Operational space weather forecasting tools: focus on the United States and European resources

Rungployphan Om Kieokaew[1] and Simone Di Matteo[2,3]

[1] Univ Toulouse, CNES, CNRS, IRAP, Toulouse, France; [2] The Catholic University of America; [3] NASA Goddard Space Flight Center, MD, USA

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Context and objectives

Space weather is a natural hazard well-defined by the United Nations Office of Disaster Risk Reduction that impacts power grids, airlines, trains, pipelines, telecommunication, and spacecraft operators. In case of an extreme space weather event nowadays, equivalent to the Carrington event in September 1859, it can lead to a socio-economic loss of over several billion euros.

"Are we ready for the next major solar storm?" is a project funded by the Transatlantic Research Partnership in order to survey the United States and European facilities for space weather prediction to mitigate global, future risks. Our objectives are:

1) To compile an inventory of current and future development of operational space weather tools for solar storm and geomagnetic storm predictions.

2) To assess the current capability of the state-of-the-art tools and datasets for space weather prediction for extreme events.

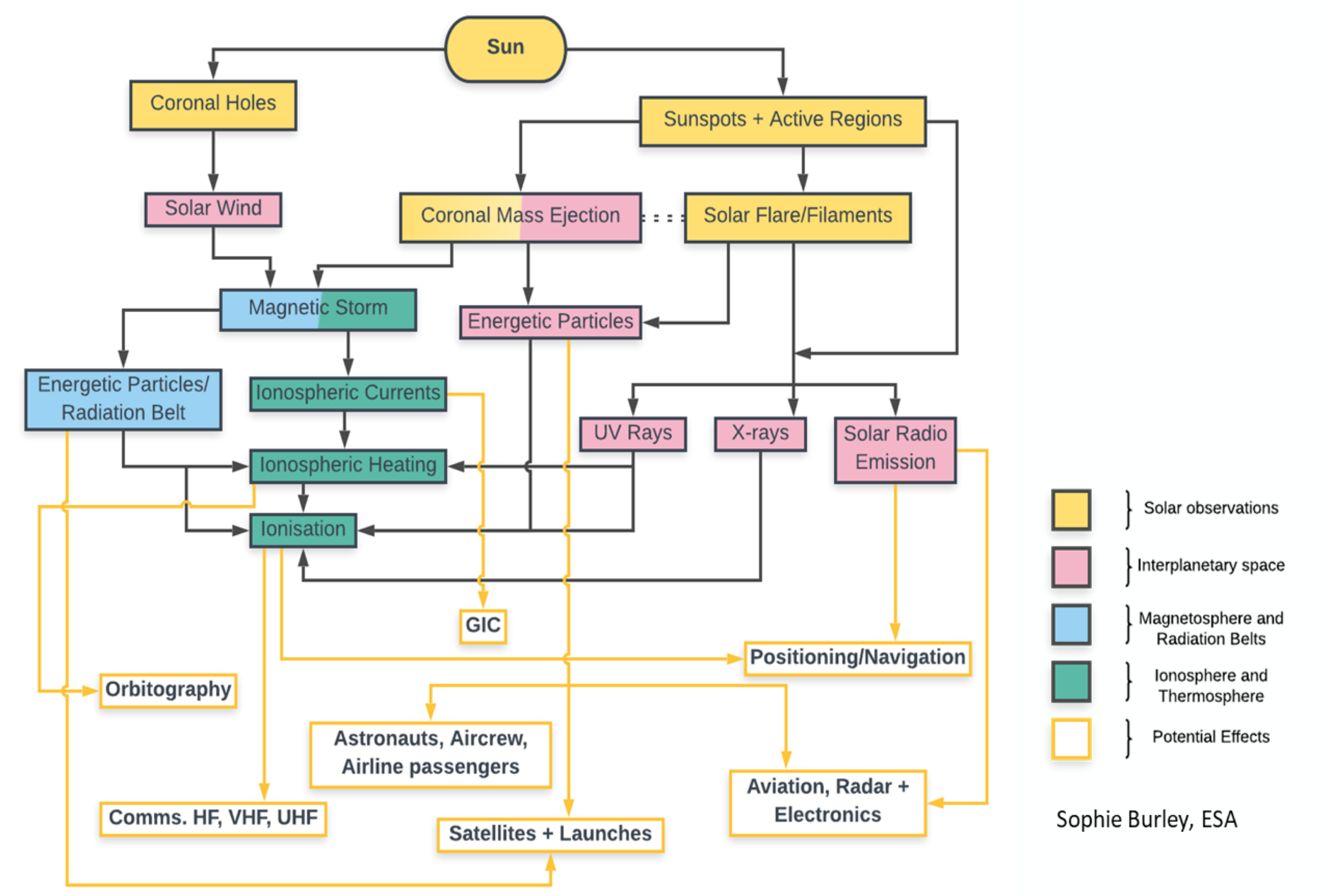

***Figure 1**: Space weather is driven by the Sun through its features and transient eruptions. Through various mechanisms, several systems can be impacted in near-Earth space and on the ground.*

Current operational tools: its readiness and developments

The United States: NOAA-SWPC

The Space Weather Prediction Center (SWPC), operated under the National Oceanic and Atmospheric Administration (NOAA), is a 24/7 operational center that provides space weather products and services to users since 2007. Table 1 shows the current operational forecasting tools by NOAA-SWPC.

Europe: ESA-S2P-SWE

Space weather forecasting is one of the three focused areas of the Space Safety Program (S2P) initiated by the European Space Agency (ESA) since 2009. As part of the S2P, the ESA Space Weather Service Network (SWE) has been established to develop, test, and demonstrate European space weather capabilities with end users in the loop to strengthen Europe's resilience to potentially damaging space weather events. Table 2 shows selected operational forecasting tools available through the ESA-SWE portal (accessed 05/26).

Table 1: Operational forecasting tools provided by NOAA-SWPC

Tools	Data products	Lead time (update frequency)	Dependency / inputs
WSA (Wang-Sheeley Arge) – **Enlil**	Heliospheric solar wind with CMEs: plasma density, radial wind speed at L1	1-4 days (1 min)	GONG magnetograms and CME cone files from SOHO/LASCO
REFM: Relativistic Electron Forecast Model	>2 MeV electron fluence at GEO	1-3 days (1 day)	30-days of solar wind speed from ACE
GGA: Geospace Geomagnetic Activity	Kp and Dst indices	30-60 mins (1 min)	Real-time solar wind measurements at L1
GGMP: Geospace Ground magnetic perturbation	ΔB map over the globe and North America	30-60 mins (1 min)	Real-time solar wind measurements at L1
WAM-IPE: Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics	Neutral atmosphere global map; global ionosphere TEC, maximum usable frequency and their anomaly	2 days (6 hours)	Forecasted 3-hour Kp and daily F10.7
CITPe: Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics	Global Total Electron Content (TEC) map	30 mins (10 mins)	Averaged past F10.7 measurements, real-time ACE data
OVATION: Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting	Auroral location and intensity at the North and South poles	30 mins (5 min)	Real-time measurements at L1

Table 2: Similar forecasting tools provided by ESA-S2P-SWE

Tools	Data products	Lead time (update frequency)	Dependency / inputs
EUHFORIA* (demo): EUropean Heliospheric FORecasting Information Asset	Heliospheric solar wind with CMEs: plasma density, radial wind speed upstream of Earth	3-6 days (1 day)	GONG magnetograms and CME cone files from SOHO/LASCO
HESPERIA: High Energy Solar Particle Events foRecastIng and Analysis Relativistic Electron Alert System for Exploration	Energetic proton (SEP) flux profiles at L1 for energy ranges 15.8-39.8 MeV and 28.2-50.1 MeV; solar protons with energy >500 MeV	30-90 mins (?)	Electron measurements from SOHO/EPHIN and ACE/EPAM instruments
Indices forecast by Swedish Institute of Space Physics (IRF)	Kp and Dst indices	2-4 hours (1 min)	Real-time solar wind data from SWPC
AIDA: Advanced Ionospheric Data Assimilation	Vertical TEC (vTEC) over the globe	30 mins – 6 hours (?)	GNSS receivers (slant TEC measurements) and ionosondes worldwide, Radio Occultation from COSMIC-2
Ionospheric Scintillation Products for Arctic	Rate Of change of Total Electron Content Index (ROTI) over the Arctic region	15, 30, 45, 60, and 180 mins (15 mins)	F10.7 27-day forecast by BGS, IMF real-time by SWPC (short-term forecast; ≤1h), Kp 3-hour forecast by SWPC
Aurora forecast service by Space and Earth Observation Center (FMI)	Auroral oval and expected location for Finland and Norway	3, 6, 9, and 12 hours (1 hour)	Magnetometers in Finland and Norway, all-sky camera images

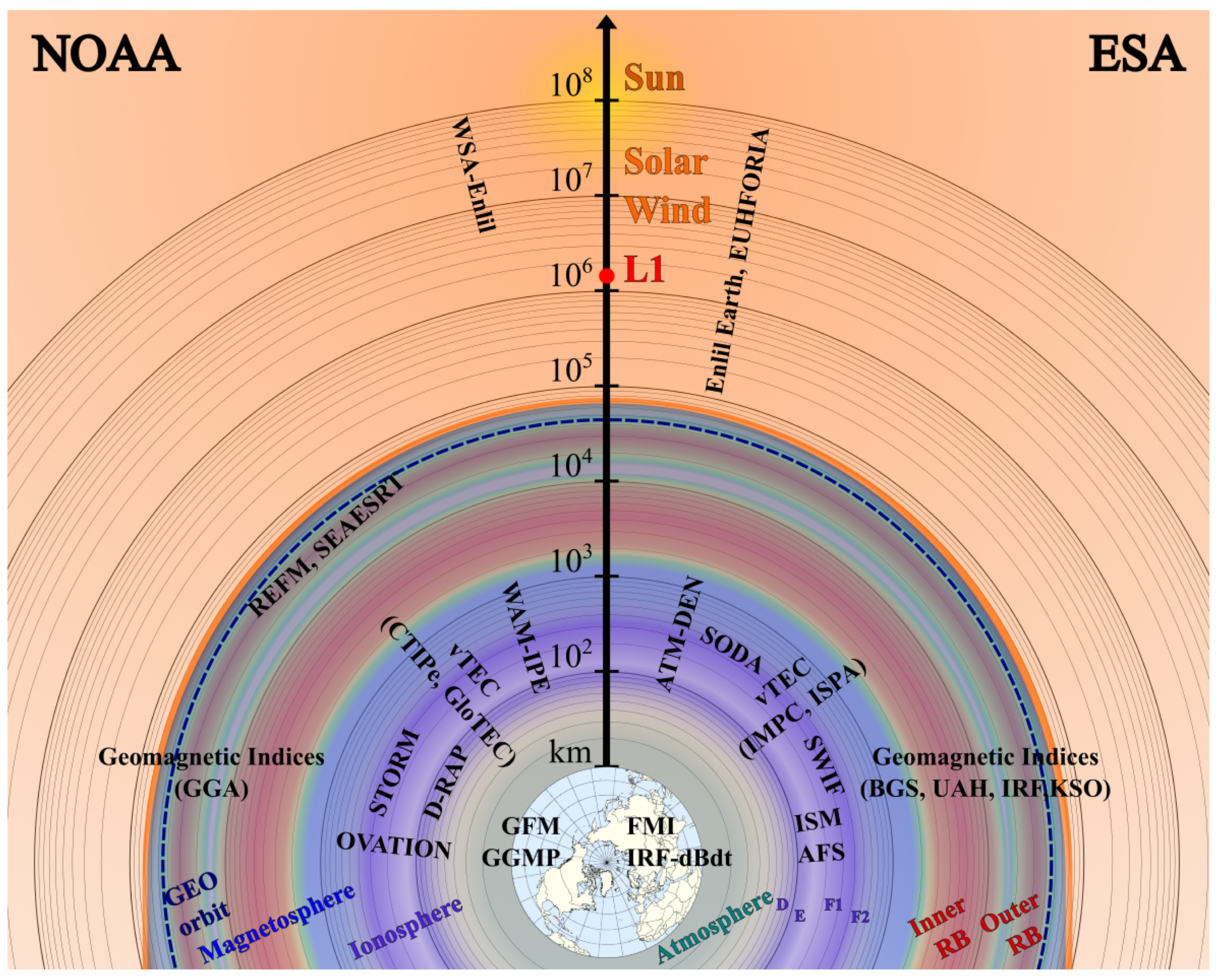

***Figure 2**: The polar-log plot of the spatial coverage of the current operational tools provided by NOAA-SWPC (left) and ESA-SWE (right).*

Current state and gaps

Spatial coverage

- Forecasting tools are available with spatial coverage as shown in Fig. 2 for NOAA and ESA.
- The radiation belt is poorly covered. Only GEO is covered for NOAA. For ESA, the service is available for demo (RB-FAN); the current operational product for GEO (SaRIF) is interrupted.

Forecast horizon (lead time)

- A few days of lead time for solar wind; varying lead time for Earth-directed CMEs.
- ≥ 30 mins lead time for magnetospheric and ionospheric perturbations.
- We need longer lead time, with uncertainties, to prepare for mitigation of space weather impacts.

Validation

- Though most tools provide 24/7 forecasts, they have not been validated with extensive datasets.
- Camporeale & Berger (2025), for instance, validated the SWPC flare forecasts and found that they do not outperform the baselines (persistence, climatology,..).
- ESA tools, despite available, mostly lack validation.

Sovereignty, Reliability, Robustness

- The current tools rely on real-time monitoring at L1 (ACE, SOHO) that has been in service for nearly 30 years; a few ground service (GONG, magnetometers, ..) and ground receivers. We need more monitoring especially at L5 to advance prediction lead time.
- Some European-based tools rely on US-based data sources or facilities. There is an urgent need to develop our own resources to improve our sovereignty.

Summary & Perspectives

Although we the operational tools from both NOAA and ESA are available, they have not been extensively validated which could lead to distrust by the public users. The uncertainties are mostly lacking, and the forecasts rely on a few satellites and ground-based monitoring. To prepare for extreme events, we need to advance the lead time and diversify our forecast tools, develop more sovereignty especially in Europe, and enhance the robustness of the tools.

References

NOAA-SWPC https://www.swpc.noaa.gov/
ESA-S2P-SWE https://swe.ssa.esa.int/

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