Scientific Challenges Pertaining to Space Weather Forecasting Including Extremes
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Recommendations for the Community

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Background

This document was developed by a group that formed after the *Chapman Conference on Scientific Challenges Pertaining to Space Weather Forecasting Including Extremes,* which was held on February 11-15, 2019 in Pasadena, California, USA. All signatories to this document either contributed directly to its authorship, or endorse and agree with most of its content. Only Chapman conference attendees were asked to endorse or contribute.

The desire for a recommendations document was identified at the conference. Discussions at the conference were captured and are published at Zenodo.org along with survey results (the table of contents of meeting artifacts is at DOI:10.5281/zenodo.3693004). A series of teleconferences, starting on November 7, 2019, was held to discuss the content for these recommendations. Paper drafts were then sent to all conference attendees, and a final telecon held before release. The conference also resulted in a special collection in the journal *Space Weather* (Verkhoglyadova et al., 2020).

Executive Summary

Observations determine space weather capabilities: the indispensable element of any predictive capability for space weather is observations. The quantity, locations, accuracy and latency of relevant observations determines the sorts of predictions that can be achieved reliably. We recommend that the research community develop robust methods for determining the observations needed to achieve specific predictive capabilities. Such methods should be as quantitative as possible and be tailored to specific space weather prediction scenarios. Developing such methods will permit prioritization of observations for predictive purposes. To achieve this capability requires joint participation by the full spectrum of the space weather community, ranging from basic research to operational application, including academia, government and the commercial sector.

Space weather prediction requires the development of new approaches: the complexity of space weather physics requires that the research community embark on an effort to develop new and possibly disruptive approaches for space weather prediction. Adapting the techniques that have succeeded in terrestrial weather is not sufficient. Space weather prediction requires coupling different physical domains over the vast region from sun to Earth. We recommend the convening of a workshop open to the space weather community to “brainstorm” new predictive approaches and justify why they are needed. We further recommend that predictive space weather capability development should consider a community-based approach, similar to what has been achieved in climate modeling (e.g. the Community Earth System Model). Community-based modeling focuses the efforts of multiple research and implementation groups on an openly accessible backbone suite of capabilities and tools that are open to inspection and development at the source code level. Funding agencies should support community-based modeling that advances space weather prediction and understanding.

1. Advancing Space Weather Prediction

Enormous progress in observing, understanding and modeling the physical processes that constitute "space weather" have been made over the past 20 years. The progress made in *predicting* space weather, while significant, may be viewed as less spectacular. It is essential that the space weather community recognize this discrepancy: scientific understanding and modeling have progressed far more than predictive capabilities.

We believe the fundamental reasons for the discrepancy can be attributed to the following:

- Continuously available low latency observations directly relevant to space weather prediction have not advanced to a significant degree.
- The inherent complexity of space weather requires developing new approaches to predictive modeling. Research models designed to advance understanding should not be considered as the sole basis for implementing predictive capabilities.

Observational data are widely recognized as playing a critical role in model development and validation. Integration of observations into predictive models has received less attention but is critical for accurate prediction. Acquiring observations will continue to consume most of the resources devoted to space weather. Modeling approaches that use observations effectively are critical to future success.

2. The Need for New Approaches

Space weather development is currently based primarily on a "research to operations" paradigm. Research-grade models designed to increase scientific understanding, and that incorporate the latest scientific insights, become candidates for transition to an operational capability. However, such models are typically not designed originally to achieve specific predictive capabilities.

The highest prediction accuracies are achieved when real-time or near real-time observations are used to influence the computational outcome of space weather prediction models. The authors and endorsers of this paper believe that achieving reliable and useful prediction is an enormous challenge that the research community has not yet addressed in a way that is commensurate with that challenge[1]. The enormity of the challenge dictates that entirely new and "disruptive" approaches be developed. This includes understanding how to define the temporal and spatial scales, and the lead times, for which prediction is practical given the planned available observations. Practical predictive outcomes depend not only on our understanding of

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[1] We note that SCOSTEP has recently adopted predictability as the theme of its long-term scientific program PRESTO (2019-2024). See SCOSTEP (2020).

the physical processes involved in space weather, but depend also on the available observations from a vast area spanning the sun, to the magnetosphere of the Earth, to the bottom of the ionosphere. Model descriptions that can account for observations acquired across these vast scales in space and time will form the basis for more accurate predictions as the field of space weather advances.

The scientific community has been effective in defining research objectives that lead to improved understanding and that might lead to improved prediction (e.g. the COSPAR roadmap, Schrijver et al. 2015). This community has also been effective in developing approaches to assessing space weather capabilities (https://www.iswat-cospar.org). However, there is no widely accepted approach to estimating predictive accuracy given a specific observational scenario. This is a major gap that should be addressed.

In this context, we intend prediction to be quantitative: that the values of specific measurable physical variables are predicted with specific lead times, and uncertainties are associated with those predictions. The highest prediction accuracies will be achieved when real-time observations are available to incorporate into predictive models.

Innovating new predictive methodologies: Regular patterns in nature can lead to predictable outcomes despite that those patterns are not fully understood or described theoretically. Reductionist first-principles modeling may not be the sole means of generating useful quantitative predictions with associated uncertainties. Machine learning and data-driven modeling based on dynamical systems theory, or other means, are being explored to develop predictive methodologies.

From a scientific perspective, predictions that can be made despite an incomplete understanding or lacking a first-principles approach are still useful, as they may be a prelude to more complete physical understanding.

3. Synthesis and Recommendations

Given the above considerations, we offer the following recommendations:

1. Quantify the predictive skill resulting from specific space weather observing scenarios
   The space weather community should develop a quantitative capability for assessing how planned observing systems affect the accuracy of space weather predictions. Such a capability would apply to specific prediction scenarios because each domain of predictive capability (e.g. ground induced currents, solar energetic particles, spacecraft drag, radiation belt fluxes, ionospheric irregularities, etc.) benefits from various observations in unique ways. The dependence of prediction accuracy on observation latency should be amenable to quantitative evaluation. In the terrestrial weather enterprise, sophisticated

approaches have been developed that provide quantitative information on the forecasting benefits of specific observing systems. These approaches are used as an aid in planning the deployment of observing systems needed for weather forecasting, including the data latency requirements. The space weather community has not yet developed widely accepted techniques for determining the forecasting impact of specific observations, nor how the latency of those observations affects prediction accuracy[2].

Advancing predictive skill using near real-time observations is not straightforward. Considerable scientific and programmatic challenges must be addressed. An international committee should be formed to recommend how to accelerate progress, drawing on the strengths of both the research and applications communities. The proposed committee should draw from academia, government and the commercial sector. The committee should consider where new space weather observations may originate, considering both government and non-government sources.

2. Community-based workshops focused on new methods of space weather prediction

A series of workshops specifically focused on space weather prediction should be initiated. The purpose of the workshops is to "brainstorm" new approaches. A briefer "kickoff" workshop should be held initially to justify why a new series of workshops is needed, and to develop a community consensus on the foci for an ongoing series of workshops that brings value. The workshop agendas could be developed initially by focusing on high priority questions identified during surveys taken at the Chapman conference (see DOI:10.5281/zenodo.3693004). Agenda topics of a "kickoff" workshop are suggested as follows:

- Space weather prediction successes and challenge areas
- Theoretical discussion of what, in our current understanding, limits the reliability of space weather predictions
- Discussion and justification of why "disruptive" approaches to space weather prediction are needed and how such approaches can be nurtured and assessed
- Initiating a community-based approach to space weather prediction

We recommend that the kickoff meeting be a single-day workshop held adjacent to an existing space weather meeting where scientists and other stake holders in space weather congregate, for example the annual Space Weather Workshop in the United States, typically held annually in April, or European Space Weather

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[2] An evolving database of space weather related observations is maintained by the World Meteorological Organization (the OSCAR database) at https://www.wmo-sat.info/oscar/applicationareas/view/25

Week, held annually in the Fall. We further recommend that future workshops remain focused on the theoretical, computational and observational challenges inherently associated with space weather prediction, and do not replace or supplant current efforts that are focused on user needs and space weather capabilities assessment.

We recommend that predictive space weather capability development should consider a community-based approach, similar to what has been achieved in climate modeling (e.g. the Community Earth System Model). Community-based modeling focuses the efforts of multiple research and implementation groups on an openly accessible backbone suite of capabilities and tools that are open to inspection and development at the source code level. The workshop can address those aspects of space weather prediction that are most amenable to a community-based approach. Funding agencies should support community-based modeling that advances space weather prediction and understanding.

Appendix A: Scientific Aspects of Space Weather

This appendix provides additional context and further discussion of ideas relevant to the recommendations. We discuss the space weather paradigm as it was originally developed, and how it is based on the reasonable assumption that research progress translates directly to increased predictive skill. A related concept is that predictive skill will improve as scientific understanding improves. Finally, we suggest that a focus on predictive skill has scientific as well as practical benefits.

The origins of the conference from the perspective of the conveners is that the space weather discipline would benefit from a strategic evaluation. A conference emphasizing discussion could help crystallize and influence future research directions within the field. Now is an opportune time to influence future research directions. Enormous progress has been made since the National Space Weather Program's origins at the National Science Foundation in 1994 (see Robinson and Behnke, 2001 for the significance of the year 1994), and since a Chapman Conference titled “Space Weather” was held in the year 2000. The Center For Integrated Space Weather Modeling (CISM) and the Living With a Star (LWS) research programs were landmark efforts started in the early 2000s intended to connect scientific knowledge to societal impacts, of which prediction is a major component. These programs advanced the discipline of space weather considerably, but the level of maturity of space weather prediction remains less advanced and systematic than the terrestrial counterpart. More recent efforts by the International Space Weather Action Teams, supported by the Community Coordinated Modeling Center, are helping to advance the goals of the International Living With a Star-COSPAR space weather roadmap. The National Space Weather Action Plan is a program that emphasizes resilience to extreme space weather.

One aspiration for the Conference was to build on these and other recent space weather assessment and roadmapping efforts. A sampling of these is listed in Table 1. In particular, the COSPAR roadmap contains very useful suggestions for the research needed in different space weather domains, and where modeling improvements are desirable. This white paper makes recommendations intended to help fulfill the COSPAR and other roadmaps effectively.

None of these documents provides a roadmap that directly addresses how to improve space weather prediction. They are extremely valuable for understanding and measuring capabilities, and advancing understanding and modeling. However, the many factors limiting prediction accuracy per se are not fully addressed.

Table 1. Sampling of space weather assessment and roadmapping efforts.

Title	Year	Comment
Solar and Space Physics: A Science for a Technological Society	2013	Decadal strategy included space weather. Observational and O2R and R2O needs.
National space weather strategies and action plans	2015 and 2019	Emphasis on societal response to extreme space weather
COSPAR Roadmap	2015	Prioritizes science focus areas
NASA Living With a Star 10-year Vision	2015	Establishes strategic science areas requiring further understanding
Roadmap for Reliable Ensemble Forecasting of the Sun-Earth System	2018	Sun to magnetosphere. Research roadmap coupling observations, modeling, machine learning
Space Weather Modeling Capabilities Assessment (CCMC)	Ongoing	Assessing space weather capabilities. See Knipp et al. (2018)

A.1 The Space Weather Paradigm

The term “space weather” can be defined in many ways. We wish to focus on how it is conducted as an activity. This is encapsulated in Robinson and Behnke’s first chapter of the AGU Space Weather Monograph from 2001. That article contained a figure that summarizes how the space weather enterprise was viewed at the time, reproduced below as Figure 1.

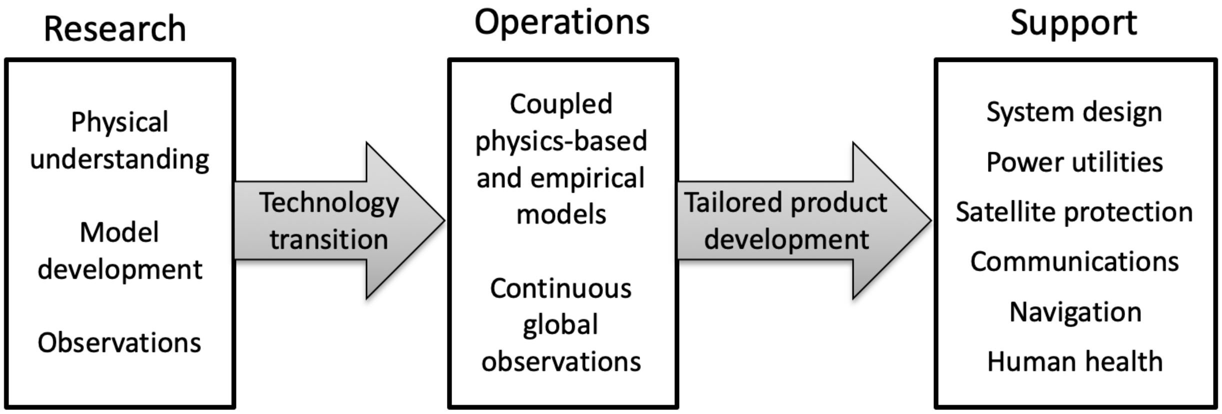

Figure 1: The original paradigm defining space weather development. From Robinson and Behnke (2001), based on Figure 2-5 in NSWP (2000).

In many respects, the paradigm of Figure 1 has survived to the current day. The recommendations in this white paper suggest a revised paradigm should be considered.

In the last 20 years of space weather development we have learned that the research component of this paradigm is far more complex than originally anticipated. Consider the path from research to operations shown in Figure 1. Does the normal course of scientific research result in “technology” that is useful for operations? Scientific research founded on peer-review builds knowledge. Is such knowledge sufficient to enable predictive “technology” of the sort required for space weather?

A possible interpretation of Figure 1 is that model development arises after physical understanding is obtained. Is model development a relatively straightforward technical activity that is well-defined once understanding is obtained? Or is model development itself in need of a research component? If the latter, is research related to model development of value to science or simply of value to operations? We suggest that modeling is central to the scientific process of acquiring knowledge. As such, model development is a research activity that is beneficial to both science and operations.

A.2 The Complex Relationship Between Understanding and Modeling

First principles models have become essential tools in scientific inquiry. There is an ongoing need to refine how such models are used to acquire scientific information. Models are developed as a byproduct of scientific knowledge that exists in varying degrees of certainty. Models applicable to a specific domain of space weather can exist despite incomplete physical understanding of that domain.

First principles models are often used in the practice of operational space weather. Such models typically originate with the scientific community, not the operational community. In the context of research, first-principles models are used in the evaluation of scientific hypotheses by generating output that is testable against observations.

In nearly all instances relevant to geospace and Heliophysics, the agreement between models and observations is only partial: agreement is reached for specific locations and times. At other locations and times agreement is clearly not reached within observational error. To reduce ambiguity and the need for subjective judgment in interpreting comparisons between model and observations, multiple model validation campaigns are often needed, perhaps even new model development, as discussed by Halford et al. (2019).

Additional sources of ambiguity exist. For example, there may be multiple alternative hypotheses that lead to similar levels of agreement between model output and observations. Model output is nearly always an approximate representation of the underlying theory, leading to model uncertainty as a complicating factor when using models to evaluate scientific hypotheses. Finally, models nearly always incorporate computational heuristics that are not based on a fully developed or fully understood underlying physical theory. This results in additional ambiguities of scientific interpretation.

Despite these issues, there is a strong consensus within the scientific community that modeling is a valuable activity for scientific advancement, along with the need for observations and theory. Given that space weather applications and scientific advancement both benefit from first principles modeling to make progress, the following question presents itself: are there valuable modeling-related activities that simultaneously benefit both research and applications? Or are these two endeavors so fundamentally disparate that there is no reason to consider them together?

A.3 The Synergistic Relationship Between Scientific Research and Space Weather Prediction

Given the complex task of modeling geospace phenomena, more emphasis and resources should be devoted to model *interpretation*. We suggest that the activity of model interpretation benefits from using models in a predictive context. Comparing how models perform both retrospectively and in a predictive context provides valuable information that could lead to more rapid model improvement and physical insight.

Model validation is required before results using models can be published. During model development, models are tuned against past observations. Due to the complex nature of space weather and its several interacting and strongly driven domains, it is difficult to extrapolate how validated models will perform in a predictive context.

Predictive modeling addresses to what degree the modeling techniques and decisions made to obtain agreement with past observations are biased towards the specific events that were the focus during the model development stage. A balanced research program that includes both retrospective and predictive model assessment will lead to more rapid advancement of scientific knowledge and ultimately better predictions using model output (a practical benefit).

Modeling specific events for research purposes requires using observations to constrain the possible solutions of the first-principles equations that are being solved. Ambiguities in model interpretation should be reduced as observational constraints are incorporated more effectively.

We remark that assimilative methods applied to space weather and geospace science are likely to be more varied than what occurs in the context of atmospheric weather prediction. Geospace regimes are strongly driven, and encompass a broad range of physical regimes and scales. The value of assimilative methods was recently emphasized at an NSF-sponsored conference focused in space weather forecasting [Nita et al., 2018].

A.4 Summary

This appendix discusses ideas that support the recommendations. The recommendation to develop new methods for space weather prediction is justified by the complexity of the space weather prediction problem. First principles models that solve the so-called primitive equations of an underlying theory must incorporate observational constraints to predict the time histories of physical variables at specific locations and times. This data assimilation problem is challenging and likely must be tailored for the various space weather domains. The methods used in numerical weather prediction are unlikely to be directly applicable across all of space weather. Whatever data assimilative predictive method is adopted, its success will depend on the availability of recent observations.

A focus on prediction by the research community will likely lead to fundamental advances in knowledge. Models tuned to agree with past observations may provide fundamentally different results when used to predict the future. Discrepancies between reproducing past data and predicting future observations indicates there is knowledge to be gained.

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