



COMMENTARY

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Recommendations for Advancing Heliophysics and Space Weather Modeling Through Open Science

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†Mostafa El Alaoui sadly passed away during the preparation of this paper.

Key Points:

- Open science in heliophysics and space weather modeling poses unique challenges with respect to experimental data and analysis software
- We outline a pathway for advancing heliophysics and space weather modeling through open science, based on Corti et al. (2026), <https://doi.org/10.22541/essoar.176824639.92354528/v2>

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Citation:




































































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Abstract Numerical models are essential for advancing fundamental research in heliophysics and for operational forecasting of space weather events. Open science can accelerate progress, but applying an open science approach to numerical models requires careful consideration; models are not data analysis software and often demand substantial domain expertise, experience, and computational resources to be used correctly. This commentary distills the recommendations from Corti et al. (2026), <https://doi.org/10.22541/essoar.176824639.92354528/v2> and proposes a pathway for advancing heliophysics and space weather modeling through open

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science. Rather than focusing on open science policies and practices, we recommend concrete actions to make models usable by the broader community (open use), increase confidence and transparency throughout the Research-to-Operations-to-Research (R2O2R) pipeline (open validation), enable collaborative model improvement (open development), and strengthen partnerships (open collaboration). Together, these recommendations address several of the open science challenges experienced by contributing authors in developing, validating, using, and hosting advanced models, as identified during the 2024 Open Science Workshop held at College Park, USA. The recommendations also highlight the importance of a culture of shared responsibility, adherence to best practices, and proper recognition of prior work. The Heliophysics Open Modeling Environment will serve as a platform for modelers and model users to work together, facilitate community modeling, and increase the scientific return on modeling investment.

Plain Language Summary Scientific models are crucial for advancing research and forecasting in heliophysics and space weather. To enable efficient community science and build trust in scientific results, models should be openly accessible to everyone with minimal barriers. At present, many advanced heliophysics and space weather models are available for open use through simulation service providers such as the Community Coordinated Modeling Center and the VSWMC. Nevertheless, the complexity and computational requirements of advanced scientific models pose challenges for creating open and replicable workflows. We distill the recommendations from Corti et al. (2026), <https://doi.org/10.22541/essoar.176824639.92354528/v2> and propose a pathway for advancing heliophysics and space weather modeling through open science, organized around four overlapping themes: making models broadly accessible (open use), increasing trust in simulation results (open validation), enabling the community to develop models collaboratively (open development), and building trusting working relationships (open collaboration).

1. Why Modeling Matters in Heliophysics and Space Weather

The “U.S. Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033” acknowledged that the return on investment of numerical models in heliophysics and space weather is often as valuable as that of space- and ground-based observations (National Academies of Sciences, Engineering and Medicine, 2025). Despite receiving substantially less funding than observational missions and facilities, heliophysics and space weather modeling has led to major scientific breakthroughs by enabling the interpretation of space mission data, motivating new science and space weather missions, and furthering the space weather enterprise. Models are essential for advancing understanding, testing new theories against observations, and enabling space weather forecasting. The future health of heliophysics and space weather modeling therefore relies on the continuous development of innovative modeling capabilities as well as their adoption and use by the community at large. Open science promotes the efficient use of past scientific achievements by encouraging the sharing of data, software, and results, thereby enabling broad community access and participation to accelerate progress. However, applying open science practices and policies to complex heliophysics and space weather models requires careful consideration. Advanced models are more complex than typical software and often demand substantial expertise to understand their workflows, inputs, configurations, and outputs. They also often need copious amounts of storage and computing resources that most users cannot afford. The key questions that we aim to address are: how do we develop the next generation of models in ways that advance research and space weather forecasting, and how can an open science approach make this process more effective and efficient?

2. Strengthening the Modeling Community Through Bottom-Up Initiatives

To advance modeling through an open science approach, the Community Coordinated Modeling Center (CCMC; ccmc.gsfc.nasa.gov) organized an Open Science Workshop in June 2024. One outcome of the 2024 workshop and subsequent discussions was the need for the community of developers and users to speak with a united voice to ensure that open science efforts recognize the unique role of models. In a bottom-up approach from the community, the Heliophysics Open Modeling Environment (HOME) emerged as an overarching activity in the COSPAR International Space Weather Action Teams (ISWAT; <https://iswat-cospar.org/O5>) initiative. The mission of HOME is to advance heliophysics and space weather through open science by creating a platform for modelers and model users to work together, fostering community-driven modeling, and maximizing the scientific

3 Successes and Challenges in Open Science Implementation

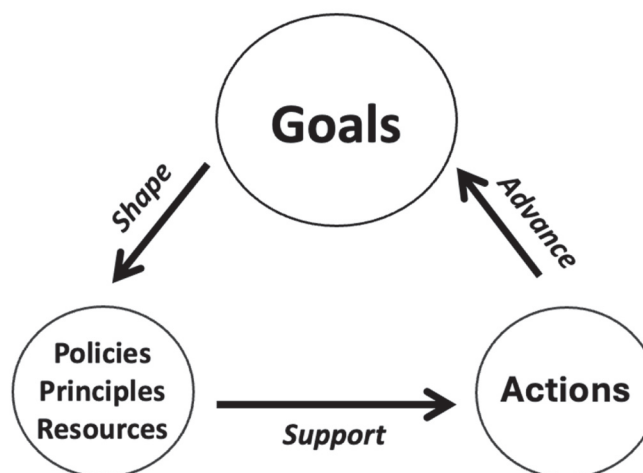


Figure 1. Overview of how goals shape policies, principles, and resources, how these then support actions, and how actions advance the field toward goals.

return on modeling investment. Corti et al. (2026) discusses the challenges of open science in modeling, as experienced by contributing authors in developing, hosting, using, and validating current heliophysics and space weather models. The paper also summarizes the progress made, in part, through HOME, and presents the results of an open science survey reflecting the perspectives of nearly 30 modeling teams in the U.S. and Europe.

3. Successes and Challenges in Open Science Implementation

In survey results, most modelers agree that properly supported open model development can lead to broad community involvement and more rapid progress in refining existing and developing future heliophysics and space weather models. Simulation service providers such as the CCMC and the VSWMC (Virtual Space Weather Modeling Center) have demonstrated the benefits of enabling open use of models and openly sharing simulation results. Modelers mostly agree that making a model available for open use at a simulation service provider makes their model more accessible to the community than an open-source code release. The survey also shows that open science is more broadly accepted than in the past. Nevertheless, open science in heliophysics and space weather modeling poses several challenges:

- **Open science policies, principles, and tools should be treated as the means to achieving an outcome, not as outcomes in themselves.** As shown in Figure 1, policies, principles, and tools should not become ends in themselves, but support concrete goals and actions. Ideally, clearly defined goals guide policies, and policies support actions to advance the field toward those goals. At present, the open science debate in modeling is often focused more narrowly around compliance with open science policies, rather than on making progress. Key missing elements are clear goals and actions that acknowledge the unique demands of modeling, including expertise, resources, storage costs, and high-performance computing (HPC) infrastructure.
- **Conceptual challenges remain, often leading to misleading conclusions, such as oversimplified analogies in the open science debate.** Examples of such analogies include treating models as data analysis software, observations, and datasets, as discussed in Corti et al. (2026). The danger of such weak analogies is that the practical requirements to make models and simulation results open are thereby obscured. For instance, funding agencies may believe that depositing code in a publicly accessible repository is the end goal, rather than one of many steps in the open science process. An open-source code release alone does not make models usable by the broader community.
- **The terms progress and innovation in the open science debate are often, but inappropriately, used interchangeably.** Open science will help promote progress by accelerating new model developments, but it is debatable whether it will also lead to more innovation in modeling. Continuing to build on an existing model

might help improve a model's capabilities more rapidly through community contributions, but this does not necessarily lead to the introduction of new ideas. Hence, besides focusing on making models open-science compliant, there should also be incentives for developing new modeling approaches.

- **Open science in modeling does not come as a free by-product of model development.** Nearly all modeling teams in the survey point to a lack of financial and legal support from funding agencies to sustain code maintenance, documentation, development, and transition from closed/legacy codes to open-source codes. Without dedicated funding and guidance on legal and licensing issues, unfunded open science mandates are likely to lead to compliance without meaningful changes in practice.

4. Recommendations

To address these and other challenges discussed in Corti et al. (2026), we propose a path forward around four overlapping themes. The four overlapping themes are **open use**, **open development**, **open validation**, and **open collaboration**. These themes shift the focus from compliance with open science mandates to concrete goals and clear actions. These goals and actions emerged in a bottom-up approach through the workshop and follow-on discussions. In Table 1, we present high-level recommendations, with a more detailed list provided in Corti et al. (2026). Each recommendation in Table 1 targets one or more groups, including developers (both scientists and software engineers), model users (from the research, education, operations, and private sectors), simulation service providers (such as the CCMC and VSWMC), publishers, and funding agencies.

4.1. Open Use Aims to Make Advanced Heliophysics and Space Weather Models Accessible for Research and Forecasting With as Few Impediments as Possible

Advanced models in heliophysics and space weather often need significant experience, technical expertise, and computational resources for effective use. At present, hosting models at simulation service providers such as the CCMC and VSWMC is the most effective approach for broad community use of advanced models. But enabling open use of advanced models needs sustained support and funding. Actions include funding modelers to produce and maintain code documentation; develop educational materials, and onboard their models at simulation service providers; sustain simulation service providers as essential infrastructure; and ensure that simulation runs are discoverable through comprehensive metadata, citable through unique run identifiers, and properly referenced in publications.

4.2. Open Validation Aims to Strengthen Confidence in Models, Increase Transparency in the Research-to-Operations-to-Research (R2O2R) Pipeline, and Advance Our Space Weather Forecasting Capabilities

The process of model validation is mostly uneven; validation results are often difficult to compare, and shared validation infrastructure is lacking. Actions include creating community-wide agreement on events, metrics, and essential physical quantities to enable consistent validation across models and domains, as well as building open validation infrastructure to facilitate community modeling challenges. Priority should be placed on forecasting challenges such as CCMC Scoreboard projects, where models are evaluated in a realistic, quasi-operational setting.

4.3. Open Development Aims to Enable Community Involvement and Collaborative Improvement of Models Throughout the R2O2R Pipeline

Survey results indicate that modelers are mostly confident that open development can accelerate the creation of new research and forecasting capabilities. Nevertheless, challenges remain around best practices, workflow management, and recognition mechanisms for development work, as well as creating incentives for innovation in modeling. Actions include making source code publicly available as early as possible and following practices such as version control, automated testing, and documentation. Critical to the success of open development is the establishment of credit mechanisms that acknowledge modeling teams whenever their models are used or modified, as well as funding incentives for innovative model development. In the long term, these actions can

Table 1
Recommendations for Advancing Heliophysics and Space Weather Modeling, Understanding, and Forecasting Through Open Science

Theme	Action	Objective	Target Group
Open Use	Support and fund modelers to enable open use of models	Fund developers to create code documentation, example runs, and tutorials required for open use of models by the heliophysics and space weather community.	Funding agencies
	Sustain simulation service providers for open use of models	Sustain simulation service providers, such as the CCMC and VSWM, as essential infrastructure for open use of models and simulation results, and model validation. Provide sufficient computational resources to support the open use of state-of-the-art, computationally intensive models.	Funding agencies
	Support model onboarding at simulation service providers	Support onboarding of models into collaborative computing environments at simulation service providers for making the newest modeling capabilities available for open use by the community. Recognize and fund modelers' time devoted to onboarding models.	Funding agencies, Simulation service providers
Open Validation	Support open use of simulation run results	Ensure that simulation run results are findable through comprehensive metadata, citable through unique run identifiers, and cited when used in publications. Support open tools for post-processing, visualization, and analysis.	Developers, Simulation service providers, Run producers, Publishers
	Communicate model capabilities and limitations	Improve transparency in communicating model capabilities and limitations to users and funding agencies.	Developers
	Standardize model validation procedures	Establish shared validation practices, including benchmark events, metrics, and essential physical quantities. Build open validation tools for tracking model progress over time. Support regular reports to assess the state-of-the-art in modeling.	Developers, Users, Simulation service providers, Funding agencies
Open Development	Evaluate space weather forecasting models in a quasi-operational environment	Evaluate space weather forecasting models (a subset of physics-based models) in a realistic, quasi-operational setting to support R2O2R. Support unbiased community-wide projects like Scoreboards at the CCMC, and ensure modelers have adequate resources to be able to participate. Support regular reports summarizing the status of forecasting capabilities.	Developers, Users, Simulation service providers, Funding agencies
	Create incentives for innovation in modeling	Create incentives, including sufficient computational resources, for innovation in modeling so that open science supports not only faster progress in existing models but also the emergence of innovative modeling approaches.	Funding agencies
	Provide license and legal support for open development	Support open model development by clarifying guidelines for selecting open-source licenses, intellectual property issues, and handling of multi-institution or legacy code licensing.	Funding agencies

Table 1
Continued

Theme	Action	Objective	Target Group
	Recognize and credit model developers in open development	Create incentives for open development by ensuring that model developers receive credit, citation, and acknowledgment when their models (or codes) are used by the community. Publishers should require citing modeling papers, referencing model websites, code repositories, simulation service provider websites, and acknowledge model funding.	Funding agencies, Publishers
	Support Source-to-Impact Space Weather Community Modeling	Collaboratively develop source-to-impact modeling capabilities by leveraging initiatives and programs such as COSPAR ISWAT, NASA's Centers of Excellence, DRIVE Centers, and LWS Strategic Capabilities. Build upon infrastructure at the CCMC, such as collaborative modeling environments, real-time modeling systems, and open validation tools.	Funding agencies, Developers, Users, Simulation Service Providers
	Release model source code as early as possible for collaborative model development	Enable community involvement and collaborative model improvement throughout the development process. Incorporate a code of conduct in model repositories, outlining rules and expectations to support collaboration with the broader community.	Developers
Open Collaboration	Strengthen open collaboration initiatives	Support and participate in community-wide collaboration on focused science and space weather forecasting challenges through initiatives like COSPAR ISWAT.	Funding agencies, Users, Developers, Run producers, Simulation service providers
	Foster collaboration between simulation and data service providers	Improve interfacing between simulation and observational data archives by harmonizing naming conventions and developing shared API calls. Simplify the retrieval of physical quantities for model validation and data assimilation.	Simulation and data service providers, Funding agencies
	Foster collaboration between operational forecasting centers and the modeling community	Strengthen collaboration between operational forecasting centers and the modeling community. Foster collaboration to jointly develop forecasting tools, work together in open validation efforts to identify promising forecasting models, and design displays/dashboards tailored to end users' needs.	Operational centers, Developers, Simulation service providers, Funding agencies
	Unite the community to advance modeling through open science	Sustain HOME as a platform for modelers and model users to work together, facilitate community modeling, maximize the return on investment in modeling, and advance modeling, understanding, and forecasting in heliophysics and space weather.	Funding agencies, Users, Developers, Run producers, Simulation service providers, Operational centers

Note. Summarized from Corti et al. (2026).

support the flagship community modeling envisioned in the U.S. Decadal Survey (National Academies of Sciences, Engineering and Medicine, 2025).

4.4. Open Collaboration Aims to Accelerate Progress in Research and Forecasting by Strengthening Partnerships Across the Modeling Community, Simulation Service Providers, Data service Providers, and Operational Forecasting Centers

Collaborative efforts in the modeling community are often hampered by unclear expectations, weak credit mechanisms, and limited shared environments for exchanging data, methods, models and findings. Actions include working together on focused science and space weather challenges; improving interfacing between simulation and observational data archives; and improving collaboration between the modeling community and operational forecasting centers for joint development efforts and efficient identification of promising forecasting models suitable for future transition to operations.

5. Synthesis

The high-level recommendations in Table 1 (summarized from Corti et al., 2026) shift the focus from open science policies to goals and action in terms of four overlapping themes. These goals and actions emerged naturally from grassroots community efforts and reflect modelers' experiences in making their models compliant with open science practices and policies. In this way, our recommendations go beyond the open science imperative, which could potentially lead to pro forma compliance in the form of an open code release, which does not, on its own, make a model more broadly useful to the general community. The four overlapping themes of open use, open development, open validation, and open collaboration are furthermore written in the language of modelers who understand the real-world requirements to make open science actionable, rather than relying on imperfect analogies. Common oversimplifications include treating models as data analysis software rather than tools for numerical experiments, handling simulation runs as observational datasets, and confusing simulation service providers with observational data repositories (see arguments in Corti et al., 2026). Defining clear goals helps identify the actions needed to advance the field toward those goals. When the direction is clear, pathways in need of additional funding to enable the community to make progress more effectively and efficiently can be identified. At the same time, while building on existing models is important, it should be complemented by incentives for innovation in modeling.

An important pathway is sustained investment in computational resources. Stable HPC infrastructure that is accessible to both model developers and users is of pivotal importance for the four themes identified in Corti et al. (2026): open use, open validation, open development, and open collaboration. Without adequate computational resources and technical support to maintain them, advances in state-of-the-art modeling frameworks will not translate into modeling capabilities that the broader community can use, validate, and build on.

Finally, culture is an important aspect that is often overlooked in the open science debate in modeling. Corti et al. (2026) gives clear suggestions for best practices for modelers and, equally important, best practices for users accessing a model through source code or a simulation service provider. Progress can only be made when all parties share responsibility and adhere to best practices, including crediting prior work and sharing results. Heliophysics Open Modeling Environment recognizes that, to advance modeling through open science, proper recognition and incentives for open science through a culture of collaboration across domains will be needed to realize its potential.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

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