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Global landscape of space weather observations, research and operations ☆

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Abstract

The recognition of space weather hazards is increasingly growing, highlighting the importance of monitoring and forecasting it. High precision satellite positioning techniques have become essential in various areas of social and economic infrastructure. However, it is well-known that Global Navigation Satellite Systems (GNSS) can be affected by space weather-induced ionospheric variations. This poses a challenge as it can impact the reliability and accuracy of GNSS-based systems.

Space weather phenomena can also have significant effects on aviation systems and electric power grids. Given that many of these phenomena occur on a global scale, it is crucial to have a comprehensive monitoring and observation network. Currently, numerous ground-based observations are managed by local government or academic bodies. In contrast, space-based observations are typically operated by space agencies, often necessitating international coordinated collaboration to undertake significant projects in this field. The paper puts a strong emphasis on the need for collaboration between various entities in each nation and between national programmes.

In this paper, the authors provide an overview of the international landscape for space weather research and operations at the nation-state level. They also highlight the activities of various national and regional space agencies involved in space weather research and monitoring for enhancing our capabilities in monitoring, forecasting, and mitigating the impacts of space weather phenomena on critical infrastructure and systems.

1. Introduction

1.1. Growth of space weather

The initiatives of the International Geophysical Year (1957–1958) are widely accepted as a significant trigger for space science. In the same time-period the launch of the first artificial satellite provided the first foundation in the search for knowledge around environmental impacts on technology, particularly in ionospheric research and in the Earth's magnetosphere with its coupled current system.

The science of space weather is a combination of many other older scientific disciplines stretching across astrophysics and geophysics that gradually became stronger, revealing connections of the space environment and society. It is a science encompassing the mix of chemical reactions with gravity and electromagnetic waves and fields interacting with various parts, both neutral and ionized, of the atmosphere of our planetary system, in a very complex chain of connections. Space weather has impacts on meteorological conditions and technological systems such as ozone destruction and radio blackouts respectively. An interesting discussion on the transition of interest in Space Weather from a perspective of physical sciences such as solar-terrestrial physics to a broader interest in applications of space weather science from the perspective of economic and societal needs is provided by Koskinen et al. (2017) where the latter includes applications to economic and societal needs. Hence, space weather extends our need to expand scientific research across much broader boundaries to examine impacts on the many sectors of society which are sensitive to space weather events (e.g., Oughton et al., 2017) in a very complex and interconnected way.

1.2. Growth of cooperative links

The near-space environment, which in the context of technological impacts of space weather is here defined as the extraterrestrial space between the Earth's surface and anywhere else we have our instruments for monitoring space weather has become our new field for exploring else-where, transferring information and making deals, much like the ocean was the environment which allowed the exploration of continents in the past. However, nowadays communication, precise position and time are the new challenges. We are observing the solar surface, Earth's magnetic field and ionosphere with ground and space based instruments for monitoring space weather conditions (e.g., ionospheric disturbances which affect radio communication or precise satellite positioning).

The recent growth of our dependence on space activities, including services provided by instruments on board satellites, and precise geo-referencing, as well as the importance of long distance electrical conductors has motivated global society to discuss and invest more in both research and space weather monitoring. Today, space weather is a science that is being largely certified by industry. It is now clear from many resources the importance of cooperation to face this global phenomenon with regional challenges (e.g., Plainaki et al., 2020). Clearly, cooperation in most cases is motivated by specific contributions in science or data exchange that in a more global scope needs coordination.

This paper will present some initiatives based on a mature science existing in solar terrestrial physics being strengthened by international cooperation to offer better space weather science and services. Also, no less important are the problems faced in building and sustaining the results of these efforts. Among the difficulties are unstable economic conditions, and the creation, maintenance, and renewal of qualified people.

Taking aviation as an example of coordination, in 2002 users identified space weather events as a potential safety hazard at the International Civil Aviation Organization (ICAO)[1,2] Meteorology Divisional Meeting. In 2008 the World Meteorological Organization (WMO) agreed with the International Space Environment Services (ISES), to engage in space weather services, in partnership with relevant international organizations. In May 2010, WMO established a team of space weather specialists named the Interprogramme Coordination Team on Space Weather (ICTSW). In June 2016 the WMO established the Inter-Programme Team on Space Weather Information, System and Services (IPT-SWeISS) to pursue the work and achievement of the former ICTSW. In 2015 the ICAO Meteorology Panel (METP) assigned responsibility to regional space weather centres and global consortia of space weather centres for developing space weather information and alert services for international air navigation. In late 2019 global space weather services started for the aviation community by three organizations, US, European consortium named PECASUS (European Consortium for Aviation Space weather User Services), the consortium of Australia, Canada, France and Japan (ACFJ).

What we learned from this new enterprise is the need to coordinate the evolution of the science of modeling of Sun-Earth interactions with the data ingestion from the many instruments in space and on the ground. This is an example of services provided by these organizations that range from the early observation of space weather events to providing alerts to the end users of sensible systems or service affected by solar storms.

Although cooperation is nowadays a standard procedure for research, for space weather services, we may consider that the first global coordinated cooperation was recently conceived for aviation with the ICAO discussion inside WMO. Two international consortiums were formed, PECASUS and ACFJ, to be elected as global centers to provide services in partnership with the NOAA SWPC to ICAO. The most recent evidence of awareness of this is the "WMO-ISES-COSPAR Coimbra Declaration" (https://cosparhq.cnes.fr/assets/uploads/2023/02/WMO-ISES-COSPAR_Coimbra_Declaration_Final.pdf) that is identified at COSPAR, WMO and ISES websites and discussed in more details in the accompanying paper (Ishii et al., 2024).

> ``*During meetings in Coimbra, Portugal, from 30th September to 1st October 2022, two representatives of the leadership of each of the World Meteorological Organization (WMO), the International Space Environment Service (ISES), and the Committee on Space Research (COSPAR), met, in response to the invitation letter from UNOOSA dated 1 July 2022 inviting the three organizations WMO, COSPAR and ISES to lead efforts to improve the global coordination of space weather activities in consultation and collaboration with other relevant actors and international organizations, including the Committee on the Peaceful Uses of Outer Space. ….*".

1.3. Data collection

This paper presents a glimpse into the growth of science and organizations for some examples of societies in support of our understanding of their recent infrastructure and key needs. This, in our assessment, is part of the understanding necessary for scientific research on the influencing agents of the near space and impacts on society. However, the number of organizations and institutions working in the field is too large to be comprehensively included in any analysis. The content here is a result from a call inside the COSPAR Panel on Space Weather (PSW) where some members voluntarily participated with an agreed short report. Some of the members who contributed reports have already published an extensive description of the science developed and instrument framework in their organization or region that we will refer to in this work. Additional contributions are included in the accompanying paper (Ishii et al., 2024).

[1] International Civil Aviation Organisation (ICAO) Space Weather Advisories, 2019. https://www.icao.int/airnavigation/METP/Panel%20Documents/SWXA_Additional%20Information.pdf.

[2] A list of acronyms is given in Appendix A.

The draft report A/AC.105/C.1/2021/CRP.14 of 19[3] April 2021 of the Expert Group on Space Weather on the actions arising from the mandate approved by Scientific and Technical Subcommittee (STSC) of UN/COPUOS presented the result of two 2020 Surveys of the COPUOS Member States, and that of relevant international space weather organisations, regarding their space weather activities. According to this report, it is recognized that "better communication and more effective liaison with appropriate regional and global international space weather organizations would improve space weather science and services. It becomes quite clear that the exchange of space weather data and expertise (Recommendation D.2) through international collaboration and dissemination is needed. "Out of the 36 (90 %) member state responses that do undertake space-weather research, 14 (35 %) would welcome further assistance. This gives a total of 16 (40 %) of responding countries interested in further assistance with the conductance of space-weather research (A/AC.105/C.1/2021/CRP.14).

Recently the United Nations Office for Disaster Risk Reduction published the "Hazard Definition and Classification Review: Technical Report"[4] and the "Hazard Information Profiles: Supplement to UN/DRR- ISC Hazard Definition & Classification Review – Technical Report".[5] These two documents provide an important resource to support the implementation of disaster risk reduction and risk-informed investment, aligned with the Sendai Framework for Disaster Risk Reduction 2015–2030. They also support the Sustainable Development Goals of Agenda 2030, the Paris Agreement on Climate Change, and the Addis Ababa Action Agenda on Sustainable Financing. It is noteworthy that the space weather phenomena are already considered within the list of natural hazards in these two documents.

Our review summarizes some contributions to space weather science and services with emphasis on recent progress in each institution/organization describing the landscape.

1.4. Organization of paper

The work was organized from the short report provided by the Institutions/Organizations using the following template, as discussed during the panel sections of PSW.

- **Instruments framework:** important contributions for the ground and space-based space weather measurement infrastructure
- **Scientific framework:** a brief summary of the space weather research roadmap of the country/institution/organization (with link to further information / recommendation papers, if existing). Include modeling capabilities as instruments for research.
  - o Programs for development/improvement space weather modeling/forecasting capabilities.
  - o Activities on data preparation and sharing.
  - o Space weather monitoring/forecasting.
- **Coordination efforts:** Report on national coordination of space weather services or contributions to international operational space weather services

Report on key needs: some information on data gaps and models needed in the country/organization/institution (if any). Suggestion for combined international teaming to close a specific space weather capacity gap.

- **Planning efforts:** some text about main research interests of the country/institution/organization.

2. Instrument framework

Collaborative efforts and international networks play a crucial role in handling and sharing data from various instruments and observatories related to space weather. It is indeed common for different organizations and networks to have their own set of instruments and data collection methodologies. SuperMAG (https://supermag.jhuapl.edu), as an example, is a collaborative project that focuses on the study of geomagnetic disturbances using ground-based magnetometer data from multiple international observatories. GIRO (https://giro.uml.edu) is another example for ionosondes.

Global Navigation Satellite System (GNSS) receivers have become valuable tools for studying the Earth's ionosphere and space weather effects. These receivers provide measurements of Total Electron Content (TEC), which is a key parameter for monitoring ionospheric conditions and understanding the impact of space weather on satellite-based navigation and communication systems.

The number of geodetic grade GNSS receivers globally is substantial, and many of them have not yet been fully integrated into space weather services. However, efforts are underway to include GNSS data in various space weather monitoring and forecasting systems. The GNSS landscape presented here will be limited to the reports of the organizations contributing to this paper.

While the details of instruments and networks may not be covered comprehensively here, it is important to recognize the significance of collaborations and data-sharing initiatives in advancing research and understanding in the field of space weather.

[3] https://www.unoosa.org/oosa/oosadoc/data/documents/2022/aac.105c.1l/aac.105c.1l.401_0.html.

[4] https://www.undrr.org/publication/hazard-definition-and-classification-review-technical-report.

[5] https://www.undrr.org/news/launch-undrr/isc-hazard-information-profiles-supplement-undrr/isc-hazard-definition

2.1. Americas & Africa

2.1.1. LAMP/UBA-IAFE(CONICET)-IAA/Argentina

This Argentinean group (https://spaceweather.at.fcen.uba.ar) is making significant contributions on developing ground-based and space instruments in Argentina and at global level. The following Table 1 shows the most important instruments.

2.1.2. UNLP/MAGGIA Laboratory/Argentina

Important instruments are shown in Table 2.

2.1.3. UNT/TSWC/Argentina

The Tucumán Space Weather Center (TSWC) (https://spaceweather.facet.unt.edu.ar/) is a space weather program by Universidad Nacional de Tucumán (UNT) working in partnership with Universidad Tecnológica in Tucumán and in Bahía Blanca. The group has contributed significantly in building instrumentation capacity for Argentina, the region with a global scope by deploying space weather instrumentation and providing real-time measurements.

Currently, the following instruments shown in Table 3 are in regular operations in the frame of the TSWC.

It is worth mentioning that the TSWC currently is developing the Argentinean-Chilean-validated ionospheric database (ACVID) based on ionosonde manually corrected data. This joint project is sponsored by the SCOSTEP/PRESTO program and involves the 2 ionosondes (Tucumán and Bahia Blanca) in operation in Argentina and a ionosonde in Chile (currently installed in La Serena (29.9°S, 71.3°W)). Nowadays, thanks to the ubiquity of GNSS receivers, there exist different national GNSS networks that allow TEC measurements along the South American continent. Even so, up to date, very few studies have considered the vertical distribution of the ionosphere of such a geographic region, and the information about the layers' distribution and dynamics is key to solving its multiple unknowns and improving the accuracy of current ionospheric and space weather studies.

In addition, Argentina has other groups and institutions that provide real time measurements for space weather such as CONAE that provides space-based measurements from Argentinean space missions such as SAOCOM satellite, RAMSAC/IGS GNSS network that provides real-time data for Argentina and to global networks, CASLEO/ El Leoncito that is an astronomical scientific facility including

Table 1
Important instruments of LAMP.

Location	Instrument	Comments
Antarctic peninsula – Argentina Marambio Base (64.2S, 56.3 W)	Water Cherenkov detector (electromagnetic and muon branches of secondary cosmic rays)	Operative since March 2019, 5 min real time telemetry [e.g., observations of Forbush decreases and GLEs] – Product on-line in real time
SAOCOM [from cooperation agreement with CONAE] – Regional and Global	SAR L-band polarimetric	TEC studies from polarization SAR images from satellites
Antarctica – Argentina San Martin base (68°08′S 67°06′W)	Riometer La Jolla Science (at 30 MHz)	Ionospheric conditions at high latitudes
Antarctica – Argentina San Martin base (68°08′S 67°06′W)	IPS-42 Ionosonde Mca. KEL Aerospace	Ionospheric conditions at high latitudes
Antarctica – Argentina San Martin base (68°08′S 67°06′W)	Magnetometer EDA Fluxgate	South America regional indices
Antarctica – Argentina Belgrano II base (77°51′S 34°33′W)	IPS-42 Ionosonde Mca. KEL Aerospace	Ionospheric conditions at high latitudes
Antarctica – Argentina Belgrano II base (77°51′S 34°33′W)	Magnetometer EDA Fluxgate	South America regional indices
Antarctica – Argentina Belgrano II base (77°51′S 34°33′W)	Proton Precession Magnetometer	South America regional indices
Antarctica – Argentina Belgrano II base (77°51′S 34°33′W)	Riometer La Jolla Science (at 30 MHz)	South America regional indices
Antarctic peninsula – Argentina Marambio Base (64.2S, 56.3 W)	e-CALLISTO (2 instruments ongoing)	Monitoring solar radio bursts
Antarctic peninsula – Argentina Marambio Base (64.2S, 56.3 W)	All-sky imager (ongoing, Boston University/ LAMP)	ionospheric activity at high latitudes
El Leoncito Observatory – San Juan, Argentina (31.8S,69.3 W)	Solar Telescope (H)	Observing solar prominences and filaments
El Leoncito Observatory – San Juan, Argentina (31.8S,69.3 W)	All-sky imager (Boston University)	Monitoring Spread F
Throughout Argentina	RAMSAC, Argentina GNSS network (IGN)	Maps of TEC content in the ionosphere above Argentina – Product on-line in real time
El Leoncito Observatory – San Juan, Argentina (31.8S,69.3 W)	Water Cherenkov detector (electromagnetic and muon branches of secondary cosmic rays) – Ongoing.	Monitoring radiation at high altitude

Table 2
Instruments of UNLP.

Instrument	Comments
Trelew Observatory_magnetometers (3 elements)	Magnetometer system
Trelew Observatory_Riometer (3 elements)	Ionospheric opacity
Trelew Observatory & MAGGIA Lab_GNSS (1 element)	GNSS receivers
Trelew Observatory & Sao Paulo University_VLF (2 elements)	Discharge of atmospheric electricity
South America GNSS network (about 250 elements)	GNSS receivers
MAGGIA Laboratory (11 elements)	GNSS receivers
SAOCOM LA & LB	Faraday Rotation
Inhouse integration GNSS receiver (by Luciano Mendoza, MAGGIA Lab) (7 elements)	Low-cost receivers, double-frequency and multi-constellation observations
SMN-magnetometers (3 elements)	Magnetometer system

Table 3
Instruments of UNT/TSWC.

Location	Instrument	Comments
Tucumán (26.9°S, 65.4°W)	Ionosonde – AIS-INGV (collaboration UNT- INGV-UTN)	Low latitude station. In operation since 2007. Real-time.
Bahia Blanca (38.7°S, 62.3°W)	Ionosonde – AIS-INGV (collaboration UNT- INGV-UTN)	Mid-latitude station. Real time.
Tucumán (26.9°S, 65.4°W)	GNSS multi-frequency & multi-constellation reciever. Collaboration UNT- INGV	TEC, Scintillation. Real-time
Ushuaia (54.8°S, 68.3°W)	GNSS multi-frequency & multi-constellation reciever. Collaboration UNT- INGV – SMN (National Meteorological Service)	TEC, Scintillation. Real-time
Tucumán (26.9°S, 65.4°W)	Continuous sounding Doppler HF radar. Collaboration UNT – Institute of Atmospheric Physics (Czech Republic)	Updated in 2022. 3D observations of AGWs/TIDs Real-time
Tucumán (26.9°S, 65.4°W)	Magnetometer fluxgate – EMBRACE Magnet Collaboration UNT – INPE	Real time. South America geomagnetic index.
Tucumán (26.9°S, 65.4°W)	Riometer	Atmospheric absorption
Tucumán (26.9°S, 65.4°W)	Water Cherenkov detector (electromagnetic and muon branches of secondary cosmic rays)	Planned for 2027

instrumentation for solar observations, SMN with many atmospheric observatories and other instruments covering the country (providing real-time data), among many more.

2.1.4. CRAAM/Brazil

The instruments operated at Center of Radio Astronomy and Astrophysics Mackenzie (CRAAM)/Engineering School (EE)/Presbyterian Mackenzie University (PMU) identify the study of different aspects of space weather: the origin of Solar Flares and their impacts on the Earth's atmosphere. CRAAM is operating the Solar Submillimeter Telescope (SST, 212, 405 GHz) along with POEMAS (45, 90 GHz) complemented by Hα and Mid-Infrared (15 THz, 30 THz) telescopes. The imprints of space weather dynamics on the Earth's atmosphere are monitored by two extended networks: The South America VLF Network (SAVNET) and the Atmospheric electric Field in South America (AFINSA).

2.1.5. EMBRACE/Brazil

The Brazilian program EMBRACE to monitor and forecast space weather events has been a Regional Warning Center since 2009 in ISES. It is operated by the National Institute for Space Research (INPE) of the Ministry of

Science, Technology and Innovation in Brazil. The program operates a network of ground based INPE's instruments distributed over the country and in some neighbor countries in partnership with other federal Brazilian institutions, described in Table 4. The data is publicly available at https://embracedata.inpe.br.

The locations of the instruments are shown in Fig. 1.

An extensive discussion of the instruments operated by EMBRACE and partners in Latin America is published in Denardini et al., 2016b.

2.1.6. NRCanada/CANADA

Canada's high latitude location has meant that it is both more affected by space weather effects and better placed to observe space weather phenomena. Both factors have led to extensive networks of ground-based sensors extending from the polar cap through the aurora oval to the sub-auroral zone. Natural Resources Canada (NRCan) operates the Canadian Geomagnetic Observatory Network and the Canadian Active Control System (CACS) network of GNSS receivers. Many university groups also operate significant networks for monitoring magnetic disturbances, auroral precipitation, and ionospheric disturbances. Canada also operates the 5 Canadian radars of the Super-DARN network and the RISR-C incoherent scatter radar at Resolute, Nunavut. Several Canadian power utilities are also recording geomagnetically induced currents (GIC) and AC harmonic distortion at sites on their networks.

The Dominion Radio Astrophysical Observatory (DRAO) of the National Research Council (NRC) operates the Solar Weather Monitoring program that produces one of the most widely used indicators of solar activity known internationally as the 10.7 cm solar radio flux, or F10.7. A next-generation solar flux monitor (NGSFM) that makes solar flux measurements at five additional wavelengths has just been completed. Canada has also contributed to space-based measurements of space weather both through its own satellites and through providing instruments for international satellite missions. Currently operational missions include the CASSIOPE/e-POP satellite and the Canadian Electric Field Instruments (CEFI) on the Swarm satellites. The instruments are described in Table 5.

2.1.7. The Space and Plasma Physics Laboratory (SAPL) of the University of Chile/CHILE

The laboratory plans to make available the Total Electron Content (TEC) code and the TEC maps reconstructed from the data obtained from the Chilean dual frequency receiver network.

2.1.8. LANCE/Mexico

The instruments are shown in Table 6.

2.1.9. IGP/Peru

The following instruments described in Table 7 contribute to the space weather products.

2.1.10. NOAA/United States of America

NOAA relies on an extensive set of continuous space-based and ground-based measurements from around the globe to provide space weather alerts, watches, warnings and situational awareness. These observations span the Sun-Earth domain, from the surface of the Sun to Earth's upper atmosphere, and they are the basis for operational space weather products and services that address the needs of government and private industry, including electric power, aviation, satellites, navigation, communication, satellite orbit determination and space traffic coordination. The space-based and ground-based measurements are used not only for operational space weather services but also for basic research and for the development and validation of numerical prediction models that will improve services. NOAA obtains its observations through a combination of NOAA programs and partnerships with other U.S. federal agencies, international partners, and private industry.

NOAA's anticipated baseline of space-based observations (Program of Record 2025) includes: spacecraft at the L1 Lagrange point in the solar wind (Deep Space Climate Observatory (DSCOVR) and the Space Weather Follow-on L1 (SWFO-L1) with an anticipated launch in 2025), spacecraft in geostationary orbit (Geostationary Environmental Operational Satellites (GOES)), and the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC-2) in low-Earth orbit. In particular, the upcoming SWFO-L1 mission will include a new compact coronagraph to provide essential measurements of coronal mass ejections. NOAA is especially inter-

Table 4
Important instruments of EMBRACE.

Instrument	Comments
CALLISTO	e-CALLISTO spectrometer
SPECM	Solar spectrometer 1–18 GHz
All-Sky Network (eight instruments)	Antenna Adapted from Cuiabá
GMND (one element)	Muon Telescope Scintillator
–Digisonde Network (eight elements)	Ionospheric Sounders
EMBRACE Magnet (network of 19 elements)	Magnetometer System
EMBRACE – GMS (six elements on going)	GIC Monitor System
GNSS Network (more than 180 elements, 14 with scintillation S4)	GPS Receivers
VHF (one element)	VHF Radars

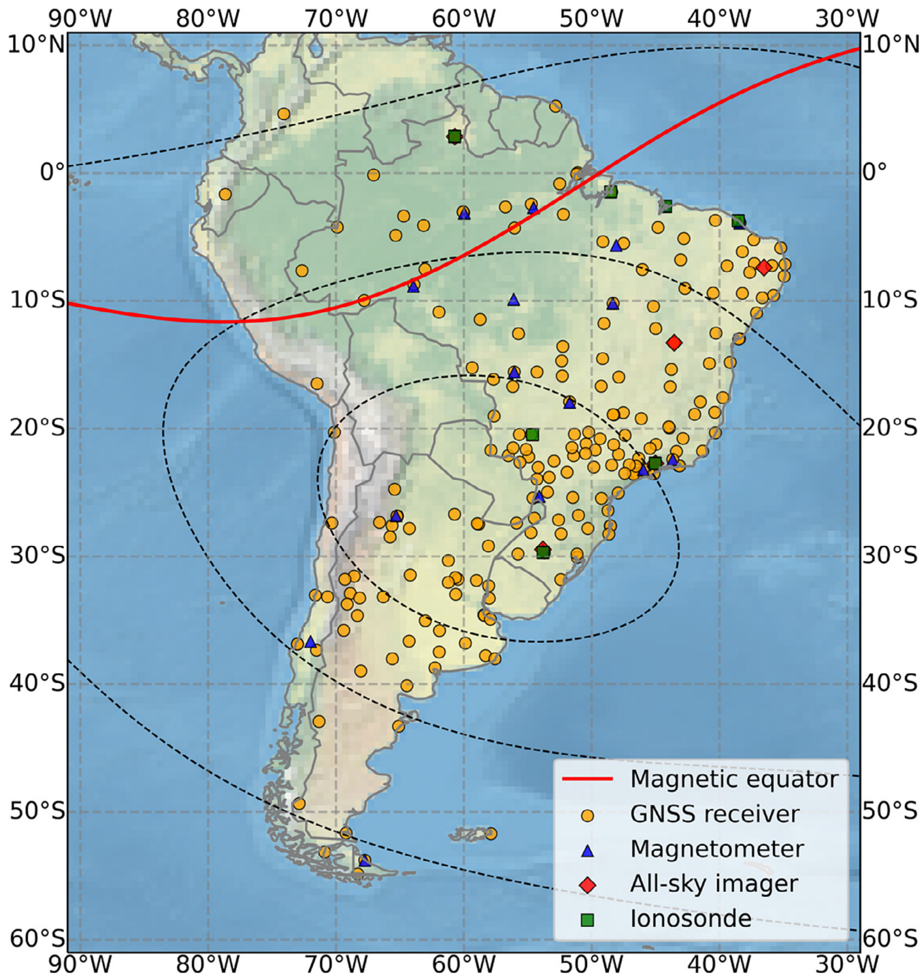

Fig. 1. EMBRACE networks of instruments operating in near real time for different applications. The GNSS network includes Argentinean and IGS receivers. In red is the magnetic equator and the contours shows the South Atlantic Magnetic Anomaly.

Table 5
Instrument of NRCanada.

Facilities/Instruments	Operator	Data Access
Canadian Magnetic Observatories	NRCan/CHIS	https://geomag.nrcan.gc.ca/index-en.php
CACS GNSS receivers	NRCan/CGS	https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/data-donnees/cacs-scca.php?locale=en
CARISMA magnetometers	U. Alberta	https://www.carisma.ca/
THEMIS-C magnetometers	U. Calgary	https://aurora.phys.ucalgary.ca/themis/data.html
AUTUMNX magnetometers	Athabasca U.	https://autumn.athabascau.ca/
GO-RIO riometers	U. Calgary	https://www.ucalgary.ca/aurora/projects/rio
Auroral imagers	U. Calgary	https://www.ucalgary.ca/aurora
CHAIN Ionosondes	U New Brunswick	https://chain.physics.unb.ca/chain/pages/stations/
CHAIN scintillation receivers	U New Brunswick	https://chain.physics.unb.ca/chain/
SuperDARN radars	U. Saskatchewan	https://superdarn.ca/
ICEBEAR radar	U. Saskatchewan	https://icebear.usask.ca/
RISR-C incoherent scatter radar	U. Calgary	https://amisr.com/amisr/about/resolute-bay-isrs/
Solar radio flux measurements	NRC/DRAO	https://nrc.canada.ca/en/research-development/products-services/technical-advisory-services/solar-weather-monitoring
CASSIOPE/ePOP	U. Calgary	https://epop.phys.ucalgary.ca/
Swarm/CEFI	U. Calgary	https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Swarm

Table 6
Important instruments of LANCE.

Facilities/Instruments	Description
MEXART radiotelescope	Interplanetary Scintillation (IPS) observations of solar wind
CALLISTO (5 instruments)	e-CALLISTO spectrometer
All-Sky Network (2 instruments)	
Neutron Monitor (2 instruments)	Mexico City and Sierra Negra Cosmic Rays detectors
GNSS-SSN Network (more than 80 elements)	GNSS receivers
Schumann station (1 instrument)	Schumann resonances measurements
LANCE Ionosondes (5 instruments on going)	Ionosonde network 1–30 MHz
LANCE Magnetometers (5 instruments on going)	Magnetometer System
LANCE–GICS (5 instruments on going)	GIC Monitor System

Table 7
Space weather measurement infrastructure.

Facilities/Instruments (numbers of instruments)	Description
Jicamarca VHF radar	high-power large-aperture (HPLA) VHF radar
JULIA MP	medium-power VHF radar
SIMONe-Peru	Multistatic specular meteor VHF radar
AMISR-14 (14-panel Advanced Modular Incoherent Scatter Radar)	medium – power UHF radar
TIDDBIT radar	Ionospheric Sounders
HF radar	Ionospheric Sounders
VIPIR (4)	Ionospheric Sounders
Magnetometer (15)	Fluxgate magnetometers
GNSS(10)	GNSS receivers
Fabry Perot Interferometer (3)	Interferometer for mesospheric winds studies
All Sky Imager (3)	Camera for mesospheric winds studies
EDAS prototype (1)	SDR receiver for spread F studies
ScintPi 3.0 (1)	GNSS receiver for spread F studies

ested in the planned missions of international partner agencies, such as ESA's Vigil mission to include a spacecraft at the L5 Lagrange point. Key ground-based instruments include the Global Oscillation Network Group (GONG), globally distributed ground magnetometers, and GNSS receivers to measure total electron content and scintillation. Long-term continuity and expansion of these measurements are essential, and new capabilities such as an operationally supported global network of ground-based neutron monitors are needed.

NOAA is working to secure the observations needed to address space weather user needs by establishing a dedicated operational observing system. Within NOAA's National Environmental Satellite, Data, and Information Service (NESDIS), space weather has been elevated to a third pillar in NOAA's observing infrastructure, together with geostationary and low-Earth orbit systems. The observations obtained by NOAA's operational system will be shared with and combined with the measurements made by national and international partners and private industry.

2.1.11. NSF/United States of America

The National Science Foundation (NSF, https://www.nsf.gov) is an independent US federal agency created by Congress in 1950 to promote the progress of science. NSF sponsored institutions include National Center for Atmospheric Research (NCAR) and National Solar Observatory (NSO).

The NSF instrument descriptions are shown in Table 8.

A pioneering CubeSat-based research program launched in 2008 within NSF's Division of Atmospheric and Geospace Sciences was responsible for the first systematic support of CubeSat-based science investigations and led to a growing engagement with universities (National Academies of Sciences, 2016; Robinson and Moretto, 2008; Sharma, 2022).

Achievements and lessons learned from successful small satellite missions for space weather oriented research are discussed in the recent review paper by Spence et al., (2022).

2.1.12. SANSA/South Africa

A list of instruments is presented in Table 9.

2.1.13. Centre for atmospheric research, national space research and development agency/Nigeria

The instruments described in Table 10. contribute to the space weather products.

Table 8
Significant observational instruments include.

Instruments	Description
Magnetometers	
Thermosphere / ionosphere radars	PFISR, RISR-N, Millstone Hill, Jicamarca, SuperDARN
Solar observations	Big Bear Solar Observatory
	Extended Owen's Valley Solar Array
	Mauna Loa Solar Observatory
	Neutron monitors
	Daniel K. Inouye Solar Telescope (DKIST)
	National Solar Observatory Global Oscillation Network Group (GONG)
Distributed Small Instruments	Magnetometers, Airglow Imagers, Fabry-Perot Interferometers, Lidars, GNSS Receivers, meteor radars,etc.

Table 9
Space weather measurement infrastructure.

Data instrument network to monitor Space Weather Domain	Instrument
HF Communications – Ionospheric	Ionosonde (Digisonde DPS-4D) – contributes to DIDBASE
	SuperDARN Radar
	Riometer
	HF Doppler Radar
	HF Beacon transmitter (WSPR)
	VLF Receiver
GNSS (Global Navigation Satellite System) Application	GNSS receivers
	Ionospheric Scintillation Monitors
Radiation Dose	Neutron monitors – NMDB
Geomagnetic storms	Fluxgate Magnetometers – forms part of INTERMAGNET
Solar Events	e-Callisto

Table 10
Space weather measurement infrastructure.

Equipment	Quantity, Remarks
All-Sky Imager	1, Optical observations Nagoya University, Japan
Fabry Perot Interferometer	1, National Centre for Atmospheric Research, Boulder, USA
Digisonde	1, University of Ilorin
CAR GNSS Initiative	4, Centre for Atmospheric Research
GNSS Network	15 (Office of Surveyor General of the Federation operates 12)
HF Doppler Radar	1 (CAR and University of Lagos)
Magnetometers	8, MAGDAS, AMBER, low-cost (out of operation)

2.2. EUROPE

2.2.1. UNIGRAZ/Austria

The Kanzelhoehe Solar Observatory (KSO) is an astronomical observatory affiliated with the Institute of Geophysics, Astrophysics and Meteorology out of the University of Graz.

Table 11 contains important contributions for the ground and space-based space weather measurement infrastructure.

Additionally, there exists a sunspot drawing device that projects the image of the Sun with a diameter of 25 cm onto a drawing table attached to the main telescope. All instruments are mounted on the patrol instrument. For papers on the KSO instrument and data description see Pötzi et al. (2013, 2021) and Pettauer (1990).

Data products at KSO are:

H-alpha, White-light, Ca II K:

- raw FITS files with full header information
- grayscale jpeg images without heliographic grid (N and W direction annotated) and large scale inhomogeneities removed
- coloured jpeg with heliographic grid
- coloured jpeg with heliographic grid and large scale inhomogeneities removed
- one dark current image per day
- daily movie
- flat field images once per month
- daily graphical observation log

H-alpha:

- sensitive filament maps (Pötzi et al., 2015)
- flare data and movies
- H-alpha light curves overlaid with GOES full-Sun SXR flux
- prominence limb images (overexposed H-alpha images)

Table 11
Important instruments of Kanzelhöhe.

Instrument, Location	Description
H-alpha patrol, Kanzelhöhe Observatory	6562.8 Å, F/L = 82/2000 mm, filter width = 0.4Å 10 images/minute automatic flare and filament detection near real time chromospheric images
Photosphere patrol, Kanzelhöhe Observatory	5450 Å, F/L = 130/1950 mm, filter width = 100Å 3 images/minute
CaIIK patrol, Kanzelhöhe Observatory	3933.7 Å, F/L = 70/1500 mm, filter width = 3Å 10 images/minute
E-Callisto, Lustbühel Observatory	radio antenna, automized burst detection and near real time catalogue
drawing device, Kanzelhöhe Observatory	daily sunspot drawing for obtaining the sunspot relative number

Other data products and old data products:

- daily sunspot drawings and sunspot relative numbers (see Pötzi et al. 2016)
- NaD intensitygrams (5890 Å), dopplergrams and magnetograms between 2000 and 2002, details in Cacciana et al. (1999) and Ambrož & Pötzi (2018)

Data access:

- main archive at http://cesar.kso.ac.at
- mirror archive at: https://kanzelhohe.uni-graz.at
- ftp archive at: ftp.kso.ac.at
- ESA-SSA interface: https://swe.ssa.esa.int/web/guest/kso-S107a-federated

For papers on the KSO data products, archive and digitization, see Pötzi et al. (2007, 2010, 2021).

At the Observatory Lustbühel Graz (OLG), an e-Callisto radio antenna is maintained. ROBUST (real-time observations of radio bursts), an automated radio burst detection and alert platform, is now operational using international e-CALLISTO data. It provides detection times for type III solar radio bursts in both image and text file formats, which effectively creates a near-real-time catalog. Results can be downloaded under swe.uni-graz.at –> Services –> ROBUST.

2.2.2. FMI/Finland

Table 12 describes a list of instruments operated and/or manufactured by Finnish institutes.

2.2.3. France

The Table 13 describes a list of instruments operated and/or manufactured by French institutes.

2.2.4. DLR/Germany

The Table 14 describes a list of instruments of DLR.

2.2.5. UGOE/Germany

UGOE contributions to space weather observations from space are presented in Table 15.

2.2.6. ASI/Italy

2.2.6.1. Ground-based space weather measurements. The Italian scientific community has been operating an extended set of observational ground-based assets that on a regular basis monitor the state of the Sun, the Earth's magnetosphere and ionosphere, and the solar and galactic cosmic ray intensity, providing often near-real-time data relevant to the conditions of the Sun and the geospace. Because of their spatial distribution and qualitative measurements, the ground-based observations obtained by the Italian assets contribute to the international datasets currently available for scientific analysis of space weather phenomena. An indicative map of the main ground-based observing systems with Italian contribution (or leadership) showing the coverage provided by Italian space weather sensors has been provided in Fig. 4 in Plainaki et al., (2020) (see for details their Tables 2,3,4,5,7,8). Such assets include solar and radio telescopes, HF ionospheric radars, ionosonde and digisonde instruments, GNSS receivers, geomagnetic observatories and stations, and a neutron monitor. They are often part of the European and global sensor provision networks, resulting thus in a potential mutual benefit in a more global Space Weather context.

2.2.6.2. Space-based space weather measurements. Space-based observations are of fundamental importance for addressing high priority science issues to mitigate the related risks of space weather impacts on technology, infrastructure, and human activities.

The Italian Space Agency (ASI) has participated several times in space missions with science objectives related to Heliophysics and space weather, often with lead roles; indeed, an important field for the Italian scientific and industrial communities interested in heliophysics and space

Table 12
Important instruments.

Facilities/Instruments	Description
Ground magnetometers (the IMAGE network, Finnish Meteorological Institute (FMI) and Sodankylä Geophysical Observatory (SGO)), geomagnetic observatories (Sodankylä, Nurmijärvi)	The International Monitor for Auroral Geomagnetic Effects (IMAGE) https://space.fmi.fi/image/www/index.php?
Pulsation magnetometers (SGO)	https://www.sgo.fi/Data/Pulsation/pulsation.php
Auroral all-sky cameras (FMI and SGO)	Magnetometers – Ionospheric Radars – All-sky Cameras Large Experiment (MIRACLE) All-Sky Cameras – Imaging the Auroras https://space.fmi.fi/MIRACLE/ASC/
Network of ionospheric tomography receivers (FMI and SGO)	https://www.sgo.fi/Data/Tomography/tomography.php
FINNREF GNSS receivers used for ionospheric tomography	https://www.maanmittauslaitos.fi/en/research/research/other-research-and-measuring-stations/finnref-gnss-stations
Participation to the eSWua network of GNSS scintillation receivers (FMI)	Electronic Space Weather upper atmosphere (eSWua) https://www.eswua.ingv.it/
Participation in EISCAT ionospheric radar (SGO, University of Oulu (UO), FMI)	https://www.sgo.fi/Eiscat/
Participation to the AARDDVARK network of VLF-receivers (SGO)	the Antarctic-Arctic Radiation belt (Dynamic) Deposition – VLF Atmospheric Research Konsortia (AARDDVARK). https://www.sgo.fi/Data/aarddvark/
Sodankylä ionosonde (SGO)	https://www.sgo.fi/Data/Ionosonde/ionosonde.php
Spectral riometers (SGO and FMI)	https://www.sgo.fi/Data/Riometer/riometer.php
KAIRA (Kilpisjärvi Atmospheric Imaging Receiver Array) (SGO)	The Kilpisjärvi Atmospheric Imaging Receiver Array (KAIRA) https://kaira.sgo.fi/
ELF-VLF receiver campaigns (SGO)	https://www.sgo.fi/Data/VLF/VLF.php
Meteor radar (contribution to the UK-FI SLICE project, SGO)	The Sodankylä – Leicester Ionospheric Coupling Experiment (SLICE) Meteor Radar https://www.sgo.fi/Projects/SLICE/
Oulu neutron monitor (SGO)	https://cosmicrays.oulu.fi/
Suomi-100 nanosatellite (Aalto University(AU), FMI)	https://www.suomi100satelliitti.fi/index_eng.html
SunStorm nanosatellite (instrument by ISAWARE Ltd, funded by ESA)	https://www.esa.int/ESA_Multimedia/Images/2021/08/Sunstorm

Table 13
Important instruments.

Facilities/Instruments	Description
Observatoire de RadioAstronomie de Nançay	radioheliograph (NRH – 140–450 MHz) Radio telescopes operating between 10 MHz to 1 GHz VLF receiver (AWESOME instrument, Amplitude and Phase)
Observatoire de Paris, site de Meudon	Spectroheliograph
Observatoire du Pic du Midi	CLIMSO coronagraph
REGINA network	39 GNSS stations, real-time
SAGAIE network	5 GNSS stations, real-time (contribute also to ESA's Monitor project)
Observatoire de Chambon la Forêt, Port Alfred, Port-aux-Français	magnetometers
SuperDARN	radar
Kerguelen and Terre Adélie	Neutron monitors
Swarm	Absolute magnetometer
CHAMP (GRACE, GOCE, GRACE-FO)	accelerometers (manufacturer: ONERA)
SOHO	LASCO C2 coronograph
Jason-3	AMBRE, AMBER 2.0 (0 – 30 keV)
Jason-2/3	CARMEN-3/ICARE-NG

weather, is the development of scientific payloads. Indicatively, we refer to the ESA Solar Orbiter mission, where Italy participates with hardware contributions for the METIS coronagraph (Italian PI-ship) and the SWA experiment. Italy also provides an important software contribution for the StiX telescope on board Solar Orbiter dedicated to the development of reconstruction algorithms for solar X-images. The ASPIICS coronagraph on board the formation flying Proba-3 mission of ESA will test the capability to perform the first ever coronagraphic observations in artificial eclipse condition (one spacecraft will carry the occulter for the second hosting the coronagraph). Italy also provides important support for the EUVST telescope on board the future JAXA/Solar-C mission. Space weather is currently being studied also through particle and field measurements by the HEPD and EFD instruments, respectively, of the Italian Limadou collaboration in the context of the CNSA/CSES mission.

In the context of planetary space weather, Italy participates in the ESA/JAXA BepiColombo mission with the SERENA experiment (Italian PI-ship) dedicated to the study of the Sun-Mercury interactions. Planetary space

Table 14
DLR contributions to ground based space weather monitoring and analysis.

Name	Device(s)	Type of measurement	International use
GIFDS (Global Ionospheric Flare Detection System) Network	VLF-receiver	Hz VLF amplitude and phase measurements of multiple VLF signals	International Space Weather Initiative (ISWI)
SOFIE (SOlar Flares detected by Ionospheric Effects) Network	VLF-receiver	0.5 Hz VLF amplitude measurements of a single VLF signal	ISWI
RTSW (Real Time Solar Wind) Network Station	VT-063 6 m parabolic antenna	Use range from 2.2 – 2.3 GHz. ACE (2.27835 GHz),r DSCOVR (2.21500 GHz)	NOAA Operational Service (US Weather Service)
EVNET (Experimentation and Verification Network)	High rate (50 Hz) JAVAD GNSS receiver	Observation of GNSS-Signals from GPS, Galileo, GLONASS and BeiDou.	European Space Agency (ESA), International Civil Aviation Organization (ICAO)
e-Callisto (Compound Astronomical Low frequency Low cost Instrument for Spectroscopy and Transportable Observatory)	e-Callisto spectrometer (45–870 MHz)	GNSS spectrum 1–1.6 GHz (spectrum 10–75 MHz, time resolution of 0.25 s with 200 channels per spectrum)	ISWI
Beacon	Beacon receiver	Calculation of the differential phase of two simultaneously transmitted satellite signals (e.g. DMSP at 150 and 400 MHz)	
All Sky Imager	Optical Camera	Optical Camera	Collaboration with The University of Electro-Communications (Japan) and Bahir Dar University (Ethiopia).
He-Lidar	Light detection and ranging (Lidar)	Helium density measurement in 800 km height (feasibility study)	

Table 15
UGOE instruments.

Name	Device(s)	Type of measurement	International use
STEREO/SECCHI on board the NASA STEREO satellites	Coronagraphs, EUV Imager, Heliospheric Imager	EUV, White-Light	Space weather observations and forecasts of CMEs, active regions and flares, multipoint analysis of CMEs together with SOHO coronagraph observations
NASA Parker Solar Probe WISPR (Wide-field Imager for Solar PRobe)	Wide Angle camera aka Heliospheric Imager	White-Light	Analysis of the solar wind, coronal structures and CMEs close to the Sun
ESA Solar Orbiter SoloHI (Solar Heliospheric Imager)	Wide Angle camera aka Heliospheric Imager	White-Light	Analysis of the solar wind, coronal structures and CMEs close to the Sun to the inner heliosphere covering almost the full sky
SCOPE (Solar Coronagraph for OPErations)	Coronagraph	European Prototype Coronagraph Study	Onset and detection of CMEs
NASA PUNCH (Polarimeter to UNify the Corona and Heliosphere)	White-Light Imagers, spectrograph	White-Light, EUV	Imaging of solar wind and CMEs full sky
Vigil aka L5 or Lagrange mission of ESA	Remote sensing imager, wide angle camera	White-Light	Detection of CME onsets and imaging of evolution to Earth
Vigil aka L5 or Lagrange mission of ESA	STEREO/SECCHI coronagraphs and heliospheric imager	White-Light	CME modelling and propagation forecast to Earth for mission development including definition of remote sensing requirements

weather aspects are also studied through JIRAM, the image spectrometer in the near infrared (Italian leadership), on board the NASA/Juno mission to the Jovian system (Bolton et al. 2017). Jiram provides maps of the H_3^+ IR aurora emission at Jupiter.

In the past, fundamental contributions have been provided for the UVCS experiment on board NASA/ESA SOHO, for the CIS instrument on board the ESA/Cluster mission and for PAMELA (Italian leadership) on board the Resurs-DK1 by Roscosmos.

The main missions/experiments with science objectives related to circumterrestrial and planetary space weather, in which there is a significant Italian participation, have been recently discussed in Plainaki et al. (2020) (see, for instance, their Table 9).

2.2.7. INGV/Italy

INGV is equipped with multi-constellation GNSS receivers capable of tracking in realtime GPS, GLONASS, Galileo, Beidou and Geostationary signals. The receivers provide I and Q components of the tracked signals needed to evaluate amplitude and the phase signals at 50 Hz sampling frequency. The receivers are equipped with a firmware that provides in real-time TEC, Rate of TEC change (ROTI), scintillation indices, and also the parameters related to the system performance (Lock time, Signal to Noise ratio, etc.). The devices cover the European sector from the Arctic (Svalbard and Greenland) up to the Mediterranean area, the African sector (Kenya in the framework of NORISK project (https://norisk.rm.ingv.it/), and Nigeria), Latin America and Antarctica. The network is already part of big endeavours, as the PECASUS operations (pecasus.eu), and offer the users an extensive monitoring capability to improve specifications, nowcasting and forecasting modelling of ionospheric irregularities. Furthermore, the GNSS data can offer the users the opportunity to develop algorithms capable of assisting high accuracy positioning applications (i.e. precision agriculture, autonomous driving, Search and Rescue operations, maritime, etc.) also over sectors not covered by Augmentation Systems (e.g. Arctic). The access to near real-time as well as long historical data series offers the users the possibility to investigate the geospacer weather and climate over more than one solar cycle, also for studying global change related processes.

An All-Sky Imager (ASI) will be installed in Gibilmanna (Sicily) by 2025. The ASI is a Boston University-designed instrument described in Baumgardner et al. (2007). The system uses different narrow-band filters to capture, among the others, the oxygen "redline" of 630.0 nm generated by the recombination of ionospheric plasma at a height of approximately 300 km.

INVG runs in Rome one of the oldest ionospheric observatory all over the world, currently equipped with a DPS-4 Lowell Digisonde and with an AIS-INGV ionosonde.

Another AIS-INGV ionosonde is operating in Sicily at Gibilmanna. Other ionosondes managed by INGV are running in Argentina, in San Miguel de Tucuman, near the southern peak of the equatorial anomaly and in Bahia Blanca at mid latitude South. In 2023, a new ionosondes was installed in Malindi (Kenya) in the framework of the NORISK project (https://norisk.rm.ingv.it/). Another ionosonde will be installed in Lerici (northern Italy) by the end of 2025. They are ionospheric monitoring systems, developed by INGV, able to measure the main ionospheric parameters making them available in real-time (Zuccheretti et al., 2003). Critical frequencies and virtual heights of main ionospheric regions are measured, as well as the density profile. Normal monitoring soundings rate is 10 or 15 min; if necessary measurements can become more frequent up to a measure every minutes. INGV has been operating ground based ionospheric soundings in Rome and Sicily for several decades having one of the oldest and complete data set of ionospheric parameters.

INGV applies an open data policy: all the ionospheric meaurements are available on SWIT-eSWua system (https://www.eswua.ingv.it). It offers the users the possibility to freely access all the data acquired by the instruments managed by INGV. Fig. 2 shows the ionospheric monitor-

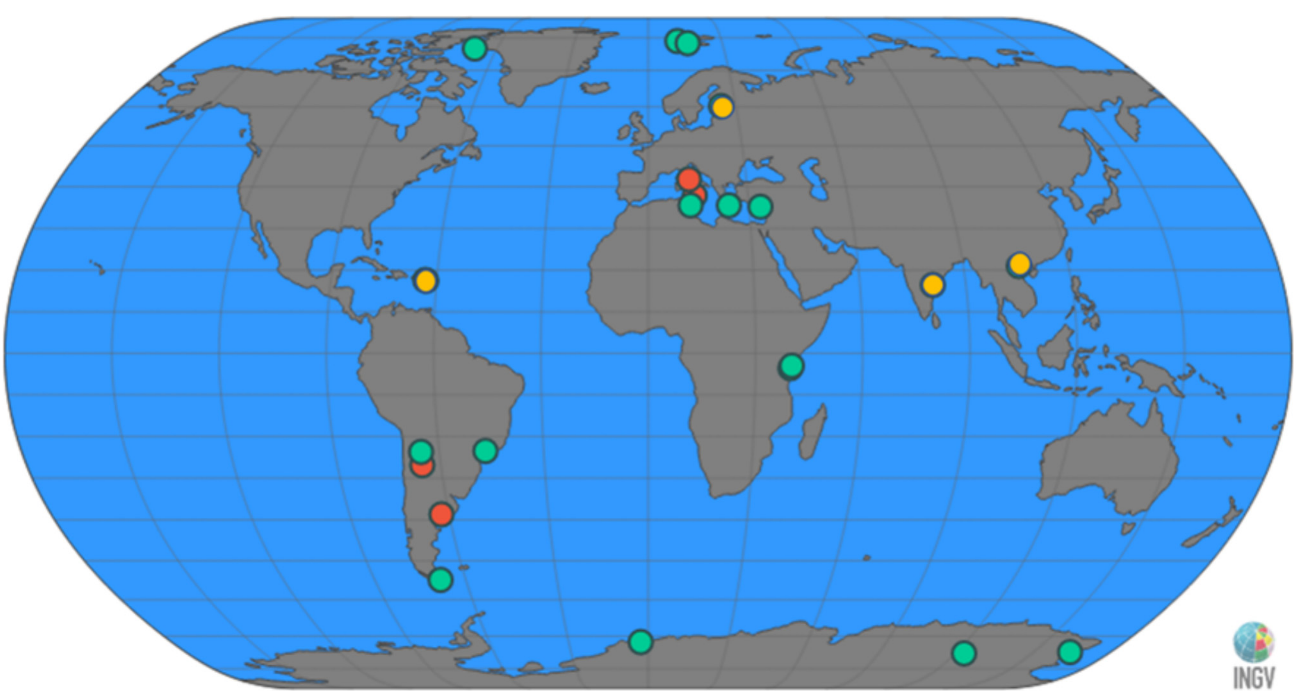

Fig. 2. Ionospheric monitoring network available on eSWua: INGV ionosondes (red dots), INGV GNSS receivers (green dots), GNSS receivers from other institutions (yellow dots).

ing network available on eSWua. The eSWua website provides a GUI for the visualization of near-real time data as well as historical time series for the GNSS TEC and scintillation receivers and ionosondes data. A dedicated RESTful web-service provides direct access to Level 1 and Level 2 data in JSON interchange format. Web-based tools provide access to raw data and ease the discovery and retrieving of ionospheric parameters and dataset. The website also hosts data from other institutions.

Thanks to its multi-instrumental capabilities INGV has a large expertise in disseminating space weather information. In this framework the Space Weather Communication Working Group of INGV issues weekly the space weather bulletin on the Mediterranean area (https://roma2.ingv.it/index.php/monitoraggio-e-sorveglianza/prodotti-del-monitoraggio/bollettini-di-space-weather).

Post-processing analysis of INGV data are significantly contributing to the understanding of space weather events, such as the Mother's Day storm, occurred in May 2024 (Spogli et al., 2024).

2.2.8. ROSHYDROMET + RAS/Russia

Russian Space Systems (ROSCOSMOS) operates several space vehicles for ROSHYDROMET that are equipped with space weather suites.

Elektro-L (Russian Электро-Л) is series of geostationary space vehicles with Elektro-L N2/3/4 in operation and Elektro-L N5 planned in 2025. These satellites are equipped with space environment suites (particle counters, X-ray radiation flux meters).

The Elektro-M (Russian Электро-М) will start replacing Elektro-L in 2030. This platform will feature different equipment.

Arctic-M (Russian Арктика-М) is a planned group of four satellites for studying polar weather and ocean conditions. Two first built using Electro-L series equipment, the other two are expected to use Electro-M series equipment. They will operate in a Molniya orbit, enabling continuous monitoring of Russia's northern and Arctic regions. Two satellites were launched from Baikonur Cosmodrome in 2021 and 2023, with four more planned by 2026.

Meteor-M (Russian Метеор-М) are sun-synchronous meteorological space vehicles. 4 are currently in operation and 5 more are planned before 2030. This type also carries space environment suites.

Ionozond (Russian Ионозонд) is a space-weather satellite project consisting of four Ionosfera (Russian Ионосфера) and Zond-M (Russian Зонд-М) sun-synchronous satellites. These feature full range of space weather equipment: solar telescopes, coronograph, radiation meters, 150/400Mhz transmitters, ionospheric sounders, cosmic ray spectrometers. 2 Ionosfera SVs are in operation and 2 more planned by 2027, Zond-M is expected to launch in 2025.

Roshydromet also operates several riometer stations: Amderma, Bugulma, Dikson, Izvestiya, Tiksi, a GNSS ground station network with more than 200 stations.

Roshydromet and Russian Academy of Sciences (RAS) also operate 30 geomagnetic observatories throughout the Eurasia. Also, RAS runs the RATAN-600 radiotelescope Solar group.

RAS operates 12 neutron monitors across the Russian Federation that spans more than half the celestial sphere by longitude.

2.2.9. UAH/Spain

The Space Weather Research Group is maintaining the instrumentation for space weather purposes at the campus of the University of Alcala (LAT 40° 30′32″ N, LON 3° 20′ 30″ W) appearing in Table 16.

2.2.10. IRF/Sweden

Table 17 describes the space weather instruments of the Swedish Institute of Space Physics (IRF).

2.2.11. MET OFFICE/UK

Table 18 describes UK instruments and infrastructure.

New instrumentation to be introduced during and after the Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) programme (2020–2024) includes:

- in-situ radiation measurements at LEO (550 km)(2023) and upper LEO (1200 km) altitudes (2025)
- Aviation-borne radiation sensors (civil and military flights – 20 sensors – from 2024)
- Radiosonde-based radiation sensors (launching from Camborne, 15 sensors) (under test)
- Ground neutron radiation monitoring instrument at 2 UK sites (Camborne (implemented 2024), Lerwick (implemented 2025))

2.3. ASIA & Oceania

2.3.1. Bureau of Meteorology/Australia

Many of the products and services produced by the Australian Space Weather Forecasting Center (ASWFC) of the Australian Bureau of Meteorology are driven by data provided by a network of space weather observing equipment that extends from Antarctica to subequatorial latitudes as illustrated in Fig. 3.

The Bureau's Space Weather network (SWN) includes two solar optical and radio observatories, vertical incidence ionosondes, magnetometers, GNSS Total Electron Content (TEC) and scintillation monitors, riometers, and neutron monitors. All observed data is freely available via the Space Weather Services World Data Centre.

Table 16
Space weather instruments of UAH-SWE.

Facilities/Instruments	Description
UAH-MA	Flux gate magnetometer providing the local disturbance index (LDi) and the local current index (LCi) at UAH through ESA Space Weather Portal https://swe.ssa.esa.int/
ART (Alcala RadioTelescope)	Radio telescopes operating at 1.42 GHz with polarimetry in real time
UAH-GNSS	GNSS station, real time monitoring
UAH-VLF	VLF receiver (Amplitude)
Hα telescope	Solar telescope to observe filaments and prominences. In the near future an automatized filament detection and tracking system will be provided.

Table 17
Space weather instruments of IRF.

Instrument (Provider)	Link
Magnetometer(IRF)	https://www2.irf.se/Observatory/?link=Magnetometers
Pulsation Magnetometer (IRF)	https://www2.irf.se/maggraphs/puls.php
Riometer (IRF)	https://www2.irf.se/Observatory/?link=Riometers
Ionosonde (Irf)	https://www2.irf.se/Observatory/?link=Ionosondes
ALIS 4D (IRF)	https://alis.irf.se/
All-sky camera (IRF)	(under development) https://alis4d.irf.se/ https://www2.irf.se/Observatory/?link=All-sky_sp_camera

Table 18
UK Space weather measurement infrastructure.

Facilities/Instruments	Description
Magnetometers	operational at 3 locations (Hartland, Eskdalemuir, Lerwick) plus 3 new sites introduced during SWIMMR programme (Co Fermanagh, Market Harborough, Herstmonceux), BAS (Halley)
Magnetotelluric observations:	extensive array of observation sites (initially northern UK, now extending to southern UK) for research / survey purposes (no near real time data)
Riometers	BAS (Halley) Lancaster (Arctic)
Ionosondes	2 locations (Chilton, Stanley)
LOFAR	1 station (Chilbolton) is part of a wider European radio telescope for solar / heliospheric / ionospheric observations
Heliospheric Imagers	Lead design build for Stereo, PUNCH, planned for Vigil
Coronagraph cameras Space	PUNCH (contribution)
X-ray imager	SMILE
Magnetometers	Solar Orbiter, IMAP, planned for Vigil
Plasma analyser	Solar Orbiter, planned for Vigil
Thermosphere / ionosphere radar	Contributions to SuperDARN, EISCAT, EISCAT-3D
Solar radio observations	eCallisto (Glasgow)
Ion and Neutral Mass Spectrometer	Plans for deployment being discussed

2.3.2. China/NSSC

China's space-based and ground-based space environment monitoring networks and platforms that provide important contributions are listed in Table 19.

2.3.3. India

Table 20 presents the important contributions for the ground and space-based space weather measurement infrastructure of India.

2.3.4. New Zealand

Table 21 presents the important contributions for the ground-based space weather measurement infrastructure of New Zealand.

1. AARDDVARK network is a global network of subionospheric VLF operated by the University of Otago and British Antarctic Survey. Details can be found at the network website: https://space.physics.otago.ac.nz/aarddvark/ and Clilverd et al. (2019). Space weather examples of the use of this data is monitoring electron precipitation from the radiation belts (e.g., Neal et al. 2015) and solar flare monitoring (George et al. 2019; Belcher et al., 2021).
2. There is only one magnetic observatory in New Zealand, operated by GNS Science at Eyrewell (near Christchurch). They also operate another observatory near Scott Base, Antarctica. Observations are available through the INTERMAGNET network of observatories (https://intermagnet.github.io/). A new network

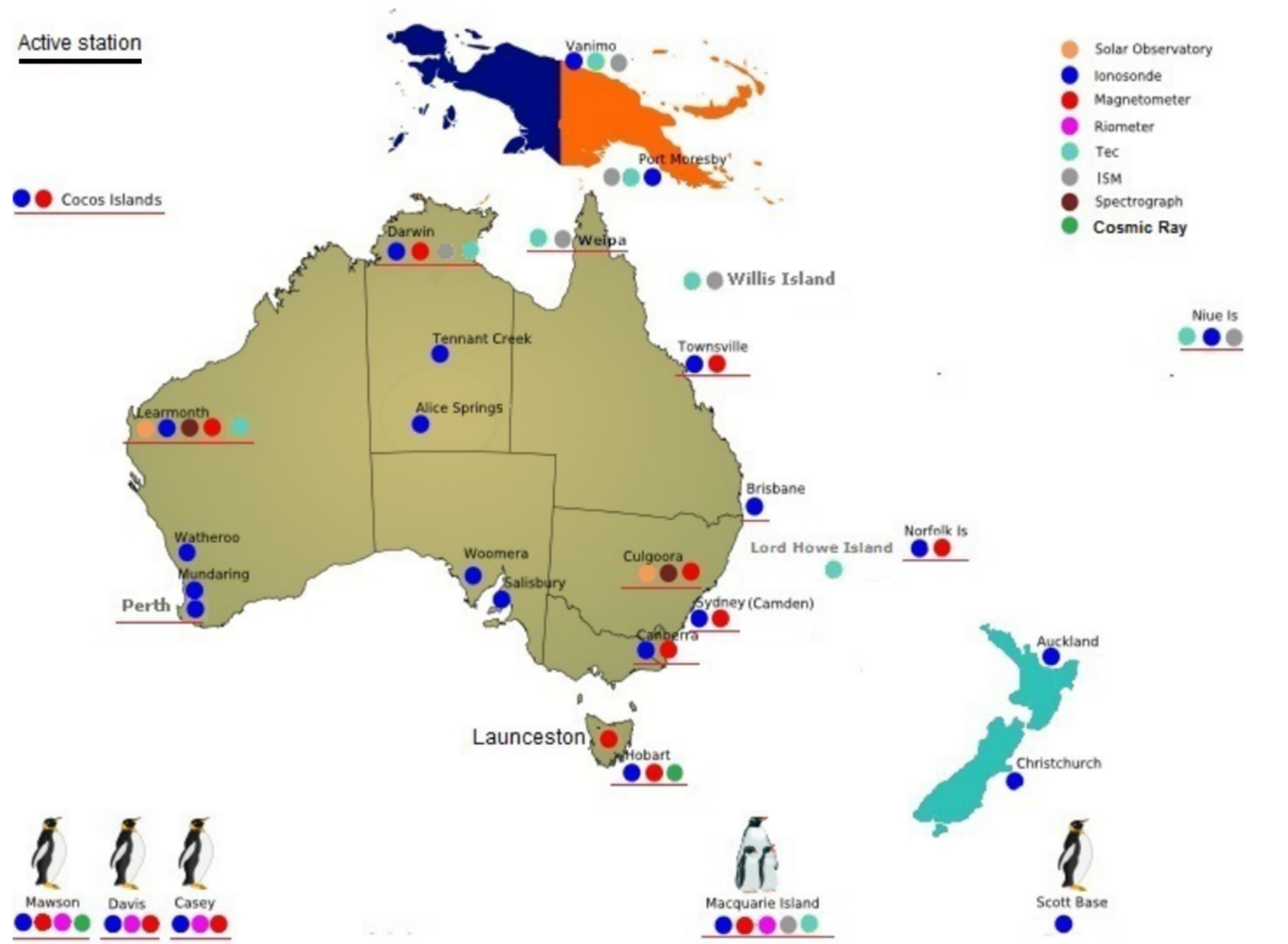

Fig. 3. The Australian Bureau's Space Weather Network showing active and closed stations contributing to the World Data Centre and ASWFC services. Active stations are underlined. Instrument status changes regularly with ongoing remediation and upgrades and some instruments at active stations may be presently offline (https://www.sws.bom.gov.au/World_Data_Centre/2/1/1, accessed 17th December 2024).

of magnetic field variometers has been deployed across the country, as part of the Solar Tsunamis research programme described later in this manuscript. This data is described at: https://solartsunamis.otago.ac.nz/mana/

3. New Zealand runs one station of the Automatic Whistler Detector and Analyzer (AWDA) network, located in Dunedin. AWDA is a ground-based plasmaspheric monitoring network organised by Eötvös Loránd University (ELTE), Hungary (Lichtenberger et al., 2010).
4. The GeoNet earthquake monitoring system includes > 250 GNSS stations which can provide a dense grid of Total Electron Content measurements of the ionosphere above New Zealand (https://www.geonet.org.nz/about, see for example Zhang et al. 2022).
5. Transpower New Zealand Ltd., the system operator of New Zealand's electrical power transmission network, monitors quasi-DC geomagnetically induced currents at ~ 60 different transformers in > 20 substations (Mac Manus et al., 2017; Rodger et al., 2020). Even order harmonic distortion measurements, which can be used to investigate space weather stressing of transformers, are also made by Transpower throughout the New Zealand power network (>130 substations) (Rodger et al., 2020).

2.3.5. NICT/Japan

National Institute of Information and Communications Technology (NICT) is the only organization to provide operational space weather information services in Japan. NICT is a member of International Space Environment Service (ISES) and a part of ICAO space weather global centers operating 24/7 for monitoring and forecasting space weather.

It is important to monitor and forecast the ionosphere for the use of HF telecommunications and GNSS. On the other hand, it is also difficult to forecast the ionosphere. NICT has a strategy to improve the forecasting skill.

As operational observations of ionosphere, NICT has four domestic ionosonde sites in Japan and one in Syowa, Antarctica whose data provides in real time on the public

Table 19
China's space environment monitoring networks and platforms.

Category	Networks and platforms	Important contributions
Space-based platforms	The Solar wind Magnetosphere Ionosphere Link Explorer (SMILE)	It will expand the knowledge of the interaction between the solar wind and the Earth's magnetosphere (Wang and Branduardi-Raymond, 2018; Branduardi-Raymont et al., 2018). The launch time is scheduled to be in late 2025.
	The Advanced Space-based Solar Observatory (ASO-S)	It pursues the simultaneous observations of magnetic fields, solar flares, and CMEs on a single satellite aiming to help scientists uncover the physical mechanism of solar eruptions (Gan et al., 2019,2022). ASO-S was successfully launched in October 2022.
	The Chinese Hα Solar Explorer (CHASE)	It scans the whole solar disk in the Hα waveband, and hence provide an opportunity to reveal the precursor of solar activities (Chen 2018; Li et al., 2019).
	The second generation Chinese FengYun series meteorological satellites	It improves China's high-frequency monitoring of the atmosphere and observation ability of a number of smaller-scale and shorter-duration weather phenomena (Xian et al., 2021)
Ground-based networks	The Chinese Meridian Project (CMP)	It is one of major scientific infrastructures of China. Phase I was started in 2008, and was completed in Oct. 2012. Phase I includes 15 observatories, 87 instruments along 120 degrees east longitude and 30 degrees north latitude (Wang et al., 2010). Phase II of the Chinese Meridian Project was started in 2019 and was successfully completed in 2024. Approximately 300 instruments have been deployed at 31 stations across the country and polar regions (Wang et al., 2024a).
	The New Vacuum Solar Telescope (NVST)	It is a one-meter vacuum solar telescope designed for high-resolution imaging and spectral observations (Liu et al., 2014).

Table 20
Table of ground-based instruments and planned space program of India.

Instrument	Institute, Location	Capabilities
Global Oscillation Network Group	USO/Physical Research Laboratory, Udaipur	Full Disk Magnetogram, Hα Imaging, Dopplergrams
Multi Application Solar Telescope	USO/Physical Research Laboratory, Udaipur	Hα Imager, G-band imager, Dopplergram, Spectropolarimetry
Hα Telescope	Aryabhatta Research Institute of Observational Sciences, Nainital	Prominence, Filament and Flare associated high cadence Hα observations
Ca-K, Hα, White Light Telesopes	Indian Institute of Astrophysics, Kodaikanal Solar Observatory	Long-term solar activity monitoring, Plages, Prominences, Filaments and Sunspot Observations
Radioheliograph	Indian Institute of Astrophysics, Gauribidanur	Dynamic spectrum of radio signatures from solar transients
Giant Metre Wave Radio Telescope	National Centre for Radio Astrophysics, Pune	Spectroscopy in 15–600 MHz for solar studies at high time resolution
Aditya-L1 Space Mission (In development)	Indian Space Research Organization (ISRO) and participating PI and Co-I Institutions	Near-UV imaging and spectroscopy, Coronal spectroscopy and magnetometry, Soft and hard X-ray spectrometers, In-situ plasma analyzer and magnetometer

Table 21
Important Instruments in New Zealand.

Instrument	Institute, Location	Capabilities
subionospheric VLF in the AARDDVARK network	global, but receivers concentrated in the Antarctic and Arctic	ground based D-region monitoring by subionospheric VLF as PI of the AARDDVARK network. See point 1 below.
ground-based magnetometers	Observatories at Eyrewell, and near Scott Base, Antarctica. Also a variometer network across the country, including the Chatham Islands.	geomagnetic field monitoring. See point 2 below.
Automatic Whistler Detector and Analyzer	Dunedin	ground-based plasmaspheric monitoring. See point 3 below.
GNSS (global navigation satellite system) stations	across the country	Total Electron Content measurements. See point 4 below.
Power grid measurremenets of space weather impacts	Many substations in the North and South Islands	quasi-DC geomagnetically induced currents at $\sim$ 60 different transformers in $>$ 20 substations and Even order harmonic distortion measurements (>130 substations). See point 5 below

website (https://wdc.nict.go.jp/Ionosphere/en/index.html,). In addition, we have an ionospheric observation network named "SEALION" in Southeast Asian countries in cooperate with universities and research organizations in each country(https://aer-nc-web.nict.go.jp/sealion/). One of the main purposes of SEALION is to monitor the equatorial plasma bubbles (EPBs) which can cause serious trouble for use of GNSS. A prototype is now prepared of EPBs warning system for GNSS users with ionosonde and VHF radar measurements. Table 22 shows the network of instruments.

2.3.6. KSWC/Korea

Korea Space Weather Center (KSWC) is the official source to deliver operational space weather information and forecast & warning in Korea. Korea joined the International Space Environment Service (ISES) as a regional warning center in 2013. Table 23 shows future plan of the ground and satellite-based space weather measurement infrastructure in Korea.

2.3.7. Thailand Space Related Agency (TSA)/Thailand

Currently, the main agencies and universities in Thailand which actively contribute to space weather including Geo-Informatics and Space Technology Development Agency (GISTDA), National Astronomical Research Institute of Thailand (NARIT), King Mongkut's Institute of Technology Ladkrabang, Mahidol University, Chiangmai University, Mahasarakham University and Rajamangala University of Technology Thanyaburi.

The research area of space weather is listed in the White Paper on Frontier Research in Earth-Space System as well as the Thailand Space Master Plan (2023–2037).

In addition, under the grants from ASEAN IVO projects funded by NICT (Japan) during 2019–2023, KMITL has also installed several GNSS receivers at the National University of Laos, Laos, and Cambodia Academy of Digital Technology (CADT), Cambodia.

Table 24 shows the future plan of the ground and satellite-based space weather measurement infrastructure in Thailand.

2.3.8. TUA/Turkey

Currently, the Space Weather Application Center has been established as a "Unit" within the Turkish Space Agency, and preparations for infrastructure and facility establishment are continuing.

Table 22
Important instruments of NICT.

Facilities/Instruments	Description
Wakkanai/Sarobetsu Observatory	Ionosonde (VIPIR2) 1–30 MHz
Kokubunji Observatory	Ionosonde (VIPIR2) 1–30 MHz
Yamagawa Observatory	Ionosonde (VIPIR2) 1–30 MHz Solar radio telescope 70–9000 MHz
Ogimi Observatory	Ionosonde (VIPIR2) 1–30 MHz
GEONET (GSI)	1080 GNSS stations (6 h after), 200 stations in real time
L1 receiver	For ACE/DSCOVR
Chiang Mai Observatory	Ionosonde (FMCW) 1–30 MHz
Chumphon Observatory, Thailand	Ionosonde (FMCW) 1–30 MHz VHF radar
Back Lieu Observatory, Vietnam	Ionosonde (FMCW) 1–30 MHz
Koto Tabang Observatory, Indonesia	Ionosonde (FMCW) 1–30 MHz
Cebu Observatory, Philippine	Ionosonde (FMCW) 1–30 MHz
HIMAWARI satellite (JMA)	Electron/proton flux
Kakioka observatory (JMA)	magnetometer

Table 23
Future infrastructure plan of space weather measurement in Korea.

Classification	Instruments	Scientific contribution	Tentative establishment year
Geomagnetic field	Magnetometer	3-Axis observation of 1-Min geomagnetic field	2026
Ionosphere	Ionosonde	Monitoring electron density at Pusan	2026
Solar Radio Noise (Replaced)	Solar Radio	Monitoring Solar radio noise at 0.3–18 GHz	2026
Solar Radio Flux (Replaced)	Solar Radio	Radio Flux measurement at 2.8 GHz	2026
Ground station	SWFO-L1 IMAP	CME detection Solar Energetic Particle	2026
Satellite observation (GK5/KSEM-II)	KSEM (Korea Space Environment Monitor) –II r	Geostationary orbit with Particle detector (Proton, Electron), Magnetometer, and Satellite Charging monitor	2032

Table 24
Important instruments of TSA and KMITL (Thailand).

Classification	Instruments (Amount)	Scientific contribution	Present/Tentative establishment year
Ground station	GNSS receivers under National CORS network (200 +) https://ncdc.in.th/portal/apps/sites/#/ncdc-eng	GNSS data for ionospheric study	Present
Ground station	Ionosonde stations in collaboration with NICT, Japan (2) (Wichaipanich et al., 2010, Rungraengwajiake et al., 2013)	D, E, F layer parameters	Present
Ground station	Satellite beacon receivers in collaboration with Kyoto University, Japan (4) (Watthanasangmechai et al.,2016)	Scintillation parameter	Present
Ground station	Optical sky images in collaboration with Nagoya University, Japan (2) (Srisamoodkham et al., 2021)	Images for equatorial plasma bubbles (EPB) study	Present
Ground station	The Princess Sirindhorn Neutron Monitor at Doi Inthanon (1) (Ruffolo et al., 2016)	Neutron study	Present
Ground station	VHF radar station (1) (Thanakulketsarat et al., 2023)	equatorial plasma bubbles (EPB) study	Present
Ground station	Space Weather Forecasting Center (1)	Space Weather Service	Present
Ground station	VHF receiver (1)	Effects of sporadic E and E layer on communications	Present
Ground station	(Expansion of network) GNSS receivers	Total electron content (TEC), Rate of TEC change index (ROTI) maps	Present
Geomagnetic field	High-precision three-component fluxgate Magnetometer FRG-602 (Myint et al., 2025)	3-Axis observation of 1-Min geomagnetic field	Present
Polar satellite observation (TSC-1)	Polar Orbiting Ion Spectrometer Experiment (POISE) (Chaiwongkot et al., 2024)	Monitoring solar radiation storms, use of geomagnetic filter to determine ionic charge states, Hyper spectral images	2027
Lunar-orbit observation (TSC-2)	Ion and electron/positron spectrometer	Monitoring solar radiation storms, determination of Jovian and cosmic electron/positron flux variations up to ~ 200 MeV	To be determined and revised

*TSC = Thailand Space Consortium.

3. Scientific framework

Many different groups working on science related to space weather have also become service providers mainly due to their nation's needs for protection.

However, it is difficult to separate what has brought each other the most strength, the scientific curiosity or the need for services. They are quite interchangeable in scientific proposals in space weather, taking advantage of the need for security in the operation of sensitive technology or services.

Considering the participants of this work, it is possible to perceive a clear growth of publications in the area, but somewhat irregular among the Countries (see Fig. 4).

3.1. AMERICAS & AFRICA

3.1.1. LAMP/UBA-IAFE(CONICET)-IAA/Argentina

LAMP (acronym from Spanish 'Laboratorio de Meteorología del esPacio') is an interdisciplinary and interinstitutional Argentina Space Weather Laboratory. It depends in the following three institutions: Instituto de Astronomía y Física del Espacio (IAFE, UBA-CONICET), Departamento de Ciencias de la Atmósfera y los Océanos (DCAO, FCEN, UBA) and Instituto Antártico Argentino (IAA, DNA).

The LAMP activities cover a wide range of space weather including

- Fundamental science research, design and development of instrumentation;
- Capacity building of human resources and infrastructure;
- Development of Antarctic capacities;
- Articulation with different national and international space weather actors;
- Research to Operation and Operation to Research (R2O2R) activities;
- Real-time monitoring of space weather conditions.

See, for example, Lanabere et al. (2018).

LAMP deployed a laboratory of space weather at the Argentine Marambio base in the Antarctic Peninsula. The main instruments at this Antarctic laboratory are Neurus (a water Cherenkov radiation detector to observe the flux of galactic cosmic rays modulated by the solar wind and shielded by the geomagnetic field, that was designed and built by LAMP at the space laboratory of IAFE (Dasso et al., 2015), an in-house meteorological station, a GPS receiver used to time-stamp the recorded data, an in-house magnetometer, and several other instruments. The recorded data at the laboratory has been uninterrupted since its inauguration in March 2019 (for more details, see Gulisano et al., 2021).

LAMP also participates in a recently signed collaboration agreement in Argentina, between three major organisations: the national research organization (CONICET), the National meteorological service (SMN) and the Argentine space agency (CONAE) to develop the Argentinean space weather Plan, and thus to move forward space weather activities in Argentina.

Finally, LAMP participated in the interinstitutional protocol for information management of the probability of serious disturbances in electric supply due to natural threats, approved by the Science and Technology Minister (Resolution 138/2016), providing the incentive to include space weather as one of the risks, in the final document. Additional information regarding LAMP can be found at its web page: https://spaceweather.at.fcen.uba.ar/2/lamp/.

One of the operative SWx activities carried out by LAMP consists of a daily monitoring of different aspects of the Sun-Earth system. The observer is in charge of mon-

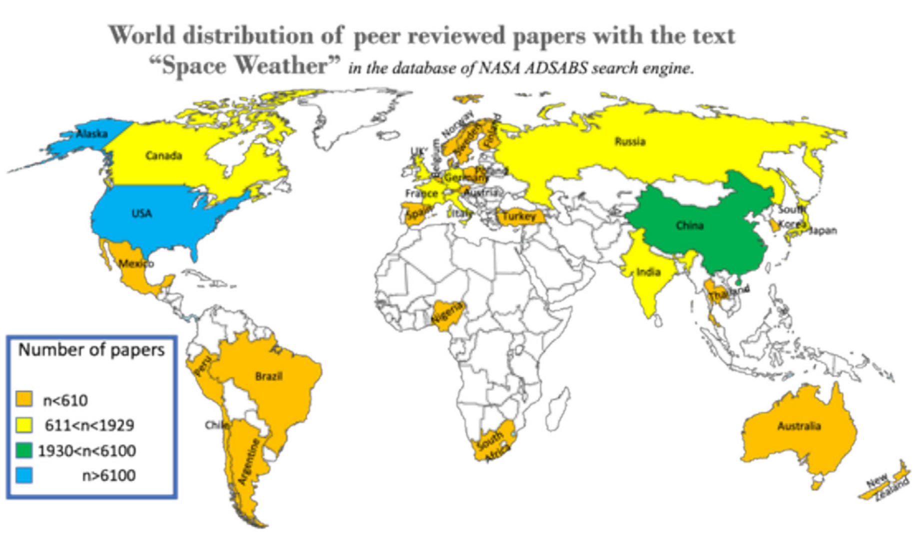

Fig. 4. Search for peer reviewed papers with the text "Space Weather" in the database of NASA ADSABS search engine (According to a recent assessment made in 2023). Countries without color in the figure were not reported by the representative in the panel.

itoring all the variables under a specific protocol, during a whole week.

In order to keep a characterization of the Argentine region, the monitoring of real-time data from instruments installed in Argentina from different institutions is included.

Also developed our special products and provide them in real-time. These products cover all the spectrum of space weather, covering: solar activity (solar corona, identification of every active region present at the Sun, and level of the flux of X-rays), interplanetary medium (Interplanetary Magnetic Field IMF, with different levels of risk, magnitude of solar wind velocity, and polarity of the IMF in which the Earth is embedded), radiation belt conditions (energetic electron fluxes and fluences), global geomagnetic field (Kp and Dst indices), ionosphere state (TEC maps above Argentina), and cosmic rays flux at high (polar) latitudes (Antarctic fluxes measured from a Water Cherenkov detector working in a space weather mode). All these products are public and are offered in a web site portal, which can be found at: https://spaceweather.at.fcen.uba.ar/2/index.html. We also provide a subscription space weather alert service by email.

3.1.2. UNLP/MAGGIA LABORATORY/Argentina

MAGGIA Laboratory is a group of specialists with experience and dedication, both in teaching and in scientific and technological research, to address issues related to the study of space weather, GNSS Meteorology, Geodesy, Geodynamics and the development of specific Instruments. They have developed high resolution ionospheric vertical total electron content (vTEC) maps in near-real-time. The code relies on the public Global Navigation Satellite Systems (GNSS) infrastructure in South America, incorporates data from multiple constellations (currently GPS, GLONASS, Galileo and BeiDou), employs multiple frequencies, and produces continent-wide vTEC maps with a latency of a few minutes (Mendoza el al., 2019; Mendoza et al., 2020). The main aims are studies on the coupling between elements of the Sun-Earth system, particularly the relationship between the mid latitude ionospheric anomaly and solar wind (Natali et al., 2021); and the vTEC and the low atmosphere variation (Villagran Asiares et al., 2021). Also studied are the flare and eclipse effects on the ionosphere and magnetospheric field (Meza et al., 2021, 2022).

3.1.3. UNT/ TSWC/Argentina

The main scientific research at the Tucumán Space Weather Center (TSWC) at the Universidad Nacional de Tucumán (UNT) is related to monitoring, analyzing and forecasting the conditions on the upper atmosphere and space weather. The research is focused on the complete coupled chain of events from the Sun to the upper atmosphere (especially, but not exclusively, at low latitude, Molina et al., 2020), and the variability of the ionosphere due to different forcing (e.g. solar eclipse, space weather events, AGWs/TIDs, etc) using data acquired and curated by the group (Barbas et al., 2022; Bravo et al., 2022; Chum et al., 2023; among others). The group has a strong multidisciplinary approach and have experience in data-driven modeling, in particular in Artificial Intelligence based models (Molina et al., 2025; Torres et al., 2024; Torres et al., 2023).

As mentioned previously, the Argentinean-Chilean-validated ionospheric database (ACVID) includes manually corrected ionospheric measurements from ionosondes in Argentina and in Chile. Of interest is instrumentation deployment for space weather and development of HF radar systems and remote sensing (Molina et al., 2016). Another research interest is machine learning, software development and data management for space weather. The TSWC is an interdisciplinary research group that participates in several space weather panels and working groups. There is a strong network of collaborating institutions within the country (CONAE, SMN, other Universities) and abroad (INPE, INGV, CAS, among others).

Training and capacity building has a key role in the group. There has been an official postgraduate curriculum in space weather, remote sensing and data science (data management and data-driven modelling) applied to space weather since 2019. In 2022, the International Center for Theoretical Physics (ICTP) hosted the “International Workshop on Machine Learning for Space Weather: Fundamentals, Tools and Future Prospects” which was an unique event for ICTP and for the region.

3.1.4. CRAAM/Brazil

The Center of Radio Astronomy and Astrophysics Mackenzie (CRAAM) is involved in the high-frequency study of solar flares from few tens of GHz (109 GHz) up to few tens of THz (1012 THz). This is possible by combining SST, POEMAS, MIR observations, complemented by Hard X- Ray (HXR) and γ-Ray records. It gives a diagnostic of the highest energy particles accelerated during flares radiating (gyro-)synchrotron non-thermal emission in a magneto-active plasmas. At the same time, part of the emission might be of thermal origin, since the free-free opacity is particularly enhanced in the dense and cold layers of the chromosphere (e.g., Trottet et al., 2015).

Once the products of the flare including radiation and particles have escaped from the Sun’s atmosphere they reach and enter the atmosphere of the Earth. At this time, (free) electron density increases as a result of photoionization and/or ionization by impact, and the local electrical conductivity is also increased. This is particularly visible in the lowest electron density region of the ionosphere, i.e., the D-region. Then, the D-region can be used as a huge and sensitive detector of external (e.g., space weather events, cosmic bursts) and/or internal (waves) disturbances. The SAVNET instrumental facility monitors the D-region variability by detecting phase and amplitude anomalies of subionospheric propagating waves (1–

30 kHz). It is then found that 100 % of solar flares above B2.5 GOES-Class are detected in the D-region, and that the lowest detection limit varies as the solar activity cycle (e.g., Raulin et al., 2010). The use of the SAVNET network was also essential to show for the first time that the height of the (undisturbed) base of the D-region (bottom of the ionosphere) is lower within the South Atlantic magnetic anomaly region (e.g., Magalhães et al., 2019). Since High-Frequency (HF) absorption is dominant in the D-region we can in principle estimate and compare it with other existing models, (e.g., D Region Absorption Prediction (D-RAP)).

Finally, a suitable Very Low Frequency (VLF) receiver network may provide a 24-hours visibility of the sky, in order to monitor Gamma-Ray Bursts (GRB) and other cosmic bursts. The ground- based network complements space mission detectors, and does not suffer from Earth's occultation (e.g., Raulin, et al., 2014).

The Atmospheric electric Field in South America (AFINSA) network objective is to study the variability of the Global Atmospheric Electric Field Circuit (GAEC). The circuit is established between fair weather regions (90 % of the surface of the globe) and storm regions (10 %), the latter acting as generators for the circuit. GAEC can serve as the coupling interface between external (space weather) disturbances and changes on the Earth's surface. GAEC is used to indirectly estimate the global lightning production which in turn can reveal global water vapor content and global temperatures. Interestingly, we have shown that while large X-Ray solar flares do not impact GAEC, Solar Energetic Particle events do produce an increase of the observed potential gradient (e.g., Tacza et al., 2018; 2022).

3.1.5. EMBRACE/BRAZIL

The Brazilian Space Weather Study and Monitoring Program (EMBRACE) is operated by the Space Weather Division (DICEP) of the National Institute for Space Research (INPE). EMBRACE is the Brazilian regional warning center inside ISES to issue alerts, discuss and propose mechanisms and defense procedures for technological space systems. There is a group of researchers to monitor and analyze the Sun-Earth environment, such as the Sun, magnetosphere, the ionosphere, and the effects of currents induced in the Earth, to predict possible influences on technological and economic activities, leading to applications of these parameters to society.

Therefore, the EMBRACE/INPE program develops software products with the potential to promote better services with a set of innovative actions for monitoring the space weather environment. The program is increasing the density of the ground network of instruments every year. The program is participating with a real time downlink for lower latency products delivery for COSMIC 2 mission and the new mission SPORT for the research of equatorial plasma bubbles that was launched on November 26, 2022. The program promotes workshops with the Brazilian technological sectors to discuss the services. EMBRACE also participates in international capacity building workshops from COSPAR, the last one being held in 2018.

The beginning of space weather science in Brazil and Latin America is explored in the review of Denardini et al., (2016a).

3.1.6. NRCanada/Canada

The importance of space weather for Canada has been recognized for a long time (Boteler, 2018). Canadian researchers in universities and government have taken advantage of the unique perspective afforded by Canada's location under active space weather regions to study these phenomena. Canada's Space Strategy[6] commits to using space-based data to support science excellence, innovation and economic growth, including study of how the Earth interacts with the Sun (e.g. space weather) and the 2020 Solar-Terrestrial Science Roadmap[7] describes the specific activities for such studies. A space weather socioeconomic impact study[8] reported that space weather events can have a significant impact on Canada's critical infrastructure that is essential to national security, the economy and the health of Canadians.

The response to space weather is specified in federal emergency management plans where geomagnetic storms have long been included in the hazards considered. More recently, space weather is one of the hazards being examined as part of the National Risk Profile[9]: Canada's first strategic, national-level disaster risk assessment, designed to provide a national picture of the disaster risks facing Canada, and the existing measures and resources in the emergency management systems to address them. This is examining space weather in terms of the four components of the emergency management strategy: prevention and mitigation, preparedness, response, and recovery.

3.1.7. SAPL-UChile/Chile

Researchers, at the Chilean Space Weather Service at the Space and Plasma Physics Laboratory (SAPL), are studying different aspects of the sun – solar wind –magnetospheric – ionospheric (SSWMI) system with particular emphasis on space weather applications. Presently, they are studying total electron content (TEC), errors in Global Navigation Satellite System (GNSS) derived positioning (EGDP), and geophysical Induced Magnetic Fluctuations

[6] https://www.asc-csa.gc.ca/eng/publications/space-strategy-for-canada/.

[7] https://aurora.phys.ucalgary.ca/public/doc/Canadian_Solar-Terrestrial_Science_Roadmap_2020.pdf.

[8] Space Weather Socioeconomic Impact Study on Canadian Infrastructure, Final Report (CSA File 9F045-17-0348; Contract No. 45-7014173), Hickling Arthurs Low, https://sqreports.s3.ca-central-1. amazonaws.com/2020/Final_Report_Space-Weather_Socioeconomic_Impact_20190327.pdf.

[9] https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/ntnl-rsk-prfl/index-en.aspx.

(GIMF), taken as global indices or high-resolution spatial patterns, with particular emphasis on storms and substorms. They have already developed their own code to construct high resolution spatial TEC maps from a very dense Chilean network in combination with other South American dual frequency GPS receivers. They are currently working on constructing equivalent EGDP maps. To have a picture of the state of the ionosphere, they are complementing these measures with an analysis of the GIMF around the Earth. Certainly, the final driver of all of these dynamics being the Sun and the solar wind, they are constructing solar wind driven nonlinear dynamic models, particularly of GIMF, that are based on robust artificial intelligence techniques that are being developed. They recall that the magnetosphere is a high dimensional multifractal complex system (Valdivia et al., 2006; Valdivia et al., 2013; Toledo et al., 2021), that is driven by a high dimensional turbulent solar wind, therefore, determining which are the relevant variables and driver of such a system, obtained from the same artificial intelligence techniques used for the forecasting, become extremely relevant when trying to propose reliable forecasting techniques for space weather applications (Blunier et al., 2021).

The measures (TEC, EGDP, and GIMF) give useful information about the state of the ionosphere and magnetosphere as part of the SSWMI system, and therefore, they provide emergent and relevant space weather-related themes that aim to provide valuable knowledge for future technologies (mining, natural disaster management, remote communications, precise farming, power grid management, etc.). As part of the project, they are analyzing the possibility of constructing robust system science models, based on machine learning, to nowcast/forecast indices and spatial patterns of TEC, EGDP, and GIMF, during storms and substorms, from solar wind parameters.

Hence, the understanding of ionospheric disturbances, as characterized by TEC, EGDP, and GIMF, particularly through high time and space resolution maps, provide invaluable information about the behavior of the ionosphere and its effect on radio blackouts, communication, positioning, electric networks, etc. Furthermore, it has also been shown that the dynamics of the ionosphere can influence the energy deposition in the troposphere and vice-versa (Pedatella et al., 2019), therefore, TEC can bring relevant information to improve climatological models of the lower layers of the atmosphere.

They have constructed their own code to calculate TEC from the RINEX files and the satellite trajectories, as shown in Fig. 5(left) for the temporal evolution along the magnetic meridian of Chillán (36.6° S, 72.0° W), Chile, during the day of the solar eclipse which occurred in Chile in December 2020, using high-resolution Chilean data with some additional South American stations. Fig. 5(right) displays the difference in TEC during the day of the eclipse with respect to the previous days, which clearly shows a 5–10 TECU reduction due to the eclipse (see Bravo et al., 2022). The code is named PYTEC and has been validated against other standard codes (Bravo et al., 2022).

In addition, they are working on having EGDP maps simultaneously with the TEC maps, and then try to correlate them with GIMF and solar wind parameters.

3.1.8. LANCE/Mexico

In 2014, the legislators changed the civil protection law in Mexico and included space weather events in the list of natural hazard phenomena. In the same year, the Mexican Space Weather Services (SCIESMEX in Spanish) was established (Gonzalez-Esparza et al., 2017), and in 2016 the Space Weather National Laboratory was also established (LANCE in Spanish). LANCE-SCIESMEX is constructing an observational network of space weather phenomena covering the whole country. The multidisciplinary group develops studies of space weather events detected in Mexico to understand regional phenomena and local vulnerabilities better. In addition, SCIESMEX-LANCE established a collaboration with the National Protection System and the Mexican Space Agency to develop public policies toward incrementing the country's resilience against space weather hazards. The research roadmap is the following:

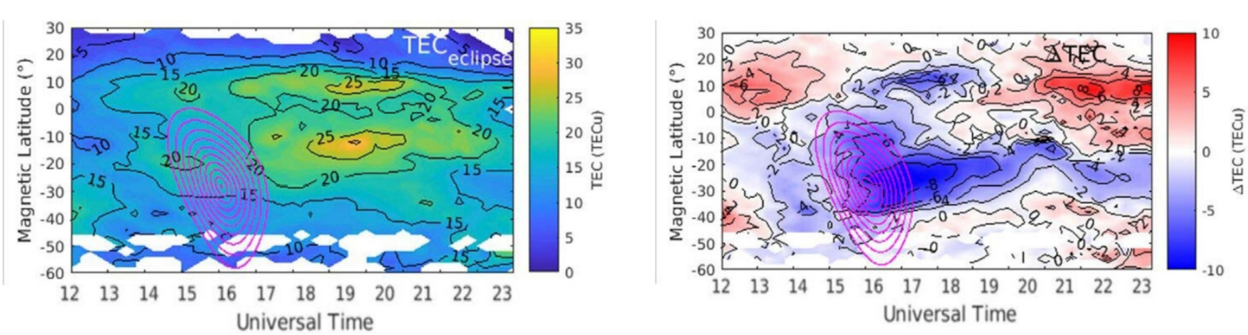

Fig. 5. Temporal evolution of TEC, using the validated PYTEC code, along the magnetic meridian of Chillán (36.6° S, 72.0° W), Chile, during the day of the solar eclipse (left), which occurred in Chile in December 2020. The variation of TEC (right) between the day of the eclipse and a reference defined by the previous days, which clearly show the effect of the eclipse (see Bravo et al., 2022). The colormap is obtained by a linear interpolation of the nonuniform positioned data. A single receiver can produce various TEC measurements. The purple contours define amount of the eclipse darkness at the ground (adapted from Bravo et al., 2022).

- To study large-scale solar wind structures employing MEXART Interplanetary Scintillation observations.
- To measure regional magnetic indices in real-time.
- To study regional ionospheric properties with the ionosondes network.
- To analyze geomagnetic induced currents in the national electric grid.
- To study space weather events affecting Mexico (including solar, interplanetary, magnetic, ionospheric, GICs and cosmic ray data).

3.1.9. Center for Atmospheric Research, National Space Research and Development Agency/Nigeria

Space weather study, monitoring and services are coordinated and operated by the Centre for Atmospheric Research which was established in January 2013. The Centre is an autonomous activity Research and Development arm of the National Space Research and Development Agency which is a parastatal under the Federal Ministry of Science, Technology and Innovation. The Centre is committed to research and capacity building in the atmospheric and related sciences; dedicated to understanding the atmosphere—the air around us—and the interconnected processes that make up the Earth system, from the ocean floor through the ionosphere to the Sun's core; and provides research facilities and services for the atmospheric and Earth sciences community. The Centre for Atmospheric Research has 'Space Weather' as one of the main items on its agenda. The Upper Atmosphere Division of the Centre is responsible for studies and research in ionosphere, space weather and solar terrestrial interaction. The Centre works with researchers and scientists in different universities and institutions across the country with interest in space weather studies. The Centre co-organizes international and national capacity building workshops of relevance to space weather and COSPAR activities. For example, the 2022 International Colloquium on Equatorial and Low Latitude Ionosphere was held from 18 to 23 September and had 21 instructors and 61 participants from across the globe.

3.1.10. Space weather services

The Centre for Atmospheric Research has implemented its space weather agenda among others through providing daily space weather services since 16 January 2018. The daily and monthly forecasts in the form of TEC maps and movies have been freely provided at https://www.carnasrda.com. The webpage also provides daily nowcasting of space weather parameters such as the solar wind speed, the solar wind density, the sunspot number, the 10 cm solar radio flux (10.7 cm flux), the interplanetary magnetic field component (Bt and Bz) and the disturbance storm time index Dst. The space weather services have been of great benefit to the general public and in particular patrons of space technology dependent systems/operations. "e.g. "The traffic on the webpage and services has increased to the tune of 5282 visits and 1983 downloads between its inception in 2018 and 2022-07-31.

3.1.11. NIGTEC and AfriTec Models

The NIGTEC is a model of the ionospheric GNSS TEC over Nigeria (Longitudes 2–15 degrees East, Latitudes 4–14 degrees North). It was developed by the Centre for Atmospheric Research and made available to the public. The model is used to obtain the ionospheric GNSS TEC at all locations over Nigeria. Also, the AfriTEC is the first regional total electron content (TEC) model over the entire African region and was developed using radio occultation (RO) observations from GPS receivers onboard the COSMIC satellites. The models are available at https://www.carnasrda.com.

3.1.12. Virginia Tech – Nigeria Bowen Equatorial Aeronomy Radar – VT-NigerBEAR

Bowen University, Iwo, Nigeria; Virginia Tech, USA; and the Centre for Atmospheric Research are in partnership to set up an ionospheric research radar on the design principles of the Super Dual Auroral Radar Network (SuperDARN) within the campus of Bowen University, Iwo, Nigeria. The idea of a SuperDARN-type radar operating at low latitude was motivated by the realization that the technique would render valuable measurements if located in the vicinity of the geomagnetic equator, which runs through Nigeria. Hence, the radar at Bowen University is named: "Nigeria Tech – Nigeria Bowen Equatorial Aeronomy Radar (NigerBEAR)", being the first of its kind in the magnetic equatorial region and low (geographic equatorial) latitude. The project has reached an advanced stage as the antennae have been mounted already. The facility awaits the deployment of the indoor transmitter and receiver electronics. The VT- NigerBEAR shall obviously enhance our research capability and produce new science results that could improve our understanding of the equatorial-low latitude ionosphere and space weather. It shall facilitate a multi-technique approach to study the lower/upper atmosphere and is envisioned to become a key component of global lower/upper atmosphere research infrastructure.

3.1.13. Participation in international activities

Nigeria has active participation in SCOSTEP, United Nations International Space Weather Initiative and the United Nations New Expert Group on Space Weather. Nigeria hosts SCOSTEP Visiting Scholars (SVS). Three SVS scholars have visited the Centre for Atmospheric Research: George Ochieng (25 Feb – 15 May 2021); Hager Salah: (1 Jul – 28 Aug 2022) and Theogene Ndacyayisenga (2 Jul – 31 Aug 2022).

3.1.14. IGP/Peru

The Geophysical Institute of Peru (IGP) monitors the equatorial upper atmosphere through its primary facility, the Jicamarca Radio Observatory (JRO). Established

63 years ago, this facility houses one of the world's most powerful large-aperture radars, the Jicamarca VHF radar. The High-Power Large-Aperture (HPLA) Jicamarca radar is capable of estimating ionospheric parameters such as electron density, temperature, composition, and ion velocity at the magnetic equator. Given its advantageous location, the IGP/JRO also served as a hub for additional instrumentation that supports equatorial measurements, including magnetometers, digisonde, ionosondes, and additional radars.

The main scopes of research at IGP/JRO are to understand the different processes and conditions as a result of the Sun and the Earth surrounding space. Radiation and particles emitted by the Sun into space can modify the physical characteristics of the space environment around Earth. When the radiation and particles from the Sun interact with plasma, neutral particles, the Earth's magnetic field and electrical currents present in the upper atmosphere, different phenomena and physical processes are generated that can cause disturbances and affect normal propagation of radio signals that travel through the ionosphere, as well as alter the operation of space vehicles. As a consequence of these effects, the characteristics of the ionosphere or upper atmosphere are modified, altering the plasma density, currents and electric fields. In addition, plasma structures are generated in the ionosphere that are characterized by turbulence and irregularities in their density and are known as plasma bubbles. Therefore, it is important to monitor and study the effects of space weather in order to have a better understanding of the impact it can have on the technological systems widely used by society. Among the systems that may be affected are satellite systems used for various socioeconomic activities applied to telecommunications, global positioning and navigation, monitoring of disaster risk management networks, scientific research, and even for military and defense use.

The strategic location of the IGP/JRO, right on the magnetic equator, allows for relevant measurements of the upper atmosphere at this latitude where particular physical phenomena occur. One of the most important phenomena is known as equatorial Spread-F, which consists of the formation of plasma bubbles during hours of the night that normally originate in the lower part of the ionosphere and then ascend to heights above 700 km. When radio signals pass through these irregularities or plasma bubbles, they are disturbed, causing distortion and disruption of communications links. In addition, there is another relevant physical phenomenon in this low-latitude ionospheric region known as the equatorial electrojet, which consists of a stream of electrically charged particles that circulates around the Earth at the magnetic equator at an altitude of approximately 100 km. Disturbances in the electrojet can produce variations in the Earth's magnetic field.

In addition to the radar system, the IGP has a distributed instrument network called LISN (Low-Latitude Ionospheric Sensor Network). This network is a collaborative effort with various national and foreign institutions and consists of GNSS receivers, ionosondes, and magnetometers. These instruments are installed in various parts of Peru and nearby countries in South America such as Brazil, Bolivia, Argentina, and Colombia. The GNSS receiver system provides measurements of the total electron content in the ionosphere (TEC), which are used to generate TEC maps in longitude and latitude coordinates in the South American sector on a continuous basis. Additionally, the signals from the GNSS receivers allow us to investigate the occurrence of ionospheric scintillation associated with Spread-F irregularities. The scintillation is determined by measuring the level of fluctuations in the captured signals. These disturbances occur when GNSS signals propagating through the ionosphere pass through bubbles of plasma. This causes signal interruption or errors in position calculation. Other relevant physical parameters of the ionosphere can be obtained daily by means of ionosonde instruments, such as the estimation of electron density with their corresponding heights in the region of the F layer of the ionosphere. On the other hand, the Earth's magnetic field is monitored by magnetometer instruments. The measurements obtained make it possible to determine variations caused by ionospheric processes such as disturbances in the electrojet or by effects of geomagnetic storms.

In addition to the instruments that capture electromagnetic signals, optical instruments are available, such as airglow cameras and Fabry-Perot interferometers, which are used to study the dynamics of neutral winds in the upper atmosphere, as well as the occurrence of irregularities. of plasma related to the scattered F in the ionosphere.

The IGP, in this way, has been contributing to the monitoring and research of space weather through observations with various types of instruments and also contributes by generating and providing scientific information to contribute to a better understanding of the effects of space weather on the Peruvian territory.

3.1.15. SANSA/South Africa

The South African National Space Agency (SANSA) has operated the Regional Warning Center (RWC) for Space Weather (SWx) in Africa since 2010 and the only operational 24/7 Space Weather Centre in Africa since November 3, 2022. In 2018, South Africa, through SANSA, was designated by the International Civil Aviation Organisation (ICAO) as a Regional Centre for the provision of SWx information to international air navigation. SANSA is in a position to work together with all the affected sectors and government to make provision for a space weather capability that addresses the nation's requirements and leads the country towards mitigation measures against this risk. Over the past 11 years SANSA has developed the capability to monitor and forecast space weather as well as prioritizing research projects that enhance the modeling ability of the centre. SANSA is also a partner in a number of regional and international space weather projects each of which contributes towards enhancing the knowledge and expertise needed to provide these services.

The research priority at SANSA is on the products and services development to meet the users' needs with focus on the Aviation sector. The SANSA space science research and space weather objectives are summarised below:

- Provision of research-based data, space weather products and services to benefit the nation.
- Conduct cutting edge applied research and lead the development of new innovative technologies that adds value to space weather services.
- Provision of a Space Weather Centre platform that provides the foundation for delivering products and services.
- Develop capacity and grow awareness in space science research and space weather through leadership, human capital development, and science engagement activities aimed at the public, learners, and policy makers.
- Build South Africa's reputation in space weather research nationally, regionally, and internationally.

3.1.16. NOAA/United States of America

NOAA is working with its partners in government, academia, industry and internationally to strengthen scientific research and the transition of research into operations. In 2022 a framework for research-to-operations and operations-to-research (R2O2R) was released by the White House Office of Science and Technology Policy (https://www.whitehouse.gov/wp-content/uploads/2022/03/03-2022-Space-Weather-R2O2R-Framework.pdf). This framework provides a formal interagency structure to ensure an effective space weather R2O2R process to improve existing capabilities and to move new capabilities from research to operations. NOAA's operational numerical modeling suite includes the Wang-Sheeley-Arge/Enlil model that predicts the background solar wind and coronal mass ejection arrival time at Earth, the University of Michigan Geospace model that predicts the regional geomagnetic response to the solar wind, the Whole Atmosphere Model/Ionosphere Plasmasphere Electrodynamics model that predicts the upper atmosphere and ionosphere, the Geoelectric model that predicts the regional geoelectric field and associated induced currents, and the CARI-7 aviation radiation model.

To effectively improve current operational models and bring new capabilities into operations, NOAA's Space Weather Prediction Center is establishing a Space Weather Prediction Testbed (SWPT). The testbed is completed and first Testbed Exercise will be done in April 2025. The testbed will also obtain direct feedback from space weather users to ensure that new capabilities are well aligned with user needs. The Testbed will work closely with the newly formed Architecture for Collaborative Evaluation in partnership with the NASA's Community Coordinated Modeling Center (CCMC), which is the first "proving ground" established under the R2O2R Framework.

An architecture exists for the collaboration of NASA/CCMC and SWPC/NOAA, configured to mirror the NOAA operational environment as closely as possible. These included the following,

- Evaluate and validate models and capabilities before transition to operations.
- Reduce the need to modify model code and to revalidate after transition to operations. Enhance operational-grade models and software.
- Grant collaborators access to ACE to work with others (see Fig. 6).

3.1.17. NSF/United States of America

NSF supports research and observational infrastructure in Aeronomy, Magnetospheric Physics, Solar-terrestrial Physics, Solar Astronomy, and Space Weather. Most recent programs with space weather focus include SWQU (Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties) and ANSWERS (Advancing National Space Weather Expertise and Research toward Societal resilience).

NSF is one of the original stakeholders of the CCMC multi-agency partnership and participant in the R2O2R multi-agency partnership. NSF sponsors community-driven research programs SHINE, GEM and CEDAR investigating the physics in space weather domains from the Sun to the Earth's lower atmosphere.

SHINE (Solar Heliospheric and INterplanetary Environment) covers the areas of the Sun, the heliosphere, and the interplanetary environment. It began as a grass-roots effort by researchers interesting in linking across these sub-domains with annual workshops having begun in 1999. Although SHINE leadership is still USA based, the SHINE workshops attract a large international participation, including those proposing the sessions at the SHINE Workshops. SHINE thrives on this community-led approach to the sessions along with the international involvements. In addition, since 2003 the NSF has provided funding to SHINE for students to attend the workshop, along with some support for scientists.

The primary focus of the GEM (Geomagnetic Environment Modeling) Program is the physics of the Earth's magnetosphere and the coupling of the magnetosphere to the atmosphere and to the solar wind. The GEM mission includes construction of the coupled geospace modeling system with predictive capabilities. The strategy for achieving GEM goals is through a series of Focus Groups and Challenge Campaigns. GEM Steering Committee Liaison Members include representatives from all over the world.

The goal of the CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions) Program is understanding the behavior of atmospheric regions from the

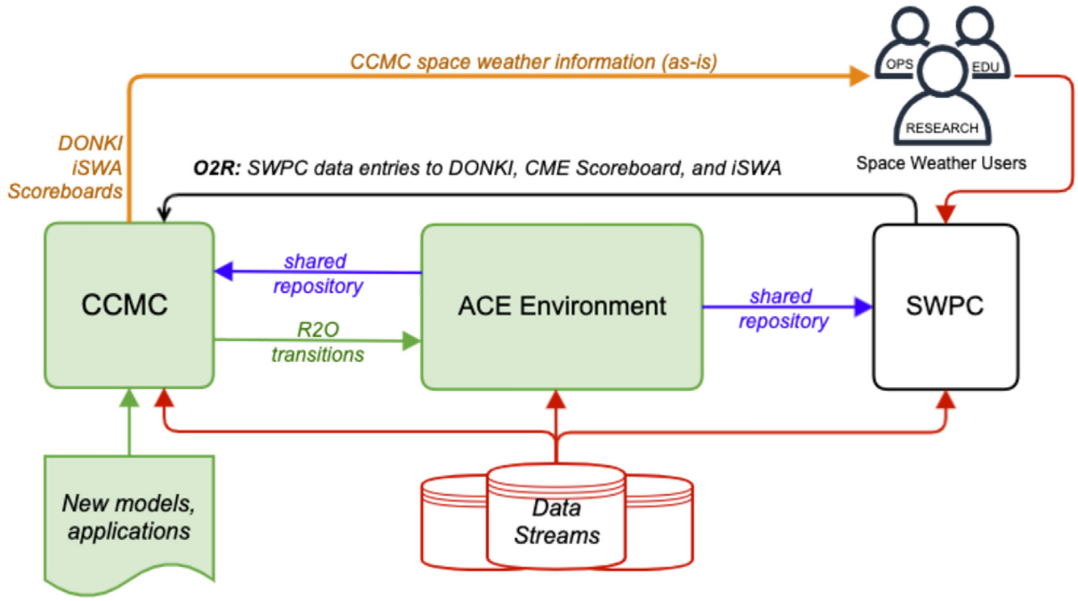

Fig. 6. NASA/CCMC & NOAA/SWPT Partnership: Architecture for Collaborative Evaluation (ACE). Credit: CCMC.

middle atmosphere upward through the thermosphere and ionosphere into the exosphere in terms of coupling, energetics, chemistry, and dynamics on regional and global scales.

SHINE, GEM and CEDAR Modeling Challenges set the scene for many community-wide validation projects picked up by the COSPAR International Space Weather Action Teams (ISWAT).

3.2. EUROPE

3.2.1. UNIGRAZ/Austria

Austrian Experts have actively contributed to the Expert Group and the drafting of the final report and we will continue to contribute to international space weather coordination as shown below.

- *Regarding recommendation 1:* Austria is part of the International Space Weather Action Teams (ISWAT) of the Committee on Space Research COSPAR and supports the coordination and the global effort of joint space weather research.
- *Regarding recommendation 2*: Austria is part of International Space Environment Service (ISES), a collaborative network of space weather service-providing organizations around the globe that aims at standardized data and its exchange via common platforms such as VSO (Virtual Solar Observatory). Austria is currently making efforts to improve coordination at the national level.
- *Regarding recommendation 4*: Austria contributed also to the Opgenoorth et al. (2019) study providing a model for the coordination of space weather activities using the European context as an example.

Our modern society is increasingly dependent on satellite-based technology for communication, navigation, and weather satellites and is therefore very vulnerable to space weather turbulence. Austria looks forward to globally coordinated space weather services.

3.2.2. FMI/Finland

Finland's location under the auroral oval has inspired long-term observations of geospace phenomena with versatile ground-based instrumentation. The system of EISCAT Incoherent Scatter radars, which started its operations in 1975, has given additional boost for supporting instrumentation in the vicinity of the radar sites. Today instrument networks are maintained mostly by SGO (SGO Observations) and FMI (MIRACLE network (fmi.fi)). Data from these networks are often used together with satellites in event studies, statistical investigations, and space weather services. Finnish research groups have an extensive record in developing advanced data analysis methods for EISCAT and other ground-based observations. Many of those tools are used in the design of space weather products as contributions to international space weather services (ISES, ESA, ICAO).

During recent years Finland has become active also in space-based space weather observations. There the focus has been in instrument development for CubeSats. Examples are the Suomi-100 satellite mission with auroral camera and radio wave receiver (by Aalto University (AU) and FMI) and the ESA SunStorm mission equipped with solar X-ray spectrometer (by Finnish company ISAWARE Ltd). UT has developed concepts of radiation monitors that can be operated in small satellites. One of them, PATE, will be tested together with the plasma brake de-orbiting solution (by FMI) in the Foresail-1 satellite mission built by the Finnish Centre of Excellence for Sustainable Space (by AU, University of Helsinki (UH), University of Turku (UT) and FMI).

Global space weather simulations are a strong area of development in Finland. FMI has been using MHD simulations (currently GUMICS-5) for some decades, while UH has a recently developed Vlasov simulation (Vlasiator | University of Helsinki) for an unprecedented accuracy of global modelling of space plasmas. Other modelling and basic research expertise includes heliosphere and solar corona modelling (UH), Solar Energetic Particles (UT), spacecraft charging (FMI), geomagnetically induced currents (FMI), upper atmospheric ion chemistry (UO, FMI), and cosmic rays and their atmospheric cascade (UO). Furthermore, UO and AU conduct space climate research including modelling long-term variability in solar activity and the impact of auroral precipitation on polar vortex dynamics.

3.2.3. CNES/France

France does not have a national roadmap. The CNRS recognizes and supports financially space-weather services through a labelling process. CNES supports radiation belt (Salammbo) and thermosphere modelling (DTM) and has funded developments of different tools (STORMS, SWIFT, HelioCast). The STORMS forecasts service runs 24/7 (Mulit-VP, Heliocast, Magnetic Connectivity Tool, SolO operations).

The NanoMagSat project is in the development phase. CubeSats are in operation (UVSQ-sat) or under development like CREME (Cubesat for Radiation Environment Monitoring Experiment, ISAE&ONERA).

The ENSO nanosatellite mission was launched on 04 December 2023 by Expleo in partnership with the Centre Spatial Universitaire de Montpellier (CSUM). It began its 4 years-long mission to monitor solar activity and its impact on Earth’s atmosphere.

3.2.4. DLR/Germany

Germany is involved in a number of scientific and political bodies advancing Space Weather. The German scientific community in the field of space weather includes a large number of internationally leading scientists and institutions. The same applies to technology developed in Germany; for example, instruments and sensors essential for the observation and prediction of space weather events. To advance research, development, and the path to 24/7 operation of space weather services, numerous activities and collaborations have been initiated by national and international organizations in recent years. The research programs of ESA with the Vigil Mission (formerly Lagrange Mission) in the Space Safety Programme (S2P) and the European Union (Horizon Europe) should be mentioned in this context. Space weather is also addressed in the EU Space Program and was explicitly integrated under “Protection of Space Resources” at the 2022 Space Summit. The Federal Republic of Germany is represented in these bodies as a member state or by its seconded experts. The relevance of the topic of space weather and its effects will increase dramatically in the coming years. This is because as our government, society and economy become increasingly dependent on sophisticated technologies and downstream services, the vulnerability of these sensitive systems to the impact of moderate to extreme space weather events will increase. Furthermore, we expect more space weather impact with the increasing solar activity until its maximum in 2025 and beyond. In March 2022 a recommendations document based on the results of the 5th National Space Weather Workshop, September 21–23, 2021, were compiled by representatives from the German space weather expert community.[10] The main recommendations to strengthen Space Weather Research and Service in Germany are briefly summarized below:

- Establishment of an internationally well networked National Space Weather Center, that bundles German competencies and capabilities and supports a national Space Weather Service.
- Establish an adequately funded National Research Program for basic and applied research, including coordinated development of observational methods and space weather models.
- Establishment and expansion of operational ground-based and satellite-based observation systems, which are operated both nationally and in close international cooperation and form the backbone of early warning systems for critical infrastructures. This acutely includes the possible German contribution of the solar magnetograph PMI to ESA’s Vigil Mission, which is currently in preparation.
- Preparation of a national risk assessment, which includes the full analysis of all systems and services affected by space weather and enables the establishment of reporting chains and preventive measures up to the coordination of rescue and relief measures after the occurrence of a disaster.
- Strengthening national support and representation of German interests in EU, and ESA as well as NATO bodies regarding German contributions to space weather research, e.g. through satellite missions, as well as bodies for international coordination of the handling of space weather events, e.g. in the International Civil Aviation Organization (ICAO) and the United Nations.

3.2.5. UGOE/Germany

The “Sun, Heliosphere and Space Weather Research Group” at the Institute for Astrophysics and Geophysics at the University of Göttingen (UGOE), Germany, led by Volker Bothmer has made numerous state-of-the-art contributions to space weather, such as:

[10] https://impc.dlr.de/fileadmin/user_upload/2022_Empfehlungspapier_Weltraumwetter.pdf; in German.

- Analysis of coronal mass ejections observed by the SOHO/LASCO coronagraphs and their space weather consequences as measured at Earth's orbit by ACE, Wind, GOES and measurements on the Earth itself (magnetometers) known as geomagnetic storms.
- Lead of INTAS Team Project 99–727, Geoeffective interplanetary structures: Their origins on the Sun and in the solar wind, Jahresbericht 2002 und 2003, Max-Planck-Institut für Sonnensystemforschung (MPS), 37,191 Katlenburg-Lindau, Max-Planck-Str. 2, https://www.mps.mpg.de/de/publikationen, 2004.
- Member of NASA's Science Definition Team for the NASA STEREO-Mission and PI of the German Stereo/Corona project as science and hardware contribution to the optical imaging package SECCHI developed for the NASA STEREO mission launched in 2006.
- PI of the EU space weather project AFFECTS (Advanced Forecast for Ensuring Communications Through Space, https://www.affects-fp7.eu/home/), 2012–2014.
- Co-I and German PI of the EU FP7 space weather projects SOTERIA (SOlar-Terrestrial Investigations and Archives), eHEROES (Environment for Human Exploration and RObotic Experimentation in Space), HELCATS (Heliospheric Cataloguing, Analysis and Techniques Service).
- Lead of the international instrument consortium for "Implementation Design Study of Space Weather Instrumentation" within a project by Astrium GmbH Friedrichshafen selected by ESA for the Space Situational Awareness (SSA) program (2010).
- CGAUSS (Coronagraphic German And US Solar Probe Plus Survey) project as German contribution to the NASA Solar probe Plus Mission selected for funding by DLR in 2012. Role: PI. Timeframe: 2012–2026 upon extensions.
- PI of University Göttingen contribution to OPTIMAP (OPerational Tool for Ionosphere Mapping And Prediction) space weather project for the German SSA center (2015).
- PI of Germany's contribution to SCOPE (Solar Coronagraph for OPErations) selected as a coronagraph prototype study for the ESA/SSA program (2016).
- NASA confirmed Co-Investigator for the WISPR camera onboard the Parker Solar Probe spacecraft, and the SoloHI camera onboard Solar Orbiter.
- PI of University Göttingen contribution to "L5 modeling" for ESA SSA space weather (2019).
- Selected member of AGU honors committee (2018).
- Selected member of ESA's SSA (Planet Safety) Advisory Group (2018).
- PI of University Göttingen contribution to the national project "Risikobewertung von Weltraumwetterereignissen" led by Airbus DS GmbH, Friedrichshafen, Germany (2018).
- PI of University Göttingen contribution to "Lagrange Missions Remote sensing instruments" for ESA (2017).
- NASA selected Co-I of the PUNCH mission (2022).

Numerous contributions to space weather workshops and space weather panels of the EU, NASA, EU, UN, ESA, NASA.

3.2.6. ASI/Italy

Since 2018, the perspectives of space weather science in Italy have been discussed within the National Space Weather Working Group coordinated by the Italian Space Agency. The effort included contributions from numerous research institutes and universities across Italy, among which are Istituto Nazionale di Astrofisica (INAF), the National Institute of Geophysics and Volcanology (INGV), National Institute for Nuclear Physis (INFN), University of Rome "TorVergata", University of Trento, University of Perugia, and the Italian Air Force. Throughout the group's activity period, interactions with the wider scientific community in Italy were made possible also through the organization of a dedicated Workshop, in ASI headquarters in late 2018. In 2020, the group proposed some perspectives for space weather science, taking into account the existing national expertise and the related achievements thus far. The perspectives were discussed also in the context of an international frame in view of a long-term plan for the support of future scientific research in the related disciplines in Italy. The whole effort was discussed in a dedicated paper (Plainaki et al., 2020) and the proposed recommendations were organized in the following macro-areas:

- Observational and theoretical research;
- Study of space mission concepts and deployment of new scientific instrumentation;
- Development of a prototype national scientific space weather data center – the ASI Space Weather Infrastructure (ASPIS).

Considering the study of space mission concepts and deployment of new scientific instrumentation, the interest was focused in the following topics:

- Solar corona and heliospheric imaging (well off of the Sun-Earth line) to investigate CMEs and solar wind;
- ENA imaging for investigating the geomagnetic activity, the planetary Space Weather conditions, and the energetic particle sources on the Sun;
- VIS–NIR polarimetry for chromospheric and photospheric diagnostics;
- X-ray polarimetric imaging to reveal the nature of the polarization of hard X-ray sources in the solar atmosphere;
- Particle detectors to measure the radiation environment in or outside the Earth's magnetosphere;
- In situ measurements of plasma properties

The research in the different Space Weather disciplines can benefit from both new space missions and/or new innovative instrumentation, including also the possibility of ridesharing or hosted payload flight opportunities. Moreover, thanks to their relatively low cost, reduced sizes and volumes, CubeSats may be a captivating alternative to classic satellites, able to achieve a series of science objectives related to space weather. In addition, Space Weather CubeSats missions may function also as technology validation opportunities, testing advanced technologies (e.g., solar sails) and also the response of miniaturized instruments to harsh space environment, even in view of future human space exploration missions. Moreover, constellations of CubeSats can provide multi-point measurements to support further investigations. In general, considering new space missions, possibly including the allocation of sensors also away from the Sun-Earth line, and/or at different distances from the Sun, would be a necessity.

The ASI Space Weather Infrastructure (ASPIS) project has been a recent joint initiative of ASI and INAF, aiming at the development of a prototype national scientific space weather data center hosting. high-quality interdisciplinary data and global information relevant to space weather science. The so called ASPIS prototype Realization (CAESAR) project, led by INAF (Laurenza et al., 2023). The main goal of the ASPIS project was to enable easy data sharing, interdisciplinary research and innovation, motivating synergies and collaboration opportunities and providing a broad set of parameters in the space weather domain (Molinaro et al., 2024). Such synergies between different science teams could be indeed essentially facilitated by an efficient access to multidisciplinary data. Within ASPIS, at a best effort basis, duplication of existing efforts has been avoided.

Individual research teams in Italy have always provided a large component in space weather science progress and continue to do so (see, for instance, Bemporad et al., 2023). However, as knowledge on the complexity of space weather grows, the possibility of breakthrough science in the next years requires the robust and dynamic interaction between groups that include observers, modelers, theoreticians, laboratory, and computer scientists. In the context, the ASPIS prototype provided an excellent opportunity link activities by different communities, hosting, organizing and visualizing interdisciplinary space weather data, as well as scientific products generated by tools already developed by science teams but still not widely distributed among all interested users (see, for instance, Molinaro et al., 2024). The development of the ASPIS prototype has been an important step for addressing a number of scientific questions related to space weather (e. g., Biasiotti et al., 2024; Laurenza et al., 2024; Pignalberi et al., 2024). In summary, the development of the ASPIS prototype provided efficient storage, sophisticated organization, and explanative visualization of interdisciplinary space weather data and products, fostering collaborations within the community and supporting the promotion of education and awareness in space weather.

3.2.7. UAH/Spain

The Space Weather Research Group at the University of Alcala (SWE-UAH) has demonstrated experience of all stages from the Sun to the Earth for more than 20 years, not only from a research field of view, but also developing space weather products. UAH-SWE leads the Spanish Space Weather Service (SeNMEs) and is involved in the ESA SSA SWE Network through the Geomagnetism-Expert Centre.

Main research at SWE-UAH is funded by the Spanish Ministry of Science and Innovation (MICINN). The main scientific efforts are dedicated to

- CMEs, associated solar activity and solar wind counterparts
- Radio burst and GNSS impact
- Local geomagnetic activity
- Forecasting solar wind and geomagnetic activity using artificial intelligence

Also, SWE-UAH has led an ESA project for the development of space weather products for Southern Europe, as the natural continuation of a previous project to identify the space weather user needs for the Mediterranean Region. Also, SWE-UAH is participating in an ESA project to retrieve solar flux from the SMOS/MIRAS Mission, which was initially planned as an Earth Observation Mission. Considering the successful results, the SMOS Mission will be considered by ESA for Space Weather Operations, taking into account the potential of near real-time solar observation at 1.4 GHz from the MIRAS instrument.

3.2.8. Roshydromet/Russia

Fedorov Institute of Applied Geophysics (IAG) is a full-featured space-weather monitoring and forecasting center. It is also a part of the China-Russia Consortium, a global space-weather center for ICAO. Primary lines of research include new ionosphere models and methods of monitoring and forecasting, solar-terrestrial physics, geomagnetic field study, and the effects of space weather on stakeholders.

3.2.9. Irf-sweden

The Swedish Institute of Space Physics (IRF) has conducted space weather research and operation for more than 20 years in close collaboration with Swedish users. Research has been funded through many different grants provided by EU and national bodies like Swedish Civil Contingencies Agency (MSB) and the Swedish Research Council (VR), with more application driven development through ESA S2P. IRF also became a member of ISES in 2000.

Over the last years it has become clear that coordination on a national level is required due to the increased Swedish space weather user community. Recently, the Swedish Coordination Team in Space Weather (CSG Rymdväder) was established that gathers the main governmental bodies interested in space weather. It was agreed on the necessity to establish a dedicated centre for space weather in the coming years, in order to achieve the national capability of space situational awareness deemed necessary.

3.2.10. Met Office/UK

Severe space weather was added to the UK National Risk Register in 2011 and the Met Office Space Weather Operations Centre (MOSWOC) was opened in 2014 to supply forecasts and alerts and to help build resilience of the UK industries and infrastructure to space weather events. A cross- Government Severe Space Weather Steering Group (SSWSG), was established in 2015, committed to increasing resilience to UK critical infrastructure. Members of the SSWSG include experts from Government Departments, academia and industry and is led by the Department for Business, Energy and Industrial Strategy (BEIS). The UK Space Energy (UKSA) works with BEIS to deliver the UK's civil space programme. UKSA also collaborates with international partners to develop the infrastructure to monitor space weather.

Research to operations focused on improving MOSWOC forecasts was initially carried out on an ad hoc basis but was boosted by the introduction of a four-year programme, SWIMMR, which began in 2020 with the aim of developing and deploying new instruments, models and services to support the UK space weather community and MOSWOC. The programme shall introduce new forecast models to mitigate space weather hazards to satellites, aviation, ground-based services (e.g power grid), satellite orbital tracking and position, navigation and timing. It is also developing a framework forsupporting the transition of models and data sets from research in the academic community to operational use for space weather forecasting by MOSWOC.

BEIS, in collaboration with the Ministry of Defence and UKSA also published a National Space Strategy in 2021 highlighting international collaboration with partners and allies, and committing to continued collaboration on space missions including monitoring of space weather events. A UK Severe Space Weather Preparedness Strategy (SSWPS) was also published in 2021. The Strategy outlines a series of commitments by the government to work with industry, academia and international partners to increase the UK's understanding and preparedness for a severe space weather event.

Future developments are driven by the SSWPS. This is based on 3 "pillars":

- The Assess Pillar focuses on enhancing our understanding of severe space weather, its impacts, and our ability to forecast events.
- The Prepare Pillar focuses on increasing the resilience of essential infrastructure and services on which we rely
- The Respond & Recover Pillar focuses on ensuring the UK can respond to events effectively and recover from them quickly

Scientific activities fall largely within the Assess Pillar. Relevant current activities include the SWIMMR programme, UK support for the ESA Vigil mission to L5 and better understanding the impacts of space weather (e.g. on aviation, power grid, etc).

While the SWIMMR programme will boost our capability significantly, space weather remains an evolving field with much scope for further research after SWIMMR's conclusion. Beyond 2024, the UK Government and the academic community will develop a potential pipeline for further research activity.

3.3. ASIA & Oceania

3.3.1. Bureau of Meteorology/Australia

Data driven modelling is heavily used to support space weather forecasting operations and in the Bureau's Research to Operation Space Weather (R2OSW) activities. Several models focusing on real-time monitoring, forecasting and the customized response to significant space weather events have been developed and continuously expanded through collaborative projects with a number of national and international organizations and universities. Some of the space weather research focus areas at the Bureau include:

Two solar flare forecasting models; Flarecast, an empirical model based on solar active region magnetic field characteristics (Steward et al., 2011, 2017), and a Flare Probability model, a statistical model used to automatically estimate the probability over the next 24 h of an X-ray solar flare with peak flux magnitude ≥ M1, ≥ M5, and ≥ X1 based on solar region characteristics. Future development plans include combining both models. The outputs of these models are made available through the WMO Information System.

A Severe Space Weather (SSW) model that provides both binary and probabilistic forecasts for SSW geomagnetic storms (Dst < -250nT) from solar parameters, underpinning alerts for critical infrastructure groups.

Ionospheric specification and forecasting products and services that include:

- ○ Near real-time global critical ionospheric frequency (foF2) maps produced using automatically scaled ionogram profiles from the Australian region and around the world, and the IRI model as a background.
- ○ A storm time ionospheric forecast model to support daily operations at ASWFC, used to guide forecasters rather than generating end-user forecasts (Kumar et al., 2017).
- ○ Regional TEC maps and related products derived from Global Navigation Satellite System (GNSS) data processing and Spherical Cap Harmonic Analysis (SCHA) (Bouya et al., 2010). Future developments include the

investigation of shorter wavelength features (ionospheric dynamics over Australia), and the detection of gradient structures and alerts of their existence and potential impacts on the operations of relevant technologies.

- Ionospheric scintillation monitoring and forecasting products include a near real-time S4 index map as recorded by the Bureau's Ionospheric Scintillation Monitors (ISMs) network, plots of recent ionospheric scintillation conditions at SWN monitoring sites, and an alert service based on the discrete monitoring sites. In addition to the S4 index map, the ASWFC also produces a wider regional map using one second sampled GNSS TEC data based on a calibrated Rate-Of-Change of TEC Index (ROTI) recorded by standard CORS dual-frequency GPS receivers. Ongoing research and collaborations with academia on ionospheric scintillation forecasts and the effects of geomagnetic storms on the occurrence of Equatorial Plasma Bubbles (Carter et al., 2014a, Carter et al., 2014b) is being operationalized to provide scintillation forecasts to be delivered by the ASWFC.
  - Geomagnetically Induced Current (GIC) modelling for the power industry aimed at predicting and understanding the impact of geomagnetic storms on power networks in Australia (Marshall et al., 2017, Marshall et al., 2019). R2OSW collaborates with a number of national organizations and universities to develop and improve GIC products and services (Marshall et al., 2013, Carter et al., 2016).

3.3.2. China/NSSC

The Chinese space weather community has been developing numerical prediction models capable of simulating the complex systems instead of focusing solely on forecasting a single index or physical parameter. Moreover, innovative approaches such as artificial intelligence are applied in space weather forecasts. Significant work has been done by the Chinese space weather community through combining the field of space environment prediction with artificial intelligence (AI) technology, including the recognition of active regions (Fang et al., 2019), solar flare prediction (Deng et al., 2023, Li et al., 2022, 2023; Liu et al., 2023; Huang et al., 2018; Wang et al., 2020, 2023b), CME and solar wind prediction (Chen et al., 2022; Fu et al., 2021; Lin et al., 2024; Shi et al., 2021; Wang et al., 2023c), geomagnetic index prediction (Luo et al., 2017; Wang et al., 2023a), and ionospheric TEC prediction (Shi et al., 2022; Xia et al., 2021; Xie et al., 2023; Zhang et al., 2024). An international team on AI in space weather has been supported by the international space science institute-Beijing (ISSI-BJ). In general, the application of artificial intelligence in space weather forecasting is still in the experimental stage and not yet fully mature. This highlights the substantial potential for further development and refinement of artificial intelligence technologies in space environment forecasting.

3.3.3. India

Space weather research focus in India was earlier limited mostly to understanding the physical mechanisms and drivers of space weather, rather than a focus on predictions. Recently, this is changing with coordinated national efforts, and individual organizations leveraging fundamental understanding towards development of forecasting capabilities which is being seen as a national need. The Indian Space Research Organization (ISRO) tasked the Aditya-L1 Space Weather Monitoring and Predictions committee to create a roadmap for utilization of data and models towards development of space weather monitoring and forecasting capabilities, which has now been submitted. The key recommendations of this report include:

- The capability to generate space weather alerts or "flags" from instruments onboard the Aditya-L1 spacecraft and their dissemination
- Development of efficient pipeline for space weather relevant data products
- Creation of centralized space weather modelling and orecasting facilities
- Develop complementary modelling capability for data-driven forecasts.
- Assimilate complementary ground- and space-based data from Indian facilities and make them available through a virtual observatory for facilitating space weather research.
- Develop the capability for monitoring and modelling deep space weather near planetary bodies like Mars, Venus and the Moon
- In the long-term develop capacity for new missions for monitoring state of the ionosphere-magnetosphere systems, multi-vantage point observations of the inner heliosphere, and missions beyond near-Earth orbit.

3.3.4. New Zealand

In New Zealand the primary space weather activity is currently scientific research and data collection. The Space Physics group of the University of Otago is probably the most active set of researchers working on space weather problems in New Zealand, with Victoria University of Wellington researchers active in investigating space weather impacts on the natural gas pipeline network (e.g., Ingham and Rodger, 2018) and power grids (e.g., Mukhtar et al., 2020). As noted earlier, New Zealand has magnetic observatories at Eyrewell and Scott Base, operated by GNS Science and contributing to the international INTERMAGNET network (http://www.intermagnet.org/).

3.3.5. NICT/Japan

NICT started its 5-year research period in 2021. NICT space weather R&O plan shows three categories; observation, forecast and service. NICT has been developing a numerical ionospheric model named GAIA for future ionospheric forecast. A data assimilation system for operational ionospheric forecast is expected to begin operating by the end of March 2026. The following data are planned to be used as input for GAIA; (1) meteorology reanalysis data, (2) ionospheric occultation data by COSMIC2/FORMOSAT7, and (3) ground based GNSS and ionosonde data.

Some applications are being developed for users even if they have no knowledge of space weather. HF-START is one of the examples, which visualize radio propagation with real time ionospheric measurements with domestic GNSS network GEONET.

- Observation: As a new trial, NICT started to develop space weather monitoring with satellite sensors. The gap area of ground-based observation will be filled with international cooperation.
- Forecast: NICT will start a numerical forecast system with data assimilation. AI-based forecast models are also used with big legacy databases.
- Service: NICT will continue to survey the needs of space weather information users and develop applications and disseminate appropriate information.

3.3.6. KSWC/Korea

Space weather research of the scientific and operational purpose in Korea is focused on the development of the early detection, accurate forecasting and customized response technologies of high-impact space weather events. Especially AI-based new technologies (e.g., Kim et al., 2019; Park et al., 2021) have been actively developed and will be applied into the operational monitoring and forecasting tasks through the Research to Operation (R2O) process.

3.3.7. TSA/Thailand

Currently, key research focus of Thai researchers includes the study of

- Cosmic rays, solar flares, solar storms (Pongkitiwanichakul et al., 2021; Chaiwongkhot et al., 2021; Chhiber et al., 2021);
- Equatorial plasma bubbles, ionospheric disturbances which can be observed by hybrid sensors such as ionosondes (sporadic E, spread F), GNSS receivers (TEC, ROTI), satellite beacon receivers (Thammavongsy et al.,2022; Maruyama et al.,2021; Kenpankho et al., 2021; Budho et al., 2020; Jamjareegulgarn et al., 2020);
- Space weather effects on modern technologies (electric power grid, satellites, communication, navigation, precise positioning);
- Local K index, and
- Artificial intelligence (AI) for space weather data

4. Coordination efforts

International discussions on space weather uncovered the need for services and stimulated scientific groups around the world. Specific examples are arranging terrestrial and space instruments to make them available in near real-time and running them in operational mode. As a result, the need for cooperation to cover the anisotropic distribution of the Sun-Earth coupling to plasma irregularities of all scale sizes, which to a large extent are directly connected with anisotropies in the Earth's magnetosphere, was quickly recognized.

4.1. AMERICAS & AFRICA

4.1.1. LAMP/UBA-IAFE(CONICET)-IAA/Argentina

LAMP is the Argentine regional warning center inside ISES (International Space Environment Service), officially appointed as the Argentine Regional Warning Center (RWC) since 2020. It provides operative products, issues alerts, and articulates with different national organizations to propose mechanisms and defense procedures for technological space systems. In particular, it has permanent dialogue with other organizations, such as the Space agency of Argentina (CONAE), the national meteorological service of Argentina (SMN), different national universities, and other national sectors with interests on space weather. LAMP participated in the recent implementation of the SWx information service to ICAO (International Civil Aviation Organization), auditing several centers as part of a space weather committee (Inter-Programme Team on Space Weather Information, Systems and Services, IPT-SWeISS) of the World Meteorological Organization (WMO).

LAMP-Neurus participated in the recent international WHPI (Whole Heliosphere and Planetary Interactions) campaign during Jan-Feb of 2020 accompanying NASA's satellite Parker Solar Probe offering our ground level high latitude Observatory measurements.

Table 25 presents a list of the main organizations with which LAMP collaborates on space weather issues (national and international):

4.1.2. UNLP/MAGGIA LABORATORY/Argentina

The main products of the laboratory are freely available. vTEC maps are in near-real-time (https://wilkilen.fcaglp.unlp.edu.ar/ion/latest.png). Different TEC products, and geomagnetic field data generated by the Trelew Geophysi-

Table 25
Collaborations.

Project/ organization name	Description
ALL4SPACE	International League for Space Weather Services between Argentina, Brazil, Chile and Mexico
ROB	Royal Observatory of Belgium/Belgium
ISWI	International Space Weather Initiative (being part as one of the two National representative from Argentina)
RAPEAS	Red Argentina Para el Estudio de la Atmósfera Superior/Argentina
CONAE	Comisión Nacional de Actividades Espaciales/Argentina
COSPAR	Committee on SPAce Research (being part of the Panel on Space Weather, PSW)
EMBRACE/ INPE	Instituto Nacional de Pesquisas Espaciais/Brazil (signed agreement of collaboration)
WMO	World Meteorological Organization (being part of the Expert team on Space Weather, ET-SWx)
ICAO	International Civil Aviation Organization
SMN	Servicio Meteorológico Nacional/Argentina (signed agreement of collaboration)
UNT	Universidad Nacional de Tucuman/Argentina
UNLP	Universidad Nacional de La Plata/Argentina
GRAPE/SCAR	GNSS (Global Navigation Satellite System) Research and Application for Polar Environment at SCAR (scientific committee on antarctic research)
DCAO	Departamento de Ciencia de la Atmósfera y Los Océanos
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
LAGO	Latin American Giant Observatory (participating on space weather programs)
AUGER	Pierre Auger Observatory (participating on space weather programs, Dasso et al. 2012).
IAA	Instituto Antártico Argentino/Argentina
IAFE	Instituto de Astronomía y Física del Espacio (UBA-CONICET)
ISES	International Space Environment Service (LAMP is the Regional Warning Center for Argentina)
ALAGE	Asociación Latino Americana de Geofísica Espacial (Latin American Space GeoPhysics Organization)
WHPI	Whole Heliosphere and Planetary Interactions
MACKENZIE	Universidade Presbiteriana Mackenzie
NASA	National Aeronautics and Space Administration/USA
SCiESMEX	Servicio de Clima Espacial México/Mexico
LANCE	Space Weather National Laboratory/Mexico

Table 26
National/International cooperation.

Organization name	Description
IMB	Institut Royal Météorologique de Belgique/Belgium
EARG	Estación Astronómica Río Grande/Argentina
CONAE	Comisión Nacional de Actividades Espaciales/Argentina
BKG	Federal Agency for Cartography and Geodesy/Germany
INPE	Instituto Nacional de Pesquisas Espaciais/Brazil
RAMSAC	Red Argentina de Monitoreo Satelital Continuo/Argentina
CITEDEF	Instituto de Investigaciones Científicas y Técnicas para la Defensa/Argentina
SMN	Servicio Meteorológico Nacional/Argentina
UNT	Universidad Nacional de Tucuman/Argentina
INTERMAGNET	International Real-time Magnetic Observatory Network (world-wide consortium of institutes)
DCAO	Departamento de Ciencia de la Atmósfera y Los Océanos
IBGE	Instituto Brasileiro de Geografia e Estatística / Brazil
SGM	Servicio Geográfico Militar/ Uruguay
IGAC	Instituto Geográfico Agustín Codazzi/ Colombia
CSN	Centro Sismológico Nacional/ Chile

cal Observatory (TRW) for INTERMAGNET (International Real-time Magnetic Observatory Network) are also available. Table 26 shows the present established cooperations.

4.1.3. UNT/TSWC/Argentina

TSWC main products are related to ionospheric parameters (derived from GNSS, ionosonde and Doppler radar system) and data avaibility (https://spaceweather.facet.unt.edu.ar/).

TSWC participated in space weather panels and working groups including panels in the Argentine space program(CONAE). It is worth mentioning that data from both ionosondes currently are used for HF operative products.

National and international collaborations are detailed in Table 27.

4.1.4. CRAAM/Brazil

CRAAM has been collaborating with Brazilian and International Operational Space Weather Services in Bra-

Table 27
Collaborations.

Project/Organization	Description
ISWI	International Space Weather Initiative (being part as one of the two National representative from Argentina)
RAPEAS	Red Argentina Para el Estudio de la Atmósfera Superior/Argentina
CONAE	Comisión Nacional de Actividades Espaciales/Argentina
EMBRACE/INPE	Instituto Nacional de Pesquisas Espaciais/Brazil (signed agreement of collaboration)
SMN	Servicio Meteorológico Nacional/Argentina (signed agreement of collaboration)
UTN- FRT	Universidad Tecnológica Nacional – Facultad Regional Tucumán/ Argentina (signed agreement of collaboration)
UTN-BB	Universidad Tecnológica Nacional – Facultad Regional Bahía Blanca/ Argentina (signed agreement of collaboration)
UNQ	Universidad Nacional de Quilmes, Buenos Aires/ Argentina
DCAO	Departamento de Ciencia de la Atmósfera y Los Océanos-UBA/ Argentina
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
LAGO	Latin American Giant Observatory (participating on space weather programs)
CAS	Institute of Atmospheric Physics CAS/ Czech Republic (signed agreement of collaboration)
INGV	Istituto Nazionale di Geofisica e Vulcanologia, Italy (signed agreement of collaboration)
STI-ICTP	Science, Technology and Innovation – International Centre for Theoretical Physics (Ionospheric Physics, Ionospheric Modelling, Space Weather group)
CInFAA	Centro Interuniversitario de Física de Alta Atmósfera (CInFAA)/Chile
IAA	Instituto Antártico Argentino/Argentina
IAFE	Instituto de Astronomía y Física del Espacio (UBA-CONICET)/ Argentina
UNS	Univerdidad Nacional del Sur/ Argentina
ALAGE	Asociación Latino Americana de Geofísica Espacial (Latin American Space GeoPhysics Organization)
RAMSAC	Red Argentina de Monitoreo Satelital Continuo/Argentina
NASA	National Aeronautics and Space Administration/USA
AGATA/SCAR	Antarctic Geospace and Atmosphere research/ Scientific Research Programme/ Scientific Committee on Antarctic Research

zil, mainly with the EMBRACE Program. There is also collaboration with space weather groups in Peru, mainly at CONIDA (Peruvian Space Agency) and IGP (Peruvian Geophysics Institute). The high quality of AFINSA data results were included in an even more extended network, GLOCAEM (Global Coordination of Atmospheric Electricity Measurements).

CRAAM was part of the pioneer initiative which resulted in the IHY (International Heliophysical Year) up to 2009, and in the International Space Weather Initiative (ISWI) since 2009.

AFINSA and SAVNET are part of the instrumental network of ISWI.

4.1.5. EMBRACE/BRAZIL

This program installs instrumentation of interest to space weather over Brazil and neighboring countries performing data collection, archiving data and disseminating relevant information through the web portal. The archive of data collection deployed to Embrace are freely distributed on the web portal (https://www2.inpe.br/climaespacial/SpaceWeatherDataShare/ e https://www2.inpe.br/climaespacial/SWMonitorUser/?lan=pt). Table 28 has the national/international cooperation constructed to run the program.

As a representative of Brazilian services for the World Meteorological Organization (WMO) and in cooperation with ICAO, EMBRACE is currently working on the new international regulations for civil aviation, establishing a partnership with the Brazilian authorities for aviation (e.g., DECEA –Airspace Control Department) to train and develop a regional center for aviation services.

Member of All4Space – A league for strengthening cooperation in Latin America was constructed early 2022. An alliance was created with four Latin American countries, Argentina, Brazil, Chile, and Mexico. The start

Table 28
National/international cooperation.

Project/Organization	Description
ALL4SPACE	International League for Space Weather Services between Argentina, Brazil, Chile and Mexico
EARG	Estacion Astronomica Rio Grande/Argentina
IBGE	Instituto Brasileiro de Geografia e Estatística
ICEA	Instituto de Controle do Espaço Aéreo
IEAv	Instituto de Estudos Avançados
INSUGEO	Instituto Superior de Correlación Geológica
ISES	International Space Environment Service
IAFE	Instituto de Astronomía y Física del Espacio
MACKENZIE	Universidade Presbiteriana Mackenzie
NASA	National Aeronautics and Space Administration/USA
NICT	National Institute of Information and Communications Technology/Japan
IMCP/NSSC	International Meridien Circle Project/National Space Science Center/China
NOAA	National Oceanic and Atmospheric Administration
ON	Observatório Nacional
ROB	Royal Observatorium of Belgium/Belgium
ROJ	Radio Observatorio de Jicamarca/Peru
SCiESMEX	Servicio de Clima Espacial México/Mexico
LANCE	Space Weather National Laboratory/Mexico
STELAB	Nagoya University Solar Terrestrial Environment Laboratory/Japan
UCH	Universidad de Chile/Chile
UEMA	Universidade Estadual do Maranhão
UFCG	Universidade Federal de Campina Grande
UFRR	Universidade Federal de Roraima
UFSM	Universidade Federal de Santa Maria
UNESP	Universidade Estadual de São Paulo
UNIVAP	Universidade do Vale do Paraíba
UCAR	University Corporation for Atmospheric Research/USA
UNLP	Universidad Nacional de La Plata/Argentina
UNT	Universidad Nacional de Tucumán/Argentina

of the services in space weather in Latin America with operational centers is analyzed in Denardini et al., 2016c.

4.1.6. NRCanada/CANADA

Canada's space weather forecast services are facilitated by its membership in the International Space Environment Service (ISES) and the exchange of data with other ISES regional warning centres. Canada is also a partner, with Australia, France and Japan in the ACFJ consortium that was selected by the International Civil Aviation Organisation (ICAO) as one of the global service providers of space weather advisories to international aviation. Canada has also contributed to the work of the International Standards Organisation (ISO) in the development of standards for managing stray current effects on pipelines.[11]

Within North America there are particularly close ties between the United States and Canada because of the infrastructure (particularly power systems) that is connected across the border. This has led to joint work through the North American Electric Reliability Corporation (NERC) in the development of geomagnetic disturbance guidelines for power utilities.[12]The Canadian Space Weather Forecast Centre has also collaborated with the US Space Weather Prediction Center in the production of real-time geoelectric field maps for the US and Canada. The Canadian Space Agency has recently signed an implementing arrangement with NASA to support heliospheric missions using Canadian ground-based instruments.

4.1.7. SAPL-UChile/CHILE

The current projects conducted by the Laboratory are contributing to strengthening the space science activities in Chile with a special focus on space weather. The support is also strengthening the existing cooperation between Chilean and American scientists and enhancing the research/training infrastructure of Chilean universities, which will also strongly energize and benefit regional universities. Furthermore, the proposed research is done in close collaboration with collaborators of the "International League for Space Weather Services" (ALL4SPACE) from Brazil, Mexico, and Argentina.

[11] ISO 21857:2021. Petroleum, petrochemical and natural gas industries —Prevention of corrosion on pipeline systems influenced by stray currents, https://www.iso.org/standard/72085.html.

[12] NERC TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events, https://www.nerc.com/pa/Stand/Reliability Standards/TPL-007-1.pdf.

4.1.8. LANCE/Mexico

LANCE-SCIESMEX represents Mexico in ISES and the World Meteorological Organization (WMO). It also participates in the ALL4SPACE alliance. Table 29 shows the present established cooperation.

4.1.9. IGP/Peru

IGP/JRO cooperates with installation, maintenance, and operation of several instruments in Peru and South American countries to monitor space weather conditions on the Peruvian and South American sector.

Most of the instrumentation data can be found at the following link:

https://lisn.igp.gob.pe/

Table 30 has the national/international cooperation constructed to run IGP/JRO.

4.1.10. SANSA/South Africa

Table 31 shows the present established cooperation.

4.1.11. NOAA, NASA, NSF/United States of America

The U.S. space weather effort is guided by the National Space Weather Strategy and Action Plan that was put in place in 2019. Following this national plan, U.S. policy to mitigate the impacts of space weather was codified by the PROSWIFT Act, which was signed into law in 2020 (https://www.congress.gov/bill/116th-congress/senate-bill/881/text).

4.2. EUROPE

4.2.1. UNIGRAZ/Austria

The University of Graz (Austria) has expert groups on solar physics (A. Veronig) and heliospheric physics (M. Temmer). Both groups actively contribute to ESA's Space Situational Awareness and Space Safety Program Space covering the following segments: Solar Weather, Heliospheric Weather and Ionospheric Weather. The data products provided are:

- real-time Halpha images and movies
- white light images
- real-time flare detection and warning in H-Alpha images
- real-time filament detection and catalog
- solar wind high-speed stream forecast (ESWF, ESWF24, STEREO + CH)
- Drag-based ensemble model of CME propagation (DBEM)
- Satellite Orbit Decay Forecast Service (SODA)

For Kanzelhöhe Observatory (KSO) ESA products on solar weather (flare and filament detection) see: Pötzi et al. (2013, 2018). For papers on UNIGRAZ ESA products on heliospheric and ionospheric weather: ESWF

Table 29
National/international cooperation.

counterpart organizations	cooperation	description
National Civil Protection System	public policies of civil protection in space weather	Collaboration to increase the country's resilience toward space weather hazards.
ALL4SPACE	cooperative research	International League for Space Weather Services, Argentina, Brazil, Chile and Mexico
ISES	cooperative operation	International Space Environment Service
EMBRACE	cooperative observations	INPE, Brazil
UBA	cooperative observations	Universidad de Buenos Aires, Argentina
NOAA	cooperative observations	National Oceanic and Atmospheric Administration
ISEE	cooperative observations	Nagoya University, Japan

Table 30
National/international cooperation.

Organization	Description
UT Dallas	University of Texas at Dallas, USA
IAP	The Leibniz Institute of Atmospheric Physics, Germany
ORION (ASTRA)	Orion Space, USA
UNICA	Universidad Nacional "San Luis Gonzaga" de Ica, Peru
Cornell	Cornell University, USA
PSU	Pennsylvania State University, USA
Marina	Dirección General de Capitanías y Guardacostas, Peru
Illinois	University of Illinois, USA
NJIT	New Jersey Institute of Technology, USA
UDEP	Universidad de Piura, Peru
BU	Boston University, USA
EMI	Escuela Militar de Ingeniería de Bolivia
UNSTA	Universidad del Norte Santo Tomás de Aquino de Argentina

Table 31
National/international cooperation.

Organization Name	Working Group
National and Regional Coordination	
Space Weather Working Group	Stakeholder Engagements
Air Traffic & Navigation Services (ATNS) and South African Weather Service (SAWS)	ACAMS/OPSCOM/ ATM/Cns implementation group
IIM/SG APIRG	Met Project 3 – AFI Region
International Coordination	
The Committee on Space Research (COSPAR)	Panel on Capacity Building (PCB)
UK Met Office	Space Weather Forecast
The World Meteorological Organization (WMO)	Inter-Programme Team on Space Weather Information Systems and Services (IPT-SWeISS) under the Task Team on Space Weather for Aviation (TT-AVI)
The United Nations Committee on the Peaceful Uses of Outer Space (UN/COPUOS)	Space Weather Expert Group (closed in 2022)
The International Civil Aviation Organization (ICAO)	ICAO METP Space Weather Centre Coordination Group
Pan-European Consortium for Aviation Space weather User Services (PECASUS)	Space Weather Information for Aviation
The International Reference Ionosphere (IRI)	Joint COSPAR-URSI Working Group

(Rotter et al., 2015; Reiss et al., 2016), STEREO + CH (Temmer et al., 2018), DBEM (Calogovic et al., 2021), SODA (Krauss et al., 2020).

In addition, Kanzelhöhe Observatory is one of the providers to the international Sunspot Numbers (full Sun and hemispheric) that are collected at Sunspot Index and Long-term Solar Observations (SILSO; Pötzi et al., 2016, Veronig et al., 2021).

4.2.2. FMI/Finland

Like described above, Finland contributes to networks producing space weather observations. At least the following services offer data on-line (but not necessarily near-real-time): IMAGE Magnetometer network (fmi.fi); SGO Real-time Data; Madrigal database at EISCAT; Electronic Space Weather upper atmosphere (eSWua) (ingv.it);

FMI operates a 24/7 space weather duty system. Its products include warnings and advice to national authorities and a public daily aurora forecast. In addition, FMI leads the international PECASUS consortium, which is one of the four global centres providing space weather services for aviation according to ICAO standards and practices. FMI and University of Turku (UT) contribute to several products in the ESA space weather portal (https://swe.ssa.esa.int/).

4.2.3. CNES/France

CNES supports modelling and instruments/observations that impact satellite operations through contracts with ONERA, the SAGAIE network, and space weather research through modest grants.

The ANR ASTRID program supports SW projects (e.g. PRISM-IRAP/TAS) and there is French participation to many on-going H2020 projects (e.g. SERPENTINE, EUHFORIA 2.0, SafeSpace, PITHIA-NRF).

4.2.4. DLR/Germany

Table 32 shows the present established cooperation with international organizations.

4.2.5. UGOE/Germany

Table 33 shows the present established cooperation.

4.2.6. ASI/Italy

The scientific key needs have been discussed in Plainaki et al., 2020, also in the context of the ILWS COSPAR roadmap; the related recommendations were also discussed in the same paper.

4.2.7. UAH/Spain

UAH is participating in the ESA SWE Network and fully involved in e-SWAN.

4.2.8. Roshydromet/Russia

Fedorov Institute of Applied Geophysics (IAG) represents ROSHYDROMET/Russia at the international bodies of the UN: ICAO and WMO. IAG is a part of the International Space Environment Service, a network of space weather providers worldwide.

4.2.9. IRF/Sweden

Table 34 shows the present established cooperation.

4.2.10. Met Office/UK

Severe space weather was added to the UK National Risk Register in 2011 and the Met Office Space Weather Operations Centre (MOSWOC) was opened in 2014 to supply forecasts and alerts and to help build resilience of the UK industries and infrastructure to space weather events. A cross- Government Severe Space Weather Steering Group (SSWSG), was established in 2015, committed to increasing resilience to UK critical infrastructure. Members

Table 32
DLR contribution to space weather international organization and coordination efforts.

Organization	Full Name	Working Group
COSPAR	Committee on Space Research	Panel of Space Weather
EISCAT	European Incoherent Scatter Scientific Association	Science Advisory Committee (SAC)
E-SWAN	European Space Weather and Space Climate Association	
IAGA	International Association of Geomagnetism and Aeronomy	GeoDAWG
IAG	International Association of Geodesy	SC 4.3 Atmosphere Remote Sensing, WG 4.3.3 Ionosphere scintillations
IAG	International Association of Geodesy	SC 4.3 Atmosphere Remote Sensing, WG 4.3.2 Prediction of ionospheric state and dynamics
IAG	International Association of Geodesy	SC 4.3 Atmosphere Remote Sensing JWG 4.3.1 Real-time ionosphere monitoring and modelling
IAG-GGOS	International Association of Geodesy-Global Geodetic Observing System	JWG 1: Electron density modeling under FOCUS AREA: Geodetic Space Weather Research
IAG-GGOS	International Association of Geodesy-Global Geodetic Observing System	JWG3: Improved understanding of space weather events and their monitoring
ISSI	International Space Science Institute	International Team ID 49 “Data Assimilation in the Ionosphere and Thermosphere
ISWI	International Space Weather Initiative	German representative of the International Space Weather Initiative
NATO	North Atlantic Treaty Organization	NMSG-187 Space Weather Environmental Modelling (SWEM)
UN-Space Weather Expert Group (closed in 2022)	COPUOUS	United Nations Committee on the Peaceful Uses of Outer Space
WMO	World Meteorological Organization	Inter-Programme Team on Space Weather Information Systems and Services (Closed, re-structuring at WMO in progress)

Table 33
UGOE contribution to space weather international organization and coordination efforts.

Organization	Full Name	Working Group
ESA	European Space Agency	Advisory Group
DLR	German Space Agency	National Panel
ESWW	European Space Weather	Program Committee

of the SSWSG include experts from Government Departments, academia and industry and is led by the Department for Science, Innovation and Technology (DSIT). The UK Space Agency (UKSA) works with DSIT to deliver the UK’s civil space programme. UKSA also collaborates with international partners to develop the infrastructure to monitor space weather.

Research to operations focused on improving MOSWOC forecasts was initially carried out on an ad hoc basis but was boosted by the introduction of a four-year programme, SWIMMR, which began in 2020 with the aim of developing and deploying new instruments, models and services to support the UK space weather community and MOSWOC. The programme will introduce new forecast models to mitigate space weather hazards to satellites, aviation, ground-based services (e.g power grid), satellite orbital tracking and position, navigation and timing. It also developed a framework for supporting the transition of models and data sets from research in the academic com-

Table 34
National/international cooperation.

Institution	Operational Space Weather Service
MSB (Swedish Civil Contingencies Agency), RF (Swedish Institute of Space Physics), METOCC (Meteorological and Oceanographic Centre of Swedish Armed Forces), SVK (Svenska Kraftnat), LFV (The Swedish Civil Aviation Administration), SMHI (Swedish Meteorological Institute), FOI (Swedish Defense Research Agency)	CSG Rymdväder (Swedish Coordination Team in Space Weather)
IRF	ESA S2P
IRF	ISES

munity to operational use for space weather forecasting by MOSWOC.

The UK Government, in collaboration with UKSA, also published a National Space Strategy in 2021 highlighting international collaboration with partners and allies, and committing to continued collaboration on space missions including monitoring of space weather events. A UK Severe Space Weather Preparedness Strategy (SSWPS) was also published in 2021. The Strategy outlines a series of commitments by the government to work with industry, academia and international partners to increase the UK's understanding and preparedness for a severe space weather event.

Future developments are driven by the SSWPS. This is based on 3 "pillars":

- The Assess Pillar focuses on enhancing our understanding of severe space weather, its impacts, and our ability to forecast events.
- The Prepare Pillar focuses on increasing the resilience of essential infrastructure and services on which we rely.
- The Respond & Recover Pillar focuses on ensuring the UK can respond to events effectively and recover from them quickly.

Scientific activities fall largely within the Assess Pillar. Relevant current activities include completing the operationalization of developments from the SWIMMR programme, UK support for the ESA Vigil mission to L5 and better understanding the impacts of space weather (e.g on aviation, power grid, etc).

While the SWIMMR programme will boost our capability significantly, space weather remains an evolving field with much scope for further research after SWIMMR's conclusion. As indicated above, the Met Office are now completing the oprationalization of SWIMMR developments, while the UK Government and the academic community continue to work on developing a potential pipeline for further research activity. Table 35 shows the present established cooperation.

4.3. ASIA & OCEANIA

4.3.1. NCCS/China

National Space Science Center (NSSC) of Chinese Academy of Sciences provides common products of space weather indices and space weather event alerts, as well as detailed analysis of space radiation conditions and their effects on satellites (Liu and Gong, 2015). Recently NSSC has provided space weather services for China space missions, including the China Space Stations and Mars Mission Tianwen-1, as listed in Table 36.

Table 35
National/international cooperation.

Activity	UK participants
WMO Expert Team on Space Weather	Met O (1 team member + 1 secondee)
ISES	Met O, UKRI STFC RAL Space, BGS
COSPAR Panel on Space Weather	UKRI STFC RAL Space, Met O
UN/COPUOS	UKRI STFC RAL Space, BGS, BAS, Met O, UKSA
ICAO space weather services	Met O (via PECASUS consortium)
ESA space safety (space weather services (input across all ESCs plus leadership ofH-ESC) and new instruments (eg Vigil, SURROUND))	Numerous, chiefly Met O and UKRI STFC RAL Space
ESA Virtual Space Weather Modelling Centre	Sheffield (CTIP), Imperial College (Gorgon), UCLan (SPARX)
IAGA, URSI, IAU	IAGA: BGS; URSI: Birmingham, UKRI STFC RAL Space; IAU: Numerous

Table 36
Space weather services provided by SEPC.

China space missions	Space weather services
China Space Station (CSS)	● long-term SEE numeric evaluation during design period ● Mid-term and short-term forecast for launch window ● daily nowcast and forecast for in-orbit period ● analysis of the space radiation conditions on the orbit ● atmosphere density forecast for orbit prediction ● evaluation of the radiation dose inside/outside the space station core module Tianhe ● space weather forecast for astronauts' spacewalk ● space weather event prediction ● time periods and energy spectrum flux prediction when CSS crosses the South Atlantic Anomaly (SAA), which helps to determine the control strategy when the satellite crosses the SAA.
Mars Mission Tianwen-1	forecasting space weather events, solar wind parameters, ionosphere density, etc

4.3.2. India

The Indian space weather monitoring and predictions roadmap recognizes the importance of national and global coordination in the peaceful exploration of outer space. The Center of Excellence in Space Sciences India (CESSI) is involved in a multi-institutional initiative to develop the tools for operational space weather forecasting (https://www.cessi.in/spaceweather). The Indian roadmap recommends a joint observing plan with instruments and missions from around the world. Science definition teams for joint science should be identified and other space agencies should be approached to form multi-instrument teams. COSPAR may be able to play a role as a facilitator for such international partnerships.

4.3.3. New Zealand

New Zealand provides representatives to relevant international scientific coordinating bodies, with examples being COSPAR, SCOSTEP, IAGA, and URSI. The country was also represented on the World Meteorology Organization (WMO) Inter-Programme Team on Space Weather Information, Systems and Services (IPT-SWeISS) up to the reorganisation of the WMO and expert groups in the last few years.

4.3.4. NICT/Japan

NICT has cooperative projects for space weather research and operation, and capacity building with oversea organizations for observation, data sharing and coopreative research. NICT also contributes to the activities in international organizations related to space weather, especially acting as director of International Space Environment Services (ISES) since 2023. In addition, NICT works for UN/COPUOS, WMO/ET-SWx, ITU, URSI, SCOSTEP, COSPAR, WDS, ICAO, and ISO. As a regional activity, NICT has acted as the secretary of Asia-Oceania Space Weather Alliance (AOSWA) since 2010. Table 37 shows the present established cooperation.

4.3.5. KSWC/Korea

Coordination for strengthening partnership among government, academia, and private sectors has been organized during the past decade and the coordinated expert group meeting has been successfully operated as a side event during the annual national space weather conference. Discussion and feedback between space weather information providers and key users through the annual meeting are substantially contributed to enhance the availability and applicability of space weather data and information. In order to extend the sectoral partnership into the regional and/or global communities (e.g., Asia-Oceania Space Weather Alliance), more close and well-organized collaboration infrastructure needs to be constructed in near future. The technology transfer and education program of advanced knowledge and experience among international communities would be very helpful to enhance the national capacities in various sectors.

4.3.6. TSA/Thailand

At present, the main private partners involved with the space weather study include satellite operators, aviation operators and regulatory agencies. In addition, Thai researchers have joined the Asia-Oceania Space Weather Alliance (AOSWA) and International Reference Ionosphere (IRI) Committee for capacity building, research sharing as well as standard development.

Table 37
International cooperation for space weather research and operation.

Counterpart Organizations	Cooperation	Description
Bureau of Meteorology (Australia), SPECTRA (France), NRCanada (Canada)	data exchange	NICT builds a consortium "ACFJ" for providing space weather information to ICAO as one of the ICAO space weather global centers
GISTDA (Thailand)	technical cooperation	support launching space weather service center in Thailand
KSWC (Korea)	cooperative observation	oblique sounding between Japan and Korea for observing ionosphere over the ocean
NARLabs (Taiwan)	cooperative research	development of data assimilation with atmosphere–ionosphere coupling model and COSMIC2/FORMOSAT7 observation
KMITL, Chiang Main Univ. (Thailand), BRIN (Indonesia), VAST (Vietnam), St. Carlos Univ. (Phillipine)	cooperative observation	establishment and operation of SouthEast Asia Low-latitude Ionospheric Network (SEALION)
SANSA (South Africa)	data exchange	ground-based magnetometer data
Geophs. Inst./Univ. Alaska Fairbanks (USA)	cooperative observation	cooperative observation of atmosphere and ionosphere in the polar region

4.3.7. TUA/Turkey

There is currently no operational center for space weather in Turkey. Therefore, it is planned to establish a "Space Weather Application Center" for the first time in Turkey in order to become a qualified node of international networks and to serve as a national alert center.

5. Report on key needs

We recognize that the COSPAR roadmap to improve scientific research of the groups/organizations/Countries are in different levels of development across the globe. Considering space weather as an enterprise that needs a combination of data, science, and methods to deliver services, we may classify the groups in different stages of maturity.

Let us suggest some levels of the science processes related to the space weather services in five important segments:

- Observations (data in near real time, sometimes dense arrays, space-based and ground-based instruments),
- Modeling for prediction (research with data assimilation, R2O),
- High performance computing (infrastructure).
- Communication (training and products to end-user),
- Leveraging and verification (benchmarking and action plan, O2R),

In our sample of reports, it is possible to identify groups that combine parts or all the above-mentioned segments. Sometimes, the science group needs cooperation to advance with their expertise due to the multidisciplinary constitution of space weather science. Sometimes a barrier for small groups is not enough investment for the required infrastructure. Thus, the "key-needs" becomes seeking cooperation for improvement.

5.1. AMERICAS & AFRICA

5.1.1. LAMP/UBA-IAFE(CONICET)-IAA/Argentina

An articulated joint effort among the Argentinean institutions having different capabilities and space weather expertise could be combined in a consortium to provide comprehensive Space Weather (SWx) information at country level to contribute more effectively to the product and knowledge generation as well as the R2O2R. This will reinforce strong points and mitigate weaknesses of the member institutions in the process.

This national center could centralize networks of instruments countrywide, sharing real-time data and providing regional operational products. Due to the peculiarities of our country [(1) long extension covering latitudes from $\sim$ 20S (e.g., Jujuy province) to −77S (Argentine Belgrano II base at Antarctic), and (2) partially overlapping with the South Atlantic Magnetic Anomaly] we need to strength our regional capacities to monitor and forecast space weather conditions.

5.1.2. UNLP/MAGGIA LABORATORY/Argentina

The laboratory seeks cooperation to strengthen the science project, e.g.

- To improve our vTEC map products, it needs to upgrade the computer resources
- To improve the ionospheric monitoring, it needs ionosondes installed close to the GNSS receivers (considering the elevation mask and avoiding interferences)

Finally, it needs more mechanisms that facilitate the exchange of both trained researchers and students between the different international institutions to enhance their capabilities in the different areas of space weather research.

5.1.3. UNT/Argentina

In addition to collaboration between institutions within the country (e.g. CONAE, SMN, Universities, etc.), efforts should be placed in the coordination of Argentinean capabilities in space weather including training and capacity building (from scientists to technicians for operations), instrumentation and instrument networks, tailored software development and space weather operative products, and scientific research.

Another key point is the design and development of instrumentation harnessing the already existing experience (e.g. satellite construction and operation, radar design and development, among many more). To enhance interoperability, there is a need for a standard policy for data sharing including data and metadata formatting, data accessibility and availability, curated databases, etc. Providing operative products relies also upon high-performance computing (HPC) dedicated infrastructure able to manage the distributed data and run the models in real-time. Many institutions have their own HPC systems (as test bed environments for R2O products) but, within the national scope, a centralized infrastructure for full-scale operative services is needed.

5.1.4. CRAAM/Brazil

Our main need at this time is a complete upgrade of the SAVNET including home-made hardware and new software based on Software Defined Radio (SDR).

Monte-Carlo simulation-based codes to get a detailed ionization excess height profile during Solar Flares, which in turn is used to estimate HF absorption, an important Space Weather product. In principle it should improve the alert level for radio blackouts.

Need for international collaboration to discuss the relevance of joining different existing regional VLF networks.

5.1.5. EMBRACE/BRAZIL

The identified key needs essential for navigation/positioning, defense, satellite orbit propagation and mission analysis are listed below:

- Real time ionosphere modelling, scintillation and TEC forecast, plasma bubbles forecast.
- Interplanetary medium/magnetosphere/ionosphere indices constructions.
- Reliable and accurate magnetic storm forecast.
- Solar activity forecast (week-month, solar cycle).
- Forecast of solar wind structures at Lagrangian point L1.
- Monitoring and forecast of electron flux variability in the outer radiation belt.
- Space based monitoring and forecasting magnetospheric waves in the radiation belts.

5.1.6. NRCanada/CANADA

Canada shares with other countries the need for improved space weather forecasting. This involves many scientific challenges to be tackled by the international science community, but a key need is the ability to identify the magnetic field structure within a coronal mass ejection (CME) when it first leaves the Sun.

A specific need in Canada is to produce 3-D earth conductivity models for calculating the electric fields that impact critical infrastructure. This will require deployment of magnetotelluric instruments at multiple sites across Canada in an 'Earthscope style' array. Improvements are also needed in real-time data transmission and use to link together observations with geophysical models and engineering models to provide critical infrastructure operators with better information about space weather impacts on their systems.

5.1.7. LANCE/Mexico

In 2014 Mexico did not have an observational infrastructure to study the regional effects of space weather. For example, there were no data on geomagnetic field and ionospheric phenomena. Furthermore, there were no historical records to study benchmarks of space weather phenomena in Mexico. However, in the last few years, a multidisciplinary working group, observational networks, and infrastructure has been developed. The key needs for the near future are:

- Communications with national civil protection personnel, and space weather users.
- Publication of space weather regional indices in real-time.
- Define user-based scales of space weather events.
- Modeling of the response of the Mexican electric grid to geomagnetic storms.

5.1.8. IGP/Peru

The identified key needs for Peru is to strengthen the cooperation with neighbouring countries and become part of international alliances to monitor space weather on a regular basis. The immediate actions are listed below:

- TEC monitoring in the South American sector.
- Realtime magnetic conditions in the Peruvian sector: regional K index and delta-H calculations.
- Coordinate the inclusion of space weather into the Peruvian risk management disaster policies.
- Become an active member of space weather monitoring for the Peruvian sector.

5.1.9. SANSA/South Africa

The identified key needs are essentially for space weather users, and they are listed below:

- Real time ionosphere modelling and scintillation
- Reliable and accurate geomagnetic storm forecast for local magnetic observation.
- Solar wind and estimated CME arrival models.
- Solar flare probability forecast.

5.1.10. NOAA/United States of America

Space weather observing infrastructure needs include maintaining long-term continuity of current operational systems, filling important gaps (e.g., L5 coronal imaging, heliospheric imaging, ground-based neutron monitors, etc.) and coordinating the planning of observing systems with government agencies, international and industry partners. Key research needs include the improvement of the utilization of data in numerical models by developing data assimilation capabilities and the effective transition of research advances into operational implementation. Within the U.S., partnerships among the government agencies and private industry are improving which should accelerate the progress in improving space weather capabilities. In addition, NOAA is fully engaged in international partnerships that can leverage the participation of all Nations to advance global space weather preparedness.

5.2. EUROPE

5.2.1. FMI/Finland

Some information is required on data gaps and models needed in the country (if any) together with suggestions for combined international teaming to close any specific space weather capacity gaps.

Beacon satellites for ionospheric tomography are currently not available; they would greatly benefit ionospheric modelling. An additional concern is about the frequency allocation for the space-based beacon transmissions (150 and 400 MHz). Preparations to protect these and other radio frequencies used in space weather monitoring are on-going with WMO and ITU.

Sustained resources for global computer simulations on solar activity and on solar wind-magnetosphere-ionosphere interactions should be available. There is a need for solutions allowing continuous near-real-time modelling for space weather services and for more comprehensive high-power computations advancing basic research on solar-terrestrial physics.

5.2.2. UGOE/Germany

Need for a national coordinating space weather center and a forecast facility using remote sensing observations of solar activity.

5.2.3. ASI/Italy

The key needs have been discussed in Plainaki et al., 2020.

5.2.4. UAH/Spain

There is need for national coordinating space weather strategy and a well articulated legal framework for the space weather risk.

5.2.5. Roshydromet + RAS/Russia

Both Roshydromet and Russian Academy of Science are devoted to making scientific data publicly available and work with national authorities to bring more data to the international community. We encourage other organizations in Russia and abroad, and international organizations to facilitate the availability of scientific data. We are open to a broad range of international cooperation.

5.2.6. IRF/Sweden

It is essential that access and continuous delivery of key measurements and observations are ensured. Today, many existing platforms (spacecraft and ground stations) provide real-time data, however, some are aging and their replacement are crucial. In many cases the platforms require international collaboration. Examples of key sources are:

Solar magnetic and coronagraph observations, from L1 but also other viewing directions,
Solar X-ray and proton data,
Near Earth Solar wind (e.g. L1).
Ground based ionospheric and magnetic data.

To effectively improve the accuracy of current forecast models for various solar wind parameters, in-situ solar wind data from more upstream platforms and/or other viewing angles at near Earth distance (e.g. L5, and/or ESA Vigil Mission) would also be essential. The closing of this gap will clearly require an internationally coordinated effort.

It is also essential that data are organised into databases that are easily accessible in standard formats together with metadata describing the data. This greatly helps the further model development and analysis.

It is also essential to have close collaboration with end users to understand the effects and to drive the research. Without end users, there is no need for space weather monitoring, research, modelling and prediction

5.2.7. Met Office/UK

There is a need for more focused international coordination to enable individual countries to better contribute to the global space weather infrastructure. One of the main commitments of SSWPS is to deepen cooperation with international partners by establishing a real-time communication system to allow mutual sharing of data during severe space weather events. We need to ensure operational and research activities are more aligned via WMO, ISES and COSPAR. Via this cooperation, we would like standards established for data and products in consistent formats for efficient sharing, collaboration and use (an activity likely led by WMO).

We are aware of many gaps in the operational space weather operational observation network. WMO and associated bodies have done great work in defining observational requirements and they and other bodies should continue to strongly make the case for actions to fill gaps in the network. Specifically, the UK has committed to playing a leading role in the ESA Vigil mission to launch a spacecraft to the L5 Lagrange point; with the UK providing financial support and a plasma analyser instrument. The UK supports a complementary follow-on mission by the US to the L1 Lagrange point to ensure continued operational in-situ measurements of Earth-bound CMEs.

There are many grand scientific challenges which require international collaboration and better funding in order to be solved (two examples are being able to predict a Coronal Mass Ejection prior to eruption from the Sun and being able to better observe or estimate the CME Bz well in advance of the CME passing the L1 point, but this is not a complete list). The national coordination of these "blue sky" research activities within the UK also needs to be improved.

5.3. ASIA & Oceania

5.3.1. China/NSSC

Many simulation models have been developed by the space physics community in the past decade. We suggest that the community take efforts to support the research to operational (R2O) process so that the models can be better utilized in operational space weather forecasting, especially for achieving near real-time, high-accuracy forecasts of the thermosphere and ionosphere. Moreover, we suggest that future plans focus on monitoring the backside of the Sun and regions far away from the ecliptic plane.

5.3.2. India

It is recognized that India needs to deploy spacecraft and ground-based facilities that can monitor and assess space weather in the near-Earth system, starting from its origin in the Sun to its impact on the magnetosphere, atmosphere and geomagnetic field. A crucial gap is the lack of large modelling groups with the expertise to model and assess the geomagnetic impact of space weather events, including hazard assessments on satellites and space-reliant technologies. Ionospheric modelling is another gap area where India needs to develop expertise for a system-wide understanding of space weather effects. Joint working groups and partnerships with international agencies like Community Coordinated Modelling Center are desirable to address these gaps.

5.3.3. NICT/Japan

The key needs/priorities identified to provide useful and relevant information to users are:

- Enhanced communications with space weather users.
- User-defined scales for space weather events.
- Improved research for reducing the uncertainty of space weather forecasts.

For communicating space weather information with domestic users, NICT hosts an annual workshop, the "Space Weather Users Forum", inviting users to education sessions and informative lectures of cutting edge technologies for space weather. For more detailed discussions, NICT manages its "commission of space weather users" as a pathway for discussing relevant space weather applications with impacted utilities.

5.3.4. KSWC/Korea

Modern society may be severely vulnerable if severe and long-lasting space weather events occur globally or regionally because modern social, economic, and industrial systems are dependent on electrical power supply, electronics, navigation, satellite communications, etc. To improve space weather services, new requirements from the main consumer groups of space weather information such as satellite operators, communication or power supply companies, and international airlines should be consistently considered and reflected in national space weather policy. In addition, integrated solutions addressing user needs should support domestic and international space weather communities through improved space weather data and services, strategic policy establishment, and preparation of long-term action plans.

5.3.5. TSA/Thailand

Recently, Geo-Informatic and Space Technology Development Agency (GISTDA), the main Thai Space Agency, started collaboration with NICT (Japan) on its Space Weather Forecasting Center. The research community and partnership in the space weather area consists of academia, governmental research agencies as well as industry. The leading institutes conducting research in this area are the Geo-Informatics and Space Development Agency (GISTDA), the National Astronomical Research Institute of Thailand (NARIT), Chiangmai University, Mahidol University, King Mongkut's Institute of Technology Ladkrabang, Chulalongkorn University, Kasetsart University and the Asian Institute of Technology. As regional and international collaborations are essential to successful research and development programs, current collaboration partners include NICT Japan, Kyoto University (Japan), Tokyo University (Japan), Shinshu University (Japan), the Electronic Navigation Research Institute (Japan), Nagoya University (Japan), and Boston College (USA).

5.3.6. TUA/Turkey

Throughout history, the Turkish nation has contributed to humanity's understanding of the cosmos – which is mostly overlooked – through numerous scientists and astronomers. Although many studies have been carried out by academic and various state institutions, Turkey's exploration of space has accelerated with the establishment of Turkish Space Agency (TUA) in 2018. Even though TUA is a newly established institution, it has a significant responsibility to gather many other institutions working in the space field under a single roof. TUA announced the National Space Program (NSP) in 2021 which is the road map for Turkey regarding space applications. NSP consists of 10 strategic goals and almost every one of them includes international cooperation and collaboration. Those 10 strategic goals of the NSP are listed below:

- **Moon Mission:** In memory of the 100th Anniversary of the Foundation of the Republic of Turkey, the first contact with the moon will be established.
- **To Merge Satellite Production Activities Under One Single Authority and the Program for Developing National Satellites:** To create an internationally competent brand on new-generation satellite production and development.
- **Regional Positioning and Timing System:** Developing a regional positioning and timing system for Turkey.
- **Access to Space and Space Port:** Ensuring access to space and establishing a space port administration.
- **Technological Research on Space Weather**: To increase our competitiveness in space by investing in space weather.
- **Observing and Monitoring Space Objects from the Earth:** To increase Turkey's efficiency in terms of astronomical observations and observe space objects from the Earth.
- **Developing Space Economy Industry:** To improve and support the space economy industry.
- **Space Technologies Development Region:** Establishing a technology development region and TUA headquarters in the Middle East Technical University region.
- **Space Awareness and Human Capital Development:** To develop effective and competent human resources in the field of space.
- **Turkish Astronaut and Science Mission:** To send a Turkish citizen to ISS with a scientific mission.

Simultaneous work is being carried out on each of these goals and the fifth goal of NSP is fully dedicated to space weather. As a first step within the scope of this objective, a nation-wide survey was conducted to determine qualified human resources in the field of space weather. Later on, training programs were prepared to increase the level of knowledge about space weather in Turkey and the first training was provided to Turkish Space Agency (TUA) employees. As a final step, a "Space Weather Application Center" will be established, and it will be the first operational space weather center in Turkey.

Initially, four types of products and services will be provided to users by Space Weather Application Center, which is still at the establishment phase. Those are:

- **Warning:** Radio signals are used in communication, navigation and remote sensing applications. When a space weather event is detected that could potentially damage such beacons, relevant users will be alerted. The relationship between pandemic and SpW, which is a current issue, will be also examined.
- **Now-cast:** First of all, it is planned to install an ionosonde. Current conditions will be determined by using the Sun, Earth Ionosphere, geomagnetism data, international "Global Positioning Systems" (GPS) network data and the ionosonde measurements taken in near-real time.
- **Forecast:** This product will make short-term predictions under certain space weather conditions, based primarily on modeling methods using retrospectively observed data.
- **Risk Management:** Risk Management will be carried out for all systems affected by space weather including remote communication, satellite issues and applications.

6. Planning efforts

6.1. AMERICAS & AFRICA

6.1.1. LAMP/UBA-IAFE(CONICET)-IAA/Argentina

The plan of LAMP for the coming years is to focus on specific open problems in the Sun-Earth relationship, as follows:

(1) to decrease the uncertainty of forecast arrival times of ICMEs (the most geoeffective solar events),
(2) to deeper understand the link between CIRs and ICMEs with the transport of Galactic Cosmic Rays, and thus leverage ground based instruments (such as Neutron Monitors, Muon Telescopes or Water Cherenkov Detectors) to forecast or indirectly observe interplanetary structures,
(3) to generally use observations of astroparticles as tracers of space weather in an interdisciplinary approach, linking them with transient conditions of the solar wind, magnetosphere or atmosphere (i.e., leading to the cascade of secondary particles),
(4) to get better insights of the variability and predictability of the atmospheric radiation levels at ground and aviation flight altitudes, and.
(5) to connect atmospheric physics with cosmic ray phenomena such as FDs (Forbush Decreases) and GLEs (Ground Level Enhancements). More broadly, one of the main aims of LAMP is to better understand the transport of energetic particles (such as cosmic rays) in the heliosphere, magnetosphere, atmosphere, and in general in the Sun-Earth system.

The plan is to use the expertise of the LAMP group (highlighted through more than 100 papers published in refereed-indexed journals on these topics, (e.g., Dasso, 2007), a publication about erosion of ICMEs with more than 130 citations in the Web of Science platform) to link interplanetary physics to the Sun and solar wind impact on the geospace environment, to develop operational products helping to improve the characterization and forecast of the status of space weather at the regional level.

The plan aims to advance and complete the R2O2R circle, progressing the basic science from the lessons learned in the operational domain, and from local and global operational initiatives.

6.1.2. UNLP/MAGGIA LABORATORY/Argentina

The main efforts planned for the next five years are related to ionospheric tomographic studies, the ionospheric correction on single frequency GNSS receivers, and the geomagnetic variability service to be delivered in near-real-time.

These can be synthesized as follow:

- The generation of VTEC maps using GNSS low-cost receivers (developed in the MAGGIA laboratory).
- The study of GNSS tomography using specific software (BERNESE and AGEO).
- The implementation of ionospheric corrections for single frequency GNSS receivers using near real-time VTEC maps.
- The generation of forecast VTEC and ionospheric index maps in near-real-time.
- The development of geomagnetic services using the fluxgate magnetometer named LEMI-025 data in near-real-time.

6.1.3. UNT/TSWC/Argentina

The main objective of TSWC for the coming years is to continue the study of the upper atmosphere and space weather from three main interdisciplinary pillars:

- The physics to understand the different phenomena occurring in the ionosphere during a space weather event (analyzing the impacts at local, regional and global levels), and under other conditions (e.g. Atmospheric Gravity Waves (AGWs), due to volcano eruptions, disturbances derived from the complex equatorial electrodynamics, variability in the ionosphere under eclipse conditions, etc).

- Data-driven models to describe and forecast different ionospheric parameters (TEC, foF2, among other important ionospheric parameters, acquired from our instruments and from other sources, in combination with solar activity proxies, solar wind parameters and geomagnetic indices). A key point is the generation of curated databases (e.g. validated ionosonde data), efficient management of distributed data and the use of modern tools and techniques. In particular, we plan to use machine learning models to forecast the state of the ionosphere and implement the models in real time. An important interest is the analysis of the uncertainties of such models and the use of techniques to enhance their reliability and accuracy and hence their interpretability (having in mind the user experience).
- Instrument deployment and networks, to enhance the availability of measurements in the South American region and particularly in Argentina. The wide range of Argentinean latitudinal regions (from low to high latitudes), special features such as the SAMA region, the south crest of the equatorial ionization anomaly in low latitude regions (e.g. Tucumán), among other geophysical characteristics, are features driving the design, development and deployment of ionospheric and space weather instrumentation.

The TSWC group has great experience in these three pillars and thus the expected outcomes are both scientific and operational.

6.1.4. EMBRACE/Brazil

Plans for 2023–2027:

- Near Earth space radiation dose and forecast – research plans to provide estimates of radiation during the planning of space systems and satellite operations with:
  - o Evaluation of disturbances produced by extreme events from the results of forecasting models of storms (Dst), magnetospheric waves, and arrival of solar wind structures.
  - o Expansion of knowledge of the South Atlantic magnetic anomaly and its relationship with particle precipitation for use in the sectors of satellite operations, aviation, among others.
  - o Dissemination of maps of the occurrence of geomagnetic variations in the Brazilian territory.

- Conductivity map survey of Brazil
  - o The fluxgate magnetometer network of Embrace (Embrace MagNet) will be expanded from 19 to about 30 instruments to fill some gaps in magnetic measurements.
  - o Distribution of real-time monitoring of the magnetic field in Brazil, with products available on the web site and open data transfer via the internet.
  - o Regional models of ground conductivity.
  - o Kp and Ksa forecast (magnetic index for Planetary and South America).

- Monitoring of ionospheric irregularities and propagation model
  - o The all-sky network of EMBRACE increased from three receivers on the east coast to five covering the country.
  - o Continuous monitoring of ionospheric irregularities over Brazil.
  - o Densification of the ground network of sensors to cover the entire nation.
  - o Improvement of the spatial resolution of irregularity maps over the South American continent.
  - o Distribution of the observations of the instruments onboard of the SPORT (Scintillation Prediction Observations Research Task) satellite mission.

6.1.5. NRCanada/CANADA

The Socioeconomic Impact Study (Hickling et al., 2019) identified the need for a formal Canada Space Weather Strategy with the following goals:

- Improve understanding of space weather impacts.
- Increase forecasting services tailored to Canadian latitudes.
- Promote greater awareness of the risks and impacts of space weather events.
- Create a space weather preparedness plan.
- Continue and enhance international engagement.

This will be examined as part of the National Risk Profile work that is currently underway.

6.1.6. SAPL-UChile /Chile

The TEC/EGDP maps can be nonlinearly correlated with solar wind parameters and magnetospheric indices (based on Geophysical Induced Magnetic Fluctuations (GIMFs)). Such work can then be translated into static and dynamical evolution models, based on neural nets (artificial intelligence), to nowcast/forecast the state of the ionosphere, as described by maps of TEC/EGDP, that are driven by solar wind parameters and magnetospheric indices. Similar work for magnetospheric indices and magnetic field spatial patterns on the surface of the Earth, driven by solar wind parameters, has been done in the past (Valdivia et al., 1996; Valdivia et al., 1999a; Valdivia et al., 1999b; Vassiliadis et al., 1999; and many others).

In this respect, there are activities on analyzing the complexities of spatial patterns of GIMFs at the surface and around the southern and northern hemispheres of the Earth (Toledo et al., 2021). These results have consequences for the accuracy and type of spatial model that can be constructed for GIMF around the Earth.

Similarly, there is work on constructing robust models of magnetospheric indices representing GIMFs, TEC and

EGDP at or near Earth, based on robust artificial intelligence techniques that the group is developing, particularly neural networks (NN), that are driven by solar wind parameters (Blunier et al., 2021). It is expected that with these data derived system science models there will be improvement in our understanding of the underlying processes that drive ionospheric variations at the relevant spatial and temporal scales that would ultimately improve space weather nowcasts and forecasts.

Such maps provide a way to monitor the solar wind-magnetosphere-ionosphere coupling that is finally responsible for the energy deposited in the ionosphere: affecting communication between ground, satellites, airplanes, and ships; producing position errors; inducing drag on satellites; etc. Maps of TEC, EGDP and GIMF will eventually be displayed on our space weather website, which already provides the SYM-H index (average of the horizontal magnetic field disturbance variation at the equator) with one-hour forecasts, solar winds indices, and images of the Sun in different wavelengths (https://cefei.ciencias.uchile.cl/climaespacial/).

The group is also looking at strategies to produce forecasts of other geophysical indices, such as AL and AU from solar wind parameters, and implement ensemble forecasts to have an estimation of the size of the uncertainties in the forecasts. Also being investigated are additional methods to produce forecasts of solar wind data using AI techniques.

6.1.7. LANCE/Mexico

- Observations: 1) solar wind disturbances using interplanetary scintillation data; 2) local geomagnetic field response; 3) regional ionosphere characteristics; 4) cosmic ray fluxes.
- Numerical modeling: evolution of interplanetary disturbances, and the response of the Mexican electricity grid to geomagnetic storms.
- Leveraging and verification: To establish the space weather benchmarks for Mexico.

6.1.8. IGP/Peru

Plan for the next years:

- Solar radar: Detect solar echoes using the main HPLA Jicamarca radar.
- Spread-F forecast: based on measurements from ionospheric sounding.
- Monitoring ionospheric conditions.
- Estimation of real-time Dst, K-index in Peru and South America.
- Real-time estimations of TEC in the South American sector.

6.1.9. NOAA/United States of America

Internationally, NOAA works closely with international partners through the World Meteorological Agency, the Coordination Group for Meteorological Satellites, the Committee on Space Research, and the International Space Environment Service. In addition, two workshops were recently held by the U.S. National Academies of Sciences, Engineering, and Medicine on planning the future space weather operations and research infrastructure. The first was held in 2019 (National Academies of Sciences, Engineering, and Medicine, 2021), and the second was held in April 2022 (National Academies of Sciences, Engineering, and Medicine. 2022).

6.1.10. United States of America

NASA, NSF, NOAA, and the US Air Force are sponsoring the Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033 that will present a prioritized strategy of basic and applied research to advance scientific understanding of the Sun, Sun-Earth connections and the origins of space weather, the Sun's interactions with other bodies in the solar system, the interplanetary medium, and the interstellar medium.

6.1.11. Centre for Atmospheric Research, National Space Research and Development Agency/Nigeria

Our national plan for the next few years is:

- COSPAR capacity building workshops
  - Organization of COSPAR capacity building workshops in Nigeria.
- Establishment of a network of magnetometers over Nigeria
  - Deployment of magnetometers to at least 10 locations in Nigeria to ensure real-time monitoring of the magnetic field in Nigeria.
  - Generating magnetic K-index for Nigeria.
- Monitoring of space weather over Nigeria
  - Densification of the ground-based network of assorted ionospheric sensors to cover the entire nation.
- Promotion of space weather services in Nigeria
  - Organisation of stakeholder forums to promote space weather services in Nigeria.
  - Obtaining input from stakeholders on their requirements with respect to space weather services.
- Ensure timely completion and operation of the Nigerian Bowen Equatorial Aeronomy Radar NigerBEAR
  - Population of the NigerBEAR site with assorted ionospheric monitors for effective multi-technique approach.
  - Capacity building in radar techniques and operation of the proposed NigerBEAR radar.

6.1.12. SANSA/South Africa

Research interests include ionospheric research, solar physics research, geomagnetic activity and GIC research. Currently SANSA has appointed the Research Chair in Space Weather to take up research in solar physics and close the gap that SANSA has in this area. SANSA is now operating a 24/7 space weather centre to monitor conditions in near-real time. SANSA's plan is to increase the human resources available to undertake research in space weather.

6.2. EUROPE

6.2.1. UNIGRAZ/Austria

The main research interests at the University of Graz with respect to space weather are: the origin and prediction of solar flares, and associated particle acceleration and energy transport; the genesis, initiation and propagation of CMEs close to the Sun, in interplanetary space and their geo-effectivity; and the properties of coronal holes and their effects on the fast solar wind.

6.2.2. CNES/France

Centre national d'etudes spatiales (CNES) supports modeling and instruments/observations that impact satellite operations through contracts with the Office national d'études et de recherches aérospatiales (ONERA), and space weather research through modest grants.

The French National Research Agency (ANR) ASTRID program supports space weather projects (e.g., PRISM-IRAP/TAS).

French participation to many on-going H2020 projects (e.g., SERPENTINE, EUHFORIA 2.0, SafeSpace, PITHIA-NRF).

6.2.3. FMI/Finland

Finland is in the process of developing its national service for Space Situational Awareness (SSA). Space weather services will be one the main elements in this initiative. Strong links from research to operations and vice versa are foreseen to support the SSA service. Furthermore, Finland seeks international collaboration and joint efforts with academia and the private sector in the maintenance and development of the system.

6.2.4. UGOE/Germany

Joint national roadmap for space weather was established through a national panel and released in spring 2022 based on a national workshop (see DLR contribution in Tables 14 and 30).

6.2.5. ASI/Italy

Some perspectives considering future scientific activities in ASI have been discussed in Plainaki et al., 2020.

6.2.6. UAH/Spain

UAH enhances its instruments for space weather monitoring with a radio telescope and a GNSS station. The main research interests at UAH cover solar activity, solar wind acceleration and transients, local geomagnetic disturbances, and GNSS disturbances. International collaboration, specifically with mid-latitude countries experiencing similar types of space weather disturbances due to location, is desired.

6.2.7. Roshydromet/Russia

The Institute of Applied Geophysics, a body of Roshydromet, plans to enhance its observing capabilities, both space and ground-based. New space-weather instruments aboard the recently launched SV Elektro-L 4 (GOMS-5) satellite and two Ionosphera-M SSO SVs would provide new capabilities for space environment monitoring. Together with the Arctic and Antarctic Research Institute (AARI) we are keeping the ground observatories (GNSS, riometers, and ionospheric sounders) up-to-date and plan to install more.

6.2.8. IRF/Sweden

IRF has its own ground-based instruments and forecasting models that run in real time. This forms the basis for IRF's current prototype of forecast and warning system that is delivered to Swedish authorities such as the Swedish Power grid Operator (SvK), the Swedish Armed Forces (FM) and MSB, both in terms of automated 24/7 service and manual warnings. IRF has, furthermore, contributed with space-borne instrumentation design for space weather related satellite missions (e.g. SWARM), providing knowledge that may also be utilized in future space weather services.

A key driving principle adopted is identifying user needs through a close dialogue with dual improvement of understanding between solar-terrestrial research and technological effects. This leads to research and development efforts including all relevant processes from Sun to Earth in order to identify key variables and improve predictions and warnings.

6.2.9. Met Office/UK

MOSWOC, through collaboration with national and international partners, is working towards a Sun to Earth modelling system with data assimilation where possible. This should lead to improved forecasts, but to achieve this, improved individual models and a much more extensive observation network are required in addition to the coupling framework. The SSWPS sets out a desire for further research post-SWIMMR but the details need to be further defined.

Internationally, activities such as the COSPAR roadmap and COSPAR/ISES/WMO cooperation helps focus research and R2O-O2R efforts. In addition, regular UK

Space Safety meetings bring the whole UK community together to provide feedback on ESA Space Weather and SST activities. This also acts to bridge the gaps between UK Space Weather and Space Surveillance and Tracking (SST) interests.

6.3. ASIA & OCEANIA

6.3.1. China/NSSC

Some institutions in China have particular interests in thermosphere and ionosphere modeling research. Moreover, Earth-Moon space weather and space environment research is also in their vision. Among the eight scientific goals of the International Lunar Research Station, one is dedicated to study the Earth-Moon space environment, which will provide an in-depth understanding of the changes and interactions of the Earth-Moon space environment through moon-based imaging and in-situ detection.

6.3.2. India

India is fast becoming a space-reliant nation with perhaps one of the most successful and ambitious space programs among developing nations. The nation's reliance on space-based infrastructure such as telecommunications, navigation, geo-spatial imaging and weather satellites also motivates space weather preparedness. Recognizing this, Indian space science and astronomy organizations are working together to define the vision for space weather research and operations that will lead to self-reliance on the one hand, and globally coordinated efforts on the other hand.

Space Research in India was described in the Report to 44th COSPAR Assembly.[13]

6.3.3. New Zealand

Outside of scientific research and data collection, the main focus in terms of space weather operational work has primarily been on the New Zealand electrical power network. The risk to the power grid is recognised by Transpower New Zealand, and from 2015 to 2018 some of the authors undertook a Ministry for Business, Innovation & Employment (MBIE) funded initial investigation of the risks to the Transpower power network from space weather. This work established that extreme geomagnetic storms were a significant hazard to the New Zealand electrical transmission network (see, for example, Rodger et al. (2017) and Ingham and Rodger (2018)), exploiting the availability of geomagnetically induced current measurements, and detailed information on the electrical network itself.

In turn this research stimulated a new MBIE-funded project to mitigate the risk to New Zealand's energy infrastructure during extreme space weather events, the Solar Tsunamis MBIE Endeavour programme, which started in 2021 and runs through to the end of 2025. The focus is on the electrical power and natural gas pipeline networks in New Zealand – in both cases using operational experimental measurements of currents in the networks to build validated models, determine the currents during extreme geomagnetic disturbances, identify the risk-level and build mitigation plans. The logo for this new project is shown in Fig. 7. This programme involves the following institutions, research partners, and industry partners: University of Otago, University of Canterbury, Victoria University of Wellington, GNS Science, British Geological Survey, British Antarctic Survey, University of Michigan, Otago Museum, Transpower New Zealand Ltd, First Gas Ltd, ETH Zurich, NOAA Space Weather Prediction Centre, Space Weather Canada, and Space Operations NZ. This research work is already allowing Transpower to identify the level of asset risk at individual units, and enhance the existing system switching response plan to decrease the currents. The New Zealand energy industry partners have identified the key questions that need to be answered. The Solar Tsunami's research will address these questions to allow mitigation of the extreme storm space weather hazard. Through the international partnerships this New Zealand funded work will contribute to the research being undertaken into space weather and solar storms globally.

6.3.4. NICT/Japan

NICT is developing satellite sensors for monitoring the space weather environment in cooperation with Japan Meteorology Agency (JMA). RMS (Radiation Monitors for Space Weather) is a suite of sensors measuring energetic electrons (50 keV – 5 MeV) and protons (10 MeV – 1 GeV), and spacecraft internal charging. It was initially developed as a hosted payload of the follow-on geostationary meteorological satellite of Japan known as Himawari. RMS aims to monitor the outer radiation belt electrons, and solar and galactic protons, that can increase radiation exposure to astronauts and aircrews and are hazardous to spacecraft operation. To mitigate these risks from the space environment, the space weather forecast service group of NICT plans to utilize the RMS product to issue forecasts and prompt warnings for space weather users as well as the general public. The need for operational space weather moni-

Fig. 7. The logo for the Solar Tsunamis MBIE Endeavour project being undertaken in New Zealand.

[13] https://cosparhq.cnes.fr/assets/uploads/2022/07/India-2022_Space-Research-in-India-Book-WEB-Version-09–07-22_compressed.pdf.

toring in space is increasing with the expansion of space utilization, including social infrastructure, such as navigation, communication, and broadcasting. RMS will be responsible for operational space-based in-situ observations in geostationary orbit over Japan after launch.

NICT is preparing a down-link receiver for the SWFO-L1 mission in cooperation with NOAA/USA.

Real-time 24/7 monitoring of the solar wind is extremely important for space weather forecasting. In order to monitor the solar wind in interplanetary space, the Advanced Composition Explorer (ACE) spacecraft was launched at the first Lagrange point (L1) in 1997 to commence observations. Subsequently, the Deep Space Climate Observatory (DSCOVR), the successor to ACE, was launched also to the L1 point and has been monitoring the solar wind since 2015. As these spacecraft are located at the L1 point, the data cannot be downlinked to ground stations during local nighttime, so international collaboration is essential to achieve real-time 24/7monitoring. Currently, NICT is contributing to the 24/7 monitoring of solar wind as one of the centers of an international network of ACE and DSCOVR real-time receiving ground stations called the Real-time Solar Wind Network.

DSCOVR has been operating for 8 years since launch, and the SWFO-L1 project, the successor to DSCOVR, is currently underway under the leadership of NOAA, aiming for a launch in 2025. NICT has been approached by NOAA to participate in the SWFO Antenna Network (SAN), and is now preparing a SWFO-L1 ground station as one of the SAN members.

6.3.5. TSA/Thailand

In the future, particularly toward the 25th solar maximum, there needs to be increased efforts to reach out to a wider educational segment, and public and private sectors. An urgent need is also required to prepare national action plans on severe space weather events so that there are concrete plans and steps to prevent disasters and disruptions to the whole of society.

7. Discussion

Here we discuss the cooperation and coordination between nations and organizations illustrated by the activities within each nation.

It is necessary to observe the space environment in real-time for operational space weather monitoring, on the other hand, the importance of real-time measurements is not relatively high for academic use and in some cases it can be a resource intensive task. This divide can present difficulties improving the R2O-O2R cooperation between academia and operational organisations. It shows the importance of sharing needs and setting goals that are worthwhile for both communities.

Ground-based and satellite-based observations have different beneficial aspects. As shown in the previous sections, many countries have ground-based observations for space weather monitoring, on the other hand, there are relatively few countries that have satellite-based operations for monitoring space weather. Satellite-based observations can cover a wide monitoring area with passive sensors and can measure essential information (e.g., electron/proton fluxes in near-Earth space), but the costs are enormous compared with ground-based observatories. Ground-based data are shared with cross-exchange among the observational organizations/nations, on the other hand, the number of satellite-based providers are few and they distribute their data to other space weather providers. In these situations, validation of data and standardization of data formats are essential in data sharing, and for satellite observational data, cost sharing may be needed in future.

Ground-based observatories are not located uniformly and some areas are very sparse (e.g., ocean, desert). One such example can be seen in Fig. 8 which shows a global GNSS TEC map plotted by NICT. This shows that the

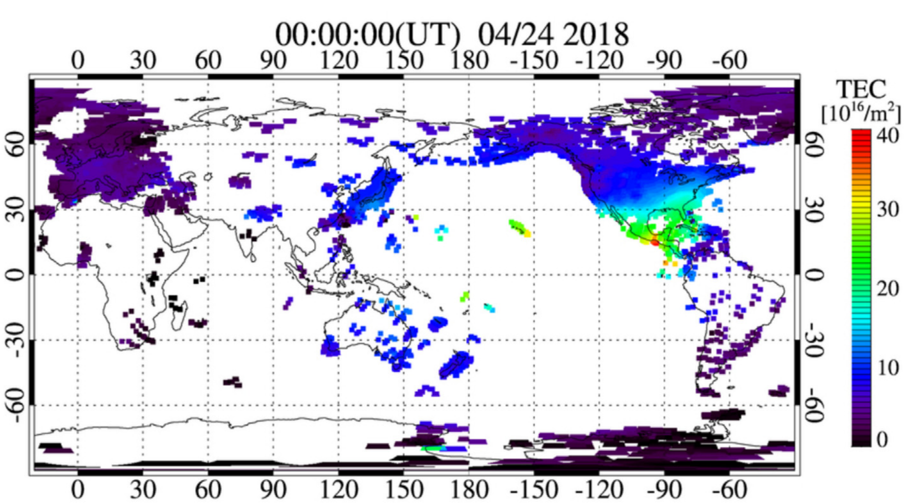

Fig. 8. Example of global map of GNSS-TEC plotted by “DRAWING-TEC project, NICT”.

GNSS receiver distribution in Europe, North America, and East Asian regions that were used by NICT are very dense but sparse in Africa and middle Asia There is an important need to reduce the sparse areas for more precise space weather monitoring and forecasting. On the other hand, space weather observations in many of these sparse areas have been reported e.g., through the ISWI program. One of the reasons for this discrepancy is that the observation activities do not connect to a coordinated global network of space weather observations. This may arise from hardware and software issues, communication networks, or any political issues. It is critical to identify the problems and solve the issues to fill the gaps of observation networks.

Comparison of model results using the same input data is an effective method for improving the quality of the models. It is important to consider the formats of the input data and output results for easy comparison. A trial commenced recently in the ICAO space weather center framework for harmonizing the alert quality amongst centers.

It is also beneficial to share information globally regarding engagement with space weather end-users. Space weather information providers sometimes interact with users who are not willing to share anomaly information potentially caused by space weather phenomena, and there may be solutions to this issue in the experiences of other countries.

The need for improving the global cooperation in space weather in a coordinated way was recognized by the body of the COSPAR PSW, strengthened here as part of the panel work, and the resulting "Coimbra Declaration" can be a milestone for future developments (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://cosparhq.cnes.fr/assets/uploads/2023/02/WMO-ISES-COSPAR_Coimbra_Declaration_Final.pdf).

8. Recommendations

In addition to the research required to improve models and the feedback from end-users (O2R), a wide coverage of instruments and tools are required to monitor, model, and forecast space weather phenomena (in the chain of R2O) to effectively mitigate the risks. Thus, sustaining and maintaining these instruments is a global concern as they are subject to aging, technical obsolescence, and budget constraints. We recognize the great contributions of the organizations reported in this paper. The availability and reliability of space weather instruments are crucial to ensure the continuity and accuracy of space weather operations, and addressing the challenges facing the maintenance and replacement of these instruments is a pressing issue for the space weather community. This requirement can be addressed by allocating a larger fraction of the resource budgets to preventative maintenance and upgrading of space weather instrumentation. There is recognition in the many forums of today's space weather service providers that having a global network of instruments to monitor and provide early warnings of space weather events is essential for mitigating the potential damage caused by these events.

While larger organizations and governments have the resources to invest in and deploy their own instruments, small groups and organizations often struggle to secure funding for their contributions. To address this issue, many cross-border cooperations are occurring and these should continue to be stimulated. However, it is important to recognize that even small contributions can be valuable in achieving global coverage of space weather instruments. We see from the many national reports in this paper that ground-based instruments are deployed and maintained by almost all groups, with less investment in terms of space-based instruments.

We also note, in many cases, that smaller groups may have unique expertise or geographic locations that can complement larger organizations' efforts. For example, a small group located in a region that has insufficient coverage provided by a larger organization, may be able to provide valuable data that would otherwise be missing from global space weather monitoring efforts. The South America Magnetic Anomaly (SAMA) region, Antarctica and Africa are such examples that need improved monitoring of ionosphere irregularities, GICs, atmosphere density profiles, etc., through an improved network of GNSS receivers, magnetometers and ionosondes amongst others. Additionally, smaller groups may be more agile and innovative, able to quickly test and deploy new technologies that could improve overall monitoring capabilities. In some of the reported key needs, it appears there is a desire to have access to methodologies to construct tools that will benefit global monitoring, such as the multi-constellation vTEC maps, that may be developed by scientists with access to the relevant data and could support capacity building efforts to grow the scientific expertise of the locals.

In addition, it should be noted that the deployment and maintenance of ground-based space weather instruments in remote areas such as the SAMA and Antarctica is generally much more expensive than on the continents due to the expensive logistics. Hence the recommendation should be that international support for instrumentation in such areas should focus on collaboration with entities that already have bases with space weather instruments in these regions such as SCAR and AARI member countries, rather than on costly proliferation of instruments in these regions.

Therefore, supporting small groups and organizations that contribute to the global network of space weather instruments is crucial for achieving comprehensive and effective monitoring of space weather events. By recognizing and valuing the contributions of all groups, regardless of size, we can work towards more resilient and secure ground and space-based infrastructure. One relatively straightforward suggestion to improve cooperation may be to promote the exchange of operational data, tools and modeling for developing expertise with potential bene-

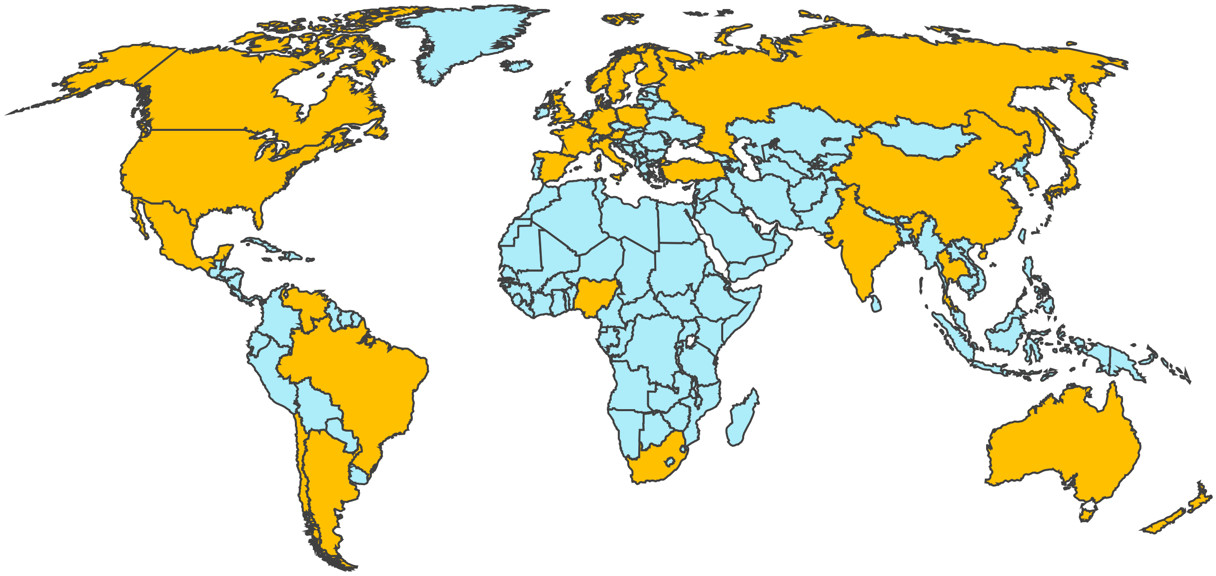

Fig. 9. Contributing countries for this paper.

fit of increasing the available experience and operational support.

Space weather has become crucial in modern life since society depends more and more on communications and navigation systems. These systems are vulnerable to the extreme changes in the solar terrestrial environment. In the past decades, several countries have been successfully working together to promote awareness and build international communities focused on space weather operations and policies. For instance, ISWI, established in 2009, focuses on capacity building and creating space weather-literate communities, especially in the developing countries. This community works together in data and information sharing, deployment of instruments and development of joint projects. Fig. 9 shows the global map of the distribution of countries contributing research papers to the COSPAR ISWAT (International Space Weather Action Teams)'s Space Weather Roadmap. However, as seen in Fig. 4, many countries in Africa, middle east and south-east Asia are not actively involved in the space weather community although some of these countries have ground-based observations.

In contrast, the annual reports of ISWI show that there are many activities in these regions (e.g., https://www.unoosa.org/oosa/en/ourwork/topics/space-weather-events-and-activities.html). In addition, we recognize that there is an African Space Agency established in January 2018. There are National Space Agencies in about 20 African countries, some of which have extensive ground-based space weather monitoring instrumentation including Uganda, Kenya, Rwanda, Ethiopia, and Egypt. (e.g., Baki et al., 2023, https://issuu.com/africansciencestars/docs/african_science_stars_issue_2/s/14089879, https://spacenews.com/african-space-agencies-have-the-potential-to-lead-the-global-space-race/).

It is important to establish global networks in ground-based space weather observations, and for that, it is necessary to connect the activities in the southern hemisphere to the global space weather network.

There are several avenues for growing space weather research and operational capabilities as follows:

- capacity building,
- academic research,
- contributing to standards.
- establishing operational services, and.
- contributing to global policy making.

These aspects differ from country to country. To be effective it is necessary to tailor support to these avenues.

In 2020, the UN/COPUOS Expert Group on Space Weather conducted a survey on space weather activities in Member States to inform ways of improving international coordination. The responses from Member States include valuable information about their involvement in space weather research and operations. By using this information to assist developing countries, we can expect to get much closer to building a global network for space weather observations.

9. Coordination efforts

Following are the coordination efforts mentioned in the reports we have discussed.

1. In the US National Space Weather Strategy, coordination efforts include:

- Establishment of an interagency coordination mechanism through the National Space Weather Coordination Committee (NSWCC).
- Collaboration with international partners through the International Space Environment Service (ISES) and other organizations.
- Public-private partnerships to enhance space weather information sharing and response capabilities.
- Coordination with the academic community to advance research and development in space weather science and technology.

2. In the European Space Weather Week report, coordination efforts include:

- Collaboration with international partners through the International Forum for Space Weather Capabilities Assessment (IFSWCA) and other organizations.
- Integration of data and services from multiple sources and providers through the European Space Weather Portal (ESWeP).
- Engagement with stakeholders and end-users through the Space Weather User Consultation Platform (SWUCP).
- Coordination with national and international organizations to promote space weather awareness and preparedness.

3. In the Japan Space Weather Initiative report, coordination efforts include:

- Coordination between government agencies, academia, and industry through the Japan Space Weather Working Group (JSWWG)
- Collaboration with international partners through the International Forum for Space Weather Capabilities Assessment (IFSWCA) and other organizations.
- Establishment of a national space weather information sharing system through the Space Weather Information Sharing and Analysis Center (SWISAC).
- Coordination with end-users to identify and address their specific space weather information needs.

4. In the report on space weather research in India, coordination efforts include:

- Coordinated national efforts to develop space weather monitoring and forecasting capabilities, led by the Indian Space Research Organization (ISRO).
- Development of a centralized space weather modeling and forecasting facility.
- Assimilation of complementary ground- and space-based data from Indian facilities through a virtual observatory for facilitating space weather research.

5. In the report on space weather research in New Zealand, coordination efforts include:

- Participation in the international INTERMAGNET network through magnetic observatories operated by GNS Science.
- Collaboration with international partners in space weather research and data collection.
- Engagement with stakeholders and end-users in investigating space weather impacts on infrastructure such as gas pipelines and power grids.

6. In the report on space weather research in Korea, coordination efforts include:

- Application of AI-based technologies to operational monitoring and forecasting tasks through the Research to Operation (R2O) process.
- Collaboration with international partners in space weather research and data collection.

7. In the report on space weather research in Thailand, coordination efforts include:

- Study of space weather effects on modern technologies and development of AI-based space weather data analysis.
- Collaboration with international partners in space weather research and data collection.

8. In the report of LAMP (Argentina):

- Focusing on specific open problems in the Sun-Earth relationship such as decreasing uncertainty in forecasting the arrival times of ICMEs, understanding the link between CIRs and ICMEs with the transport of Galactic Cosmic Rays, using observations of astroparticles as tracers of space weather in an interdisciplinary approach, better understanding the variability and predictability of atmospheric radiation, and connecting atmospheric physics with cosmic ray phenomena such as FDs and GLEs.
- Using the expertise of the LAMP group to develop operational products that can improve the characterization and forecast of the regional space weather conditions.
- Advancing and completing the R2O2R circle by progressing basic science from the experiences learned in the operational environment, and from advances in local and global operational environments.
- Further development and application of ionospheric tomography techniques and GNSS receivers for generating vTEC maps.
- Implementation of ionospheric corrections for single frequency-GNSS receivers in near-real-time.
- Development of forecast vTEC maps and ionospheric index maps in near-real-time.
- Advancement of the geomagnetic variability service using LEMI-025 in near-real-time.

In the report of Tucuman (Argentina).

There are three main interdisciplinary pillars for TSWC's objectives in the coming years:

- Research into the physics to understand the different phenomena occurring in the ionosphere during space weather events and other conditions, such as AGWs due to volcano eruptions, the disturbances derived from the complex equatorial electrodynamics, and the variability in the ionosphere under eclipse conditions.

- Data-driven models to describe and forecast different ionospheric conditions, in combination with solar activity proxies, solar wind parameters, and geomagnetic indices. This pillar aims to generate curated databases and implement machine learning models to forecast the state of the ionosphere in real-time, with a focus on enhancing accuracy, reliability, and interpretability.
- Instrument deployment and networks to enhance the availability of measurements in the South American region, particularly in Argentina, taking advantage of its unique geophysical characteristics.

The TSWC group has extensive experience in these three pillars and expects to achieve both scientific and operative results.

In the report of EMBRACE (Brazil).

Summary of the plans for 2025–2027: (detail is shown in “6. Planning efforts”).

- Near space radiation dose and forecast:
- Conductivity map survey of Brazil:
- Monitoring of Ionospheric Irregularities and Propagation Model:

10. Summary

As described in the Introduction, our assessment is part of the understanding necessary for scientific research on the influencing agents of the near space and impacts on society. The number of organizations and institutions working in the field is too large to be comprehensively included in any analysis. This is a result from a call inside the COSPAR Panel on Space Weather (PSW) where some members voluntarily participated with an agreed short report. Some of the contributions here have already published an extensive description of the science developed and instrument framework in their organization or region that we refer to in this work. Additional contributions are included in the accompanying paper (Ishii et al., 2024).

11. Concluding remarks

Space weather is a relatively new and developing field of science compared to meteorological weather; since the Carrington Event of 1859, the effects of solar activity on radio frequency use, satellite operations, and the power grid have been documented. The dawn of the space age in 1957 opened up the field of what is now called solar-terrestrial research. While each country must protect its own assets, space weather has been recognized as a global concern, and international cooperation has been established in a variety of programs.

Space weather preparedness is constantly evolving. During the preparation process of this paper, upgrades and improvements were underway in many countries. Some of these improvements were reflected in the revision of this paper, but it is not possible to include all of the new changes currently being implemented. The global space weather program described in this document applies to the period 2022–2025. Continuous improvements over the next decade are expected to result in a more robust regime than is currently in place.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mamoru Ishii reports financial support, administrative support, article publishing charges, and travel were provided by National Institute of Information and Communications Technology.

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Appendix. Table of acronyms

Acronyms	Descriptions
AARDDVARK	Antarctic-Arctic Radiation-Belt (Dynamic) Deposition-VLF Atmospheric Research Konsortia https://space.physics.otago.ac.nz/aarddvark/
ACFJ	Australia-Canada-France-Japan Consortium (ICAO)
ACVID	Argentinean-Chilean-validated ionospheric database

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Acronyms	Descriptions
AFINSA	The Atmospheric electric Field in South America
AGATA	Antarctic Geospace and Atmosphere research
AGW	Atmospheric Gravity Wave
AIS	Advanced Ionospheric Sounder
ALL4SPACE	The League for Latin America for Space Weather
AMBER	African Meridian B-Field Education and Research
AMISR	Advanced Modular Incoherent Scatter Radar https://amisr.com/amisr/about/resolute-bay-isrs/
AOSWA	Asia Oceania Space Weather Alliance https://aoswa.nict.go.jp/
ASI	Agenzia Spaziale Italiana https://www.asi.it/en/ All-Sky Imager
ASOS	The Advanced Space-based Solar Observatory
ASPIICS	Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun https://www.sidc.be/proba-3/aspiics
ASWFC	Australian Space Weather Forecasting Centre
AU	Aalto University https://www.aalto.fi/en
AUTUMNX	Athabasca University Themis UCLA Magnetometer Network https://autumn.athabascau.ca/
AWESOME	Atmospheric Weather Electromagnetic System for Observation Modeling and Education https://solar-center.stanford.edu/SID/AWESOME/
BAS	British Antarctic Survey https://www.bas.ac.uk/
CACS	the Canadian Active Control System
CALLISTO	Compound Astronomical Low frequency Low cost Instrument for Spectroscopy and Transportable Observatory
CAR	Centre for Atmospheric Research
CARISMA	Canadian Array for Realtime Investigations of Magnetic Activity https://www.carisma.ca/

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Acronyms	Descriptions
CARMEN	Measure cosmic and solar radiation reaching satellites (CNES) https://cnes.fr/en/projects/carmen
CASSIOPE/e-POP	A Space Weather Research Payload on the CASSIOPE Satellite https://epop.phys.ucalgary.ca/
CASLEO	Complejo Astronómico El Leoncito https://casleo.conicet.gov.ar/
CAWSES/ CAWSES-II	Climate And Weather of the Sun-Earth System https://www.bu.edu/cawses/
CCD	Charge-Coupled Device
CCMC	Community Coordinated Modeling Center
CEFI	Canadian Electric Field Instruments
CGMS	The Coordination Group for Meteorological Satellites https://regmex.unam.mx/
CHAIN	The Canadian High Arctic Ionospheric Network https://chain.physics.unb.ca/chain/pages/stations/
CHAMP	Challenging Minisatellite Payload
CHASE	The Chinese Hα Solar Explorer
CIRCE	Coordinated Ionospheric Reconstruction CubeSat Experiment
CLIMSO	The Pic du Midi coronagraph
CME	Coronal Mass Ejection
CMP	The Chinese Meridian Project
CMU	Chiang Mai University
CNES	Centre national d'etudes spatiales https://cnes.fr/en
CONAE	The Argentine space agency the Argentine space agency
CONICET	The national research organization (Argentina) https://www.conicet.gov.ar/
UN/COPUOS	Committee on the Peaceful Uses of Outer Space, United Nations https://www.unoosa.org/oosa/en/ourwork/copuos/index.html
COSMIC-2	The Constellation Observing System for Meteorology, Ionosphere, and Climate-2 https://www.nesdis.noaa.gov/current-satellite-missions/currently-flying/cosmic-2
COSPAR	Committee on Space Research https://cosparhq.cnes.fr/
CRAAM	Center of Radio Astronomy and Astrophysics Mackenzie (Brazil)

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Acronyms	Descriptions
CNSA/CSES	China National Space Administration /China Seismo-Electromagnetic Satellite
DCAO	Departamento de Ciencias de la Atmósfera y los Océanos (Argentina)
DEMETER	Detection of Electromagnetic Emissions Transmitted from Earthquake Regions https://demeter.cnrs-orleans.fr/
DIDBASE	Digital Ionogram DataBase https://giro.uml.edu/didbase/
DKIST	Daniel K. Inouye Solar Telescope
DLR	German Aerospace Center https://www.dlr.de/en
DMSP	Defense Meteorological Satellite Program
DNA	Nacional del Antártico (Argentine) https://www.cancilleria.gob.ar/es/iniciativas/dna
D-RAP	D Region Absorption Predictions https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap
DSIT	Department for Science, Innovation and Technology (UK) https://www.gov.uk/government/organisations/department-for-science-innovation-and-technology
EGDP	Errors in Global Navigation Satellite System derived positioning
EGI Foundation	https://www.egi.eu/egi-foundation/
EISCAT	European Incoherent Scatter
EMBRACE	Estudo e Monitoramento Brasileiro do Clima Espacial https://www2.inpe.br/climaespacial/portal/en/
EOSC	European Open Science Cloud https://eosc-portal.eu/
ESA D3C	Distributed Space weather Sensor System https://indico.esa.int/event/322/
ESA ESC	ESA Expert Service Center https://swe.ssa.esa.int/ja/expert-centres
ESA PDC	ESA Payload Data Centre
ESA SSCC	ESA SSA Space Weather Coordination Centre https://www.esa.int/Space_Safety/About_the_Space_Weather_Coordination_Centre

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Acronyms	Descriptions
ESPAS	near-Earth space data infrastructure for e-science https://cordis.europa.eu/project/id/283676
E-SWAN	European Space Weather and Space Climate Association https://eswan.eu/
eSWua	Electronic Space Weather upper atmosphere https://www.eswua.ingv.it/
EUHFORIA	EUropean Heliospheric FORecasting Information Asset https://euhforia.com/
FAIR	Findable, Accessible, Interoperable, Reusable
FCEN	Faculty of Exact and Natural Sciences (UBA, Argentina)
FMI	Finnish Meteorological Institute https://en.ilmatieteenlaitos.fi/
FWHM	Full Width at Half maximum
GIC	Geomagnetically Induced Current
GIMF	Geophysical Induced Magnetic Fluctuations
GIRO	Global Ionosphere Radio Observatory https://giro.uml.edu/
GISTDA	Geo-Informatics and Space Technology Development Agency https://www.gistda.or.th/home.php
GLE	Ground Level Enhancement / Ground Level Event https://gle.oulu.fi/#/
GLONASS	GLObal'naya NAvigatsionnaya Sputnikovaya Sistema
GMND	Muon Telescope Scintilator
GMS	GIC Monitor System
GNSS	Global Navigation Satellite system
GOCE	Gravity field and Ocean Circulation Explorer (ESA) https://earth.esa.int/eogateway/missions/goce
GOES	Geostationary Operational Environmental Satellites (NOAA) https://www.nesdis.noaa.gov/our-satellites/currently-flying/geostationary-satellites
GONG	National Solar Observatory Global Oscillation Network Group https://nso.edu/telescopes/nisp/gong/

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Acronyms	Descriptions
GO-RIO	Reospace Observatory riometer Network (Canada) https://www.ucalgary.ca/aurora/projects/rio
GRACE	The Gravity Recovery and Climate Experiment https://gracefo.jpl.nasa.gov/mission/grace-tellus/
GUI	Graphical User Interface
HEPD	High-Energy Particle Detector
HPLA	High-power large-aperture
IAA	Instituto Antártico Argentino (Argentina)
IAGA	International Association of Geomagnetism and Aeronomy https://iaga-aiga.org/
IAFE	Instituto de Astronomía y Física del Espacio (Argentina)
ICAO	International Civil Aviation Organization https://icao.int
ICARE	Influence of Space Radiation on Advanced Components
ICTSW	Interprogramme Coordination Team on Space Weather (WMO)
ICSU	International Council for Science
IGP	The Geophysical Institute of Peru (Peru) https://www.gob.pe/igp
IGP-VAST	Institute of Geophysics, Vietnam Academy of Science and Technology
ILWS	International Living with Stars
IMAGE	The International Monitor for Auroral Geomagnetic Effects https://space.fmi.fi/image/www/index.php?
IMAP	the Interstellar Mapping and Acceleration Probe https://imap.princeton.edu/
IMCP	The International Meridian Circle Program
INAF	Istituto Nazionale di Astrofisica https://www.inaf.it/en
INAG/URSI	Ionosonde Network Advisory Group/International Union of Radio Science https://www.ursi.org/files/CommissionWebsites/INAG/index.html
INFN	National Institute for Nuclear Physics (Italy) https://www.infn.it/en/

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Acronyms	Descriptions
INPE	Instituto Nacional de Pesquisas Espaciais https://www.gov.br/inpe/pt-br
INGV	the National Institute of Geophysics and Volcanology (Italy) https://www.ingv.it/en/home
INTERMAGNET	International Real-time Magnetic Observatory Network https://intermagnet.org/
IPIM-IRAP	Irap Plasmasphere Ionosphere Model https://userpages.irap.omp.eu/~mindurain/doc_ipim/index.html
IPS	Interplanetary Scintillation
IPT-SWeISS	Inter-Programme Team on Space Weather Information, System and Services (WMO)
IRAP	Institut de Recherche en Astrophysique et Planetologie (France) https://www.irap.omp.eu/en/homepage-en/
IRF	Swedish Institute of Space Physics
IRI	International Reference Ionosphere (COSPAR)
ISAWARE	Increasing Safety through collision Avoidance WARning intEgration https://www.isaware.fi/ https://ui.adsabs.harvard.edu/abs/2002ESASP.509E..71S/abstract
ISC	International Science Council
ISES	International Space Environment Services https://spaceweather.org
ISO	International Organization for Standardization
ISRO	Indian Space Research Organization
ISWAT	International Space Weather Action Teams https://www.iswat-cospar.org/
ISWI	International Space Weather Initiative
ITP	Ionosphere, Thermosphere and Plasmasphere
JAXA	Japan Aerospace Exploration Agency https://global.jaxa.jp/
JIRAM	Jovian Infrared Auroral Mapper https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO/jiram.html
JSON	JavaScript Object Notation

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Acronyms	Descriptions
JSWSC	Journal of Space Weather and Space Climate https://www.swsc-journal.org/
KAIRA	The Kilpisjärvi Atmospheric Imaging Receiver Array https://kaira.sgo.fi/
KMITL	King Mongkut's Institute of Technology Ladkrabang https://www.kmitl.ac.th/
KSO	Kanzelhöhe Observatory for Solar and Environmental Research
KSWC	Korea Space Weather Center https://spaceweather.kasa.go.kr/eng/Survey.do
LAMP	Argentinean Space Weather Laboratory
LANCE	National Space Weather Laboratory https://regmex.unam.mx/
LAPAN	National Institute of Aeronautics and Space of Indonesia
LASCO	Large Angle and Spectrometric Coronagraph Experiment https://lasco-www.nrl.navy.mil/
LCi	Local Current Index
LDi	Local Disturbance index
LEO	Low Earth Orbit
LOFAR	Low Frequency Array
LSAP	Laboratory of Space and Astrophysical Plasmas
MAGDAS	MAGnetic Data Acquisition System https://magdas2.serc.kyushu-u.ac.jp/
MAGGIA	Meteorología espacial, Atmosfera terrestre, Geodesia, Geodinámica, diseño Instrumental y Astrometría https://www.maggia.unlp.edu.ar/home_english
MCM-SWAMI	Space Weather Atmosphere Models and Indices https://swami-h2020.eu/
METIS	the multi-wavelength coronagraph for the Solar Orbiter mission https://metis.oato.inaf.it/instrument.html
METP	Meteorology Panel (ICAO)
MEXART	MEXican Array radio Telescope https://www.mexart.unam.mx/index.php
MSB	Swedish Civil Contingencies Agency https://www.msb.se/en/

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Acronyms	Descriptions
NARIT	the National Astronomical Research Institute of Thailand https://www.narit.or.th/index.php/en-home
NASA CCMC	NASA Community Coordinated Modeling Center https://ccmc.gsfc.nasa.gov/
NASA SWxC	Space Weather Centers of Excellence https://science.nasa.gov/science-news/nasa-selects-space-weather-centers-for-excellence
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA) https://www.nesdis.noaa.gov/
NGSFM	next-generation solar flux monitor
NICT	National Institute of Information and Communications Technology https://www.nict.go.jp/en/index.html
NMDB	Neutron Monitor Data Base
NOAA	National Oceanic and Atmospheric Administration https://www.noaa.gov/
NOSWE	Norwegian Centre for Space Weather https://site.uit.no/spaceweather/
NCAR	National Center for Atmospheric Research
NRC	The National Research Council
NR Canada	Natural Resources Canada https://natural-resources.canada.ca/home
NRH	Nancay Radioheliograph https://secchirh.obspm.fr/spip.php?article18
NSF	The National Science Foundation https://www.nsf.gov
NSO	National Solar Observatory
NUOL	National University of Laos
NVST	The New Vacuum Solar Telescope
OSCAR	Observing Systems Capability Analysis and Review Tool https://space.oscar.wmo.int/
ONERA	The Office national d'études et de recherches aérospatiales https://www.onera.fr/fr
PAMELA	A Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics https://pamela-web.web.roma2.infn.it/
PCB	Panel on Capacity Building (COSPAR)

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Acronyms	Descriptions
PECASUS	Pan-European Consortium for Aviation Space weather User Services https://pecasus.eu/
PITHIA-NRF	Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access services: a Network of Research Facilities https://www.pithia-nrf.eu/
PoIS	Panel on Innovative Solutions (COSPAR)
POEMAS	POlarization of Millimeter Emission of Solar Activity
POISE	Polar Orbiting Ion Spectrometer Experiment
PRBFM	Panel on Radiation Belt Environment Modeling (COSPAR)
PRESTO	Predictability of the Variable Solar-Terrestrial Coupling https://scostep.org/presto/
PSW	Panel on Space Weather (COSPAR)
PUNCH	Polarimeter to UNify the Corona and Heliosphere
R2O2R	Space Weather Research to Operations to Research
RAMSAC	Red Argentina de Monitoreo Satelital Continuo (Argentina)
RAS	Russian Academy of Sciences https://new.ras.ru/en/
RISR-C	Resolute Bay Incoherent Scatter Radar-Canada https://aurora.phys.ucalgary.ca/resu/index.html
RMUTI	Raja Mangala University of Technology Isan
ROSHYDROMET	The Federal Service for Hydrometeorology and Environmental Monitoring (Russia)
RTSW	Real Time Solar Wind
SAGAIE	Stations ASECNA GNSS pour l'Analyse de la Ionosphère Equatoriale, or GNSS ASECNA Stations for the Analysis of the Equatorial Ionosphere https://insidegnss.com/sagaie/
SANSA	South African National Space Agency https://www.sansa.org.za/
SAOCOM	SAtélite Argentino de Observación COn Microondas (Argentina) https://earth.esa.int/eogateway/missions/saocom

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Acronyms	Descriptions
SAPL	the Space and Plasma Physics Laboratory, Chile
SAR	Synthetic Aperture Radar
SAVNET	The South America VLF Network
SCAR	Scientific Committee on Antarctic Research
SCiESMEX	Mexican Space Weather Service https://www.sciesmex.unam.mx/
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
SCOPE	Solar Coronagraph for OPErations
SEALION	The Southeast Asia Low-latitude Ionospheric Network https://aer-nc-web.nict.go.jp/sealion/
SECCH	Sun Earth Connection Coronal and Heliospheric Investigation
SERENA	Search for Exospheric Refilling and Emitted Natural Abundances https://www.cosmos.esa.int/web/bepicolombo/serena
SEP	Solar Energetic Particle
SGO	Sodankylä Geophysical Observatory (Finland) https://www.sgo.fi/
SILSO	Sunspot Index and Long-term Solar Observations https://sidc.be/SILSO/home
SIR	stream interaction region
SLICE	The Sodankylä – Leicester Ionospheric Coupling Experiment https://www.sgo.fi/Projects/SLICE/
SMILE	The Solar wind Magnetosphere Ionosphere Link Explorer
SMN	National Meteorological Service, Argentine
SOFIE	SOlar Flares detected by Ionospheric Effects
SOHO	SOlar and Heliospheric Observatory https://soho.nascom.nasa.gov/
SPECM	Solar spectrometer (Brazil)
SSA	Space Situational Awareness
SSWPS	UK Severe Space Weather Preparedness Strategy https://www.gov.uk/government/publications/uk-severe-space-weather-preparedness-strategy
STEREO	Solar TErrestrial RElations Observatory https://stereo.gsfc.nasa.gov/
StiX	The Spectrometer/Telescope for Imaging X-rays (Italy) https://datacenter.stix.i4ds.net/

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Acronyms	Descriptions
STSC	Scientific and Technical Subcommittee (UN/COPUOS)
SWA	The Solar Orbiter Solar Wind Analyser
SWFO-L1	the Space Weather Follow-on L1
SWIMMR	the Space Weather Instrumentation, Measurement, Modelling and Risk
SWIT-eSWua	Electronic Space Weather upper atmosphere https://www.eswua.ingv.it/
SWN	Space Weather Network (BoM)
SWPC	Space Weather Prediction Center (NOAA)
SXR	Solar X-ray
TEC	Total Electron Contents
TGCSS	Task Group on Establishing a Constellation of Small Satellites
THEMIS	Time History of Events and Macroscale Interactions during Substorms https://science.nasa.gov/mission/themis-artemis/
TID	Traveling Ionosphric Disturbence
TIDDBIT	TID Detector Built in Texas
TNA	Transnational Access programme https://cordis.europa.eu/project/id/730897
TSC	Thailand Space Consortium
TUA	Turkish Space Agency https://tua.gov.tr/en
UAH	University of Alcala
UBA	University of Buenos Aires
UCH	University of Chile
UGOE	University of Goettingen
UHF	Ultra-High Frequency
UKSA	The UK Space Agency https://www.gov.uk/government/organisations/uk-space-agency
UNAM	Universidad Nacional Autonoma de Mexico https://www.unam.mx/
UNDRR	United Nations Office for Disaster Risk Reduction https://www.undrr.org/
UNIGRAZ	University of Graz https://www.uni-graz.at/de/
UNOOSA	United Nations Office for Outer Space Affairs
UNT/TSWC	Universidad Nacional de Tucumán/ The Tucumán Space Weather Center https://spaceweather.facet.unt.edu.ar/

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Acronyms	Descriptions
UO	University of Oulu https://www.oulu.fi/en
URSI	International Union of Radio Science https://www.ursi.org/homepage.php
USC	University of San Carlos
USO	United Schools Organisation of India
UT	University of Turku, Finland https://www.utu.fi/en
UVCS	The Ultraviolet Coronal Spectrometer https://lweb.cfa.harvard.edu/uvcs/
VarSITI	Variability of the Sun and Its Terrestrial Impact https://www.isee.nagoya-u.ac.jp/stelab/varsiti/index_e.html
VHF	Very High Frequency
VIPIR	Vertical Incidence Pulsed Ionospheric Radar
VLAB	WMO-CGMS Virtual Laboratory https://wmo-sat.info/vlab/
VLF	Very Low Frequency
WIGOS	WMO Integrated Global Observing System https://community.wmo.int/en/activity-areas/WIGOS
WIPPS	WMO Integrated Processing and Prediction System https://community.wmo.int/en/activity-areas/wmo-integrated-processing-and-prediction-system-wipps
WIS	WMO Information System https://community.wmo.int/en/activity-areas/wis
WISPR	Wide-field Imager for Solar PRobe
WMO	World Meteorological Organization https://wmo.int
WMO ET-SWx	WMO Expert Team on Space Weather https://community.wmo.int/en/governance/commission-membership/commission-observation-infrastructure-and-information-systems-infcom/standing-committee-data-processing-applied-earth-system-modelling-and-prediction-sc-esmp/expert-team-space-weather-et-swx
WMO/GMAS	World Meteorological Organization/ Global Multi-hazard Alert System https://community.wmo.int/en/activity-areas/drr/gmas
WSPR	Weak Signal Propagation Reporter

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