besides TEC maps many European research groups have developed also methods for tomographic reconstructions of electron density, which opens ways to more comprehensive comparisons with theories and models of ionospheric properties. In addition, new upgrades to the European network of Digisondes, have enabled the determination of the characteristics of travelling ionospheric disturbances. The deficiency of GNSS and ionosonde networks covering only continents is gradually getting solved by space-based receivers utilizing radio-occultation methodologies and by satellite altimetry data.

There is now increasing awareness that during quieter geomagnetic conditions, when the Sun is not active, space weather disturbances are still active, particularly at low latitude. For instance, ionospheric irregularities can be present at anytime, and can impact ground and space based communication and navigation systems. The irregularities are internally driven instabilities (e.g., a generalized Rayleigh-Taylor processes), and predicting their day-to-day-variability is a challenge. There is evidence that wind and wave forcing from the lower atmosphere might be responsible for a significant fraction of the ionospheric space weather variability, which is leading to the development of ionospheric space weather model coupled with terrestrial weather model. The wave forcing from the lower atmosphere also produces undulations on the bottom-side F-region ionosphere, which impacts HF radio wave propagation.

Examples of key topics that should be investigated using past and present ground-based and satellite data

- Coupling of and feedback between high, mid- and low latitude ionospheric conditions during SWx storms.
- The linkage between ionospheric electron density gradients, irregularities and phase/amplitude scintillation in radio signals at high, mid and low latitudes.
- Quantitative relationship between Joule heating through enhanced ionospheric fields and currents and atmospheric expansion to higher altitudes.
- The role of waves and auroral precipitation in the closure of magnetospheric currents in the auroral ionosphere.
- The scale size and temporal dynamics of the ionospheric currents responsible for large GICs.

Lithospheric impact on regional and local SWx consequences

Beyond the SWx risks imposed by the plasma regimes in geospace and the heliosphere there is an additional important input and risk factor to be considered when discussing geomagnetically induced currents, GICs. As described above the main driver for GICs, via rapid changes of magnetic field disturbances at ground level, is caused by a three-dimensional magnetospheric and ionospheric current system. However, the fast temporal changes in the magnetic field (dB/dt) caused by rapid changes in that current system do not necessarily create dangerous GIC events everywhere. The induced currents in infrastructure are caused by an electric field stemming from the induction of currents in the ground, and thus magnetic space weather events may become amplified or suppressed by the local lithospheric conductivity structure. Certain regions - of typically low lithospheric conductivity, creating larger electric fields – may give rise to local or regional problems for the same kind of space weather that may have little or no impact elsewhere, in spite of similar external magnetospheric SWx drivers. Thus the knowledge of lithospheric conductivities and their gradients (like e.g. along coastlines) will have to become an important factor in the SWx risk assessment for individual countries and regions, along with the geometry of their infrastructure along such conductivity structures.

2.2. Area 2: Support to system-science approach with Coupled Physics-based Modelling: Sun / Solar Wind / Magnetosphere / Ionosphere / Atmosphere

Any scientific effort based on observations must inevitably be complemented by the development of physics based models to explain, or eventually even predict relevant observations in each plasma regime. Predictive models are therefore critical to a robust forecasting capability, which provides workable reaction times to interests affected by space weather. In addition, our ability to successfully predict space environment and weather phenomenology constitutes a measure of the level of our scientific understanding.

Traditionally, the latter has been the primary driver of solar and space physics model development and model development has often been supported by national science programs. In recent years, however, programs like FP7 or H2020 in Europe have aimed or are aiming to support more specifically the development of models with capabilities to forecast space weather-relevant phenomenology and parameters. Many of the models created for space weather applications have been phenomenological or empirical – a focus sought likely due to both limitations of financial support and limitations of physical knowledge and physics-based models in the research field.

While phenomenological or empirical models have had demonstrable successes, we know from other fields that physics-based models, if possible, with assimilative capabilities, are the ultimate tool of choice for high-quality and longer-term forecasts. Some physics-based models have made it into forecasting: For example, in Europe, the ENLIL solar wind and CME model is in use in the UK, whereas NOAA in the US has in recent years employed ENLIL, and the University of Michigan Space Weather Modelling Framework as a geospace forecasting model, and the USAF is relying on the Utah State University assimilative model to predict ionospheric structure and evolution.

These highly promising developments are a result of recognizing the value of physics-based forecasting. Compared to weather forecasting, however, space weather modelling remains in its infancy – CME arrival time forecasting, for example, still has error bars of at best 12 hours, and the most commonly used models have still serious problems to predict magnetic field strength and direction at 1AU. Given the Earth's rotation rate, this means that we are not even able to predict at which time of the day on a given continent the disturbance will hit Earth.

Hence, there is a critical need for further development of existing models (like e.g. EUFHORIA in Belgium or Vlasiator in Finland), as well as the need to develop physics-based models for space weather applications where none exist today. The latter development may build on existing science modelling capabilities or involve targeted new model developments. Furthermore, also for space weather applications ensemble forecasting, it is critical to avoid reliance on single models and to increase forecast confidence. For this reason, multiple models with the same space weather target need to be developed and maintained.

In order to foster a productive forecasting model development, a solid and continued funding basis is essential. Programs like H2020 can provide a valuable start-up, but the history of weather forecasting shows that only concentrated and long-term continuous investment can create the cadre of expertise necessary to drive development forward.

Cooperation and coordination between the developers of models will be essential for the coupling of the most relevant models all the way from the Sun to Earth to explain and predict the entire space weather pathway for each initial solar or solar-wind driving mechanism. This includes developing a mechanism to protect intellectual property rights of models owners, while providing maximum space weather utility from model runs. An alternative mechanism is to provide funding with the explicit purpose to develop models in the open domain, which can, at least in principle, be utilized by any interested party.

Complex coupled models of the kind needed to describe many - if not most - major aspects of space weather require access to appropriate computational resources. This requirement is even more significant if models are to run in real-time or faster for forecasting purposes. In this situation, resources need to be available continuously and lie-in-wait if not utilized at the moment. Computational resources of this kind do, in fact, exist all over Europe, but the access requirements demanded by space weather forecasting constitute a significant cost factor. Development and deployment of complex models must therefore be undertaken strategically, with a vision toward the provision of computational resources for development, and to an even larger degree, during deployment for forecasting.

Further, state-of-the-art research models are typically not plug-and-play applications, but often require expert knowledge to finetune the version of the operating system, the available libraries, as well as the configuration of the model itself. Also the handling of the input/output data can be cumbersome, in particular in chained set-ups where the output of one model is used as the input for the next. For all these reasons, the "Virtual Space Weather Modelling Centre" (VSWMC) is being developed on behalf of ESA/SSA. VSWMC is a distributed system where models can run on remote nodes (typically the compute infrastructure of the model developers) but can be started up and can exchange data with one another through a central coordination node. Facilities as the VSWMC (or the CCMC in the US) are essential to efficiently simulate space weather phenomena across different physical domains as addressed by different models.

Lastly, most scientific models will in principle be sufficient to support the understanding of the physical processes that cause extreme space weather. The use of such models for dedicated forecasts, however, requires the development of appropriate and often scientifically defined, metrics for improved benchmarking and model and forecast comparisons. Measurable performance is critical for the goal of delivering actionable warnings for use by civil protection administrations or other interested parties in response to threats of impending severe space storms.

Findings:

Today’s understanding of the physics of the Sun, the solar wind and the magnetosphere / ionosphere / atmosphere system is incomplete and does not allow the reliable predictions, which are needed for operational purposes.
Even the most advanced models at our disposal have critical shortcomings and gaps, especially in coupling the immense diversity of the associated physical scales, as illustrated in the previous Chapter 1.
Most present day empirical models suffer from such drawbacks, but are nevertheless important for immediate and cost-effective progress in Space weather predictions mostly through parameterisation, and remain of value for verification/validation of other models. This translates into an urgent need for further development of advanced physics-based models and also to couple such models for various regimes in space with each other. It will be essential to run such models in **ensemble mode** as to evaluate and quantify forecast uncertainties

Only then will we be able to make **sufficiently accurate forecasts of timing, location and severity** of SWx effects in the coupled solar-terrestrial system - which are essentially required to protect our technological assets.

Recommendations for Area 2:

1. ***There should be a dedicated and sustained financial support in Europe for the development of state-of-the-art physics-based models*** *for the Sun, the solar wind and the magnetospheric/ionospheric/atmospheric/solid Earth system. The funding responsibilities need to be transparent to SWx researchers, developers, and users.*

2. *Scientific groups carrying out such overarching model efforts require a certain critical mass to be able to both digest scientific findings and implement those into advanced models.* ***We recommend to look into new funding models to support such overarching model efforts and create groups with critical mass.***

3. ***A periodic, e.g., triennial, review of development success and recommendations for future developments and investments should be implemented.***

4. *In order to define and monitor future progress of such efforts one will need to* ***develop a mechanism*** *together with space weather user groups - also using well defined scientific and operational metrics -* ***to verify/validate and compare the performance of physics-based models,*** *both throughout Europe and in collaboration with other global efforts.*

5. *Using the NASA Community Coordinated Modelling Centre, CCMC, as a role model for a test-bed of coupled predictive models,* ***coordinated European efforts*** *(like e.g. the Virtual SWx Modelling Centre, VSWMC)* ***should be supported to combine and couple state-of-the-art models into an operational chain of predictive models from the Sun to Earth.***

2.3. Area 3: Consolidation of National, Regional and European Risk Assessments

Space weather risks constitute an ever-evolving landscape. The successful mitigation of these risks requires a detailed and continuing assessment of SWx impact pathways, of the risks that flow from these pathways, and of the options to mitigate these risks. Only when mitigation options are known is it possible

a) to assess the socio-economic value of taking action (i.e., does mitigation cost significantly less than the economic loss), and thus
b) to establish requirements for mitigation including both system hardening and space weather forecasting.

Space weather risks are continuously evolving with the advance of science and technology. This is shown by the evolution of space weather impacts on technological systems since the first recorded impacts on electric telegraph systems [7], then through impacts on telephones [51], radio communication [37] power grids [41, 50], and railways [34].

In recent decades the range of impacts has expanded greatly as our modern world has made more and more use of technologies in everyday life. This is highlighted today by our critical dependence on electric power (whose supply is an area of major cooperation between European nations) and on real-time communications (both voice and internet). Looking to the near future, satellite location and timing services are now a critical element in everyday life, as recognised in Europe by the development of the Galileo GNSS system. These satellite services often underpin other key technologies such as mobile communications, autonomous vehicles and financial services. Other new dependencies emerge from the discussion of the new catch-phrase “internet of things”. While stock markets have now found a work-around for GNSS time-stamp errors caused by SWx [3], there may be a hidden GNSS risk when other actors couple their independently functioning systems together. Many actors may not be aware of where their systems embed GNSS timing devices, and hence that coordinated actions via internet can fail if SWx corrupts the timestamps provided by those devices. An important example is the concern for maritime safety authorities that loss of GNSS signals can disrupt the flow of accurate sensor data into systems used to control ships [12].

Thus the risks posed by space weather should be regularly re-assessed to identify where changes in technology have altered the potential impact of space weather, an activity in line with wider risk management practice followed by governments across Europe (e.g. see OECD Toolkit for Risk Governance, http://tinyurl.com/y3uh92h3). The promotion and sharing of that good practice within Europe is also a key objective of the EU’s Union Civil Protection Mechanism [19] (http://data.europa.eu/eli/dec/2013/1313/oj).

This Mechanism requires member states to develop risk assessments of natural and technological hazards, and to share non-sensitive information from those assessments. Thus, there is now a European framework for national and regional risk assessments that will encompass space weather alongside other societally-important hazards, e.g. as in the recent assessment of the space weather risk to the Italian power grid [57]. It is also important for Europe to share good practice on space weather risk assessment with countries in other parts of the world, most obviously the substantial programme of US work that is progressing under the auspices of the Space Weather Operations Research and Mitigation Subcommittee (www.sworm.gov). This programme is drawing in advice from European experts and hence provides a good example of international coordination. For other US considerations on Space Weather risks and mitigation needs see a recent report by *Knipp and Gannon* in J. of Space Weather 2019, and references therein.[3]

Integrating space weather knowledge into risk assessment and mitigation

We present here a scheme (Figure 1) that will help risk managers (whether in government or industry) to appreciate this chain and thus enable effective assessment of space weather risks and their mitigation. We start at the upper left of Figure 1 where we highlight that space weather is a persistent feature of the environments within which human activities take place. The Earth has been exposed to space weather since long before humans evolved on the surface of our planet. But, space weather has become significant only as we have developed technologies that are sensitive to space weather, as noted above, and as air and space travel have brought humans to regions (the atmosphere above 10 km, and space) that are more exposed to space weather.

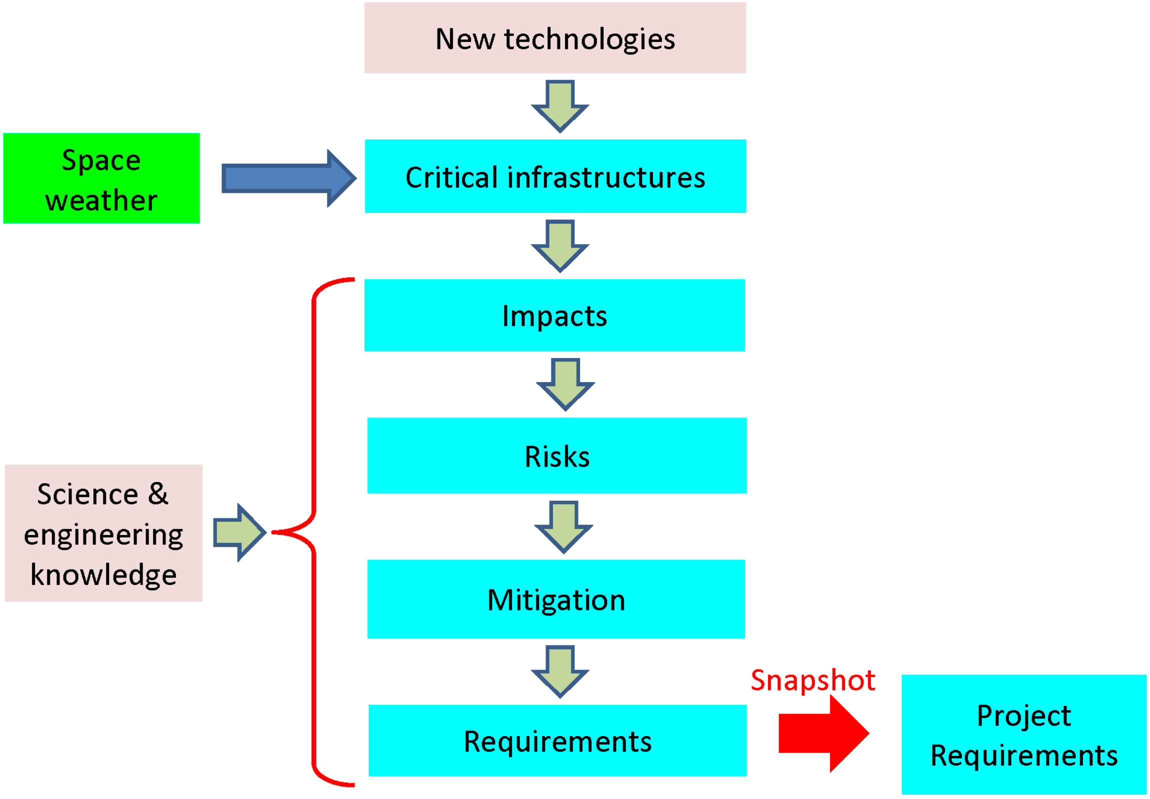

Figure 1. Risk-to-requirements chain for space weather impacts on critical infrastructures. The evolution of technology, and of scientific and engineering knowledge, requires regular reviews of the risks posed by space weather and of requirements for mitigation of those risks.

It is the interaction of space weather with technologies, particularly those embedded in critical infrastructures, that leads to adverse impacts as we show in Figure 1. These impacts evolve because technological innovation enables us to improve the performance of those infrastructures. Modern infrastructures have greatly improved the quality of life for European citizens, and for other people around the world, including those in developing countries (e.g. with the huge growth in use of mobile communications across Africa). But, as

[3] *Knipp, D. J., & Gannon, J. L. (2019). The 2019 National Space Weather Strategy and Action Plan and Beyond. Space Weather, 17. Doi: 10.1029/2019SW002254*

a side effect, they have made modern societies vulnerable to the impacts of space weather. Thus it is vital to assess the risks that arise from these impacts, and to mitigate any significant risks. Scientific and engineering knowledge is crucial to this process. It gives us insight into what are a reasonable worst-case space weather conditions to be considered by governments and industry when assessing risks. In line with risk assessment for other natural hazards (e.g. river and coastal flooding, extremes of temperature, volcanic effects, …), the reasonable worst-case is taken as an event that may occur once in one to two hundred years. The Carrington event of 1859 is widely considered to be a good example of such an event, and hence has been widely studied so as to improve our understanding of the reasonable worst case. Some risk assessments will consider more extreme cases that occur on longer time scales, if the potential impacts of those cases are catastrophic. For space weather, the prime example is the potential impact on nuclear infrastructures, such as reactor control systems, where it is standard practice to consider risks that may occur once in 10000 years [30], and hence we must consider the potential of extreme radiation storms, to disrupt electronic control systems on the surface of the Earth.

Note also that scientific and engineering knowledge is always evolving and that this drives changes in our understanding of space weather risks. A notable recent example has been the scaling up of the risks that space weather poses to power grids. At the beginning of this century that risk was set by experience gained during the great geomagnetic storm of March 1989, which led to a large-scale power blackout in Quebec [10, 25], and to transformer damage in the UK [55] and the US [59]. But more detailed assessment using a wider range of historical data showed that the risk needed to be scaled up by an order of magnitude [11, 27].

This evolution of knowledge adds greatly to the challenges that space weather poses to modern technologically-based societies. When combined with the pace of technological innovation, it creates a rapidly changing landscape for space weather risk assessments. Whilst this fits well with the modern concept of regular risk reviews, it can sometimes be a challenge to engage operators of systems at risk, who will naturally prioritise frequent risks with which they are familiar. This highlights the importance of science in understanding rare and extreme risks such as severe space weather, and also the responsibility of scientists to communicate that knowledge to operators.

There is also a growing body of evidence that everyday fluctuations in space weather can impact technological infrastructures. For example studies of US insurance claims related to electrical problems show a marked correlation with space weather conditions [54]. Similar correlations have been reported in studies on the performance of electricity markets around the world, including Europe 20, 21, 22]. Everyday space weather is also a significant factor in other sectors of the economy including precise positioning services (e.g. as shown in a recent socio-economic study undertaken for ESA by PriceWaterHouseCoopers, footnote on page 9). None of these effects are catastrophic but all suggest that infrastructure performance may be improved by taking account of space weather. However, experience suggests that operators can be reluctant to engage publicly with this issue due to concerns about reputational impact (and perhaps also as an understandable reaction to space weather being widely used in contemporary fiction as a basis for scare stories: stories that can be very entertaining but go far beyond what science can justify). Thus there is a need to encourage realistic public discussion of everyday space weather, so that operators can benefit from (rather than fear) engagement with public discussion of the topic. The structure of knowledge shown in Figure 1 can provide a way to do this – highlighting how scientific and engineering knowledge can help operators to assess space weather risks, whilst showing how these risks are a natural result of technological advances. This is already happening as some sectors (notably satellite operations) develop better links with the space weather community.

Scientific and engineering knowledge is also central to the mitigation of space weather risks. Can we use that knowledge to eliminate those risks by better engineering of vulnerable systems? Or do we need to adjust the operation of those systems when adverse space weather occurs? The former will always be the first choice if it can be done in a cost-effective manner: a good contemporary example is the migration of stock markets towards use of high-precision ground-based timing services [3], thereby eliminating the risk that space weather will disrupt GNSS timing services. However, there are important examples where it is not cost-effective to engineer out impacts, e.g. the electric transmission grid, where the risk of disruption arises from geomagnetically induced currents (GICs), which enter the grid as a side effect of the electrical grounding that is fundamental to the safe operation of all electrical systems. Thus grid operators will adjust the operation of their systems to cope with adverse space weather conditions, just as they adjust to cope with other risk factors (notably normal weather). They will also invest in some hardening of grid systems, but operational adjustments are a key element in the mitigation of risks. But they can only make those adjustments if they have good forecasts and nowcasts of adverse space weather, as well as prior simulations to help them plan for severe events.

Scientific and engineering knowledge is essential to promote a thoughtful approach to mitigation of all space weather risks, one that goes to the root of the problems caused by space weather and that does not focus on one aspect to the detriment of other aspects. A classic example is the mitigation of satellite charging where there are several processes that can cause problems, some that can be substantially mitigated by good engineering and some that require operational measures backed by forecasts. Experience shows that, without good knowledge, the spectrum of charging problems can be over-simplified to focus only on aspects that can be mitigated by engineering. The bottom line is knowledge matters, together with good human judgement on how to use that knowledge.

The final step in the chain shown in Figure 1 is requirements, the requirements for future observations and models to help us respond to space weather. We will discuss these in depth in the next section. Here we just note that these requirements must flow from an understanding of space weather risks and the options available to mitigate those risks.

Customising space weather risks to Europe

The structure shown in Figure 1 is well-suited to the European landscape since it can be applied at national, regional and European levels – and indeed at a global level to enable wider exchange of ideas and pooling of resources (mostly obviously to develop space-based monitoring of space weather conditions). It is a firm basis for increased government understanding of the risks and as well as the engagement of national critical infrastructure protection and other administrations. Increased understanding of space weather risks has already resulted in the development of an appropriate national response to the space weather threat in some European countries:

- Netherlands (see http://tinyurl.com/yxnvfe3r)
- Sweden (see https://www.msb.se/en/Prevention/Space-weather/)
- UK (see http://tinyurl.com/oqbpeoe)
- Finland (see http://tinyurl.com/y55mtm9l))

In Austria, Belgium, Italy and Norway similar assessments are under way. At a wider European level the EU Joint Research Centre supported a number of workshops and reports between 2011 and 2016, working with partners in national administrations and with the US, e.g. 33,. 34]. These JRC actions have been complemented by inclusion of space weather in other European risk management fora, e.g. multi-national meetings of civil protection officers and insurance experts.

It is very timely to increase the pace of this work - encouraging space weather impact and risk studies that recognise regional differences across Europe, whilst recognising that the interconnectedness of twenty-first century infrastructures can magnify regional impacts to create large-scale space weather risks across Europe. For example, major radiation storms can force airlines to avoid trans-polar routes and divert to lower latitudes. For some transpolar routes, e.g. Dubai-Los Angeles, these diversions may bring extra traffic into European airspace.

This increased pace needs action at both national and European levels. The EU is well-placed to encourage both levels of action via a continuation of the excellent work previously done at JRC, in particular by promoting periodic reviews of evolving space weather risks across the full range of critical infrastructure sectors (e.g. energy, transport, finance, …). Given its contacts with civil protection authorities across Europe, a JRC activity can stimulate and encourage national assessments of space weather risks across Europe. The JRC can encourage good practice, in particular the need for sector-led risk analyses. Once the impacts on individual infrastructure sectors are understood, we can understand where are the common elements that warrant action at a European level. A critical common element is the identification of space weather phenomena that drive impacts in different sectors, and the quantification of the probability that those phenomena will reach disruptive levels. This should recognise that the most extreme events can drive an equator-ward shift of space weather impacts, such that effects common in the Arctic can reach the Mediterranean region. But it should also recognise that moderate space weather can also have significant cumulative impacts –contributing to wear and tear on vulnerable systems, and to minor disruptions that are poorly understood.

Mapping space weather to future actions

It is critical to determine which actions to reduce space weather risks are worthwhile at an economic level. Thus the assessment of risks must be complemented by studies of the socio-economic impact – in particular, studies that assess how mitigation can reduce the economic impact of adverse space weather, e.g. as in recent papers [15, 46] that explore how future space weather missions to the Lagrange L1 and L5 points can maintain and enhance forecasting capabilities. These studies also show that a key element in socio-economic impact is the time required to recover following a space weather event. Better knowledge enables faster recovery and hence reduced economic impact. A good example we can learn from is the disruption of air traffic control by a solar radio burst in November 2015 [38]; this closed air space over southern Sweden for several hours leading to flight delays in Sweden and many other countries. Better awareness of current space weather conditions and their potential impact could have shortened the period of disruption to minutes rather than hours.

When turning ideas into future actions, we must recognise that the management of space weather requirements can be challenging. In particular, it is important to strike a balance between the natural evolution of requirements and the setting of clear goals for specific projects. Clear and stable requirements are the foundation of success for any project. Thus, as shown in the lower right of Figure 2, it is critical to take a snapshot of the relevant project requirements at the start of the project. Once set, changes to these project requirements should be allowed only after very careful thought.

Findings:

At present we lack a complete and true evaluation and description of European SWx risks for most individual countries and particularly for regional and over-regional risks, which are emerging from the increasing interdependencies and interconnections of the potentially affected infrastructure.

The risks emerging from SWx events - and thus the definition of user-requirements - will obviously not be the same for different parts of Europe or for European activities in other parts of the world or in space. Any such risks are also different for space and ground-based technological assets.

There is an urgent need for a coordinated European assessment of national and regional risks and consequent potential socio-economic impacts of a variety of space weather events, both for extreme and average daily solar activity.

Only on the basis of such a risk assessment a full catalogue of European User Requirements can be compiled for the development of a future European space weather service function.

Recommendations for Area 3:

1. ***Encourage and enable member-states*** *to carry out a coordinated Europe-wide effort of national risk and socio-economic impact studies of SWx events – in close collaboration between SWx scientists and engineers working with potentially affected infrastructure.*

2. ***Support the combination and expansion of national risk assessments into regional and Europe-wide risk and impact analyses****, addressing the interdependency and connectivity of many - if not all - technological infrastructures in Europe - build on laudable efforts already conducted by the EC-/JRC and in line with the EC mandate for coordination of such risk assessments (as provided by the Union Civil Protection Mechanism). We strongly recommend that space weather be included in the next iteration of the risks to be addressed by JRC.*

3. ***Support and enable awareness about and the dissemination of such risk assessments*** *to national decision makers, but also to the communities of scientists, service providers and end-users alike.*

4. ***Create an active exchange forum for tri-lateral discussions and regularly updated information exchange*** *between SWx -Scientists, End-Users and Service Providers. The annual “****European Space Weather Week”, ESWW, serves as a good model.***

2.4. Area 4: Consolidation of European User Requirements

ESA carried out extensive studies of space weather service requirements in the first decade of this century. Two parallel studies in 2000/2001 [12, 43] provided comprehensive analyses, whilst a later study looked at requirements that could be addressed on cubesats [26]. All these studies were consolidated during the first period of the ESA Space Situational Awareness programme, producing the requirements documents [16, 17, 18] on which ESA has built the space weather element of its SSA programme. Informal discussions, with ESA and across the wider community, have noted the need for continued elaboration of space weather requirements to reflect subsequent changes in space weather risks, and in our understanding of those risks. Such improvement must provide a clear and comprehensive prioritisation of requirements, addressing the spread of space weather risks across critical European infrastructures on the ground as well as in space, and engaging with the space weather risks identified by civil protection authorities across Europe. This is a challenging task as it requires a process (and sufficient resources) to engage with the specific needs of individual European countries and then to consolidate those into a coordinated and prioritised programme. The scale of the task has been demonstrated by ESA, through their funding of a 2016 study of requirements for one country (the UK). This study could provide insights for a wider requirements study across all countries, perhaps under the auspices of the EU's Civil Protection Mechanism [19].

In the rest of this section, we discuss a number of key infrastructures (power, GNSS, aviation and satellites), and outline how national and regional goals for space weather mitigation will inevitably be diverse due to natural variations in the level of space weather risk across Europe as summarised in Table 1 below. We note where there are recent scientific studies that can guide those goals and also highlight where there are already broader European and international programmes that can feed valuable insights to European requirements for mitigation of space weather risks.

The risks to the power grid are receiving increasing attention across Europe with recent peer-reviewed assessments covering Austria/central Europe [4,5], [60], the whole island of Ireland [8,9], Sweden [58], Italy [57] and Spain [56]. Other recent studies compared impacts on power grids in France and on the main island of the UK [32,33], and used parts of the Russian power grid as a test case for development of high-level risk assessment tools [55]. These assessments show that there are significant risks to power grids across Europe, and that requirements for mitigation must take account of key factors that vary between countries: (a) the roles of substorms, sudden commencements and the ring current in driving geomagnetic variations; (b) variations in ground conductivity; and (c) the topology of the power grid. As some of the risk may be different for different parts of a particular infrastructure due to local geometry and relative location to local conductivity conditions, user requirements prior risk assessment must take into account local scenarios for intense geomagnetic variations and local conditions such as ground conductivity and grid topology. For operational mitigation, requirements for nowcasts/forecasts must address local geomagnetic variations, as well as forecasts of upstream drivers of those variations, e.g. the solar wind.

Another important space weather impact is the disruption of GNSS services due to rapid changes in TEC and to ionospheric scintillation. The TEC problem has substantially been addressed by the EU/ESA investment in EGNOS [24]. This provides near-real-time (seconds) corrections to suitably equipped GNSS receivers such that GNSS-derived positions are accurate to 10 to 20 metres across most of Europe (south of 63° latitude). This is, for example, sufficient to ensure safe use of GNSS for aircraft navigation. In extreme space weather conditions where EGNOS cannot provide adequate accuracy, it will warn users to switch to alternative navigation systems. In such conditions, ionospheric scintillation may also become significant, degrading the quality of GNSS signals reaching the ground and potentially leading to loss of signal. Thus the requirements for mitigation of GNSS, beyond use of EGNOS, should focus on the need to forecast space weather conditions that can disrupt use of EGNOS, so that users can plan ahead for that disruption. These forecasts must identify which countries and regions will be impacted. There are also requirements to improve EGNOS accuracy: north of 63° latitude, and on the borders of Europe, e.g. extending good accuracy into Africa.

Space weather has a wide range of impacts on aviation, as shown in Figure 2 below. Radiation effects on avionics have the potential to disrupt control systems on modern "fly-by-wire" aircraft [13]; solar radio bursts [39] and ionospheric effects [2] can disrupt aircraft navigation and flight control systems, whilst ionospheric effects can disrupt communications with air traffic control (e.g. the September 2017 loss of communications with an Air France flight [51]). There is also a risk, in very severe events, that radiation exposure of crew and passengers may require mitigating action [39]. There are requirements to mitigate all these risks by providing pre-flight forecasts so that airlines can factor these risks into the planning of specific flights (perhaps changing routes or even grounding planes in extreme circumstances) and so that pilots can be ready to respond if problems do occur in-flight. In recent years, the International Civil Aviation Organisation (ICAO) has been developing procedures to provide these briefings. Thus European requirements should be aligned with the wider international requirements established by ICAO.

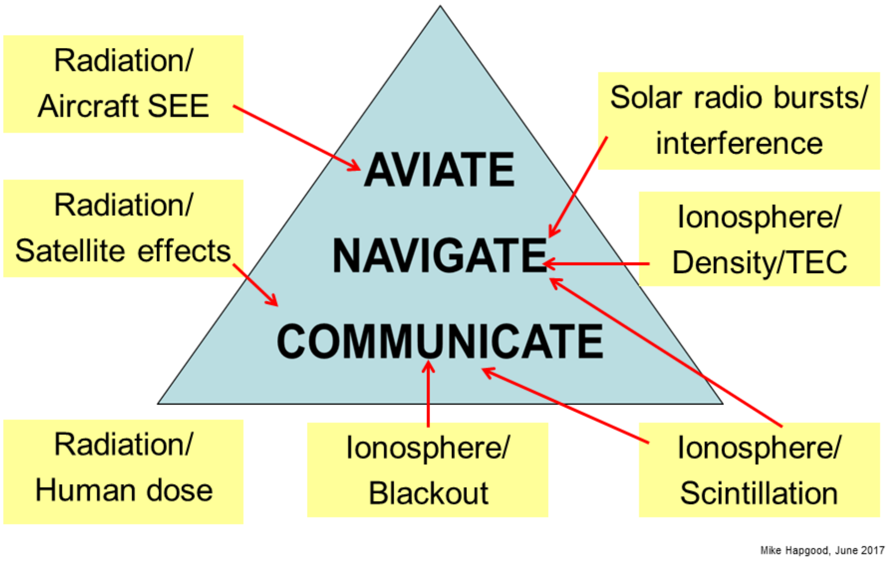

Figure 2. The "pilot's mantra" of Aviate, Navigate and Communicate captures the priority order of tasks needed to fly safely. All three tasks are at risk from adverse space weather.

Satellites are another critical infrastructure vulnerable to space weather. Fortunately satellite builders and operators, in Europe and around the world, have decades of experience of space weather. Builders can incorporate a high degree of resilience into their satellites, and operations teams are skilled at investigating and resolving anomalies caused by space weather. Nonetheless there are still major requirements for better characterisation of the worst-case space weather faced by satellites, so that builders can refine and extend their design standards, e.g. to address innovative operations such as electric orbit raising for geosynchronous satellites. In addition, operations teams have continuing major requirements for forecasts, nowcasts, and post-event analysis of adverse space weather, so that they can plan for, respond to, and analyse satellite disruption. Key requirements are for information on charged particle environments, in all Earth orbits and in interplanetary space (these particles affect satellites by surface and internal charging, single event effects in electronic devices, and radiation damage to solar arrays and other satellite systems). These requirements extend to human exploration, especially if we extend exploration to other bodies such as the Moon and later Mars. There are also requirements for information on space-weather-driven changes in atmospheric drag for satellites in low earth orbit (drag affects the scheduling of satellite operations, plus the management of collision risks and re-entry). ESA is an important end-user by itself for such requirements in respect of its own satellite operations, as are other EU-linked bodies that operate satellite systems such as Galileo and Copernicus. There are also many public and private sector users across Europe, reflecting the wide use of satellite systems and applications by governments and industry. However, there is no obvious differentiation of requirements by regions with Europe, rather there is differentiation by satellite orbit.

Table X. Examples of space weather risks to critical infrastructures: regional issues and high-level requirements

Infrastructure at risk	*Primary Risk*	*Regional issues*	*High-level requirements*
Power grid	Geomagnetically induced currents (GIC) leading to voltage collapse and power outages of many hours to a few days. In some cases, this may lead to damage to grid systems such as transformers.	Risk is greatest in northern Europe due to substorm effects. But also significant risk in Mediterranean area due to sudden commencements and ring current effects.	* Modelling of geoelectric fields and consequent GIC in power grids * Forecasting travel to Earth of heliospheric transients (CMEs and SIRs) * Modelling/forecasting magnetospheric response to heliospheric transients
Aviation	Enhanced atmospheric radiation leading to disruption of avionic systems. Also increased radiation exposure for aircrew and passengers.	Radiation flux increases with latitude, so greatest on routes that go north, e.g. Europe to West Coast of North America, irrespective of country of origin in Europe.	* Forecasts of SEP events (for pre-flight briefings) * Real-time information on SEP events (for in-flight-management) * Post-event information on radiation fluxes and fluences (to assess human exposure and for anomaly analysis)

Aviation	Loss of GNSS position due to rapid changes in TEC and/or ionospheric scintillation.	Scintillation effects are greater in polar and equatorial routes. So effects are greatest (a) on long-haul routes over these regions, irrespective of country of origin, and (b) on short-haul routes in far North of Europe.	* Forecasts of disturbed TEC levels and of ionospheric scintillation
Aviation	Loss of HF communications due to D-region absorption (SEP events, large flares, relativistic electron precipitation (REP))	SEP effects are generally limited to polar regions. Flare effects are greater at lower latitudes but limited to daytime. REP events are rare but will affect mid-latitudes.	* Forecasts of high SEP fluxes * Forecasts of large flares
Logistics	Loss of GNSS navigation due to rapid changes in TEC and/or ionospheric scintillation.	Scintillation effects increase with latitude, so risk is greatest in northern Europe.	* Forecasts of disturbed TEC levels and of ionospheric scintillation
Emergency services	Loss of GNSS navigation due to rapid changes in TEC and/or ionospheric scintillation.	Scintillation effects increase with latitude, so risk is greatest in northern Europe.	* Forecasts of disturbed TEC levels and of ionospheric scintillation
Satellites	Enhanced space radiation leading to disruption of satellite systems.	Risk varies with the satellite orbit, e.g. GEO more exposed than LEO. But most, if not all, countries have interest in most operational orbits	* Forecasts of high SEP fluxes that can cause single event effects * Nowcast of the spectrum of SPE (hardness) after onset
Satellites	Enhanced satellite charging leading to disruption of satellite systems.	Risk varies with the satellite orbit, e.g. GEO more exposed than LEO. But most, if not all, countries have interest in most operational orbits	* Forecasts of high fluences of energetic electrons, especially MeV electrons that cause internal charging, but also keV electron that can cause surface charging

In summary, there is a need for an improved set of European space weather requirements that address the risks that space weather poses to critical infrastructures and other vulnerable sectors across Europe, and that engages with space weather resilience goals set at national and regional levels. These requirements should consolidate individual needs so as to identify where those needs are best served at a European level, as in the four infrastructure examples discussed above, but also considering other major European infrastructures including gas, rail and road networks, telecommunications, food and water supplies, finance, and emergency services. These consolidated requirements should be informed by previous work by ESA, and by other players across Europe. Elaboration of the requirements would benefit greatly from a fresh analysis based on study of space weather impacts on critical infrastructures and of the priorities that flow from those studies.

Findings:

At present we require results from the full European-wide risk assessment as described in section 3 to elaborate and complement the customer requirements compiled by the ESA SSA programme [16,17,18]. ESA SSA requirements have been the baseline that was used to develop the current network of SWx Expert Centres and Expert Groups, but a continuous elaboration of the requirements will be needed to take into account the continuously evolving user landscape and scientific knowledge base.

Continuous elaboration of the understanding of the user needs for tailored services providing actionable information is mandatory and at the moment this is carried out only in the framework of the ESA SSA Programme with limited resources.

Only on the basis of a full Europe-wide risk assessment as described in section 3 can a new and complete catalogue of European User Requirements be compiled, addressing risks on all assets. In this context we note that the European space assets comprise only about 10% of all assets at risk from SWx. It is also critical that this compilation is updated typically every 5 years.

The catalogue of user requirements should be a "living document" with update intervals of e.g. every 5 years, since the infrastructures and their particular vulnerabilities and resiliencies constantly change and develop - as does the scientific understanding of potential SWx events and their associated risks.

Recommendations in Area 4:

1. ***Support and enable a coordinated European wide effort to elaborate European SWx user requirements*** *based on needs as specified by local region (such as arctic, sub-auroral, mediterranean) and infrastructure domain (communication, energy, health, finance, etc.), addressing the risks from SWx impacts on space-based and ground-based infrastructure - build on efforts already conducted by the ESA SWE Programme*[1] *and the EC/JRC for Infrastructure - and re-establish SWx as a task for the JRC activities.*

2. *There will be a need to* ***prioritise user requirements in the catalogue, based as far as possible on their value in mitigating particular impacts****, e.g. specifically forecasts helping operators to maintain power supplies, navigation or communication.*

3. *Enhance* ***the exchange and updating of information about user requirements in tri-lateral discussions*** *between SWx -Scientists, End-Users and Service Providers. For most requirements the description of context and clear rationale for the expected impact will be crucial to determine the needed forecast type and quality.*

2.5. Area 5: “R2O” and “O2R” or how can SWx scientists interface with candidate organisations for SWx services – in Europe and globally

Unlike terrestrial weather, which is a mature science, space weather is in its scientific infancy. The immature nature of the field, the complexity of data sets, and the rapidly evolving character of models make the close involvement of active researchers highly beneficial to space weather services. Practising scientists can distinguish a data glitch from valid data, and valid model output from erroneous results. Furthermore, our data sources are sparse and often ephemeral, a situation which mandates that we use any available information to form the best possible picture of space weather and to produce the best possible forecasts. We thus need a flexible approach, where every institution and country can participate to the best of their abilities, and which combines scientific and interpretative skills at many institutions. Such an inclusive model also provides rapid utilization of emerging capabilities and knowledge. Finally, it supports decision-making based on knowledge of what is possible today and what is emerging in the research community.

Despite a very restrictive budgetary situation, ESA’s SSA Space Weather Segment has been highly successful in integrating a wide range of space weather services across Europe, and in developing a Coordinated Communication Protocol (CCP) for consistent European messaging during space weather events. This success is a result of the underlying inclusive approach: while relying on a centralised management and coordination, ESA’s approach is decentralised and organised in the form of Expert Groups, creating a network of Expert Service Centres (ESCs). These ESCs integrate diverse scientific and analytic experience at many institutions and many countries. Hence, they form a total, which is much larger than any single institution can create. Scientists who generate the knowledge and the models are directly involved in the transitioning of this information into operations, and to some extent even in the operations themselves. ESA’s programme is also, to a large degree, guided by these scientific experts, and is therefore set up to evolve in the best possible way. While user helpdesk and system monitoring functions are provided by a service coordination centre, ESA’s SWx ESCs can, in fact, provide regional services and communicate directly with users, ensuring that users are aware of what is possible now and what is emerging as new capabilities, and that providers understand user needs. [4]

However, ESA’s SSA programme could be improved even further. First of all, the programme has benefitted to a large degree from scientific research and development largely funded by national sources, by the European Union, or by ESA’s science programme. We note that further progress in space weather capabilities requires dedicated research and development, which is unlikely to happen without a dedicated funding source. This continuous support does not exist to-date, and funding available for the existing programme remains severely limited. In addition, the programme should re-orientate itself toward an increased emphasis on development and production and a de-emphasis of overhead activities.

In conclusion, the ESA SSA approach toward decentralization, networking and inclusion, proximity between scientific research, transition to operation, is considered to be the best possible model to yield immediate societal benefits while simultaneously allowing the field to mature in parallel. It should be the model for a European space weather service. For

[4] *ESA SSA has carried out a study on Arctic SWx User Requirements in 2016 and is starting studies on Mediterranean User Requirements in 2019.*

further progress, it is also essential that funding sources be created, which support space weather-focused research and development in a sustained fashion. We further advocate for R2O coordination between the ESA programme, and national activities inside Europe as well as EU programmes. Finally, European Space Weather services should be contributing to, and benefiting from, related Space Weather activities world-wide.

Findings:

There is no doubt that initial SWx services and predictions of events and effects are urgently needed today by a variety of end users and decision makers to protect their assets in space and on the ground – but the present SWx knowledge base is insufficient for this task.
The development of future improved SWx services must be driven by specific User Requirements (see Chapter 4), and must be based - and constantly improved - on the basis of a thorough SWx Risk Assessment (see Chapter 3).
Future services should continuously be improved on the basis of the best available scientific knowledge – including making use of the best performing, coupled and "state-of-the-art" models available.

A promising approach to develop the required future European space weather activities and services can best be described as an iterative loop between R2O and O2R in which there should exist a continuous iteration and feedback between:
a) new improved science understanding and supporting observations,
b) evolving requirements of European end-users and infrastructure providers, and
c) improved potential to deliver SWx products (based on recent science findings),
where b) and c) should also address particular national and trans-national requirements, and eventually feed back into new challenges for the science efforts under a).

To this end a constant round-table of dialogue between all SWx partners, i.e. SWx scientists, European Policy Makers, public and private SWx service organisations and representatives from the user communities will be required at such discussions.
The decentralised ESA SSA approach of distributed and networked SWx Expert Service Centre's for various parts of the coupled Sun-Earth system (still under development), is a promising approach towards the development of future European Space Weather Prediction Centres - both fulfilling the above requirements and making the best use of the distributed European expertise and capabilities.

Recommendations in Area 5:

A European SWx effort should

1. ***utilise and coordinate existing national efforts*** *to provide regional space weather services (Examples: Belgium: ROB & VSWCM, UK: Met-Office, France: OFRAME, Italy: INSWSN)*

2. ***involve ESA, EU/EC and all member-states****, and must be driven by the European user requirements, as discussed in Chapter 4.*

3. *be conducted also in close coordination and cooperation with the already ongoing parallel developments on the* ***global scale*** *(UN-COPUOS), and with efforts of other nations (US, China,Russia, Japan, etc…)*

4. ***benefit from the experience*** *in the development of global services and 24/7 operations* ***of existing global organisations*** *such as WMO, ICAO,….*

5. ***involve Expert Scientists** in the development of future European SWx services so these services become and remain **competent in the plasma-physical context of the Sun-Earth System.***

6. *build on and expand the present decentralised and distributed **ESA-SWE Expert Service Centre (ESC) approach as a good example for such efforts.***

7. ***update the resulting European User Requirement Document on a timescale of 3-5 yea**rs - to adapt to emerging needs of the user community.*

2.6. Area 6: Define and implement a network of space and ground-based assets for future SWx observations

Currently space-weather related activities benefit enormously from a unique and existing fleet of scientific spacecraft observing the sun, the heliosphere and geo-space, supported by a multi-facetted network of complementary ground-based measurement infrastructure. These assets can still support most of the international efforts to drive forward and support an improved knowledge in the science of space weather processes (see our findings in Chapter 1). While unique in its kind the present fleet of *science-oriented* spacecraft in geospace and the heliosphere is nevertheless ageing and obviously it also does not fulfil the requirements of a future *operational* system for space weather services.

As one item of particular concern we would like to point out that most current European SWx services rely on data from ageing infrastructure such as e.g. ESA‘s SOHO spacecraft in collaboration with NASA. SOHO is rapidly approaching its 25th anniversary, having thus substantially exceeded its design lifetime of 2 (!) years. While ESA is indeed discussing with the US the coordinated development of a common space weather monitoring system, there is to date no consolidated plan yet for the successor of the SOHO coronagraphs.

In contrast, the present day ground-based scientific networks of SWx instruments can provide reliable operational service data for future space weather services, however, they still have major gaps in both coverage and temporal resolution; they often lack coordination between countries and regions and real-time data availability. Also they are rapidly ageing, often barely surviving on scattered and decreasing national funding.

Thus we find that there is a clear urgency, indeed, to use the present scientific space weather assets in space and on the ground to make scientific progress towards the definition of an effective, efficient, and sufficient global observational system. This in turn needs to be operated in concert by several stakeholders in space and on the ground.

It will also be important to define what kind of and exactly which SWx relevant parameters in the interconnected various plasma regimes of the Sun - Heliosphere - Geospace - Atmosphere system will have to be measured. The content, location and required temporal resolution of such measurements needs to be tuned to the evolving requirements to drive the newly developed advanced SWx prediction models.

As an example we note the current collaboration between Europe and the US on coordinated space weather missions to the Lagrange points L1 and L5, also to illustrate what can be achieved by coordination. The combination of complementary observations from L1 and L5 will enable better space weather forecasts, especially forecasts of CME arrivals at Earth. The latter is a simple consequence of geometry: observations from L5 give a side-on view of CMEs propagating towards Earth, such that CME speeds can be determined more accurately, whilst observations from L1 are better placed to determine when a CME is earth-directed (see simple schematic at https://youtu.be/1Mv17P7hZ_Y). Furthermore a magnetometer at L5 also can provide vector-B from a second perspective and thus resolve the intrinsic ambiguity in the transverse field direction. Simultaneous remote solar observations from L1 and L5 also provide increased surface coverage (particularly with earlier information on what happened on the far side) to improve background solar wind modelling. This ESA collaboration with the US is strongly supported and encouraged by the science community in Europe and beyond. Recent scientific studies [e.g. 1, 28, 35] have explored the advantage of space weather observations from locations such as L5.

In this context we note explicitly that this geometry is quite different from other orbits and geometries required for cutting-edge science missions, such as ESA's Solar Orbiter mission. It shows that no single mission can address all combined space weather needs.

Of course it is obvious that in particular in the various Geospace plasma regimes – i.e. in the magnetosheath, the magnetopause, the magnetotail and the inner magnetosphere (ring current region and upper ionosphere) - SWx related missions can and should not aim at the complexity of scientific multi-space craft missions such as Cluster, MMS or Themis. In order to satisfy future needs of system wide relevant SWx observations, based on present and newly derived knowledge from space weather enabling science, one will need to identify and define simpler - or rather reduced - characteristic parameters, which can be monitored 24/7 by fewer and simpler spacecraft missions in a more effective way. Such more readily available parameters (let us refer to them as so-called **"Proxies"** or rather **"Essential SWx Parameters"**) should be able to describe the state of the plasma in the coupled space plasma regimes at the sun, in the heliosphere and throughout geo-space sufficiently well, so that they can then be utilised to drive the necessary predictive models and to reach satisfactory predictions about the expected behaviour of the coupled system. However, as we have illustrated above, the scientific community presently lacks physical understanding of the Sun-Earth plasma system required to define such essential parameters sufficiently well.

Once such **Essential SWx Parameters** have been defined they can advise on the definition of the European portion in a global observational effort for SWx purposes. This will imply both the provision of dedicated missions and ground-based assets to measure space plasma parameters of relevance for space weather warnings and predictions. In close coordination between space agencies, and perhaps space weather agencies, and with respect to national and European space- and ground-based infrastructure, one should aim to build a sufficient network of operational measurement capabilities satisfying European needs and contributing to a global network (with a view to implementing the recommendations in the document on the road map for the period 2015–2025 commissioned by COSPAR and ILWS *[54]*).

This activity will have to include the development of a concept for space weather information protocols, including a potential early warning system for identifying and communicating potentially or existing severe and/or catastrophic space weather events, to be implemented through the coordination of, and developed by, existing space weather service providers and international bodies and through the activities of other national space weather service providers.

Findings:

Based on the emerging scientific understanding of space weather events and processes, scientists and space agencies together will have to define an essential and optimum set of observable parameters at the Sun and in the heliospheric, magnetospheric, ionospheric, atmospheric, and solid-Earth system, which are needed to characterise the energetic and dynamical state of the most important elements of the Sun-Earth coupled plasma regimes and to drive the required forecasts of the expected response of the system as a whole.

Based on such required sets of observables one will have to **define both a baseline and an optimum network of space and ground-based instrumentation,** which can monitor such required parameters with sufficient accuracy, 24/7 and in real-time.

We stress, however, that any future observational network must be able to do (a little) better than the bare minimum SWx requirement and - out of principle - always also allow new science to emerge in order to prepare for potentially growing future SWx user requirements.

Any future European network for space weather observations in space and on the ground should also be embedded in and be coordinated with a global effort of other agencies and nations - coordination implies both complementarity and comparability in terms of location, type of measurement, and inter-calibration. The planned ESA Lagrange mission to L5 for improved solar and solar wind monitoring in concert with other international efforts at L1 is a good example for such coordination.

However, there will still be a need for additional purely scientific and space weather enabling missions for an increased understanding of the processes in the Sun Earth system. This effort cannot be replaced by 24/7 operative missions, in particular not if they are aimed at the observations of essential SWx-parameters or proxies only.

Recommendations for Area 6:

Directed towards ESA:

1. *Create a **Forum between SWx scientists, staff of the ESA-SSA and ESA-SCI programmes and the space agencies of individual member states** for the **definition and future operation of a "fleet" of dedicated spacecraft**: large crucial cornerstone missions, small satellites at key locations and hosted payload elements for European Space Weather purposes.*

2. *For this dedicated "fleet" of SWx space assets **define a set of observables**, fulfilling the present user requirements and at the same time **allowing for future science development** to allow for an increased knowledge base for future emerging SWx requirements.*

Directed towards EU, Member States, Funding and Civil Protection Agencies:

3. *On the basis of such considerations and in collaboration with individual member states support the **maintenance, modernisation and future augmentation of ground-based instrument networks** for space weather purposes to support the space assets for SWx observations.*

4. *Each type of mission, payload or G-B instrument network should become* ***part of a specific type of European and/or global network***
   - ***Examples of network "types":*** *Solar observations, solar wind observations at L1/L5, and various Geo-space regimes: Magnetosphere, Ionosphere, Atmosphere, Ring current.*
   - ***Present G-B instrument networks comprise:***
   - *Magnetometer networks and coordination through SuperMAG, coherent radar systems SuperDARN, TEC-receivers, Ionosondes, Incoherent scatter radars like EISCAT-3D, solar radio-observations , LOFAR, GONG, NMDB, etc.*

NOTE: All data in this combined space and ground-based network of SWx assets system should be collected and disseminated under an Open Data Policy - and for potential parallel scientific use it should even include the original raw and S/C housekeeping data.

3. Conclusions, Overarching Recommendations and Future Prospects

In this report we have argued that - as in the rest of the world - there is also an urgent European need for coordination of Space Weather efforts in individual countries as well as in and among European organisations such as the European Space Agency (ESA) and the European Union (EU). This coordination should not only improve our ability to meet space weather risks, but also enable Europe to contribute to on-going global space weather efforts. **While space weather is a global threat which needs a global response it also requires tailored regional and trans-regional responses that require coordination at all levels.**

We have shown that there are six essential and indispensable activities, which urgently require coordination at European level:

1. **Enabling critical science to improve our scientific understanding of SWx:**
   Our overall description of the coupled Sun-Earth system in the space age still contains critical gaps in the scientific understanding of several mechanisms through which space weather couples from space all the way down to Earth. While significant progress can and will be made using existing scientific infrastructure including existing multi-spacecraft missions and ground-based networks, support must urgently be provided for the next generation space missions and the replacement and where needed targeted expansion of ageing ground-based infrastructure.

2. **Development and coupling of advanced models by applying a system-science approach which utilises physics-based modelling:**
   Develop better physics-based models and also define metrics that facilitate assessment of different models and to encourage their transition to operations.

3. **Assessment of risks at National, Regional and European levels:**
   European States should regularly assess their exposure to SWx risks and coordinate and combine their studies at regional and European level to cover the interdependency of technological infrastructures. This requires close cooperation between decision makers, SWx scientists, service providers, and end-users. Lessons learned should be shared amongst all European stakeholders.

4. **Consolidation of European User Requirements**
   European SWx user requirements should be (re-)assessed and prioritised taking into account regional and societal differences and needs, also addressing different needs of various infrastructure systems. This should be done on a regular basis, e.g. every 5 years, also to facilitate the exchange of information among European SWx actors.

5. **Support to R2O and O2R**
   The best available knowledge and models should be used in future SWx service organisations. Such transition from Research to Operations should be guided by teams of scientists all over Europe - following the distributed ESA Expert Service Centre approach.

6. **Define and implement an operational network for future SWx observations**
   Based on our present scientific understanding and the above assessments of risks and user requirements we need to define an *operational* space- and ground-based network that measures essential space weather parameters which in turn can drive the SWx predictions required to protect our society's infrastructure.

We also identified a number of other issues requiring attention:

A first analysis of knowledge, observational gaps and requirements for an appropriate SWx warning system with special consideration of European SWx vulnerabilities and weaknesses, but also taking into account European strengths has been carried out by the Expert Groups in the ESA SSA Space Weather Service Network. The results of this analysis have been reviewed by the European Space Weather Working Team. However, continuous elaboration of the analysis including assessment of space weather risks on European infrastructure and understanding of the user needs will be required because of the constantly evolving end user landscape and European SWx competencies.

We find that the presently ongoing SWx efforts in Europe are to large degree uncoordinated and also mostly unsustainable. This is probably at least partially due to the fragmentation of funding responsibilities in Europe. Apart from the ESA and the EU, individual states and many different agencies also fund space weather activities.

The **ESA** is presently developing pre-operational SWx-services in the framework of its Space Situational Awareness (SSA) Programme with 19 out of ESA's 22 Member States participating in the SWx segment. However, the ESA SSA programme is optional and the participating member-states contribute very diverse voluntary annual contributions, not always reflecting Net National Income. Also the scope of the services, established within this programme, is currently limited to testing, verification and validation.

The **EU** had – and still has - scattered H2020 (FPx) SWx calls, reoccurring every other or sometimes even only every third year. Even if the EU funding to SWx activities adds up to a considerable amount of approximately 60 M€ over the last 10 years, the funding offered in each call is sub-critical to develop sustainable science and service activities, and did not match the European needs. Many of these calls were (and still are) aimed primarily at the prototyping of services with relatively little regard for the scientific foundations, which are required for such services to become reliable. Most of the work required for the scientific underpinning of SWx, especially the science and data exploitation activities (see our findings below), fall into the general EU-calls, where they compete with other fileds of basic science.

Additional funding provided by individual European states is fragmented, localised, uncoordinated, and also mostly insufficient to satisfy the growing societal needs, for both the advancement of knowledge and the provision of services. Also it is difficult to build transnational and regional efforts on national funding. Moreover, the private sector is recently becoming more and more active in space, and realises its exposure to SWx-threats.

However - and yet again - the funding emerging from such sources is often too directed and topically far too narrow to satisfy SWx needs.

We would like to stress that while this diversity in funding is currently often seen as a European weakness, it could be turned into a strength, if it were coordinated according to the principle **„Let those do the work who are best at it“.** We strongly advocate a dedicated Europe-wide coordination of SWx activities. This could be done in a similar manner to how the COPERNICUS programme deals with Earth Observations.

Many countries are developing increasingly sophisticated infrastructure, which at this point can still be better prepared against SWx risks. This is a crucial step towards making our modern and technology-reliant society sustainable and resilient. Outside Europe such efforts should embrace developing nations, where such preparations are especially timely and efficient.

Final Recommendations:

Europe should collaborate with other global partners (which work with different funding structures and opportunities) to reap mutual benefits and respond and contribute to parallel world-wide initiatives from global organisations as e.g. the United Nations:

- The ESA and the EU need to coordinate their efforts and share the European responsibilities for SWx activities: science and research support, observations and service as they do for other global issues, such as the Copernicus and Galileo projects.

- The ESA in particular should take care of dedicated operational SWx missions, hosted instrumentation, data production and dissemination – and continue to develop initial service functions on the basis of the presently on-going model of distributed Expert Service Centres, ESCs.

- The EU should complement ESA’s efforts by stimulating and funding overarching SWx science & data exploitation in a continuous and sustainable fashion. It should coordinate or support additional space and ground-based SWx efforts in member states or groups of member states, which are located under or at the magnetic footprints of certain space plasma regimes or in particular geographical regions and so can serve particular SWx observational requirements.

- Member-states and local groups of member-states should coordinate their national efforts to support the overarching activities of ESA / EU with respect to national and regional priorities and abilities.

- Any dedicated European SWx organisation must serve future societal needs, based primarily on European risks and consequent user needs, but in global coordination and with the continued support from the science community.

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